

Technical Memorandum 4329

Reports of Planetary

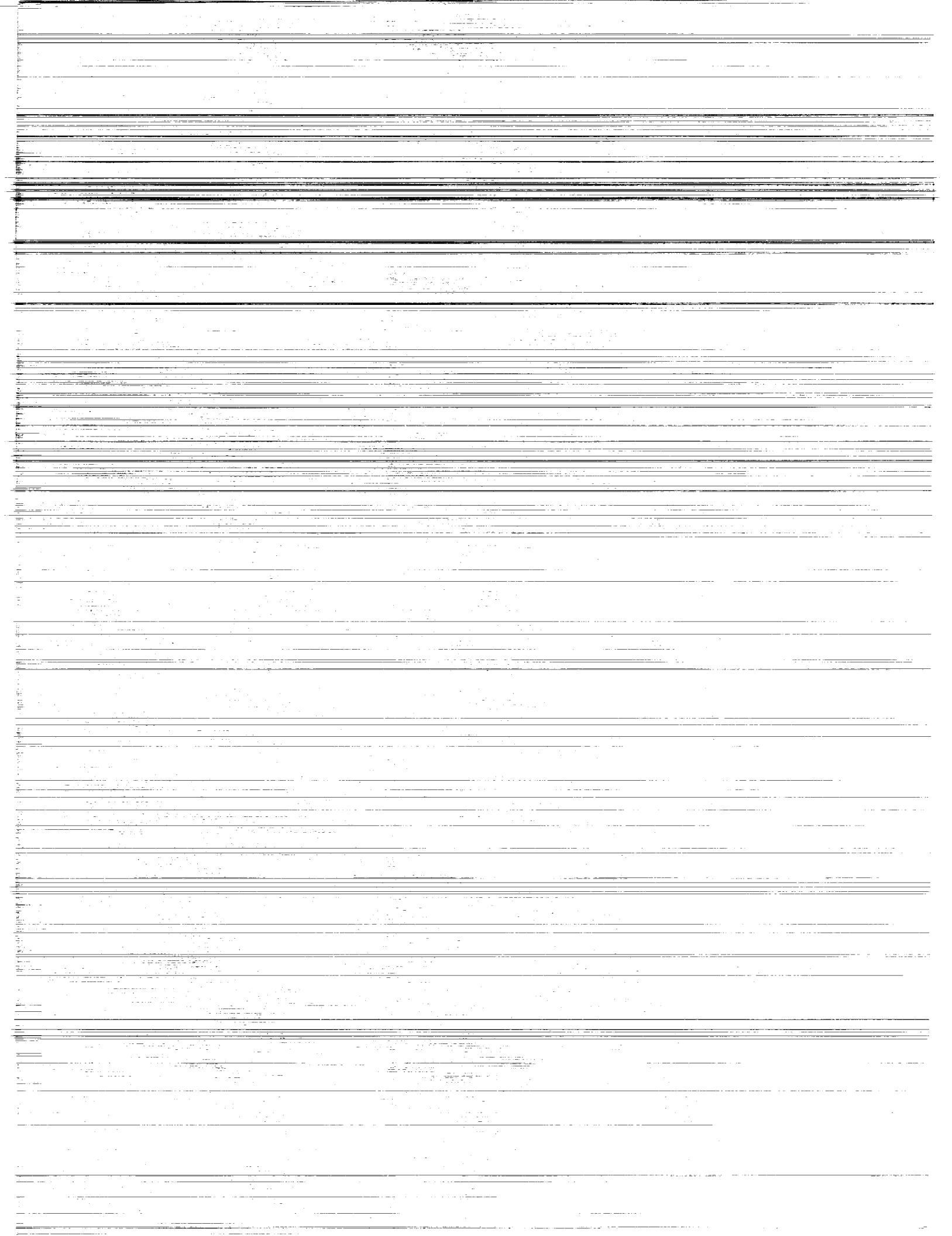
Astronomy, 1991

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Reports of Planetary
Astronomy—1991

*NASA Office of Space Science and Applications
Washington, D.C.*

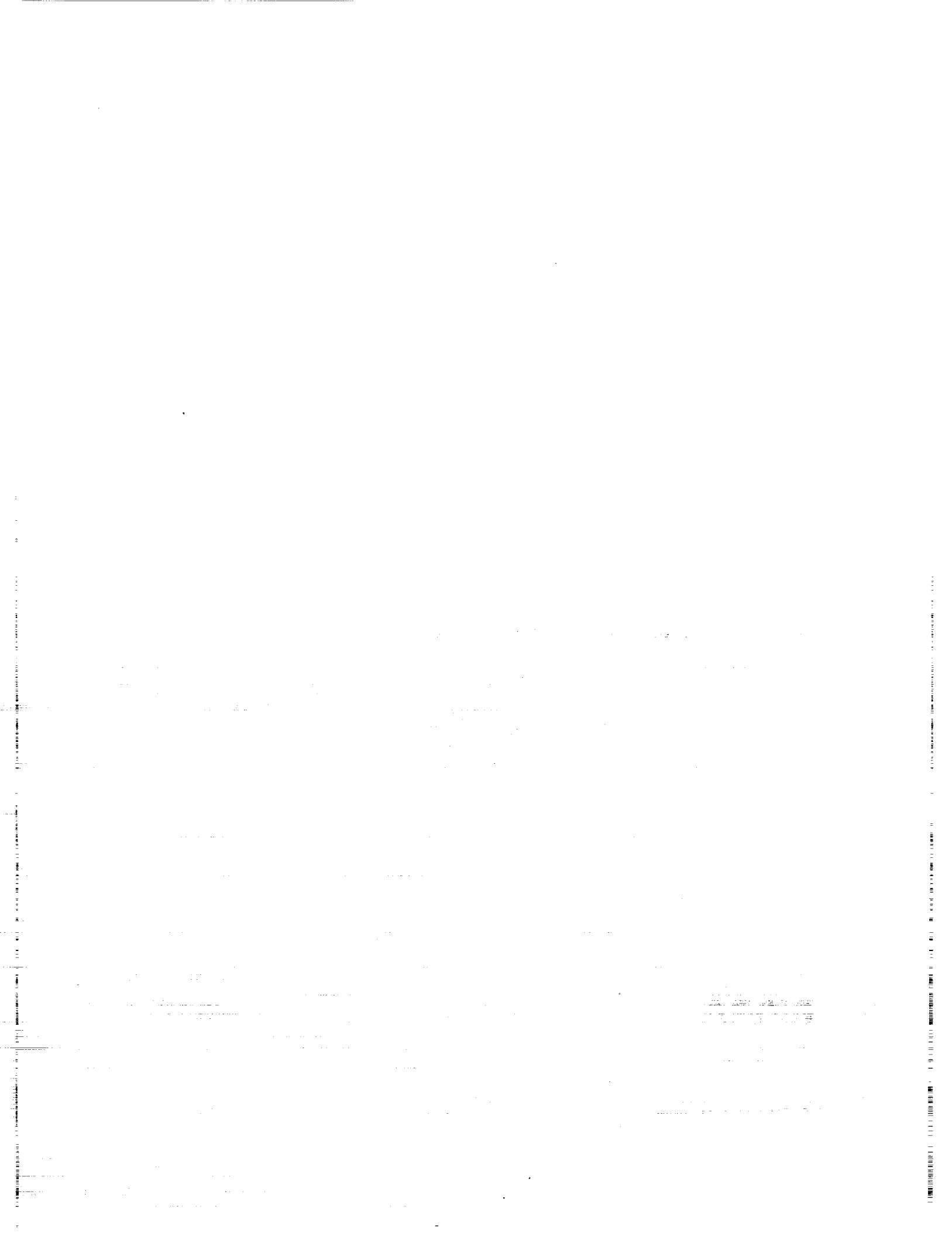


National Aeronautics and
Space Administration

Office of Management

Scientific and Technical
Information Program

1991



PREFACE

This publication is a compilation of summaries of reports written by Principal Investigators funded through the Planetary Astronomy Program of NASA's Solar System Exploration Division, Office of Space Science and Applications.

The summaries are designed to provide information about current scientific research projects conducted in the Planetary Astronomy Program and to facilitate communication and coordination among concerned scientists and interested persons in universities, government, and industry.

The reports are published as they were submitted by the Principal Investigators and are virtually unedited. They are arranged in alphabetical order.

In a second section, highlights of recent accomplishments in planetary astronomy are summarized as they were submitted by the Principal Investigators. The name attached to an individual paragraph is generally the name of the person who submitted that paragraph.

Jurgen Rahe
Discipline Scientist
Planetary Astronomy Program
Solar System Exploration Division

July 1991



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LIST OF PRINCIPAL INVESTIGATORS

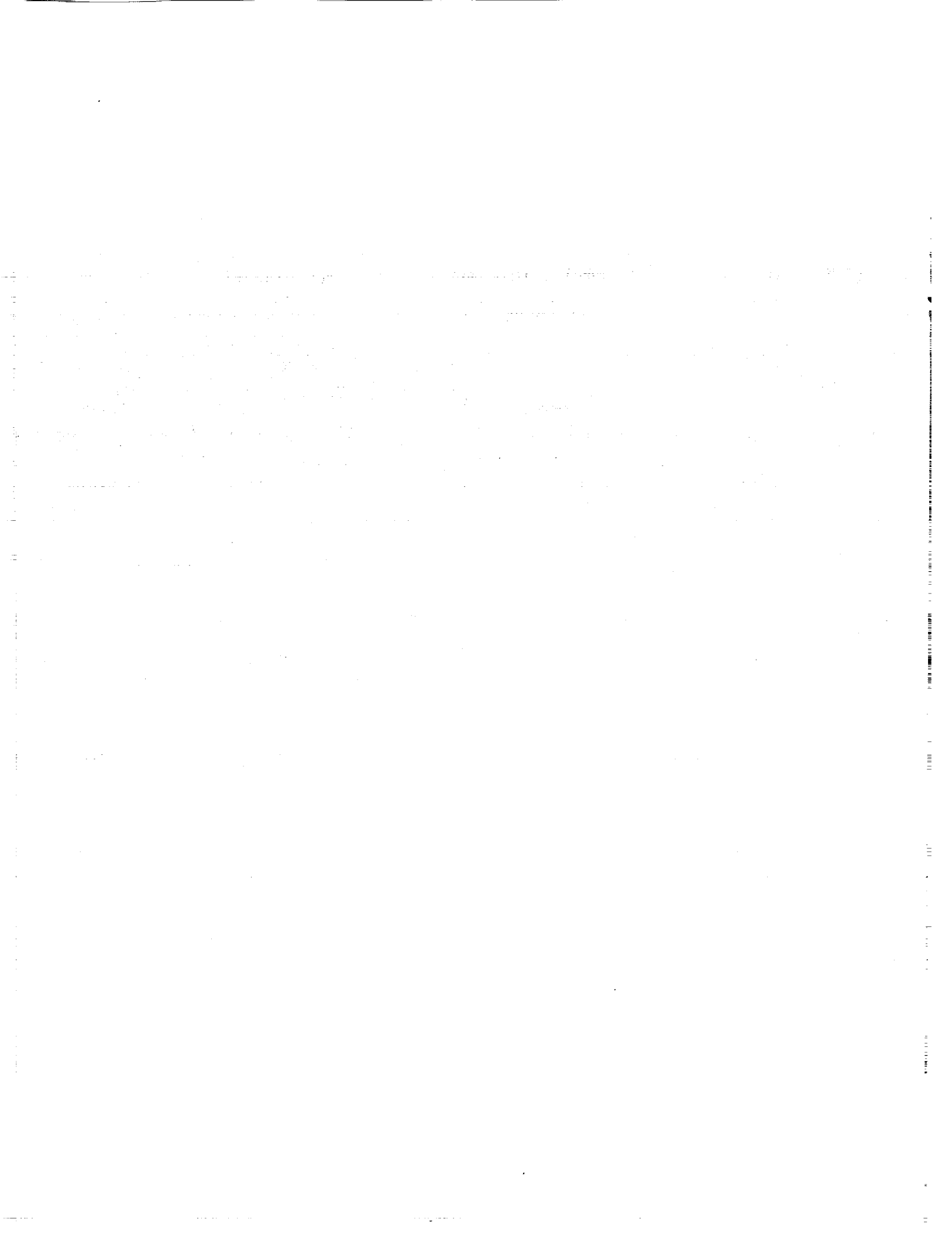
Name	Performing Organization	Title
Michael F. A'Hearn	University of Maryland	Observations of Comets and Asteroids
Michael F. A'Hearn	University of Maryland	Theoretical Spectroscopy of Comets
Reta Beebe	New Mexico State University	Long Term Changes in Reflectivity and Large Scale Motions in the Atmosphere of Jupiter and Saturn
Jeffrey F. Bell	University of Hawaii	Infrared Spectral Studies of Asteroids
Michael J.S. Belton	National Optical Astronomy Observatories	Analysis and Interpretation of CCD data on P/Halley and Physical Parameters and Activity Status of Cometary Nuclei at Large Heliocentric Distance
Michael J.S. Belton	National Optical Astronomy Observatories	Galileo-related Ground-based Observations of the Jovian System
Richard P. Binzel	Massachusetts Institute of Technology	Photometry of Pluto-Charon Mutual Events and Hirayama Family Asteroids
Edward Bowell	Lowell Observatory	Studies of Asteroids, Comets, and Jupiter's Outer Satellites
John C. Brandt	University of Colorado, Boulder	Evolution on Large-Scale Plasma Structures in Comets: Kinematics and Physics
R. H. Brown	Caltech Jet Propulsion Lab	Infrared Observations of Small Solar System Bodies
Donald B. Campbell	Cornell University	Arecibo S-Band Radar Program
C.R. Chapman	Planetary Science Institute	Planetary Astronomy
Anita L. Cochran	The University of Texas McDonald Observatory	Physical Observations of Comets: Their Composition, Origin and Evolution

Name	Performing Organization	Title
William D. Cochran	McDonald Observatory, The University of Texas at Austin	Radial Velocity Detection of Extra-Solar Planetary Systems
Dale P. Cruikshank	NASA Ames Research Center	Volatiles in the Outer Solar System
Drake Deming	Goddard Space Flight Center	Spectroscopic Planetary Detection
Drake Deming	Goddard Space Flight Center	Studies of Thermal Wave Phenomena on the Jovian Planets
James L. Elliot	Massachusetts Institute of Technology	Occultation Studies of the Solar System
Uwe Fink	University of Arizona	Planetary Spectroscopy
George D. Gatewood	Allegheny Observatory of the University of Pittsburgh	Allegheny Observatory Search for Planetary Systems
Tom Gehrels	The University of Arizona	Surveying of the Solar System
Donald N.B. Hall	University of Hawaii, Institute for Astronomy	Operation of the University of Hawaii 2.2M Telescope on Mauna Kea
Martha S. Hanner	Jet Propulsion Laboratory	Infrared Observations of Comets
Robert S. Harrington	U.S. Naval Observatory	Search for Planet X
Alan W. Harris	Jet Propulsion Laboratory	Asteroid Photometry
William K. Hartmann	Planetary Science Institute	Studies of Relationships Among Outer Solar System Small Bodies and Related Objects
Eleanor F. Helin	Jet Propulsion Laboratory	Palomar Planet-Crossing Asteroid Survey (PCAS)
Robert R. Howell	University of Wyoming	Infrared Speckle Interferometry and Spectroscopy of Io
W.B. Hubbard	University of Arizona	Interiors and Atmospheres of the Outer Planets
D. M. Hunten	The University of Arizona	Studies of Extended Planetary Atmospheres

Name	Performing Organization	Title
William M. Jackson	University of California	Laser Studies of the Photodissociation Dynamics of Cometary Radicals
Raymond F. Jurgens	Jet Propulsion Laboratory	Goldstone Solar System Radar
Roger Knacke	State University of New York at Stony Brook	Infrared Variability of Jupiter and Saturn
Theodor Kostiuk	Goddard Space Flight Center	Advanced Infrared Astronomy
Stephen M. Larson	University of Arizona	Cometary Spectroscopy and Imaging
Larry A. Lebofsky	University of Arizona	Infrared Observations of Solar System Objects
Barry L. Lutz	Lowell Observatory	Outer Planet Studies
B. G. Marsden	Smithsonian Institution	Astrometric Observations of Comets and Asteroids and Subsequent Orbital Investigations
K. Matthews	California Institute of Technology	Research in Planetary Astronomy
Robert S. McMillan	University of Arizona	The Radial Velocity Search for Extrasolar Planets
Karen J. Meech	University of Hawaii	Observational Evidence of Aging Processes in Comets
Robert L. Millis	Lowell Observatory	Occultation Studies of the Solar System
Ray L. Newburn, Jr.	Jet Propulsion Laboratory	Physical Processes in Comets
Malcolm B. Niedner, Jr.	Goddard Space Flight Center	Imaging Studies of Comets
Steven J. Ostro	Jet Propulsion Laboratory	Radar Investigation of Asteroids and Planetary Satellites
Carolyn C. Porco	University of Arizona	Stellar Occultations by Planetary Rings: 3 July 1989 28 SGR Occultation by Saturn
Andrew Potter	Johnson Space Center	Observational Studies of the Exospheres of the Moon and Mercury

Name	Performing Organization	Title
Frank Scherb	University of Wisconsin	Ground-Based Observations of Comets, the Jupiter Plasma Torus, and Io
David G. Schleicher	Lowell Observatory	Groundbased Cometary Studies
F. Peter Schloerb	University of Massachusetts	Radiative Transfer in Planetary Atmospheres
Irwin I. Shapiro	Smithsonian Institution	Radar Studies in the Solar System
Harlan J. Smith	University of Texas at Austin	Planetary Astronomy
Lewis E. Snyder	University of Illinois	Radar Interferometric Studies of Comets
Hyron Spinrad	University of California	Spatially Resolved Quantitative Spectroscopy of Comets
Stephen E. Strom	University of Massachusetts	The Evolution of Young Stellar Object Disks and Their Environment
Edward F. Tedesco	Jet Propulsion Laboratory	Visual and Infrared Studies of Asteroids and the Pluto-Charon System
Richard J. Terrile	Jet Propulsion Laboratory, California Institute of Technology	Planetary Optical and Infrared Imaging
David J. Tholen	Institute for Astronomy, University of Hawaii	Studies of Triton and the Pluto-Charon System
David J. Tholen	Institute for Astronomy, University of Hawaii	Visible and Infrared Investigations of Planet-Crossing Asteroids and Outer Solar System Objects
L. Trafton	University of Texas at Austin	A Continued Program of Planetary Study at the University of Texas McDonald Observatory
Faith Vilas	Johnson Space Center	Compositional Studies of Primitive Asteroids

Name	Performing Organization	Title
J. G. Williams	Jet Propulsion Laboratory, California Institute of Technology	Astrometric Observations of Comets and Minor Planets
Wieslaw Z. Wisniewski	University of Arizona	Physical Studies of Small Asteroids and Cometary Nuclei
Susan Wyckoff	Arizona State University	Spectroscopy of Comets
Donald K. Yeomans	Jet Propulsion Laboratory	Comet and Asteroid Dynamics

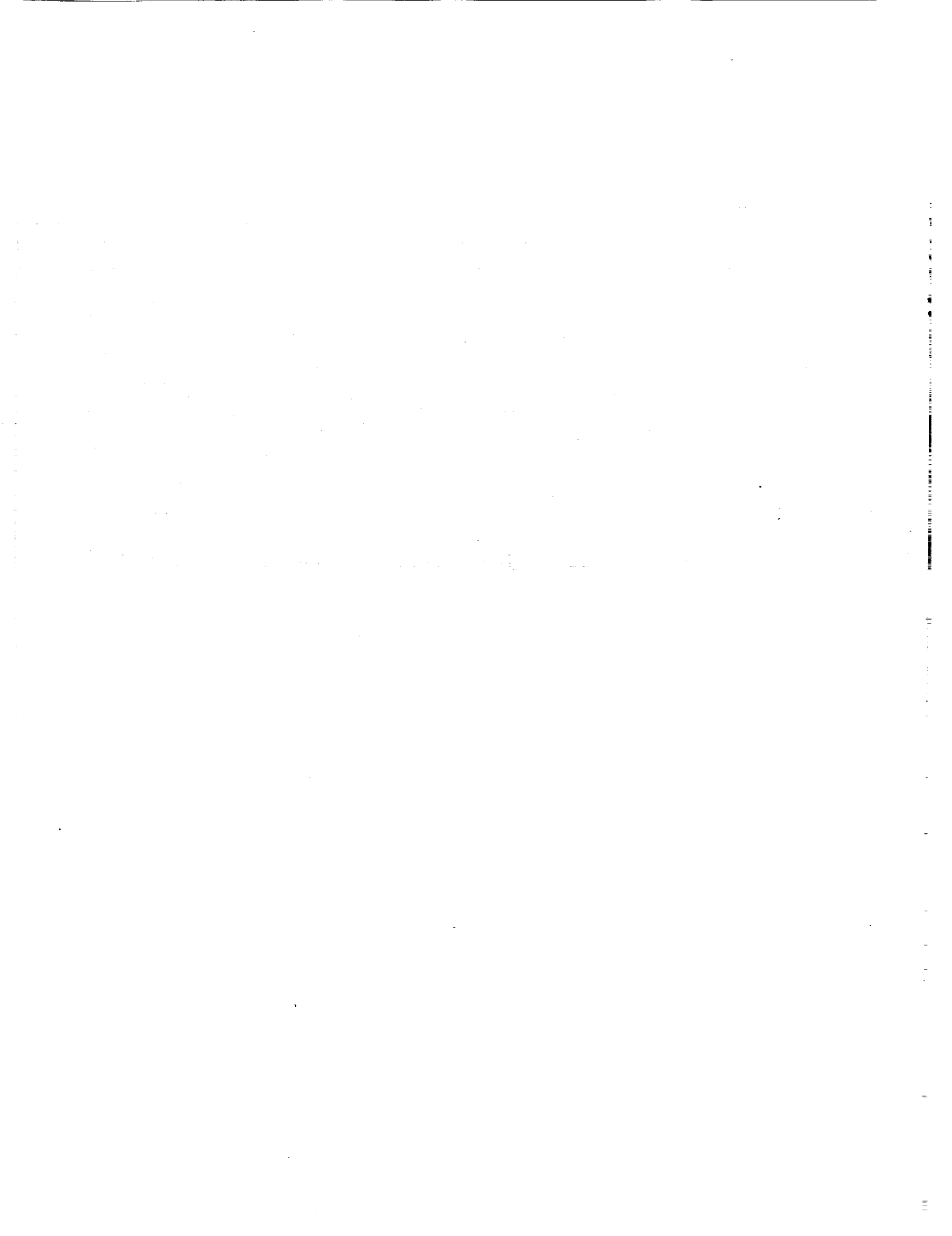


HIGHLIGHTS OF RECENT ACCOMPLISHMENTS

Halley's Spin State Determined	Michael J. S. Belton
Io's Atmosphere Detected by Ground-Based Microwave Spectroscopy	Michael J. S. Belton
Detection of CN Emission From (2060) Chiron	Edward Bowell
1990 MB: The First Mars Trojan	Edward Bowell
The Last Disconnection Events in Comet Halley in April 1986	John C. Brandt
Planetary Astronomy	C. R. Chapman
Physical Observations of Comets: Their Composition, Origin and Evolution	Anita L. Cochran
The Companion Object to HD114762	William D. Cochran
Detection of Solid C \equiv N Bearing Materials on Solar System Bodies	Dale P. Cruikshank
Studies of Thermal Wave Phenomena on the Jovian Planets	Drake Deming
Discovery of Near-Earth Asteroids by CCD Scanning	T. Gehrels
Palomar Planet-Crossing Asteroid Survey (PCAS) 1/1990 - 2/1991	E. F. Helin
Infrared Speckle Interferometry and Spectroscopy of Io	Robert R. Howell
Probing Titan's Atmosphere With a Stellar Occultation	W. B. Hubbard
Laboratory Simulation of the Surface of Halley's Comet	William M. Jackson
Goldstone Solar System Radar	Raymond F. Jurgens
Time-Lapse CCD Imagery of Plasma-Tail Motions in Comet Austin	D. A. Klinglesmith III
Ground Based Infrared Measurements of the Global Distribution of Ozone in the Atmosphere of Mars	T. Kostiuk
Ethylene Line Emission from the North Pole of Jupiter	T. Kostiuk
Storm on Saturn	S. Larson
Visual and Near-IR Spectrophotometry of Asteroids	Larry A. Lebofsky

Deuterium on Venus: Observations from Earth	B. L. Lutz
Near Infrared Imaging of the Outer Planets	K. Matthews
Outburst of Comet Halley at 14.3 AU	Karen J. Meech
Asteroid 1986 DA: Radar Evidence for a Metallic Composition	S. J. Ostro
Io's Radar Properties	S. J. Ostro
Sodium and Potassium in the Lunar Atmosphere	A.E. Potter
Radiative Transfer in Planetary Atmospheres	F. Peter Schloerb
Radar Studies in the Solar System	Irwin I. Shapiro
Observations of Formaldehyde and Search for Cyanoacetylene in Comet Brorsen-Metcalf (1988o)	L. E. Snyder
Asteroid Absolute Magnitudes and Slope Parameters	Edward F. Tedesco
1990 Marks End of Pluto-Charon Mutual Event Season	David J. Tholen
First Spacecraft Encounter With an Asteroid Approaches	David J. Tholen
Global Scale Auroral Emissions on Jupiter	L. Trafton
Tentative Identification of a Newly Discovered Class of Material on Io	L. Trafton
Compositional Studies of Primitive Asteroids	Faith Vilas
Astrometric Observations of Comets and Minor Planets	J. G. Williams
Minor Planet 1566 Icarus - Asteroid or Comet?	D.K. Yeomans

SUMMARIES OF RESEARCH PROJECTS



Observations of Comets and Asteroids

Astronomy Program
University of Maryland
College Park, Maryland

Michael F. A'Hearn

Strategy

We use all available ground-based observational techniques to study the chemical and physical properties of the small bodies of the solar system, primarily comets and secondarily asteroids. The ultimate goal is to use these bodies to understand the formation and evolution of the solar system.

Progress and Accomplishments

- i) Published paper on a Pallas occultation of many years ago, handed over last of observational details on recent occultation of Vesta to Lebofsky and Millis for analysis, and assisted in a futile attempt (clouded out) to observe an occultation Vesta (3 Jan 1991).
- ii) Carried out simultaneous optical (ccd imaging) and millimeter (BIMA/FCRAO) observations of comet Austin to compare CN and HCN (collaborated with Palmer, Snyder, dePater, Schloerb). Insufficient sensitivity to see HCN structures with BIMA. Planned addition of 6 more antennas to BIMA will improve things. Also obtained images for OH to study spatial distribution. Published production rates in a timely manner for other observers but other results require additional analysis.
- iii) Observed comet Levy with IRTF and found very unusual broad-band colors. Analysis still in progress.
- iv) Observed broad-band IR colors at IRTF for all classical Saturnian satellites except Iapetus. Data still being processed.
- v) Reprocessed images for the Near Nucleus Net of the IHW archive. Previous processing had produced undesirable quantization effects because of use of integer arithmetic.
- vi) Collaborated with S.J. Bus in reducing and analyzing spectra of an outburst of Chiron. Reported detection of CN at largest distance, by a factor 2, for any comet.
- vii) Continued calculation of constraints on model of Halley's rotation using our ccd images of the jets.
- viii) Calculated models for the variability observed in comet Levy.
- ix) Continued analysis of data from long-term photometric program on comets.
- x) Collaborated with Tegler, Campins, Cochran in futile (bad weather) search for cometary activity associated with Hidalgo.

Projected Accomplishments

- i) Additional collaboration with Bus on interpretation of photometry of Chiron.
- ii) Publish paper on Halley's rotation (submit March 1991).
- iii) Observe nucleus of comet Faye to determine size, albedo, axial ratio, etc.
- iv) Complete analysis of 14-year narrow-band photometric program.
- v) Compare ccd images of various comets for correlation between presence of structures in coma with dynamical age.
- vi) Observe Ceres (UH 88-inch) to search for outgassing associated with ice reported by Lebofsky.

Publications

Osborn, W.H., et al. 1990. Standard Stars for Photometry of Comets, *Icarus*, **88**, 228-256.

Bus, S.J., et al. 1991. Detection of CN Emission from (2060) Chiron. *Science*, **251**, 774-777.

Palmer, P., et al. 1990. Simultaneous Imaging of Optical CN Lines and Radio HCN lines in Comet Austin, in proceedings "Workshop on Observations of Recent Comets" ed. Huebner, et al. (San Antonio TX: Southwest Research Inst.) pp. 40-44.

Dunham, D.W., et al. 1990. The Size and Shape of (2) Pallas from the 1983 Occultation of 1 Vulpeculae, *Astron.J.*, **99**, 1636-1662

A'Hearn, M.F. 1991. Looking for Relationships, *Nature*, **347**, 715-716.

A'Hearn, M.F. and M.C. Festou 1990. The Neutral Coma, Chapter 3 in *Physics and Chemistry of Comets in the Space Age*, ed. W. Huebner (Heidelberg, Germany: Springer-Verlag).

Samarasinha, H. and M.F. A'Hearn, 1991. Observations and Dynamical Constraints on the Rotation of Comet P/Halley, submitted to *Icarus*.

Theoretical Spectroscopy of Comets

Astronomy Program
University of Maryland
College Park, Maryland

Michael F. A'Hearn

Strategy

We calculate theoretical spectra of various emitting species in cometary comae both to investigate physical parameters that are measurable with cometary spectra and to provide fluorescence efficiencies for the derivation of abundances from fluxes.

Progress and Accomplishments

- i) Work on the fluorescence equilibrium of S_2 , completed in the previous year, was published in *Icarus*.
- ii) We completed our modelling of SO and SO_2 , compared the results with IUE spectra of a number of comets, and concluded that neither species was present at a level far below that expected if S_2 is ubiquitous in comets and is produced by irradiation of sulfur compounds in icy grain mantles. Paper has been submitted.
- iii) Continued collaboration at a low level with D. Schleicher on modelling OH fluorescence to study the effects of quenching the lambda doublet by collisions and the Greenstein effect. Most effort at Maryland was in preparing IUE spectra for comparison with the model.

Projected Accomplishments

- i) Complete our study of the temporal variability of S_2 in IRAS-Araki-Alcock using ground-based spectra obtained by S. Larson.
- ii) Calculate theoretical models for comparison with high-resolution spectra of comet Austin obtained by H. Spinrad. Much of the work will become a thesis for Spinrad's student but we will provide models for specific species including CO_2^+ , C_3 , and NH_2 .

Publications

Kim, S. J., M. F. A'Hearn, & S. M. Larson 1990. Multi-Cycle Fluorescence: Applications to S_2 in Comet IRAS-Araki-Alcock 1983VII, *Icarus*, **87**, 440-451

***Long Term Changes in Reflectivity and Large Scale Motions in
the Atmosphere of Jupiter and Saturn***

New Mexico State University
Department of Astronomy
Las Cruces, New Mexico 88003

Reta Beebe

Strategy

This is an observational investigation that utilizes a CCD camera and multicolor filters with a committed f/40 60 cm telescope to image the temporal changes in Jupiter's and Saturn's atmospheres. The intent of this project is to maintain a continuous data base to assist in relating the Voyager data with that of Galileo and Cassini.

Progress and Accomplishments

Photometrically calibrated observations of large scale changes in the reflectivity of the Equatorial Zone and the South Equatorial Belt (SEB) spanning the 1989 brightening and subsequent darkening of the SEB have been reduced. Analysis of the data by D. Kuehn reveals that the color ratios and limb-darkening behavior can be modelled by increasing the reflectivity and optical thickness of a cloud layer at 0.7 bars and does not require an additional upper cloud layer as had previously been proposed. Analysis of the current apparition is continuing.

Multicolor images of the equatorial storm on Saturn have been map projected and intergated with early transit observations, an image from Pic Du Midi and Hubble Space Telescope (HST) observations. The onset and development of the storm has been mapped and interpreted as a planet encircling wave pattern induced by a single convective disturbance. Efforts to characterize the faint cloud patterns are continuing.

Projected Accomplishments

We will continue to observe Jupiter and Saturn and complete the analysis of the Saturnian storm. This analysis integrates the HST data and previous historical records. During this year the first HST observations of Jupiter will be obtained. The resolution of a preliminary image indicates that, one Jovian year after the Voyager encounters, a second detailed wind profile will be obtained to determine the extent to which the latitudinal variation of the zonal winds vary. We will use this information, combined with our historical database, to characterize temporal variability of the zonal atmosphere. Two papers, one on the Saturn storm by Beebe, et al. and another concerning temporal variability of Jupiter's cloud deck by D. Kuehn and R. Beebe are being revised and will be submitted to *Icarus*.

Publications

Kuehn, D.M., A Study of the Temporal Behavior of the Vertical Structure of Jupiter's Atmosphere, PhD Dissertation New Mexico State University, Dec 1990.

Infrared Spectral Studies of Asteroids

Planetary Geosciences Division
Hawaii Institute of Geophysics
University of Hawaii
2525 Correa Road
Honolulu, HI 96822

Jeffrey F. Bell

Strategy

The research objective is to improve our understanding of the surface mineralogy of asteroids and to link the vast existing body of meteorite geochemical data with specific astronomical objects which may be the targets of future NASA missions. The methodology employed is 1) use advanced astronomical instrumentation to obtain reflection spectra in the 0.3-5.2 μm wavelength range of selected asteroids; 2) compare the asteroid data with similar data on simulated asteroid regoliths of various compositions to determine the surface mineralogy and meteoritic affinities of asteroid spectral classes and specific asteroids; 3) intergrate the mineralogical information with other astronomical data, orbital dynamics studies, and meteorite geochemistry data to reconstruct the condensational, thermal, and collisional history of the present asteroids and their parent planetesimals; 4) use the information obtained to assist planning of future NASA asteroid missions such as Galileo and CRAF.

Progress and Accomplishments

Continued to observe selected members of the Eos family and other suspected K-class asteroids; provided information for selection of candidate asteroid flyby targets for Galileo and CRAF missions; designed and purchased interference filters for future broadband asteroid survey.

Projected Accomplishments

Begin observations for moderate resolution IR asteroid survey; acquire 52-color spectra of selected S-type asteroids, Earth-crossers, members of asteroid dynamical families, and suspected K-types; continue to assist planning for Galileo and CRAF mission asteroid flybys.

Publications

Thomas, P., D. P. Cruikshank, J. F. Bell, J. Veverka, and J. Lunine, Mars satellites: Geologic history. To appear in MARS, University of Arizona Space Science Series (in press).

Cruikshank, D. P., D. J. Tholen, W. K. Hartmann, J. F. Bell, and R. H. Brown, Three basaltic asteroids and the source of the basaltic achondrite meteorites. *Icarus* **89**, 1-13 (1991).

Cruikshank, D. P., W. K. Hartmann, D. J. Tholen, J. F. Bell, and R. H. Brown. Basaltic achondrites: Discovery of source asteroids. *Meteoritics* **24**, 260.

Analysis and Interpretation of CCD data on P/Halley and Physical Parameters and Activity Status of Cometary Nuclei at Large Heliocentric Distance

National Optical Astronomy Observatories
Tucson, AZ 85726

Michael J.S. Belton and Beatrice Mueller (NASA Planetary Astronomy Post-doctoral Grant Awardee).

Strategy

The scientific objectives of this work are: (1) To construct a well sampled photometric time-series of comet Halley extending to large heliocentric distances both post- and pre-perihelion passage and derive a precise ephemeris for the nuclear spin so that the physical and chemical characteristics of individual regions of activity on the nucleus can be determined; (2) To extend the techniques developed in the study of Comet Halley to the study of other cometary nuclei and to obtain new observational data.

Progress and Accomplishments

In the current year we have succeeded in determining the spin state of comet Halley, demonstrated that the nucleus has five major regions of activity, constructed the first accurate map of the locations of active regions on the surface of the nucleus, shown that one of the active regions is characterized by properties that are distinct from those of the others, and demonstrated that the interior density distribution of the nucleus is observationally constrained to emulate that of a homogeneous distribution. The spin state is found to be energetically excited with the nucleus rotating in a long-axis mode. The total spin vector is characterized by an average period of 2.84 days and it precesses, inclined at an angle of 21.4° , around the angular momentum vector once every 3.69 days. Unlike previous models that have been published, this solution for the spin state simultaneously satisfies the VEGA/GIOTTO imaging data and ground-based data on time dependent jet structures, photometric time-series, and episodic production of CN-shells in the comet's coma.

In addition to the above work we have made progress, but not yet completed, the interpretation of our post-perihelion CCD observations. Dr. Mueller has also obtained observing time on the KPNO 4m telescope to observationally extend our Halley work to the study of other cometary nuclei at large heliocentric distance.

In related work, partially supported by this grant, the principal investigator has worked with Dr. K. Meech and proposed a novel model for the structure of Chiron's dust coma that invokes the relatively large mass of this object as an essential element in explaining the "slow" outbursts of episodic activity that characterize it.

Investigation: Analysis and Interpretation of CCD data on P/Halley etc.

Publications

Belton, M.J.S., W.H. Julian, A.J. Anderson, and B.E.A. Mueller 1991, "The Spin State and Homogeneity of Comet Halley's Nucleus," *Icarus*, in press.

Meech, K.J., and M.J.S. Belton 1990, "The Atmosphere of 2060 Chiron," *Astron. J.* **100**, 1323-1338.

Galileo-related Ground-based Observations of the Jovian System

National Optical Astronomy Observatories
Tucson, AZ 85726

Michael J.S. Belton

Strategy

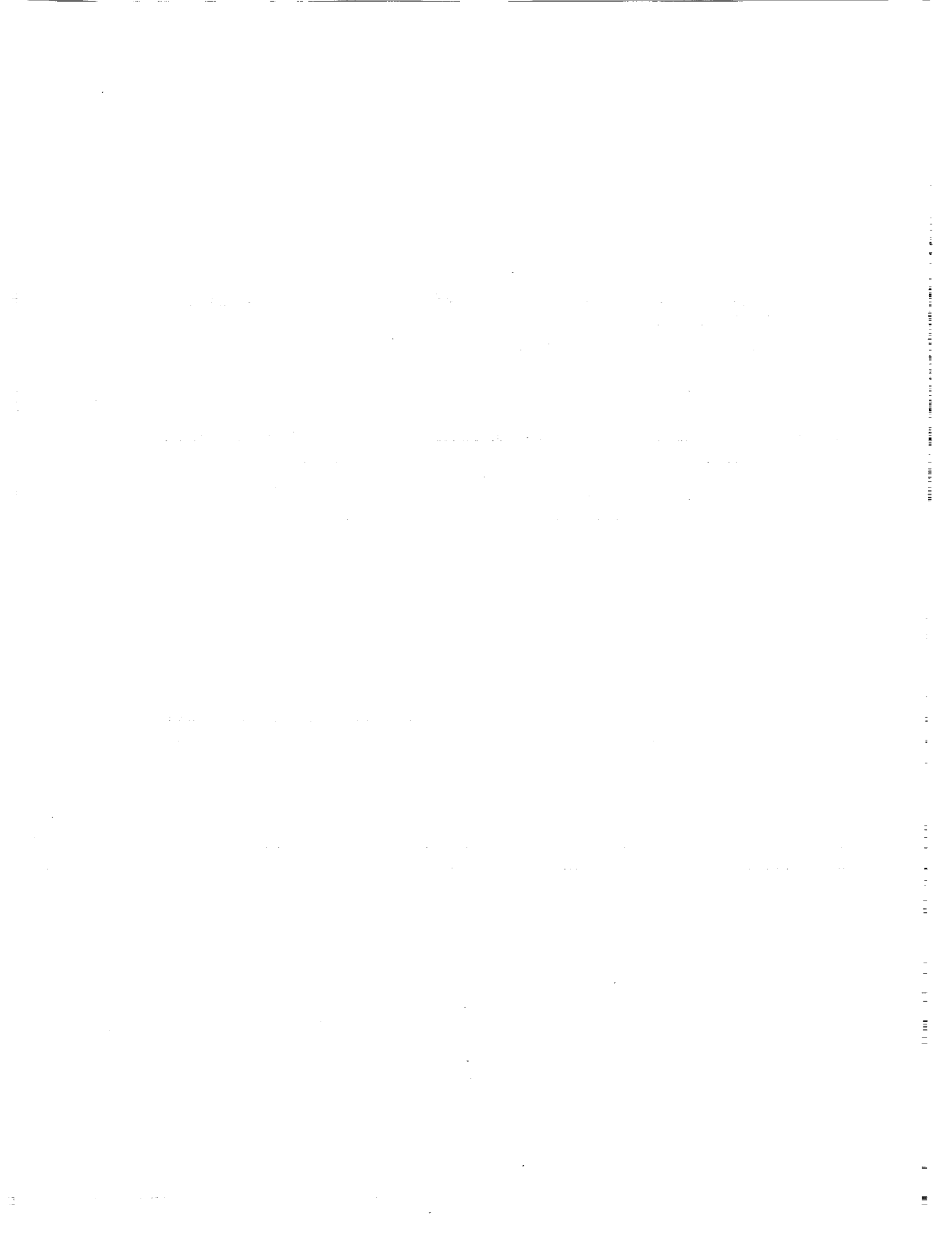
The scientific objectives of this work are to make millimeter observations of SO₂ and other neutral molecules in Io's atmosphere and to conduct a program of observational and interpretive studies of the Jovian system in connection with the Galileo mission.

Progress and Accomplishments

In the past year the principal investigator has participated in the acquisition and interpretation of microwave observations of Io using the IRAM (Spain) and the CSO (Hawaii) facilities. Fully resolved, individual rotational lines of SO₂ have been detected in the spectrum of Io for the first time as a result of this program. Two lines of different strengths and excitation have been observed so far, however, both are strongly saturated and we have not been able to cleanly separate the effects of temperature and abundance in the interpretation. We have one more observing opportunity in the current proposal year at the IRAM facility, and it is our intention to concentrate on the acquisition of data of much weaker lines so that this separation can be more easily effected. The data that we already have in hand show that the neutral atmosphere has limited extent on the disk of the satellite, as expected for an atmosphere in vapor pressure equilibrium with frosts on the surface, and is collisionally thick. The spectra show evidence for a stable component to the atmosphere (i.e., it is always present) on which is occasionally superimposed a highly variable component - perhaps related to episodic volcanic activity. We have also searched for lines of H₂S but so far have only been able to set upper limits to its column abundance. We have published a preliminary report of this work in *Nature*.

Publications

Lellouch, E., M.J.S.Belton, I. de Pater, S. Gulkis, and Th. Encrenaz 1990, "Io's Atmosphere from Microwave Detection of SO₂" *Nature* **346**, 639-641.



Photometry of Pluto-Charon Mutual Events and Hirayama Family Asteroids

Department of Earth, Atmospheric, and Planetary Sciences
Massachusetts Institute of Technology
Cambridge, MA 02139

Dr. Richard P. Binzel

Strategy

During the years of 1985-1990, nature provided earth-bound astronomers with a once-per-century opportunity to observe occultation and transit phenomena between Pluto and its satellite, Charon. Ground-based observations of these events are now being used to derive physical parameters for the Pluto-Charon system to a precision that is unlikely to be improved upon until *in situ* spacecraft observations are obtained. This program supports analysis of photometry observations from McDonald Observatory, a critical location in the International Pluto Campaign network. Knowledge of the diameters, masses, densities, and compositions derived from these observations will augment our understanding of Pluto's origin and its context within the problem of solar system formation.

A second task researches the evolutionary processes which have occurred in the asteroid belt by measuring the physical properties of specific Hirayama family members. Photoelectric lightcurve observations of Koronis and Themis family members are being used to investigate the individual catastrophic collision events which formed each family. By comparing these properties with results of laboratory and numerical experiments, the outcomes of catastrophic disruptions and collisional evolution may be more precisely determined.

Progress and Accomplishments

During 1990, observations were obtained for 4 mutual events before the season ended. Reduction and analysis of 1985-1990 photometry has provided evidence for a bright south polar cap on Pluto and a possible color difference between the poles and the equator.

New lightcurve observations have been obtained for Galileo target 951 Gaspra as well as Cassini target 66 Maja. Nine asteroids in the Koronis and Themis families plus Trojan and Hilda asteroids plus other targets of opportunity were also observed.

Projected Accomplishments

Emphasis in this year is shifting from observations to final analysis and publication of the large accumulated data sets. A preliminary least squares map for Pluto will be completed and additional mapping techniques will be investigated. Models for the long-term insolation on Pluto and the seasonal deposition of methane frost on its surfaced are being developed for a

physical interpretation of the maps. For asteroids, models for the collisional environment of 951 Gaspra are being developed before the Galileo encounter. Code for deriving pole orientations for Koronis family asteroids is being developed to investigate a possible preferential spin vector alignment.

Publications

Binzel, R. P. (1990). "Pluto." *Scientific American* **262**, 50-58, 1990.

Binzel, R. P. "Long Term Variations of a Volatile Methane Reservoir on Pluto." *Proc. Lunar Planet. Sci. Conf. XXI*, 87-88, 1990.

Young, E. F., and Binzel, R. P. "A New Pluto Albedo Map." *BAAS* **22**, 1129, 1990.

Binzel, R. P. "Long-Term Seasonal Variations on Pluto." *BAAS* **22**, 1129, 1990.

Binzel, R. P., and Madras, C. D. "Ground-Based Reconnaissance of Galileo Target Asteroid 951 Gaspra." *BAAS* **22**, 1114, 1990.

Binzel, R. P. "1990 DA." *IAUC* **4969**, 1990.

Weidenschilling, S. J., Chapman, C. R., Davis, D. R., Greenberg, R., Levy, D., Binzel, R. P., Vail, S. M., Magee, M., Spaute, D. "Photometric Geodesy of Main-Belt Asteroids. III. Additional Lightcurves." *Icarus* **86**, 402-447, 1990.

Namiki, N., and Binzel, R. P. "The Evolution of the Surface of 951 Gaspra: A Pre-Galileo Estimate." *Proc. Lunar Planet. Sci. Conf. XXII*, 953-954, 1991.

Studies of Asteroids, Comets, and Jupiter's Outer Satellites

Lowell Observatory
 1400 West Mars Hill Road
 Flagstaff, Arizona 86001

Edward Bowell

Strategy

Our work comprises observational, theoretical, and computational research, mainly on asteroids. Two principal areas of research, centering on astrometry and photometry, are interrelated in their aim to study the overall structure of the asteroid belt and the physical and orbital properties of individual asteroids.

Progress and Accomplishments

Two highlights have been: (1) *Detection of CN emission from Chiron*. Bus *et al.* (1991) reported the first detection of gaseous emission from Chiron from observations made on 1990 January 29 and 30, breaking the record heliocentric distance for such cometary emission. They concluded that the outgassing is driven by isolated outbursts of a volatile species such as CO₂ or CO from a small fraction of Chiron's surface. (2) *Realization that 1990 MB is the first known Trojan-type asteroid of a planet other than Jupiter*. 1990 MB librates about Mars' L5, and evidently has a lifetime of at least tens of millions of years. This discovery will be a major challenge to solar system dynamicists, who will wish to determine whether 1990 MB is primeval and to explore more fully the regions of planetary Trojan stability; and to observers, who will wish to search for other planetary Trojans. Using films from the 46-cm Palomar Schmidt to discover and follow up moderately bright asteroids (the GLAS survey), several thousand positions of known and unknown asteroids were published. We have secured accurate astrometry of CRAF target P/Kopff on a monthly basis, and have continued prolific astrometric measurement of archive plates. CCD astrometry of very faint asteroids has been applied mainly to the follow-up and orbit improvement of Earth-approachers. The Lowell Observatory-U.K. Schmidt Telescope Asteroid Survey (LUKAS) has proceeded slowly. Our work to acquire rotational and shape statistics on km-size asteroids has continued with CCD observations of several targets. Using archival photographic plates, we have worked on the historical light variation of Chiron. Many asteroid orbits have been calculated, and asteroid identification work has proceeded apace. A new method of asteroid orbital error analysis, based on Bayesian theory, has been developed. Work on the spatial and sky-plane distributions of main-belt and near-Earth asteroids was started. Theoretical modeling of asteroid photometry has resulted in preparation of a major paper on "Photomorphography". Work on a spherical harmonics method of determining asteroid spin vectors and on light scattering by dust has resulted in published papers.

Projected Accomplishments

We will focus our astrometric effort in three principal areas: (1) LUKAS. Completion of the comparison of two Trojan fields with digital sky survey data should result in publication of several hundred 2-month-arc orbits, including perhaps 30 Trojan orbits. We will undertake further software development for linkage and identification that will cope with the large data throughput. We also hope to expand the scope of LUKAS to encompass the acquisition of spectra for faint asteroids. Four test objective-prism plates, two of which may contain as many as 300 physically diagnostic spectra, are in hand. (2) GLAS. We will be exploring ways of semi-automatically extracting long-arc orbits for many hundreds of relatively bright asteroids per year. (3) We will start to create a faint-asteroid positional database, initially by extracting asteroid positions from the digitized U.K. Schmidt Sky Survey. We will complete the study of Chiron's historical brightness variations. CCD astrometry and photometry of selected asteroids (close-Earth-approachers, Chiron, targets for rotational statistics) will continue as before. The work on orbital error analysis will be brought to a conclusion, and work will continue on the spatial distribution of asteroids. A study of the interpretation of asteroid motion vectors will be resuscitated. Work on the theoretical interpretation of asteroid photometry will shift to a thorough analysis of rotation period determination.

Publications

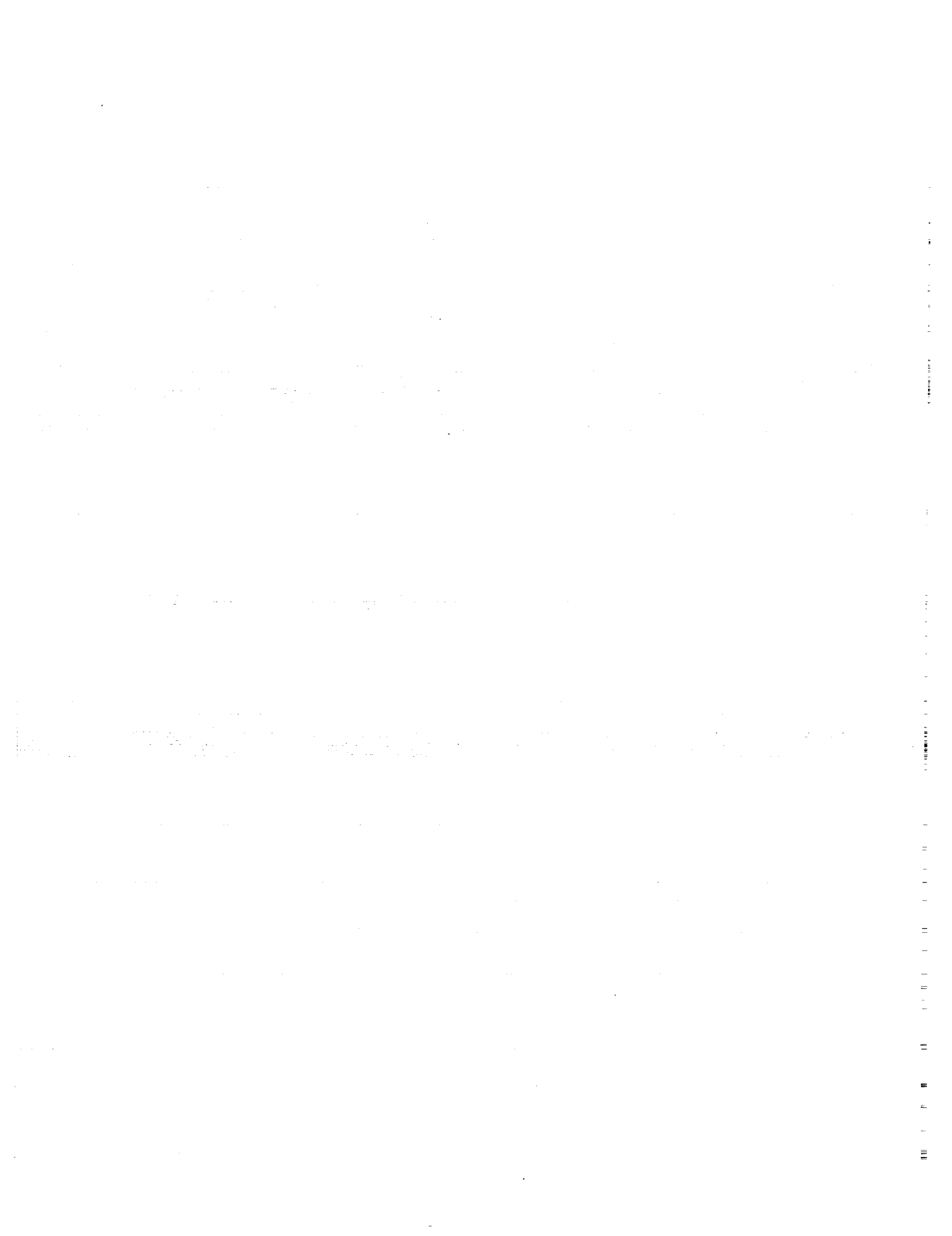
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***Evolution on Large-Scale Plasma Structures in Comets:
Kinematics and Physics***

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Strategy

The disconnection event or DE consists of the periodic loss of a comet's entire plasma tail and the growth of a new one. This spectacular phenomenon is not understood. The strategy is to assemble a data base of specific events studied in detail, determine the solar-wind conditions responsible for DEs, and develop a consistent physical model.

Progress and Accomplishments

The basic data for this project consist of (1) the duplicate archive of IHW large-scale images (Boulder, CO) and (2) in situ solar-wind data. A major accomplishment has been the essential completion of the Boulder, CO duplicate archive. Substantial progress has been made in obtaining solar-wind data, but major blocks have not yet appeared in the literature.

Analysis is complete for the sequence of DEs that took place during 13-18 April 1986. The first DE correlates well with a sector boundary crossing for the comet and a group of DEs that occurred approximately a day later could have produced by polarity reversals seen in the IMP-8 data. Thus, these DEs are consistent with the frontside, magnetic reconnection mechanism.

Projected Accomplishments

We expect to complete the analysis of all DEs under study (except 22 February 1986) during the next year and that the broad outline of our results should be apparent.

Publications

Two major papers are in press. (1) The detailed study of the 10 January 1986 DE by M. B. Niedner, J. C. Brandt, and Y. Yi, Proceedings of the 1989 Chapman Conference on Cometary Plasmas. (2) The very long awaited paper by J. C. Brandt: "Large Scale Structure of the Plasma Tail of Comet Halley During the 1985/1986 Apparition". In Comet Halley 1986, Ellis Horwood Ltd., 1991. (3) A paper entitled "The Disconnection Events of 13-18 April 1986 and the Cessation of Plasma Tail Activity in Comet Halley in May 1986" by Y. Yi, J. C.

Brandt, M. Snow, and C. E. Randall is complete and will be submitted shortly (results presented at the AAS Meeting, January 1991, Philadelphia).

Infrared Observations of Small Solar System Bodies

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Strategy

Task 1: To continue measurement of the infrared reflectance spectra of dark, primitive asteroids in the 2-5 micron wavelength region. This work, which is in collaboration with Dale Cruikshank at Ames Research Center is aimed primarily at searching for organic complexes such as CN, CH and NH in dark material on small bodies in the solar system.

Task 2: To continue the search for and study of volatiles such as nitrogen, methane, ammonia and carbon monoxide, both as free ices and hydrates/clathrates, on icy surfaces in the outer solar system, using high resolution spectra obtained with a multi-channel, cooled-grating, infrared spectrometer. Specific targets are Europa, Enceladus, Ariel, Titania, and Triton.

Progress and Accomplishments

Several spectra of dark, primitive asteroids were obtained last year and among some of those objects, we have observed an absorption that can be attributed to $X-C\equiv N$ in the matrix of dark material on these objects. This signature has also been seen in other objects such as new comets and may represent a fundamental similarity in the dark materials on these two classes of objects. New spectra of Ariel obtained in 1989 and 1990, show a strong absorption, possibly a doublet, in the 2.38-micron region, the source of which I haven't yet identified. I will be attempting to obtain additional spectra in this wavelength region at the next apparition of Uranus in order help identify the responsible compound. Our Triton monitoring is going well, and data from last year's apparition of Neptune (which were of particularly high quality) have indicated that there are small regional variations in either the longitudinal distribution or the mean optical pathlength in the nitrogen and methane ices on Triton. This year we hope to confirm this effect and possibly further quantify it.

Projected Accomplishments

Additional spectra of Ariel will be obtained at this summer's apparition of Uranus and we will be analyzing previous spectra of Ariel consistent with the task involving the search for volatile ices on satellites. Cruikshank and I will continue obtaining and analyzing reflectance data for primitive objects to further study organic material on small solar-system bodies. We will also continue our multi-year monitoring of seasonal changes in the volatile distribution on Triton. The goal of our new work on Ariel will be to obtain higher resolution data in the

region of the newly discovered absorption, as well as making further attempts to identify the responsible compound.

Publications

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Arecibo S-Band Radar Program

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Strategy

The high powered 12.6 cm wavelength radar on the 1000 ft Arecibo reflector is utilized for a variety of studies of solar system bodies. These include: 1) The radar mapping of the surfaces of Mercury, Venus, the moon and Mars in both senses (usually the two circulars) of receive polarization. 2) High time resolution ranging measurements to Mercury and Mars to obtain height profiles and scattering parameters in the equatorial region and to test relativistic and gravitational theories. 3) Measurements of the orbital parameters, scattering properties, figure and spin vectors of asteroids and comets. 4) Observations of the satellites of Mars, Phobos and Deimos, and the Galilean satellites of Jupiter.

Progress and Accomplishments

Two mainbelt asteroids, 1 Ceres and 78 Diana, plus three near-earth asteroids, 1990 MF, 4544 1989FB and 1991 AQ were observed. High time resolution ranging measurements were made to 1990 MF and 1991 AQ which greatly improved the precision with which their return can be predicted. Papers were published or submitted covering the observations of 1989 PB and 1986 DA. An attempt was made to observe Comet Austin but without success. Observations of Phobos and Deimos in November provided a measurement of Phobos' radar albedo, but no detection was obtained for Deimos indicating a lower radar albedo than Phobos. Measurements of the radar cross sections for Io and the icy Galilean satellites in early 1990 and 1991 provided additional phase coverage for these bodies. New techniques have been implemented which overcome some of the overspread problems associated with the radar imaging of Mars from earth. Images, although still at relatively coarse resolution, have been obtained in the cross-polarized (SC sense) showing the distribution of wavelength scale surface roughness. Data was obtained in two campaigns in 1990 which will provide 50m or better radar images of the moon in both senses of receive polarization. Analysis of the cross-polarized data for Venus continued with comparisons between the radar polarization properties of volcanic flows in the Eistla region on Venus and on the earth.

Projected Accomplishments

Three mainbelt asteroids are scheduled for observation, 7 Iris, 324 Bamberger and 796 Sarita. Given the rate at which small near-earth asteroids (NEA's) were discovered in 1990, it is

anticipated that there will be a number of opportunities over the next twelve months for Arecibo observations. There will be an extensive set of observations of Mercury in the summer of 1991 aimed at imaging the surface in the hemisphere not observed from the Mariner 10 spacecraft. The program of high resolution lunar observations will continue. Plans are being made to attempt some delay-Doppler observations of the icy Galilean satellites utilizing the techniques recently developed to overcome the overspread problem. Intensive analysis of the Venus polarization data will continue with emphasis on the contribution it can make to the results from the Magellan mission.

Publications

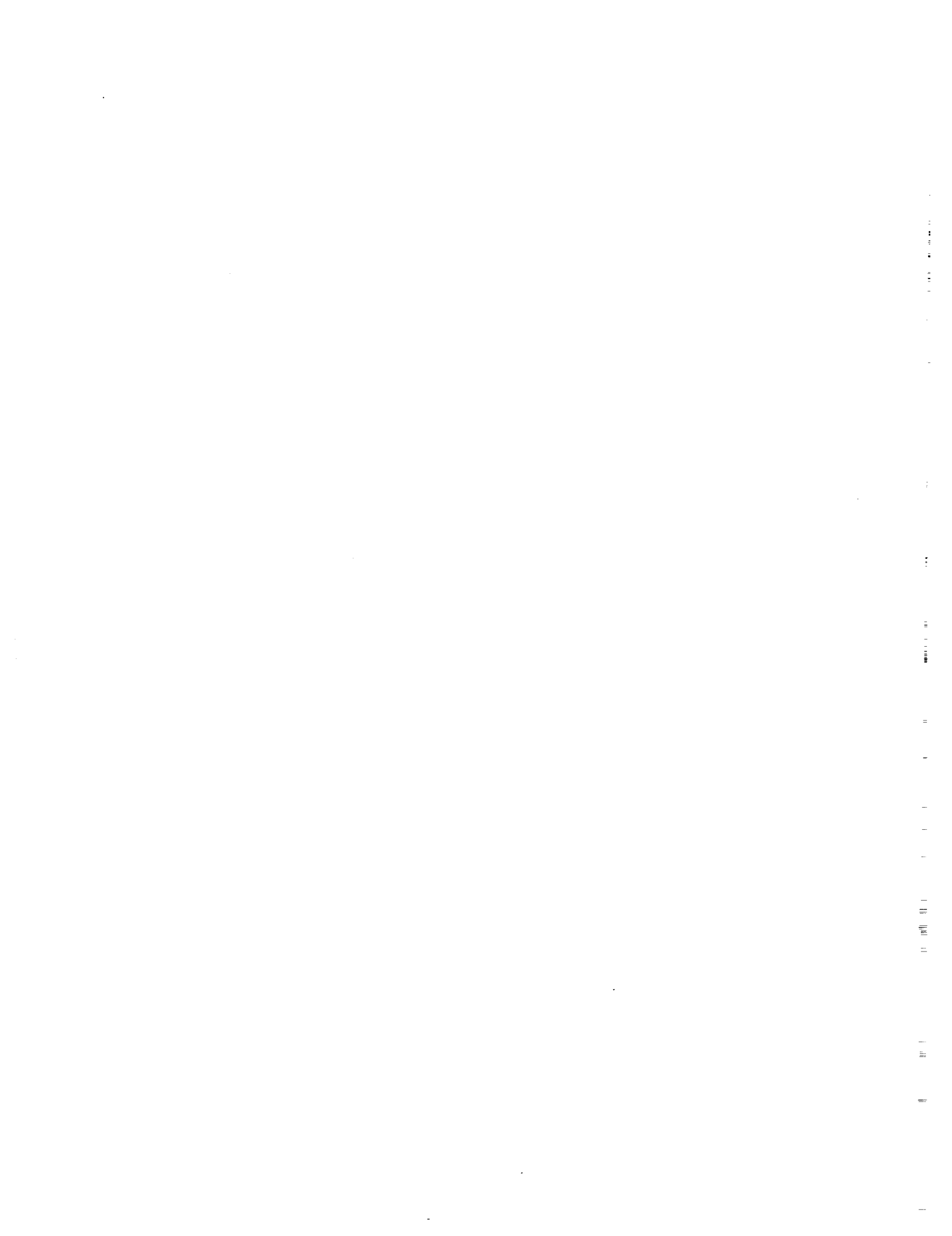
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Planetary Astronomy

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Strategy

Our goal is to use a variety of observational techniques and instruments, and to reduce, interpret, and synthesize groundbased astronomical data concerning small bodies in the solar system -- especially the asteroids -- in order to study the compositions, physical characteristics, population properties, and evolution of these bodies.

Progress and Accomplishments

Faint Asteroid Taxonomy Survey. Our goal is to use a CCD system to characterize the spectral reflectance properties of faint asteroids (mag. 17 - 19) for purposes of taxonomy, size distributions, and other population characteristics of these important small (also dark and/or distant) asteroids. Funding cutbacks permitted only one preliminary observing run at Lowell Observatory (Nov. 1990), which nevertheless provided data on several representative faint asteroids and demonstrated the practicality of the program.

Photometric Geodesy of Main-Belt Asteroids. Our goal has been to determine shapes of a sample of main-belt asteroids and to compare them with theoretical quasi-equilibrium figures for "rubble piles." We completed publication of 107 lightcurves for 59 different asteroids (in addition to 255 lightcurves published earlier). Using lightcurve extrema, we derived or refined shapes and pole positions for 11 asteroids, supplementing earlier results. Seven of our 26 program asteroids show near-equilibrium figures, but they still must have strengths of order 1 bar. We have also made preliminary use of the Simplex algorithm to fit the entire ensemble of data for the 26 asteroids; we find small but physically significant changes to the best axial ratios determined from the extrema.

Main-Belt and NEA Synthesis Studies. Our goal has been to synthesize information on population characteristics of these two groups of asteroids to understand their relationships and evolutionary history. We have clarified some of the issues regarding the S-type asteroid controversy and pursued studies of the implications of the size distribution of NEA's for impacts on the Earth.

NEA Conference. Work has progressed on planning the International Conference on Near-Earth Asteroids (June 30 - July 3, 1991, San Juan Capistrano, CA). About 200 scientists indicate they hope to attend.

Projected Accomplishments

We will conclude our analysis of shapes, continue synthesis studies, hold the NEA Conference, and continue preliminary planning for the faint asteroid survey. However, major progress in acquiring, reducing, and interpreting new data on faint asteroids requires an adequate level of funding.

Publications

Several papers/book chapters, numerous abstracts and presentations.

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Physical Observations of Comets: Their Composition, Origin and Evolution

The University of Texas McDonald Observatory

Anita L. Cochran (P.I.), Edwin S. Barker and William D. Cochran

Strategy

We wish to study the composition, origins and evolution of comets. The composition will be studied using spectroscopic observations of primarily brighter comets at moderate and high resolution to study the distribution of certain gases in the coma. The origins will be addressed through an imaging search for the Kuiper belt of comets. The evolution will be addressed by searching for a link between comets and asteroids utilizing an imaging approach to search for an OH coma.

Progress and Accomplishments

We concentrated our spectral analysis on the weaker features in the spectra. These features include many UV features which were either rarely detected before or have never before been seen (although some, such as the $\Delta v=1$ band of CN were expected). This project is a collaboration with Chet Opal of Texas and with Bob O'Dell, Chris Miller and Dirk Valk of Rice University. Among the most interesting new features are the first detection in the UV of H_2CO and the confirmation of the presence of CO_2^+ throughout this region of the spectrum. We have published two papers already on the UV spectra (one in ApJ in press and one in a conference proceeding) and we are presently working on preparing a third paper on the high quality comet Austin data. In addition, these observations have constituted parts of two Masters projects for Rice University students (Chris Miller and Dirk Valk).

We have shown that the observed CH in comets can be explained easily if CH_2 is the direct parent of CH and CH_4 is the probable grandparent of the CH. CH_3 is not seen as a by-product of this reaction path in the lab so we consider it an unimportant step. From our data, we conclude that Halley had outflow velocities very different from other comets. We also do not have to invoke more complicated parents (although we cannot exclude them) to explain our CH data. These results were published in a conference proceeding.

We have analyzed high quality spectra of P/Schwassmann-Wachmann 1 and have detected the strongest CO^+ spectrum from this comet to date. We show that the fluorescence efficiencies of Magnani and A'Hearn (1986) are consistent with the data for the most part. We demonstrate that photoionization is unlikely to be an important mechanism for producing the CO^+ . In addition, we have detected for the first time an emission feature due to CN. We also detected an unidentified feature in the spectrum. In December 1990, we obtained a series of spectra which, for the first time, detected the turn-on of the CO^+ gas. From our data, we determined the maximum rise time of the gas to be 1.2 days. We show this

"outburst" to be a non-equilibrium process and also that the dust and gas event are not necessarily related. This work has resulted in 1 paper which is in press in *Icarus* (notes) and 1 paper which has been submitted to *Icarus* (notes).

We are working on the analysis of the gas and dust measures of a variety of comets from the Faint Comet Survey. Two papers are in preparation which will contain a wealth of new data on 18 comets. Correlations of dust, CH and NH₂ measures compared with CN data will be presented for the first time. The analysis of the continuum information in the Faint Comet Survey uses the Afp formalism. Comparisons of the dust production rate with distance from the Sun, as well as the continuum brightness variation with distance from the nucleus and with wavelength, were reported at the Fall DPS meeting. The gas production was ratioed to the dust production to get a gas-to-dust ratio. This ratio is observed, in general, to increase with decreasing heliocentric distance.

Projected Accomplishments

We are concentrating on the imaging search for the Kuiper Belt of comets. We have defined our observing procedure and should be able to image easily to $m_v=24$. Our method of obtaining the data will actually allow us to probe a variety of different heliocentric distance depending on the way the images are stacked. We have had 2 observing runs and will have 2 more runs during the spring.

We will continue to observe brighter comets ($m_v < 15$) in order to study the distribution of the gas. We will concentrate on the emissions due to OH, NH, CH, and NH₂. If a really bright comet comes along, we will once more probe the near-UV region at 1 Å resolution in order to confirm our new detections from our Brorsen-Metcalf and Austin observations.

As time permits, we will be imaging a select group of asteroids with cometary orbits searching for an OH coma. We had an observing run for Hidalgo during which we encountered problems but this run did help us to define better the observing procedure.

Publications

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Radial Velocity Detection of Extra-Solar Planetary Systems

McDonald Observatory, The University of Texas at Austin

William D. Cochran***Strategy***

The goal of this program is to detect planetary systems in orbit around other stars through the ultra-high precision measurement of the orbital motion of the star around the star-planet barycenter. Our survey of 33 nearby solar-type stars is the essential first step in understanding the overall problem of planet formation. The McDonald Observatory Planetary Search (MOPS) program will accumulate the necessary statistics to determine the frequency of planet formation as a function of stellar mass, age, and composition.

Progress and Accomplishments

The MOPS has made significant progress in 1990. In particular, we have completed the installation of the stabilized I₂ cell to serve as the velocity reference system. Starlight from the telescope passes through a permanently sealed temperature stabilized I₂ cell before the light enters the spectrograph. Relative radial velocity variations are then measured by determination of the Doppler shift of the stellar photospheric lines with respect to the stabilized I₂ reference lines. Our experience with the I₂ cell demonstrates that we can now achieve rms radial velocity precision of better than 5 m s⁻¹ on most stars. In our monthly observing runs, we are now doing simultaneous observations with the I₂ cell and with the former telluric O₂ line technique, in order to determine the relative zero-points of the two systems. All future observations will be made with the I₂ cell. We have obtained spectra of all available program stars during each of our monthly observing runs. We have completed our data reduction software, and installed it on our new workstations (obtained under State of Texas funding). Our most exciting results to date concern the IAU radial velocity standard star HD114762. In 1988, David Latham discovered periodic radial velocity variations and calculated an orbital solution from his low precision (200 m s⁻¹) data. Our independent orbital solution for the HD114762 confirms Latham's 84 day orbital period, but derives a higher eccentricity for the orbit of 0.38. The mass function for this system indicates a companion with $M \sin i = 0.011 M_{\odot}$. The problem is now to determine if we are viewing a planetary system edge on, or a binary star system pole-on. We have analyzed the profiles of the stellar photospheric absorption lines (which we obtained as an automatic by-product of our radial velocity data) and we have determined that the line profile shapes are purely the result of stellar macroturbulence; the best fit stellar rotational contribution ($V \sin i$) is 0.0 km s⁻¹, with an upper limit of 1.0 km s⁻¹. This corresponds to an upper limit on $\sin i$, the sine of the inclination angle of 0.20. Thus, we determine that the companion object mass is at least 0.055 M_⊙. This means that the companion object is not a planet, but instead is a

either a brown dwarf or a low mass star in a system viewed nearly pole-on. Unfortunately, the HD114762 system is a false alarm for planet detection!

Projected Accomplishments

We will continue regular observations of the 33 stars on the MOPS list. We intend to obtain concentrated time-series observations on selected stars which show possibly periodic short-term radial velocity variations. These variations are possibly due to intrinsic pulsation modes of the star. We need to fully understand the intrinsic stellar variability in order to sort out extrinsic (orbital) from intrinsic (pulsational) radial velocity variations.

Publications

1. "A Search for Eclipses of HD114762 by a Low-Mass Companion" (E. L. Robinson, A. L. Cochran, W. D. Cochran, A. W. Shafter, and E. H. Zhang) *Astron. J.* **99**, 672-674, 1990.
2. "High Precision Measurement of Stellar Radial Velocity Variations" (W. D. Cochran and A. P. Hatzes) in *Optical Spectroscopic Instrumentation and Techniques for the 1990s: Applications in Astronomy, Chemistry and Physics*, B. J. McNamara and J. M. Lerner Eds. *Proc. SPIE* **1318** 148-157, 1990.
3. "Gravitational Instabilities in a Protoplanetary Disk" (H.-R. Noh, E. T. Vishniac, and W. D. Cochran) *Ap. J.* submitted, 1991.
4. "Constraints on the Companion Object to HD114762" (W. D. Cochran, A. P. Hatzes, and T. Hancock) *Ap. J. (Letters)* submitted, 1991.
5. "Radial Velocity Variations of K Giants" (W. D. Cochran and A. P. Hatzes) *Bull. Amer. Astron. Soc.* **21**, 1114, 1989.
6. "The McDonald Observatory Planetary Search" (W. D. Cochran and A. P. Hatzes) *Bull. Amer. Astron. Soc.* **22**, 1082, 1990.

Volatiles in the Outer Solar System

NASA Ames Research Center
Astrophysics Branch
Space Science Division

Dale P. Cruikshank

Strategy

Telescopic data on asteroids, comets, planets, and planetary satellites are acquired and analyzed in the study of volatile ices and gases that occur on their surfaces and in their atmospheres. Infrared spectral studies of certain classes of asteroids for an analysis of their mineralogical and organic constituents are included in this work.

Progress and Accomplishments

Spectra of Triton were obtained at the NASA IRTF in 1990 and are being analyzed using new lab data on both methane and molecular nitrogen. Photometry of "asteroid" 2060 Chiron by me and my colleagues show comet-like activity of this body in the form of a brightness "outburst," since confirmed by others. The overall brightness of Chiron is diminishing at the present time. Thermal measurements of 20 μm were obtained in February 1990. Spectra of numerous asteroids in the range 0.8-2.5 μm were obtained in the search for mineralogical signatures of key asteroid types, and in the study of solid X-C \equiv N bearing surface materials. An absorption band identified as the first overtone of the X-C \equiv N fundamental has been found at 2.2-2.3 μm in the spectra of two comets, several D-type asteroids, and possibly in the rings of Uranus and the dark hemisphere of Iapetus; the data for the asteroids and Iapetus were obtained by Cruikshank and colleagues. Plans to obtain a new high-resolution IR spectrum of Io were thwarted by the catastrophic failure of a facility instrument at the IRTF in February 1991.

Projected Accomplishments

Further observations of Triton at maximum attainable resolution will be obtained. Further IR data on Chiron will be obtained to explore its cometary nature. High-resolution Io spectra will be obtained and analyzed. Pluto spectra will be analyzed. Spectra of Ariel will be obtained and analyzed. Observational and laboratory studies of the solid X-C \equiv N overtone band in the spectra of asteroids, comets, and other dark-surfaced bodies will continue with the use of the IRTF and lab facilities at Ames Research Center (L. Allamandola's lab).

Publications

P.N. Thomas, J. Veverka, J. Bell, J. Lunine, and D. Cruikshank. "Satellites of Mars: Geologic History," in Mars, *** ed., Univ. of Arizona Press, Tucson, 1991 (in press).

F. Salama, L.J. Allamandola, F.C. Witteborn, D.P. Cruikshank, S.A. Sandford, and J.D. Bregman. "The 2.5-5.0 μm Spectra of Io: Evidence for H_2S and H_2O Frozen in SO_2 ". **Proc. 24th ESLAB Symp. on Formation of Stars and Planets, and the Evolution of the Solar System**, ESA SP-315, 203-208, 1990.

D.P. Cruikshank, M.W. Werner, and D.E. Backman. "SIRTF: Capabilities for Planetary Science," **Adv. Space Res.** (in press) 1991.

D.P. Cruikshank. "Solar System Astronomy from the Moon: Studies of Solid Bodies and Other Condensed Phase Matter." In **Astrophysics from the Moon**, American Institute of Physics Conference Report 207, M.J. Mumma and H.J. Smith, Eds. AIP: New York, 1990, pp 35-40. See also "Summary of Panel Discussion" (same volume, pp 33-34).

D.P. Cruikshank, D.J. Tholen, W.K. Hartmann, J.F. Bell, and R.H. Brown. "Three Basaltic Earth-Crossing Asteroids and the Source of the Basaltic Meteorites." **Icarus** **89**, 1-13, 1991.

D.P. Cruikshank, W.K. Hartmann, D.J. Tholen, L.J. Allamandola, R.H. Brown, C.N. Matthews, and J.F. Bell. "Solid $\text{C}\equiv\text{N}$ Bearing Material on Solar System Bodies," submitted, 1991.

Spectroscopic Planetary Detection

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Strategy

One of the most promising methods for the detection of extra-solar planets is the spectroscopic method, where a small Doppler shift (~ 10 meters/sec) in the spectrum of the parent star reveals the presence of planetary companions. However, solar-type stars may show spurious Doppler shifts due to surface activity. If these effects are periodic, as is the solar activity cycle, then they may masquerade as planetary companions. The goal of this investigation is to determine whether the solar cycle affects the Doppler stability of integrated sunlight. Observations of integrated sunlight are made in the near infrared ($\sim 2 \mu\text{m}$), using the Kitt Peak McMath Fourier transform spectrometer, with an N_2O gas absorption cell for calibration. We currently achieve an accuracy of ~ 5 meters/sec.

Progress and Accomplishments

We have been monitoring the apparent velocity of integrated sunlight since 1983. We initially saw a decrease of ~ 30 meters/sec in the integrated light velocity from 1983 through 1985, but after 1987 the integrated light velocity returned to its 1983 level. It is plausible that these changes are solar-cycle related, but it is still too early to be sure.

Projected Accomplishments

Wallace et al. (1988, Ap.J. **327**, 399) found that the relative wavelengths of lines in integrated light were stable over the solar cycle, and they concluded that planetary companions were detectable. However, in a recent analysis of the extensive Mt. Wilson data, Ulrich and coworkers found evidence for large scale flows with amplitudes up to 50 meters/sec. Since such flows will affect all lines, they will not be seen in relative line shifts, but they may have a significant impact on spectroscopic planetary detection. However, our continued monitoring of integrated sunlight will detect such effects if they are present, since our measurements are absolute. When solar maximum has passed (>1991), we should know whether the changes seen earlier in integrated light velocity are periodic with the solar cycle, and to what extent large scale flows present a limitation to spectroscopic planetary detection.

Publications

"On the Apparent Velocity of Integrated Sunlight," D. Deming, F. Espenak, D. E. Jennings, J. W. Brault and J. Wagner 1987, Ap.J. **316**, 771-787.

Studies of Thermal Wave Phenomena on the Jovian Planets

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Strategy

Ground-based and Voyager observations of Jupiter have provided evidence that the tropospheric temperature shows global-scale longitudinal variations which are often wavelike in character. Voyager data were reported to exhibit the presence of "slowly-moving thermal features" (Magalhaes et al., 1989 *Nature* 337, 444), wherein the jovian tropospheric temperature patterns are not advected by the equatorial zonal winds, but are found to rotate at the System III (interior) rate. Ground-based data in a broad infrared band (8-13 μm) show a wavelike structure (Deming et al. 1989, *Ap.J.* 343, 456) whose amplitude and spatial scale are similar to the reported properties of the slowly moving thermal features. This investigation is directed toward obtaining additional ground-based data in infrared spectral bands whose contribution functions are optimized for specific atmospheric regions (tropospheric at 20 μm , and stratospheric at 7.8 μm), in order to confirm the previous results, and to identify the nature and physical significance of wavelike longitudinal temperature fluctuations on the jovian planets. A 2-D infrared array detector and low resolution cryogenic grating spectrometer is being adapted to obtain maps in $\sim 2 \text{ cm}^{-1}$ bandpasses.

Progress and Accomplishments

Subsequent to our initial exploratory observations in 1987, we obtained additional 8-13 μm data in 1989, and extended the observations to include 7.8 μm data. Additional observations have been hampered by relatively poor weather over Mauna Kea, and by instrumental problems in 1991. Nevertheless, significant additional data have been obtained at 7.8 and 20 μm , and all of the data are currently being analyzed. It is anticipated that the recent data should help to clarify the nature of longitudinal temperature variations on Jupiter.

Projected Accomplishments

In FY92, the cryogenic grating spectrometer will be made fully operational, and the spectral bands will be extended to include the strong stratospheric ethane emission near 12 μm . Exploratory observations will be made of possible longitudinal temperature variations on Saturn.

Publications

"A Search for p-Mode Oscillations of Jupiter: Serendipitous Observations of Nonacoustic Thermal Wave Structure," D. Deming, M.J. Mumma, F. Espenak, D.E. Jennings, T. Kostjuk, G. Weidemann, R. Loewenstein and J. Piscitelli, *Ap.J.* **343**, 456.

Occultation Studies of the Solar System

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Strategy

Because of their high spatial resolution, stellar occultations have proven extremely effective for learning about planetary upper atmospheres, asteroids, and planetary rings. Our occultation program at M.I.T. involves (i) identifying the scientific questions that can be answered by occultation events, (ii) predicting the zone of visibility for the useful events, (iii) maintaining and improving a high-speed CCD camera for observing occultations, (iv) obtaining the observations, and (v) reducing the data and interpreting the results.

Progress and Accomplishments

Our accomplishments during the past year include (i) development of a model fitting technique that includes, for the first time, an atmospheric thermal gradient as a fitted parameter for stellar occultation data; (ii) use of this technique to test the isothermal prediction of the "methane-thermostat" model by reanalyzing our occultation data for Pluto's atmosphere—we found that Pluto's upper atmosphere is isothermal to a limit of $0.1 \text{ }^\circ\text{K km}^{-1}$; (iii) a search for Pluto occultation candidates for the years 1991-5 with the CCD strip scanning technique; (iv) a collaboration with our colleagues at Lowell Observatory to use all available data from the 1988 occultation to determine accurate radii for several levels of Pluto's atmosphere; and (v) using Walker's 1980 Charon occultation data to establish upper limits of only a few cm-Amagats for any possible atmosphere of Charon.

Projected Accomplishments

We are currently drafting manuscripts for the results of (i), (ii), (iii), and (iv). Our search for Pluto occultation candidates with the CCD strip-scanning method will be extended to the latter half of the decade, and we shall attempt to use this method for identifying Triton occultation candidates as well. Observation of several Pluto occultations this spring will be attempted if final predictions indicate that these occultations might be observable. Also, we shall be looking ahead to the 1992 probable occultation of a 13th magnitude star by Pluto, which can be used to determine whether Pluto has a haze layer in its atmosphere.

Publications

Baron, R. L., R. G. French, and J. L. Elliot 1989. The oblateness of Uranus at the 1- μ bar level. *Icarus* **78**, 119-130.

Elliot, J. L., and L. A. Young 1990. Limits on the radius and a possible atmosphere of Charon from its 1980 stellar occultation. *Icarus* **89**, 244-254.

Elliot, J. L., E. W. Dunham, A. S. Bosh, S. M. Slivan, L. A. Young, L. H. Wasserman, and R. L. Millis 1989. Pluto's atmosphere. *Icarus* **77**, 148-170.

Planetary Spectroscopy

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Strategy

Our effort is divided into instrumentation and observational research. In the area of instrumentation our primary objective is the maintenance and slow improvement of our CCD camera and data acquisition system for continuing use of any interested LPL user. The main goal of our observational research is CCD spectroscopic and imaging studies of the solar system in support of spacecraft investigations. Our studies include the physical behavior of comets, the atmospheres of the gaseous planets, and the solid surfaces of satellites and asteroids.

Progress and Accomplishments

During the past year we integrated a new CCD controller from Photometrics into our data acquisition system. This new controller will allow sub-array readout and binning. It has received very favorable comments from Dr. Hunten's group who have used it extensively. Users include: K. Wells, R. Kozlowski, A. Sprague, B. Rizk, K. Garlow, and H. Caudill. Our system was also used for an extended observing run on the asteroid/comet Chiron by M. Buie and K. Meech. Our own observation program last year involved spectroscopy of a representative sample of comets to determine differences in chemical composition. We observed Wild 4, P/Schwassmann-Wachmann 3, Austin, P/Peters-Hartley, Levy, P/Russell 3, P/Kopff, and P/Encke. P/Kopff is the target of the CRAF mission; comet Austin was the brightest comet last year. In addition we obtained a very high quality spectrum of Triton, as well as a spectrum of Pluto which we are monitoring every year for potential atmospheric changes since its perihelion 1989 Sept.

Our analysis efforts concentrated on continued analysis of comet P/Halley data. We completed a paper on "The production rate and spatial distribution of H₂O for comet P/Halley" *Ap J.*, **364**, 687-698, 1990. This paper derived a pre-perihelion fit to the H₂O production rate of $Q(\text{H}_2\text{O}) = 4.36 \times 10^{29} \times r^{-2.59}$. The post-perihelion data agreed roughly with this fit but gave an enhancement by a factor of ~1.8 and showed strong variations due to P/Halley's variability. We also completed a paper on "Composition comparison between P/Halley and P/Brorsen-Metcalf" *Icarus*, **91**, in press (1991). When compared to common H₂O production rates, the dust production rate of P/Brorsen-Metcalf was weaker than comet Halley by a factor of 20, NH₂ was down by 41, C₂ by 75, and CN by 70% indicating a significant difference in chemical composition between the two comets. In our new spectrum

of Triton the 8900 Å methane ice band can be clearly seen for the first time and accurately measured. We set a methane ice grain size between 20 and 200 μm and concluded that methane ice is widely distributed on Triton's surface. We have expended a considerable effort in extracting spatial profiles from our P/Halley spectra. We have analyzed three pre-perihelion and three post-perihelion dates and have determined Haser model scale lengths for C₂, CN, NH₂, and OI. We found that good scale lengths could be determined for pre-perihelion dates but the post-perihelion data were severely affected by P/Halley's time varying production rate. This work is being submitted for publication.

Projected Accomplishments

We have begun a more complex analysis of our spatial profiles that includes time varying production and a CHON coma model. Following the determination of spatial profiles and scale lengths, we will begin the last major analysis program using our extensive P/Halley spectral library, i.e., the variation of the production rates of C₂, CN, NH₂ and the continuum with heliocentric distance. For our investigation of possible chemical differences among comets we will analyze spectra of a variety of comets taken within the last two years. Observationally we are planning to obtain further spectra of both periodic and new comets to extend our comet library searching for compositional differences. We also will try to obtain better SNR spectra of Triton and improve the data base and analysis for this intriguing object.

Allegheny Observatory Search for Planetary Systems

Allegheny Observatory of the University of Pittsburgh

George D. Gatewood***Strategy***

The newly developed Multichannel Astrometric Photometer (MAP) and a completely rebuilt (including new optical system) red-light 0.76-meter Thaw refractor of the University of Pittsburgh's Allegheny Observatory are employed in an astrometric observational program to detect Jupiter-like planets in orbit about nearby stars. Now in its fifth year, the program includes 15 stars and is obtaining approximately 12 good observations per year of each of them, sufficient to assure an annual normal point precision of 0.001 arcsec (1 mas) per object (Gatewood, G., et al., 1990, Ap. J. **364**, 114). While the observational program is small, it will yield the first astrometric information about planetary systems in general. The detection of jovian objects (similar in mass and orbital period to Jupiter) will yield information about specific planetary systems. If several are detected these will be suggestive of patterns involving both the characteristics of the planets and the stars which they orbit. Since, however, the technique being applied will also yield a statistically well-defined negative result, a failure to detect such systems will place the first constraints on the probable nature of planetary systems.

The astrometric technique is most sensitive to nearby planetary systems and to massive planets that have orbits that place them within the regions around a star where the temperature is sufficiently low to permit the existence of water ice grains. Thus it covers a different search space than that of radial velocity techniques. Currently the only astrometric survey program, it is complimentary to other detection programs and some target stars have been included to assure overlap with them. The minimum detectable mass varies with the particular target star from objects almost twice as massive as Neptune to bodies almost twice as massive as Jupiter.

Projected Accomplishments

1991 will be the sixth year of observation for several program stars. An initial analysis shows that all but one are moving linearly. The exception, Barnard's star, shows a small perturbation which could be a statistic variation or could indicate the presence of a small planet in an orbit with a period of 5 or more years. Preliminary analysis of this and several other stars will be published in 1992.

Publications

The following papers are from the overall Allegheny Observatory astrometric-photometric programs. They indicate its success and detail some photometric data for stars in the planetary system search program.

Gatewood, G. 1990, Castelaz, M., Persinger, T., Stein, J., Stephenson, B., and Tangren, W. 1990, Ap.J. **364**, 114.

Persinger, T., and Castelaz, M.W. 1990, A.J. **100**, 1655.

Surveying of the Solar System

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Tom Gehrels

Strategy

Some populations of objects in the solar system are poorly known, and the long-range goal of this program is to improve that situation. For instance, we are working with Drs. C. J. and I. van Houten of the Leiden Observatory in a continuation of the Palomar-Leiden Survey to investigate the statistics of Trojan asteroids. We are also developing new techniques of sky surveillance by scanning with CCD, particularly for the discovery of near-Earth asteroids.

Progress and Accomplishments

We are observing full time during the dark half of each month with the Spacewatch Telescope which is the 91-cm Newtonian reflector of the Steward Observatory on Kitt Peak. This telescope became usable for the discovery of near-Earth asteroids when the 2048 x 2048 CCD, with pixel size 27 microns, became available. This Tektronix CCD is now in operation with a Solbourne work station and sophisticated software. We are finding typically 2,000 main-belt asteroids and two near-Earth asteroids per month; only the latter are followed with astrometry.

Projected Accomplishments

The discovery of near-Earth asteroids is to be further improved by refinements in software, operation, and design of new equipment.

Publications

Gehrels, T. (1991). Scanning with Charge-Coupled Devices. Space Science Reviews, in press.

Rabinowitz, D. L. (1991). Detection of Earth-approaching Asteroids in Near Real-Time. Astron. J., in press.

van Houten, C. J., van Houten Groeneveld, I., Wisse-Schouten, M., Bardwell, C., Green, D.W.E., and Gehrels, T. (1991). The Second Palomar-Leiden Trojan Survey. Icarus, in press.



Operation of the University of Hawaii 2.2M Telescope on Mauna Kea

University of Hawaii
Institute for Astronomy

Donald N.B. Hall

Strategy

NASA's planetary astronomy program provides part of the funding for the operation of the University of Hawaii's 2.2 meter telescope. This funding provides access by planetary astronomers to a guaranteed fraction of the observing time on this telescope. At present this fraction is approximately 20%. Proposals for use of the planetary observing time coming from within and outside the University of Hawaii compete for this observing time on an equal basis, and applications are judged on scientific merit by a time allocation committee at the University of Hawaii. Current scheduling periods and corresponding deadlines are:

<u>Observing Period</u>	<u>Due Date</u>
April-July	January 31
August-November	May 31
December-March	September 30

Applications for observing time should be addressed to The Director, Institute for Astronomy, 2680 Woodlawn Drive, Honolulu, HI 96822. A newsletter is published shortly before each observing deadline, and it contains the latest information on instrument availability. Requests to be added to the mailing list for this newsletter can be sent via e-mail to 88inch@galileo.ifa.hawaii.edu.

Progress and Accomplishments

A major instrumental highlight in the past year has been the commissioning of a 256 x 256 near-infrared camera which utilizes a Rockwell NICMOS-3 array. At the $f/10$ focus, image scales of 0.37 and 0.75 arcsec/pixel are available. A new, high quantum efficiency Tektronix 1024 x 1024 CCD saw first light on the telescope in February 1991, and will be available as a regularly scheduled instrument from April 1991. Data from both of these new detectors are transmitted directly to the Sun workstation for immediate analysis by the observers.

The autoguider software has been enhanced to permit guided tracking on objects having non-sidereal motions (i.e., solar system objects). This feature has been very well received by the planetary community.

The Coudé spectrograph has been considerably modernized in the last year. Improvements include a new direct CCD camera and associated remotely operated optical system for slit and

field viewing and guiding. A new camera mount giving remote CCD focus and translation has also been installed.

Projected Accomplishments

In the coming year, higher resolution imaging in the near-infrared and optical will be possible with the commissioning of the new optimally figured f/31 secondary mirror. This will be mounted on a tip-tilt platform to remove image motion produced both by the atmosphere and telescope shake. A new spectrograph designed to make use of the properties of this f/31 secondary mirror is expected to be commissioned in August 1991. Another improvement planned for the coming year is enhanced communication between instrument and telescope computers.

Publications

Cruikshank, D.P., Tholen, D.J., Hartmann, W.K., Bell, J.F., and Brown, R.H. (1991) "Three Basaltic Asteroids and the Source of the Eucrites" *Icarus*, **89**, 1.

Hammel, H.B. (1990) "CCD Imaging of Neptune at Methane-band Wavelengths" *Adv. Space Res.*, **10**, 99.

Hartmann, W.K., and Tholen, D.J. (1990) "Comet Nuclei and Trojan Asteroids: A New Link and Possible Mechanism for Comet Splittings" (1990) *Icarus*, **83**, 1.

Hartmann, W.K., Tholen, D.J., Meech, K.J., and Cruikshank, D.P. (1990) "2060 Chiron: Colorimetry and Possible Cometary Behavior" *Icarus*, **83**, 1.

Jewitt, D.C. (1990) "Observations of Cometary Nuclei" in *Asteroids, Comets, Meteors III*, p. 347.

Jewitt, D.C. (1990) "Cometary Photometry" in *Comets in the Post-Halley Era*, in press.

Lockwood, G.W., Thompson, D.T., Hammel, H.B., Birch, P., and Candy, M. (1990) "Neptune's Cloud Structure in 1989: Photometric Variations and Correlation with Ground-Based Images" *Icarus*, in press.

Luu, J.X., and Jewitt, D.C. (1990) "Cometary Activity in 2060 Chiron," *A.J.*, **100**, 913.

Meech, K.J., and Belton, M.J.S. (1990) "The Atmosphere of 2060 Chiron," *A.J.*, **100**, 1323.

Meech, K.J. (1990) "Aging in Comets," in IAU colloquium 116 (in press).

Ridgway, S.E., Jewitt, D.C., Campins, H., Luu, J., Joy, M., Sisc, C., and Telesco, C. (1990) "An Albedo Map of Comet Brorsen-Metcalf," in *Astrophysics with Infrared Arrays*.

Infrared Observations of Comets

Jet Propulsion Laboratory

Martha S. Hanner

Strategy

Selected comets are observed in the near-infrared (1-2.2 μm) and thermal infrared (3.5-20 μm) with the NASA Infrared Telescope Facility (IRTF) and other telescopes as appropriate, in order to characterize the physical properties of the dust grains -- their composition, size distribution, emissivity, and albedo. Systematic variations in these properties among comets are looked for, in order to understand the heterogeneity of comet nuclei. Spectrophotometry of the 10 μm silicate emission feature is particularly emphasized. The rate of dust production from the nucleus and its temporal variability are also determined. Knowledge of the dust environment is essential to S/C design and mission planning for NASA's CRAF mission.

Progress and Accomplishments

10 μm spectrophotometry of Comet Levy was obtained at the IRTF; a strong silicate feature was detected with an 11.3 μm olivine peak similar to that in Comets Halley and Bradfield (1987). This result is significant in showing that crystalline olivine grains are prevalent in both new and evolved comets. A paper on Comet P/Brorsen-Metcalf has been submitted for publication. Although its orbit is similar to that of P/Halley, the dust properties are very different; no silicate feature was present. We interpreted the observations with a model of large grains in the coma. A paper on the dust coma of P/Giacobini-Zinner has been submitted for publication.

Projected Accomplishments

IRTF time has been obtained for extending the spectrophotometry of the 10 μm region to the fainter, short-lived comets with favorable geometry, as well as continuing to observe bright comets as targets of opportunity. Papers on Comet Austin and Comet Levy are in progress. The observed shape of the silicate feature in Comets Halley and Levy is being compared with models for the emission from inhomogeneous, irregular particles.

Publications

Hanner, M. S., Newburn, R. L., Gehrz, R. D., Harrison, T., Ney, E.P., and Hayward, T. L. (1990). The infrared spectrum of Comet Bradfield (1987s) and the silicate emission feature. *Astrophys. J.* **348**, 312.

Hanner, M. S., and Tokunaga, A. T. (1990). Infrared techniques for comet observations. In *Comets in the Post-Halley Era*, ed. R. L. Newburn, M. M. Neugebauer, and J. Rahe, in press.

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Search for Planet X

U.S. Naval Observatory

Robert S. Harrington

The effort this year will be entirely observational. The region of the sky in which we believe Planet X should now be, based on perturbations observed in the motions of Uranus and Neptune, was determined last year, and there has been no reason to update that determination. A limited area of that region was photographed last year, and that will be continued this year. A given area is photographed with our twin 20-cm astrograph in New Zealand on two successive nights near the time that area is in opposition, and these plates are blinked in Washington to identify anything that has moved. The predicted region is in the South, which requires observations from a southern station, and it is in opposition in the April to June period, which means observations have not yet started this year. Blinking will be done as soon as the plates are received in Washington, but it will only be at the very end of the fiscal year before we have any results, positive or negative.



Asteroid Photometry

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Alan W. Harris

Strategy

Photoelectric lightcurves provide fundamental information about asteroids: rotation periods, pole orientations, shapes, and phase relations, which yield some information about the surface physical properties. This task is to carry on a program of such observations to increase the overall data base, obtain data on newly discovered asteroids, and to observe asteroids which are the subject of other complementary observations, such as occultations, radar, and IR.

Progress and Accomplishments

To date, approximately 1/3 of all known asteroid rotation periods and about 1/2 of all precision phase relations derive from TMO observations. A notable highlight this year was the demonstration, from high precision phase relation observations, that a three-parameter phase relation model is necessary to fit all asteroid phase relations. At a fundamental level, this means that the single- and multiple-scattering properties of asteroid surfaces differ from one to another, not just the ratio of single- vs multiple-scattering. Another accomplishment was the first use at TMO of a CCD camera for asteroid photometry, which enables us to follow up essentially all new asteroid discoveries, most of which are too faint for conventional photometry with the 24" telescope.

Projected Accomplishments

We propose to continue the asteroid program, with emphasis on measuring phase relations of low and high albedo asteroids at very low phase angles, collaborative observations in support of occultation and radar targets, and follow-up of newly discovered near-earth asteroids. An important new thrust will be to use a CCD camera, already available at TMO, for photometry of fainter asteroids. This will allow us to follow up essentially all newly discovered near-earth asteroids. A number of administrative and editorial duties will also be covered under this task: President of IAU Comm. 15, Chairman of Div. on Dynamical Astronomy of the AAS, Co-organizer of ACM 91 and Co-editor of its proceedings.

Publications

Harris, A.W., et al. Asteroid Lightcurve observations from 1981. *Icarus*, in press.

Harris, A.W., et al. (1990) Recent results from asteroid photometry. *Bul. Amer. Astron. Soc.* 22, 1112-1113.

Harris, A.W., et al. (1991) Photoelectric lightcurve and phase relation of 47 Aglaja. (Abstract, ACM 91 meeting).

Harris, A.W. (1991) High precision phase relations of dark, light, and intermediate asteroids. (Abstract, ACM 91 meeting).

***Studies of Relationships Among Outer Solar System Small Bodies
and Related Objects***

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Strategy

This program involves telescopic observations of colorimetry, spectroscopy and photometry of small bodies of the solar system, emphasizing possible relationships among outer solar system asteroids, comets, and certain satellites. Earth approacher targets of opportunity and lab spectroscopic studies are included.

Progress and Accomplishments

The current year of the program is very productive. Our discovery that a band at 2.2 μm can be associated with $\text{C}\equiv\text{N}$ bearing solid organic material in asteroids, comets, the Uranian rings, and Iapetus, has been announced in 1991 LPSC and 1990 DPS abstracts. We completed an MKO UH-88 run in March 1990, netting lightcurve data on 7 Trojan and Hilda asteroids. We also completed an IRTF observing run in December 1990 with astrometry on Galileo target asteroid 951 Gaspra, and new bolometry and/or colorimetry on other asteroids and comets. We completed a new paper on our discovery that 3 Earth-approaching asteroids show spectra matching basaltic achondrites and this was published in *Icarus* in 1991. Three other papers were published in *Icarus* in calendar 1990. Also, I am serving on the NASA Discovery Program Science Working Group on low-cost missions to small bodies, at the invitation of Wes Huntress and Joe Veverka.

Projected Accomplishments

We have several papers in progress. We have submitted a paper on the first identification of solid $\text{C}\equiv\text{N}$ bearing organic materials on outer solar system bodies. We are preparing a laboratory study of spectra of organic asteroid-candidate materials and another paper on Trojan lightcurves. We anticipate at least one Mauna Kea observing run in 1991 to study outer solar system bodies, especially 2061 Chiron.

Publications

Cruikshank, Tholen, Hartmann, Bell, and Brown (1991). Three Earth-Approaching Asteroids and the Source of the Basaltic Meteorites, *Icarus*, **89**, 1-13.

Hartmann and Tholen (1990). Comet Nuclei and Trojan Asteroids: A New Link and a Possible Mechanism for Comet Splittings, *Icarus*, **86**, 448-454.

Hartmann, Tholen, Meech, and Cruikshank (1990). 2060 Chiron: Colorimetry and Cometary Behavior, *Icarus*, **83**, 1-15.

Hartmann (1990). Additional Evidence About an Early Intense Flux of C Asteroids and the Origin of Phobos, *Icarus*, **87**, 236-240.

Palomar Planet-Crossing Asteroid Survey (PCAS)

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Strategy

The objective of this program is the discovery and follow-up of planet-crossing asteroids, related inner-belt asteroids and comets. The primary program is carried out with the 0.46 m Schmidt telescope at Palomar Observatory. The results, subsequent observations, and analysis provide insight into their populations, orbits, origins, physical characteristics (composition, size, shape), potential for impact, relationships to comets and meteorites, and for future spacecraft mission candidates.

Progress and Accomplishments

14 Near-Earth Asteroids (NEA's), 5 Apollos and 9 Amors, were discovered in the last 14 months, an unprecedented number of discoveries in such a short period. This high discovery rate reflects still greater sky coverage, improvement in focus and threshold detection. In addition, 254 other asteroids of all classes were discovered, reported and given designations including 43 high inclination asteroids (17 Hungarias and 26 Phocaeas). Several of the NEA's (1990 MF, 1990 OS, 1990 UA and 1991 AC) made close approaches to the Earth allowing successful radar observations. An unexpected, very bright discovery was made, 1990 SQ and observed for over 5 months. It is the brightest asteroid yet found in the earth-crossing population. It has an absolute magnitude, $H=12.5$, ~10 km in diameter. (1627 Ivar had been the previous record holder.) At the other extreme, two very faint, $H=20$, were found. They have very low inclinations of <1 degree which when combined with their other orbital elements indicates that they could be Earth impactors in the future. 13 asteroids have been permanently numbered and another 15 previously numbered have been officially named. Of the newly numbered, two are NEA's. Our best observed mission candidate, 1982 DB, was recovered and numbered (4660). It offers several opportunities for low delta V spacecraft missions in the next decade.

Projected Accomplishments

Continuing progress is anticipated in the automated identification and measurement procedures. With diligence and fine tuning, we plan to maintain and improve our results. However, a major increase in our rate of discovery will require an upgrade to a large CCD array retrofitted on the 0.46 m Schmidt. Along with our primary NEA program, we will continue our studies and analysis of inner-belt asteroid regions.

Publications

Helin, Eleanor F. and Brian P. Roman (1989) "High Inclination Inner-Belt Asteroids: Hungarias and Phocaeas", in *Asteroids, Comets, Meteors III*, (Lagervist, C-I., Lindblad, B.A., Lundtedt, H., and Rickman, H. Eds), pp.105-108.

Helin, E. F. and R. S. Dunbar (1990) "Search Techniques for Near-Earth Asteroids", *Vistas in Astronomy*, V. 33, No. 1, pp. 21-37.

Helin, E.F., Roman, B.P., Alu, J.T. (1990) "Comets Discovered by PCAS in 1989", *Lunar and Planetary Science Conference XXI Proc.*, Part 2, p.492.

Helin, E.F., Roman B.P., Lawrence K.J. (1990) "Near-Earth Asteroids: Need for Physical Observations at Discovery Apparition", *Meteoritical Meetings*, Perth, Australia, Sept. 1990.

Helin, E.F., Roman, B.P., Lawrence K.J. (1990) "Proliferation of Near-Earth Asteroid Discoveries", *AAS, DPS*, Charlottesville, Va., Nov. 1990.

Discovery and Astrometric Position Publications

International Astronomical Union Circulars:

1990: 4951, 4952, 4954, 5001, 5018, 5025, 5041, 5044, 5045, 5056, 5063, 5064, 5103, 5120, 5147, 5150

1991: 5171, 5177, 5194, 5198

Minor Planet Circulars:

1990: 15603-607, 15625-629, 15811-820, 15946-948, 15967-977, 16122-124, 16145-146, 16294-301, 16335-342, 16480-483, 16521-526, 16652-655, 16671-674, 16772-776, 16802-827, 16958-986, 17106-130, 17331-346

1991: 17525-562, 17710-717

Infrared Speckle Interferometry and Spectroscopy of Io

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Robert R. Howell***Strategy***

The goal of the project during the last year has been to continue the speckle monitoring of volcanic hot spots on Io, and to begin observations of the 1991 series of mutual events between Io and Europa. The former provide a time history of the volcanic activity, while the latter give the highest spatial resolution and the best sensitivity to faint spots. A minor component of the program is lunar occultation observations of young T Tauri stars. The occultations provide milliarcsecond resolution which let us search for circumstellar material and determine which systems are multiple.

Progress and Accomplishments

Speckle observations were obtained during the 1990 opposition which showed continued changes in activity in the Loki region. Mutual event observations were begun on January 1, 1991. The data obtained so far show major activity at Loki, and also detect a weaker spot at Pele. The Loki spot is clearly resolved. A very preliminary reduction of the data suggests it is roughly circular and has a diameter of 150 km.

The detection of Pele confirms earlier speckle observation from the Arizona group led by McLeod and McCarthy. The basic source is clearly long lived, despite the disappearance of the plume between the two Voyager encounters. When the Wyoming 5 micron data is combined with other wavelength observations obtained by the JPL group at IRTF, it is clear that Loki is a relatively cool source while Pele is hotter.

Lunar occultations show extended material around several stars, including DG Tau. In addition, several other stars are binaries. There does seem to be a correlation in that the multiple systems DO NOT contain extended material.

Projected Accomplishments

The major goal of the coming year is to finish the observations of the mutual events, and to analyze and publish that data. The location of bright hotspots can be done quickly with the existing data, but more detailed modeling is required to detect fainter ones. Several occultations of the Loki hot spot were obtained, each which gives a cut through the object at two position angles. It should be possible to use "tomographic" reconstruction techniques to obtain a rough 2-D image of this spot. That would allow a much more detailed study of the nature of the volcanism at this active center.

Publications

Nash, D. B., and Howell, R. R. 1989. "Hydrogen Sulfide on Io: Evidence from Telescopic and Laboratory Infrared Spectra." *Science* **244**: 454-457.

Chen et al. 1990. Discovery of Five Pre-Main-Sequence Binaries in Taurus. *Ap. J.* **357**: 224-230

Interiors and Atmospheres of the Outer Planets

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W.B. Hubbard***Strategy***

This theoretical/observational project constrains structure of outer planets atmospheres and interiors through observational data. The primary observational tool is through observations of occultations of stars by outer solar system objects, which yield information about atmospheric temperatures and dynamics, and planetary dimensions and oblateness. The theoretical work relates the data to interior structures in a variety of ways.

Progress and Accomplishments

We continue analysis of the massive data set from the 1989 occultation of 28 Sgr by Saturn and Titan. Our 28 Sgr occultation data are competitive in precision with the Voyager RSS/PPS data. Unlike the Voyager measurements, we have nearly simultaneous cuts through the ring system from several stations at different distances from Saturn's center. From observations of ~15 sharp-edged fiducial ring edges from 5 stations, we have ~100 timings which constrain the solution. Our solution for the pole, radius scale, and Saturn's center is an essential first step for analysis of all the 28 Sgr data. The resulting astrometry should have an absolute accuracy ~10 km for the position of Saturn's ring center (= mass center) with respect to 28 Sgr, and a relative precision ~1-2 km for the position of ring features with respect to each other. During 1990 we successfully observed an asteroid occultation by Kleopatra, but lack of other observations may preclude a determination of Kleopatra's diameter from this event.

Projected Accomplishments

We plan to continue reducing and analyzing the prodigious amount of occultation data (~1 gigabyte) gathered during 1989. The analysis is yielding detailed information on the structure and shape of the upper atmospheres of Jupiter, Saturn, and Titan. The Titan data base has grown due to contributions from other observers in Europe and England. Our Neptune occultation data will be reanalyzed using the improved knowledge of Neptune's pole and ring system from the 1989 Voyager encounter.

Publications

Results for Titan's Atmosphere from its Occultation of 28 Sagittarii, W.B. Hubbard, D.M. Hunten, H.J. Reitsema, N. Brosch, Y. Nevo, E. Carreira, F. Rossi, and L.H. Wasserman, *Nature*, **343**, 353-355, 1990.

The Size and Shape of (2) Pallas From the 1983 Occultation of 1 Vulpeculae, D.W. Dunham, J.B. Dunham, R.P. Binzel, D.S. Evans, M. Freuh, G.W. Henry, M.F. A'Hearn, R.G. Schnurr, R. Betts, H. Haynes, R. Orcutt, E. Bowell, L.H. Wasserman, R.A. Nye, H.L. Giclas, C.R. Chapman, R.D. Dietz, C. Moncivais, W.T. Douglass, D.C. Parker, J.D. Beish, J.O. Martin, D.R. Monger, W.B. Hubbard, H.J. Reitsema, A.R. Klemola, P.D. Lee, B.R. McNamara, P.D. Maley, P. Manly, N.L. Markworth, R. Nolthenius, T.D. Oswalt, J.A. Smith, E.F. Strother, H.R. Povenmire, R.D. Purrington, C. Trenary, G.H. Schneider, W.J. Schuster, M.A. Moreno, J. Guichard, G.R. Sanchez, G.E. Taylor, A.R. Upgren, and T.C. Van Flandern, *Astron. J.*, **99**, 1636-1662, 1990.

Studies of Extended Planetary Atmospheres

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Strategy

Telescopic observation and analysis of planetary atmospheres (including Moon and Mercury) and the Io torus; occultation observations; supporting laboratory studies.

Progress and Accomplishments

Further observations of sodium and potassium in the lunar atmosphere have shown that the scale height is nearly always large, corresponding to temperatures between 600 and 1000 K, although data from 1988 were close to the expected 350 K. We published a model (Kozlowski et al.) fitting these results by the postulate that most atoms adsorb to the surface for a large fraction of a second, to be released by photodesorption in which excess photon energy goes into kinetic energy of the released atom. These results were also reported at the DPS, as well as an invited review by Hunten. Many of our observing runs during 1990 were clouded out, but the data we have are mostly reduced.

In the occultation program, analysis of the Titan results is nearly complete and a paper is in preparation. A single successful observation of Kleopatra was obtained in Colorado, but without additional chords it is not of great value. An expedition to Florida early in January 1991 to observe Vesta was rained out. Apart from some bugs that have now been repaired, the data systems are performing well.

A report of a potassium enhancement over Caloris on Mercury is now published (Sprague et al.) but the interpretation appears to be controversial. We still believe that enhanced degassing is strongly preferable to the proposed alternative by Killen et al, which invokes auroral effects.

Water vapor on Mars was mapped at four epochs during the last apparition. The seasonal behavior resembles that obtained during the Viking epoch, although other years have been different. A paper is in press (Rizk et al.).

The work on intra-cavity laser spectroscopy of methane is going extremely well but very slowly in light of Wells's many other duties.

Projected Accomplishments

Observations and analysis of sodium and potassium on the Moon and Mercury will continue. We are in the midst of building a true coronagraph with a 15 cm aperture to enhance the lunar observing, with reduction of scattered light and a plate scale more suited to the size of the atmosphere. The Mars water-vapor observations are continuing, and we hope in addition to search for the excess water vapor observed in the subsolar region by the Pioneer Venus Infrared Radiometer. We continue to collaborate with N. Schneider, now at the University of Colorado, in observations of the Io system at the 61-inch. These will include an attempt to repeat his spectacular absorption spectra of Io's atmosphere, obtained by observing another satellite as Io eclipsed it.

Publications

R.W. Kozlowski et al. (K on moon), GRL 17, 2253 (1990); A.L. Sprague et al. (Caloris) Science 249, 1140 (1990); Rizk et al. (Mars water), Icarus, in press. Sprague et al. are preparing a comprehensive paper on the lunar work.

Laser Studies of the Photodissociation Dynamics of Cometary Radicals

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In the past year we have shown that in the 193 nm photolysis of C_2H , the C_2 radical is produced in a variety of electronic, vibrational, and rotational states. The relative population of the vibrational and rotational states of $C_2(A^1\Pi_u)$, $C_2(B^1\Sigma_g^+)$, and $C_2(a^3\Pi_u)$ have been determined in a static gas cell and in a pulsed molecular beam. It seems as though the original angular momentum of the C_2H molecule appears as part of the angular momentum of the C_2 radical. We are now trying to discover the mathematical relationship that governs this mapping. This work has supplied new information about the bond dissociation energy of the C_2 radical. We have also detected $C_2(b^3\Sigma_g^-)$ and $C_2(1^1\Delta_g)$ in the photolysis of C_2H via time resolved infrared emission spectroscopy. In the former case vibrational excitation up to $v''=4$ is observed. All of our results suggest that the C_2 models in comets need to consider the presence of vibrationally excited C_2 radicals in comets.

The laser induced fluorescence spectra of the C_3 has been observed as a product of the 193 nm photolysis of allene and propyne. The populations of the rotational levels are identical in both cases. This result has led us to conclude that an isomerization reaction occurs in the photolysis of propyne which leads to the same C_3H_2 intermediate that is formed in the photolysis of C_3H_4 . Since the former molecule is one of the most abundant in the interstellar medium it is also likely that its precursor is also present in comets. This would explain why C_3 is observed in comets.

Publications

1. 1989 W.M. Jackson. Recent Laboratory Photochemical Studies and Their Relationship to the Photochemical Formation of Cometary Radicals. Accepted for publication by Kluwer Academic Publishers.
2. 1990 Yihan Bao, R.S. Urdahl, and William M. Jackson. Detection of $C_2(B^1\Sigma_g^+)$ in the Multiphoton Dissociation of Acetylene at 193 nm. *J.Chem.Phys.* **94**, 808.
3. 1990 R.S. Urdahl, Yihan Bao, and W.M. Jackson. An Experimental Determination of the Heat of Formation of C_2 and the C-H Bond Dissociation Energy in C_2H . Accepted for publication by *Chem.Phys.Letts.*

4. 1991 W.M. Jackson, Yihan Bao, and R.S. Urdahl. Implications of C_2H Photochemistry on the Modeling of C_2 Distributions in Comets. Submitted for publication by J. Geophys. Research.

Goldstone Solar System Radar

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Strategy

This task provides for the planning, experiment design, and coordination of the data acquisition and engineering activities in support of all Goldstone planetary radar astronomy. Activities related to up-grades of the receiver systems, transmitter systems, and data processing support systems are currently intense. Also covered in this task is the hardware and software maintenance of the data processing facility (VAX 11/780 and FPS 5210) used by many of the GSSR investigators.

Progress and Accomplishments

We have supported new radar observations of Mercury, Venus, Mars, the Galilean moons, the Saturnian moon Titan, the asteroids 1977 Cuyo, 194 Prokne, 1990MF, 1990OS and comet Austin. Radar observations of Venus completed our efforts on the pole determination. New ranging measurements of Venus are improving the ephemeris that guides the Galileo spacecraft. New experiments included dual polarization VLA imaging of Titan, high resolution ranging of asteroid 1990MF, expanded coverage of Venus, Stokes parameters for Mars, real-time interferometry on Mars, and Mars CW imaging. Many of these experiments will provide new scientific insights to the radar scattering properties and surface morphology of these objects. Several of these experiments pushed the Goldstone signal processing system to new limits. The magnetic tape database is complete for all past data, but much of the new data remains to be cataloged. A SUN workstation was added to replace the current display system. Data verification programs were developed for all current data acquisition formats.

Projected Accomplishments

During the winter and spring, the Goldstone radar cone will be rebuilt to house the new 500KW transmitter providing added sensitivity for the Titan experiments. Observations of Titan using the Goldstone/VLA combination are scheduled. Observations of Mercury for relativity continue. New programmed local oscillators (PLO's) are being built to replace the twenty-year-old ones. An improved receiver systems, the up-graded X-band transmitter, and new PLO's will become available this year. Considerable effort will be required to determine if these systems meet specifications prior to the Titan tracks. Work progresses on defining a complete set of functional requirements for the radar system. Some efforts are under way to find a graceful way to replace our aging VAX's with more economical computers.



Infrared Variability of Jupiter and Saturn

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Strategy

Infrared spectroscopy provides unique insights into the chemistry and dynamics of the atmospheres of Jupiter and Saturn, and of the enigmatic satellite of Saturn, Titan. The 5 micron spectral region of these objects is transparent to deep levels, and is therefore particularly useful for the identification of molecules that are present at very low (parts per billion) concentrations. In Titan, 5 micron observations probe atmospheric layers at or near the surface. Ground-based spectroscopy complements Voyager, Galileo and Cassini measurements. The spectroscopy is sensitive to lower mixing ratios for selected molecules, while the on-board mass and infrared spectrometers probe molecules and levels that are inaccessible from the ground. The observations also provide time-based data for preparation of the upcoming missions.

Progress and Accomplishments

In the past year we initiated 5 micron observations of Titan with the goal of investigating trace molecular constituents and atmospheric structure. These observations revealed the surprising result that Titan is a factor of 2-3 times fainter at 5 microns than it was at the time of the last observations at this wavelength in 1975. At the present time we do not know the origin of the variability, or if it is a seasonal or orbital effect. Clearly such a major change in brightness has significant implications for the understanding of the atmosphere and/or surface of Titan. We also obtained the first low resolution 5 micron Titan spectrum. The data contain evidence for CO near 4.3 micron, and for an unidentified absorber at longer wavelengths.

Projected Accomplishments

With the discovery of Titan's 5 micron variability, we will concentrate the current year's effort on this object. Observing time has been granted for photometry to follow Titan's infrared brightness during an orbital period. We are also organizing long-term observations to follow Titan during the Saturn year. We believe that such data will be important, both for their intrinsic interest and to support the Cassini-Huygens probe. Intermediate resolution (R=50) observations with the Aerospace Corporation BASS spectrometer have also been scheduled on the IRTF. This multiplexing instrument will provide unprecedented sensitivity to further explore Titan's 5 micron spectral region.

Publications

K. S. Noll and R. F. Knacke 1991, "Discovery of Strong Variability of Titan at 5 μm ," in preparation.

Advanced Infrared Astronomy

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Strategy

This task supports the application of infrared heterodyne spectroscopy and other high resolution techniques, as well as infrared arrays to ultra-high resolution studies of molecular constituents of planetary atmospheres. High spectral and spatial resolution measurement and analysis of individual spectral lines permits the retrieval of distributions of atmospheric molecular abundances and temperatures and thus, information on local photochemical processes. Determination of absolute line positions to better than 10^{-8} permits direct measurement of gas velocities to a few m/sec and thus, the study of dynamics. Observations are made from ground based observatories (e.g. NASA Infrared Telescope Facility on Mauna Kea, Hawaii).

Progress and Accomplishments

Jupiter - First measurements of ethylene on Jupiter were analyzed to reveal localized enhancement near the N polar hot spot (180° long., 60° lat.). Single line emission near 10.5 μm indicated a 13-fold increase in C_2H_4 abundance over that in the quiescent regions, or a 115K increase in temperature near 10 μbar . Most of the observed enhancement in line emission was found to originate near 10 μbar . Analysis of simultaneous measurements at 12 μm (ethane) and 2.1 μm (H_2 , H_3^+) by L. Trafton, U. Texas, showed no significant activity in the S polar region in Dec. 1989. An attempt to study the temporal variability and morphology of the stratospheric emission from the principal hydrocarbon constituents (CH_4 , C_2H_2 , C_2H_6) from Jupiter's polar regions was prevented by bad weather at the IRTF. This attempt will be repeated in FY92. *Mars* - Global distribution of ozone in the atmosphere was determined from single line measurements near 9.7 μm . Inversion of simultaneously measured CO_2 line profiles permitted the retrieval of needed temperature profiles. An ozone column burden of $<2.2 \mu\text{m-atm}$ for Ls~204 was retrieved, consistent with results from existing photochemical models. Direct measurements of global winds were made using Doppler shifts of 10 μm CO_2 absorption and emission lines. Data are presently being analyzed. *Venus* - The study of global circulation is continuing with observations of Doppler shifts of mesospheric and thermospheric CO_2 features during opposite phases near Venusian inferior conjunction. Analysis is in progress. Zonal, subsolar-antisolar, and predicted mesospheric return flow will be retrieved from these data.

Projected Accomplishments

We propose to study the temporal variability and morphology of the stratospheric emission from the principal hydrocarbon constituents (CH_4 , C_2H_2 , C_2H_6) from Jupiter's polar regions. The focus will be to image the polar hot spots and auroral regions and determine any correlation with 2-4 μm observations and ultraviolet auroral activity as observed simultaneously with the IUE. The goal is to investigate the energy source for the IR enhancement (e.g. energetic particles) and resultant species distribution around the north polar hot spot, which would be dependent on the changes in local photochemistry and diffusion of the product hydrocarbons in the Jovian stratosphere. The study of Jovian ethylene variability will continue. Observations of global circulation on Venus using the 10 μm CO_2 spectra will continue and will be correlated with mm-wave results. A comprehensive global circulation model will be developed. Ethane abundances on Saturn and Titan will be determined using line spectra measurements. An attempt to measure Titan's global circulation will also be made using the measured C_2H_6 lines.

Publications

- 1990 "Ethane Abundance on Neptune", T. Kostiuk, F. Espenak, P. Romani, D. Zipoy, and J. Goldstein, *Icarus* 88, 87-96.
- 1990 "Miniaturized, 9-12 Micron Heterodyne Spectrometer with Space Qualifiable Design Features", D. A. Glenar, M. J. Mumma, T. Kostiuk, H. Huffman, J. Degnan, H. Dave, U. Hochuli, and P. Haldemann. SPIE Vol. 1235, *Instrumentation in Astronomy VII*, 933-942.
- 1990 "Ground Based Measurements of the Global Distribution of Ozone in the Atmosphere of Mars", F. Espenak, M. J. Mumma, T. Kostiuk, and D. Zipoy. *Icarus* (to be published).
- 1990 "On the Detectability of the Jovian Oscillations with Infrared Heterodyne Measurements", B. Mosser, D. Gautier, and T. Kostiuk (submitted to *Icarus*).
- 1990 "Absolute Wind Velocities in the Lower Thermosphere of Venus Using Infrared Heterodyne Spectroscopy", J. Goldstein, M. J. Mumma, T. Kostiuk, D. Deming, F. Espenak, and D. Zipoy. (submitted to *Icarus*).
- 1990 "A Self-Consistent Picture of Circulation in Venus' Atmosphere from 70 to 200 km Altitude", J. Goldstein, M. J. Mumma, T. Kostiuk, and F. Espanak. (submitted to *Icarus*).

Cometary Spectroscopy and Imaging

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Strategy

The objective of this continuing observational program is to investigate the spectroscopic and morphological characteristics of comets and selected minor planets over a wide range of heliocentric distances as they may suggest or constrain models of cometary processes, their formation environments and evolution. Direct images of all observable comets ($M_v < 22$) and 300-800nm spectra of the brighter ones are obtained (weather permitting) on a monthly basis with a novel CCD spectrograph-camera. The direct images may be used for astrometry, photometry and studies of coma and tail morphology. In some cases, anisotropic dust emission can provide information on the nucleus spin vector. Spectra may provide data on strengths of the principal emissions for comparison of gas/dust ratios of a large sample of comets. Long integrations of minor planets in comet-like and nearby orbits are made to search for faint comae.

Progress and Accomplishments

Direct CCD images and sometimes spectra were obtained (and reported in the indicated IAU Circulars) of Comets Arai (1990B), Austin (1989C1); IAUC 4973, Encke, Gehrels 2, Harrington-Abell (1990m), Helin-Roman-Alu (1989w, 1989y), Holt-Olmstead (1990k), Honda-Mrkos-Padjusakova, Johnson (1990h), Kearns-Kwee, Levy (1990c); IAUC 5098, Lovas 1 (1990p), McKensie-Russell (1989f1), Metcalf-Brewington (1990a), Mueller 2 (1990j), Mueller 3 (1990l), Peters-Hartley (1990d), Russell 4 (1989g1), Shoemaker-Levy 1 (1990o), Shoemaker-Levy 2 (1990p); IAUC 5149, Shoemaker-Levy 3 (1991d); IAUC5183, Skochenko-George (1989e1), Schwassmann-Wachmann 1, Schwassmann-Wachmann 3, Taylor (1990n), Tuttle-Giacobini-Kresak (1989b1), Tsuchiya-Kuichi (1990i), VanBiesbroeck (1989h1), and Wild 4 (1990a); IAUC 4954. 300- 860nm spectra of minor planets 41, 66, 130, 181, 229, 489, 559, 691, 776, 951 and 1301 were also obtained. Deep CCD integrations of 1990 UL₃ showed a tail leading it to be renamed Comet Shoemaker-Levy 2 (1990p). 360-950nm spectra of Comet Austin (1989c1) were obtained simultaneously with 900-1200nm spectra by Tegler *et al.* from which relative band fluxes of the blue and red CN systems have been measured. Continuum band images of Comet Austin were obtained simultaneously with 10 micron images obtained by McFadden *et al.*

Projected Accomplishments

Continued monthly imaging, spectral and astro-metric observations of comets and minor planets with emphasis on mission target objects. An offset guider for the CCD camera/spectrograph will be added to eliminate the apparently random, few arcsec guiding errors in the 1.5 m Catalina Telescope. Analysis of the tails of some 30 comets at large heliocentric distance is underway, and papers on ion tails will be submitted for publication.

Publications

Larson, S.M. (1990) Near-nucleus H_2O^+ structures in comets Brorsen-Metcalf, Okazaki Levy-Rudenko, and Austin. *Workshop on Observations of Recent Comets (1990)*, Ed. W.F. Huebner, J. Rahe, P.A. Wehinger and I. Konno, Southwest Research Institute, San Antonio, TX.

Kim, S.J, A'Hearn, M.F. and Larson, S.M. (1990). Multi-fluorescence: Application to S_2 in Comet IRAS-Araki-Alcock 1983VII, *ICARUS* **87**, 444-451.

Johnson, J.R., Larson, S.M. and Singer, R.B. (1991). Remote sensing of potential lunar resources: I. Global compositional mapping. Submitted to JGR.

Infrared Observations of Solar System Objects

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Strategy

This program is our ongoing groundbased infrared studies of Solar System objects. This is a broadbased program that includes collaboration with scientists at other institutes and several graduate students at the University of Arizona. Our overall objective is to study the spectral and physical properties of small Solar System bodies. Our work spans the entire Solar System from a study of the mineralogy of Mercury, to several studies of asteroids, and to studies of Triton, Pluto, and Charon. From these studies we hope to understand better the origin and evolution of these bodies and how they fit into the context of the origin and evolution of the Solar System as a whole.

Progress and Accomplishments

In the last year, we have submitted for publication 5 papers (2 published and 2 in press). We also expect to submit 3 papers in the near future on the diameter and thermal properties of Vesta, a book chapter on asteroid studies, and on the near IR spectrum and composition of Mars' satellite Deimos. We have had several successful telescope runs in the past few months on the visual and near IR spectra of dark asteroids and satellites and are presently reducing these data.

Projected Accomplishments

Over the next year our work will include: Continued studies of dark asteroids and satellites, study the distribution of water and other low-temperature materials in the Solar System, study the nature of shocked material on asteroid surfaces, study the relationship between asteroids and comets, and make more extensive correlation of all of these observations with laboratory spectra of meteorites.

Publications

Lebofsky *et al.* (1990), Jones *et al.* (1990), Marcialis and Lebofsky (1991), Marcialis *et al.* (1991), Gaffey *et al.* (1991).

Pitfalls to direct comparison of cometary and asteroidal light curves, R. L. Marcialis and L. A. Lebofsky, submitted to *Astron. J.* 1990.

The nature of low albedo asteroids from 3- μ m spectrophotometry, L. A. Lebofsky, T. D. Jones, P. D. Owensby, M. A. Feierberg, and G. J. Consolmagno. *Icarus* **83**, 12-26 (1990).

The composition and origin of the C, P, and D asteroids: Water as a tracer of thermal evolution in the outer belt, T. D. Jones, L. A. Lebofsky, J. S. Lewis, and M. S. Marley. *Icarus* **88**, 172-192 (1990).

CVF spectroscopy of Pluto: Correlation of composition with albedo, R. L. Marcialis and L. A. Lebofsky. *Icarus*, in press, 1991.

The albedos of Pluto and Charon: Wavelength dependence, R. L. Marcialis, L. A. Lebofsky, and E. F. Tedesco. Submitted to *Icarus*, 1991.

Asteroid surface compositions from earthbased spectroscopy, M. J. Gaffey, L. A. Lebofsky, M. Nelson, and T. D. Jones, in press, 1991.

Outer Planet Studies

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Strategy

The research supported by this grant focuses on observational studies of the composition, structure, and variability of planetary, satellite, and cometary atmospheres. The techniques used include spectroscopy, spectrophotometry, and photometric imaging in the spectral region from 3000 Å to 5 μm. In addition to carrying out basic research into the origin, evolution, and current state of the solar system, these studies provide "ground-truth" support for observations of the solar system by NASA's missions, including the *Voyager* and *Galileo* spacecraft, the *Hubble Space Telescope*, and the proposed *CRAF-Cassini* mission.

Progress and Accomplishments

Major accomplishments during the past year include 1) publication in the *Astrophysical Journal* of a study of CH₃D in the spectrum of Neptune and a determination of its mixing ratio in its atmosphere; 2) publication in *Icarus* of a study of the aboriginal deuterium enrichment in protosolar ices and its relationship to the interstellar medium; 3) publication in *Science* of the detection and study of HDO in the spectrum of Venus and a determination of the implied D/H ratio in its atmosphere; 4) publication in the *Astrophysical Journal* of a study of the brightness, albedo, and temporal variability of Neptune; 5) completion and publication in the *Astrophysical Journal* of a study of NH₂ in Comet P/Giacobini-Zinner; 6) acceptance for publication of a study of the gas and dust production rates in P/Halley 1910; 7) continuation of our narrowband photopolarimetric imaging of Jupiter; 8) initiation of a study of the dust and gas components of Comet IRAS-Iraki-Alcock; and 9) continued observation of the spectra of Triton and Pluto in the region between 7500 Å and 3.3 μ.

Projected Accomplishments

Major efforts proposed for the coming year include 1) completion of the study of the dust and gas components of Comet IRAS-Iraki-Alcock, 2) search for minor non-equilibrium constituents in the atmospheres of Jupiter and Saturn, and 3) analysis of the spectra of Triton and Pluto to determine the amount of CH₄ in their atmospheres and on their surfaces.

Publications

Beaver, J. E., Wagner, R. M., Schleicher, D. G., and Lutz, B. L. (1990). Anomalous Molecular Abundances and the Depletion of NH_2 in Comet P/Giacobini-Zinner. *Astrophys. J.* **360**, 696P701.

de Bergh, C., Bézard, B., Owen, T., Crisp, D., Maillard, J.-P., and Lutz, B. L. (1991). Deuterium on Venus: Observations from Earth. *Science* **251**, 547P548.

de Bergh, C., Lutz, B. L., Owen, T., and Maillard, J.P.P. (1990). Monodeuterated Methane in the Outer Solar System. IV. Its Detection and Abundance on Neptune. *Astrophys. J.* **355**, 661P666.

Howell, E. S., Lutz, B. L., and Slipher, V. M. (1991). Gas and Dust Production in Comet P/Halley (1910II). *Astrophys. J.*, in press.

Lockwood, G. W., Thompson, D. T., Lutz, B. L., and Howell, E. S. (1990). The Brightness, Albedo, and Temporal Variability of Neptune. *Astrophys. J.* **368**, 287P297.

Lutz, B. L., Owen, T., and de Bergh, C. (1990). Deuterium Enrichment in the Primitive Ices of the Protosolar Nebula. *Icarus* **86**, 329P335.

Russell, C. T., Caldwell, J. J., de Pater, I., Gougen, J., Klein, M. J., Lutz, B. L., Schneider, N. M., Sinton, W. M., and West, R. A. (1990). International Jupiter Watch; A Program to Study the Time Variability of the Jovian System. *Adv. in Space Sci. Res.* **10**, 239P242.

*Astrometric Observations of Comets and Asteroids and Subsequent
Orbital Investigations*

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Strategy

Astrometric observations are made with the 1.5-m reflector at the Oak Ridge Observatory.

Progress and Accomplishments

The transformation of the Oak Ridge astrometry from a photographic program to a CCD program can now be considered complete, and the number of observations being made is now approaching an order of magnitude greater than in the old photographic program. The dead time between exposures is now typically down to only 2.5 minutes. The backlog of reductions that had accumulated during the changeover was eliminated, and the identification, measurement and reduction process is now so automated that essentially all the reductions from a month with even 400 observations can be completed in only three days. The possibility of developing an autoguider, using a second CCD, was considered, but it was concluded that there would be no increase in efficiency. Instead, a simple tracking system using a short-focus guide telescope has been introduced. There therefore exists now the option of offsetting an exposure to allow for the motion of the object being observed, although most of the objects observed hitherto have in fact been bright enough to allow tracking at the sidereal rate. We made the last known observations of five new comets and eight new earth-approaching minor planets. Last-minute astrometry of 1990 MF and 1991 AQ was obtained during bright moon to ensure the success of radar-bouncing efforts. Several unusual numbered minor planets were observed, as well as of (243), (449) and (951) in response to requests in connection with NASA missions. Observations at Oak Ridge were made of as many as 64 percent of the minor planets that were newly numbered during the year, and 28 percent of the new numberings were made solely because of Oak Ridge observations. The influence on new numberings is so overwhelming that the increase in the volume of the Oak Ridge observations has allowed the introduction of more stringent, but appropriate, requirements for numberings.

Projected Accomplishments

Observations are expected to continue much as usual as occasion demands. Although the CCD data provide both astrometric and photometric information, we have hitherto done little with the latter, something we hope to be able to correct during this next year.

Publications

2952 observations were published during the past year on 83 Minor Planet Circulars and 9 IAU Circulars. Orbit computations were in the same publications.

As far as observations are concerned, the MPCs have been declared a refereed journal, and observations from Oak Ridge plates are contained on MPC Nos. 16123-16326, 16150-16156, 16346, 16482-16483, 16530-16537, 16656, 16677-16678, 16774, 16828-16830, 16935-16936, 16938, 16988-16992, 17086-17087, 17133-17136, 17275-17276, 17278-17280, 17349-17356, 17489-17492, 17565-17577, 17684-17687 and 17720-17725.

Research in Planetary Astronomy

California Institute of Technology

K. Matthews, B. T. Soifer*Strategy*

This program has focused on the study via near infrared observations of the outer planets and their satellites. In the last year these observations have emphasized imaging observations using the Cassegrain infrared camera at the f/70 focus of the 200 inch Hale telescope.

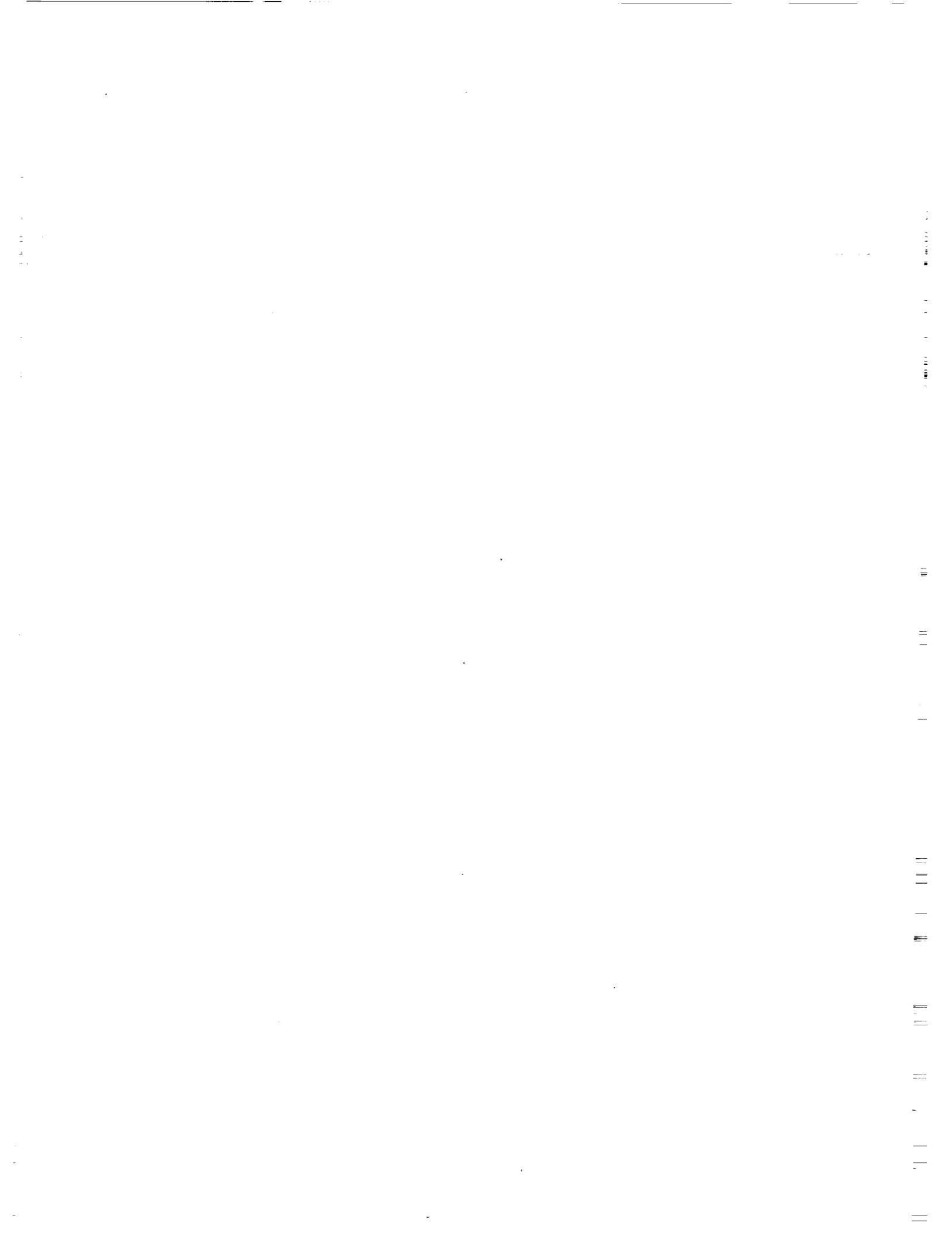
Progress and Accomplishments

Images have been obtained in the 2.0-2.4 μm atmospheric view of Saturn, Uranus, and Jupiter. This is a unique window on the outer planets, because the strong methane and molecular hydrogen absorptions allow us to detect features in the stratosphere of the planets.

From 2.0-2.4 μm Saturn shows a bright band between 25 and 50 degrees north latitude, while the planetary disk disappears completely at the 2.3 μm in the depth of the methane band. The bright band must be due to aerosols in the atmosphere of Saturn above the 300 mbar pressure level.

Uranus remains bland and featureless in the near infrared images. Neptune showed a previously unobserved haze and a feature prominent in the Voyager visible light images. Neptune's northern hemisphere showed a thin haze that is present even in the 2.3 μm images. This haze must be at a very high altitude because of the strong methane absorption. A bright feature, believed to be a companion to the "Great Dark Spot," appears in occasional images in the southern hemisphere of Neptune.

In addition to the planetary disk images, we believe that we have recovered the newly discovered Neptune satellite 1989 N1 in K band images. The object is quite faint, K=19 mag.



The Radial Velocity Search for Extrasolar Planets

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Strategy

We are making radial velocity measurements to search for planets orbiting stars other than the Sun. The reflex acceleration induced on stars by planets can be sensed by measuring the small, slow changes in the line-of-sight velocities of stars. To detect these planetary perturbations, our data series must be made on a uniform instrumental scale for as long as it takes a planet to orbit its star. We have been operating a spectrometer of extreme stability and unprecedented sensitivity to changes in stellar radial velocities.

Progress and Accomplishments

Between December 1986 and February 1991 (inclusive) we have made 1610 observations of 16 near-solar type stars on 379 nights. (This total does not include our spectral "slope calibrations" on stars, our "check" observations of the Moon, nor about 10,000 observations of bright K giant stars.)

Our data show our instrument has the stability necessary to detect the reflex acceleration induced by a Jupiter-mass planet on a solar type star, if the orbit has a period less than 12 years and a favorable inclination to the line of sight. To be certain of this, we have been observing the solar spectrum reflected off a lunar crater (among other calibration sources). Our 393 observations of the Moon spread over 4 years have a standard deviation of ± 7 m/s, to which the random short-term "precision" contributes ± 5 m/s. Precision and accuracy add vectorially, so our systematic errors are ± 5 m/s.

Another measure of the performance of our instrument is the scatter of our observations of the faintest star on our program, Sigma Draconis. We have 91 observations of this K0 V star spanning 3.6 years. For detecting long-period signals it is appropriate to consider how well the averages of the four observing seasons agree. The standard deviation of the four seasonal averages is ± 3.3 m/s.

We have discovered new types of velocity variations intrinsic to three K giant stars. One binary system in the literature has been refuted by our data, and another binary star system has been discovered. All these findings have been published.

Projected Accomplishments

We will continue the observations for several more years so that we can see at least one full planetary orbital period in the series.

We are developing a new instrument that will be more sensitive to light and more accurate than our present one.

Publications

McMillan, R. S., Smith, P. H., Perry, M. L., Moore, T. L., and Merline, W. J., 1990 Proc. SPIE 1235, Instrumentation in Astronomy VII, 601-609: "Long-term Stability of a Fabry-Perot Interferometer Used for Measurement of Stellar Doppler Shift".

Observational Evidence of Aging Processes in Comets

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Strategy

The emphasis of my NASA research is to search for systematic differences among two groups of comets: periodic comets which spend most of their time in the vicinity of the inner Solar System and the new comets which are believed to be passing through the inner Solar System for the first time. Such differences are expected, but have never been observed, in part because there has never been a systematic observational program aimed at addressing this question. Understanding possible physical and compositional differences between these two groups will lead to a better understanding of the cometary formation conditions in the early Solar System. The method employed in this investigation is to study the activity in the comets as a function of distance by obtaining CCD observations of the comets at frequent intervals on both the pre- and post-perihelion legs of their orbits in order to ascertain the distances at the onset and turn-off of activity through comparison with sublimation models.

Progress and Accomplishments

During the past year, there have been 8 successful observing runs (CCD imaging and photographic plates) totalling 34 nights using the University of Hawaii (UH) 2.2m, Kitt Peak (KPNO) Schmidt, and Cerro Tololo Interamerican Observatory (CTIO) 4m and Schmidt telescopes. The runs have produced 58 faint program comet observations at different heliocentric distances. Among these observations include probable recoveries of comets Grigg-Skjellerup and Giacobini-Zinner at large heliocentric distances. In addition, wide-field observations of comet plasma tails were obtained in a related study of the tails in both periodic and Oort comets. A third project was undertaken in 1991 January to search along the path of the Kreutz sungrazing comets to search for fragments of the progenitor cometary body in order to place constraints on the homogeneity of the nucleus, or on the size of the population of fragments in the orbit. A program of monitoring the activity in Chiron has intensified since the discovery of its cometary activity. Chiron has begun to show rapid short-term brightness fluctuations and in 1990 December began to develop a tail.

Monitoring of comet Halley has led to the discovery of a large outburst in brightness at a heliocentric distance of 14.3 AU, approximately 1 year after the activity had ceased and it had reached its expected nuclear brightness.

Considerable progress has been made on the analysis of the extensive data set on the distant comets. However, approximately 3-5 days are required to reduce each night of observation because of the need for extremely accurate flattening in order to study to extent of comae and surface brightness profiles and structures in the distant, faint comets. Work is continuing in this area. The analysis of the Chiron data has shown considerable short term activity. In addition, the December observations showed the development of a tail.

Projected Accomplishments

Although continued coverage of the program comets will be high priority this year, the highest priority will be given to the reduction of the extensive data which has been accumulated to date, and the analysis of these observations. Astrometry of all of the year's comet observations will be kept up-to-date. Along these lines, I have undertaken a project to obtain the facilities necessary to perform the astrometry at the IFA. This program should be operational within a couple months. Continued monitoring of comet Halley is planned over the next few months to investigate the cause of the outburst activity.

Publications

Meech, K. J. (1991) "Aging in Comets," IAU Colloq. 116 (in Press).

Meech, K. J. and M. J. S. Belton (1990). "The Atmosphere of 2060 Chiron," *Astron. J.* **100**, 1321.

Buie, M. W. and K. J. Meech. "A Synthesis of 2060 Chiron Observations," in preparation.

Occultation Studies of the Solar System

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Strategy

Occultations of stars by planets, satellites, planetary ring systems, and asteroids offer opportunities to study the occulting bodies in ways not otherwise possible from the surface of the Earth. For example, one can detect even an extremely tenuous atmosphere and can measure the temperature and density profiles of the atmosphere in regions not ordinarily sampled by spacecraft. Occultations also permit direct measurement of the size and shape of solar system objects too small to be directly resolved by groundbased telescopes. The accuracy of such determinations is typically 1%-2% and, moreover, is independent of the distance to the object. In this investigation, we identify upcoming occultations through wide-ranging computer searches, provide accurate predictions for the more important events, and observe selected occultations with our specially designed portable photometric equipment.

Progress and Accomplishments

During the past year, we continued analysis of the data from the 9 June 1988 occultation of P8 by Pluto. The thrust of this investigation, undertaken jointly with James Elliot at MIT, is to derive the structure and extent of Pluto's atmosphere from a simultaneous fit to observations from eight different sites. After much experimentation with a numerical approach to this problem, an analytic technique has been developed and good progress made toward finishing the work. This effort can be expected to yield the best possible values of the ratio of temperature to mean molecular weight in the atmosphere and of the radius of the top of the postulated haze layer or steep thermal gradient. Also, during the year we provided refined predictions for occultations by Triton, Kleopatra, and Vesta. Unfortunately, our efforts to observe the Kleopatra event were foiled by widespread cloudiness.

Projected Accomplishments

Next year we plan observations of occultations by Vesta, Kleopatra, Ceres, and possibly Pallas and Triton. The analysis of the global properties of Pluto's atmosphere will be completed and the results published. A comprehensive computerized catalog search for occultation of stars by asteroids and satellites will be completed and predictions for events occurring in 1992 and 1993 will be published. We also plan a concerted astrometric effort in collaboration with colleagues at the U.S. Naval Observatory aimed at providing accurate predictions for possible upcoming occultations by Pluto and Triton.

Publications

Dunham, D.W., and 45 other authors including Wasserman, L.H., Bowell, E., and Nye, R.A. of Lowell Observatory. The Size and Shape of (2) Pallas from the 1983 Occultation of 1 Vulpeculae. *Astron. J.* **99**, 1636, 1990.

Hubbard, W.B., Hunten, D.M., Reitsema, H.J., Brosch, N., Nevo, Y., Carreira, E., Rossi, R., and Wasserman, L.H. Results for Titan's Atmosphere from Its Occultation of 28 Sagittarii. *Nature* **343**, 353, 1990.

Lebofsky, L.A., Hubbard, W.B., Asphang, E., Hunten, D.M., Millis, R.L., Franz, O.G., and Wasserman, L.H., A'Hearn, M., Schnurr, R., Klemola, A.R., Osborn, W., Vilas, F., Potter, A.E., Maley, P.D., and Manly, P.L. Diameter, Rotation, and Thermal Properties of Asteroid 4 Vesta. *Bull. Amer. Astron. Soc.* **22**, 1112, 1990.

Wasserman, L.H. No Occultation of SAO 187435 by Triton. *IAU Circ. No.* 5058, 1990.

Physical Processes in Comets

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Strategy

Post-Halley, comets are known to be irregular objects, with most nucleus activity very localized and with the dust coma capable of fragmentation and apparently a source of gas. Older, one-dimensional strategies which assume steady isotropic outflow of material can give poor time-and-space-averaged results, at best. With two-dimensional data, images through interference filters, one can hope to see dust structures that give evidence of the proper geometry for data reduction, study gradients along the axes of symmetry and evidence of fragmentation, and seek evidence for gas abundance gradients associated with the dust. High quality data from brighter comets can then be used to suggest improved data reduction procedures for fainter ones. To obtain such data, large image-quality interference filters have been procured for use with a CCD camera at Lick Observatory, where the scale of the 1 m Nickel reflector is ideal for brighter comets. Whenever possible, data is taken simultaneously with other telescopes and equipment, especially spectroscopy at the Lick 3m or infrared photometry at the IRTF on Mauna Kea.

Progress and Accomplishments

The first data obtained with the new techniques was from P/Brorsen-Metcalf in 1989. Experience from that observing run allowed a much better data set, better photometrically and more complete, to be obtained on Comet Austin during 1990. Both sets are now being processed on the UC Berkeley computers, while models are being developed to fit the data. Completion of older IRTF data-writeups await the return of coworker M. Hanner from sabbatical leave. The proceedings of the Bamberg conference "Comets in the Post-Halley Era" have been completely edited. The 50 papers fill over 1300 pages in two volumes and will be available April 15 from Kluwer Academic Publishers.

Projected Accomplishments

Observations will be made of any comets of opportunity that reach an apparent magnitude of 6 or 7, and observations will be taken during the especially favorable apparition of P/Faye in November. Publication will be completed of older observational data already acquired.

Publications

Newburn, R., Neugebauer, M., and Rahe J., "Comets in the Post-Halley Era," Kluwer, Dordrecht, 1991.

Drechsel, H., Vanysek, V., Newburn, R., and Rahe, J., "Comets in the Post-Halley Era," *Comm. on Astrophys.*, XIV (5), 311-316, 1990.

Imaging Studies of Comets

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Daniel A. Klinglesmith III (NASA/GSFC)
David J. Westpfahl (NMIMT)

Strategy

The Joint Observatory for Cometary Research (JOCR) is administered on a NASA/GSFC contract with New Mexico Institute of Mining and Technology (NMIMT). JOCR's historical mission has been to provide understanding of large-scale interactions between bright comets and solar wind using wide-angle (Schmidt) imagery and spacecraft data; in this pursuit the JOCR has excelled. The 16" Newtonian/Cassegrain telescope has been upgraded (cf. b.) to permit filtered-, narrow-field CCD imaging of both bright and faint comets. Thus, to JOCR's original mission has been added the goal of obtaining narrow-band imagery of the near-nuclear region of bright comets, with emphasis on ionisation processes and total gas production. A 300mm lens/CCD system exists with 2 degree FOV and the use of comet filters; this system bridges the gap between the wide-field (8x10 deg.) Schmidt plates and the several-arcmin. field of the 16" telescope. JOCR is located under dark skies on South Baldy mountain (el. 10,600 feet) near Socorro, NM, and is one of the last truly dark sites in the continental U.S.

Progress and Accomplishments

Dr. D. Westpfahl has assumed the JOCR leadership role for NMIMT, and is working with Drs. D. Klinglesmith and M. Niedner in upgrading the facility and developing plans for future cometary observations. The comets Austin and Levy campaigns were successful, particularly the Austin run with the filtered 300mm/CCD system. Hundreds of dataframes taken in H₂O⁺ (6205A) were obtained, and the best sequences on active nights were converted to video (movie) format. The development of DEs and folding tail rays are shown in great detail and are being analyzed. The 16" Newtonian/Cass. telescope has been converted optically to f/5 operations, and is now under computer control with tracking in two axes. Cometary filters for C2, H2O+, cont., etc. emissions are on hand for the 300mm lens and 16" CCD systems. A sensitometer for calibration of Schmidt plates was obtained on loan from KPNO.

Projected Accomplishments

Data from the Austin and Levy observing runs will be further scrutinized, as solar-wind and IMF data for 1990 will soon be available to add to the analysis already performed. Other comets of opportunity, including faint comets, will be observed to the maximum extent possible.

Publications

Klinglesmith, D. A., Niedner, M. B., and Shore, S. 1988, "A solar wind-induced extreme ion tail disturbance in comet Bradfield 1987", *Bull. Am. Astron. Soc.*, 20, 732.

Klinglesmith, D. A., Niedner, M. B., Oliverson, R. J., and Westpfahl, D. 1990, "A tail wagging event in comet Austin", *AAS Comet workshop*, 1990 June 15-16, p. 128.

Delva, M., Schwingenschuh, K., Niedner, M. B., Gringauz, K. I. 1991, "Comet halley plasma tail observations & in situ solar wind properties", *Plan. Sp. Sci.*, in press.

Radar Investigation of Asteroids and Planetary Satellites

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Strategy

Radar reconnaissance of near-Earth asteroids, mainbelt asteroids, the Galilean satellites, the Martian satellites, and large Saturnian satellites, using the Arecibo 13-cm and the Goldstone 3.5-cm systems. Measurements of echo strength, polarization, and delay/Doppler distribution of echo power provide information about dimensions, spin vector, large-scale topography, cm-to-m-scale morphology, and surface bulk density. The observations also yield refined estimates of target orbital elements.

Progress and Accomplishments

Radar signatures have been measured for 35 mainbelt asteroids and 27 near-Earth asteroids since this task began ten years ago. Observations of the near-Earth asteroid 1989 PB, conducted shortly after its optical discovery, yield a sequence of delay-doppler images that reveal it to consist of two distinct lobes that appear to be in contact, or nearly so. 1989 PB may have formed as a result of collisional disruption of a much larger object in the main asteroid belt, when two fragments that had been dispersed by that collision at low relative velocity became gravitationally bound to each other. Echoes from the near-Earth object 1986 DA show it to be significantly more reflective than other radar-detected asteroids. This result supports the hypothesis that 1986 DA is a piece of NiFe metal derived from the interior of a much larger object that melted, differentiated, cooled, and subsequently was disrupted in a catastrophic collision. This 2-km asteroid, which appears smooth at cm-to-m scales but extremely irregular at 10-to-100-m scales, might be (or have been a part of) the parent body of some iron meteorites. Phobos' 3.5- and 13-cm echoes reveal surface characteristics very different from those of most near-Earth asteroids, but similar to those of the largest C-class asteroids. The radar signatures of Europa, Ganymede, and Callisto have recently been measured at 3.5, 13, and 70 cm and are extremely unusual at all three wavelengths.

Projected Accomplishments

1) Publication of all delay-doppler asteroid radar astrometry obtained during 1980-1990, along with refined orbital estimates and disc-integrated radar properties for all astrometrically observed targets. 2) Delay-doppler resolution of echoes from 324 Bamberga and 3103 (1982 BB). 3) Measurement of the 3.5-cm signature of a large S-class object (7 Iris).

Publications

Ostro, S. J., and E. M. Shoemaker (1990). The extraordinary radar echoes from Europa, Ganymede, and Callisto: A geological perspective. *Icarus* **85**, 335-345 (1990).

Ostro, S. J., D. B. Campbell, A. A. Hine, I. I. Shapiro, J. F. Chandler, C. L. Werner, K. D. Rosema (1990). Radar Images of Asteroid 1627 Ivar. *Astron. J.* **99**, 2012-2018.

Ostro, S. J., J. F. Chandler, A. A. Hine, I. I. Shapiro, K. D. Rosema, D. K. Yeomans (1990). Radar Images of Asteroid 1989 PB. *Science* **248**, 1523-1528.

***Stellar Occultations by Planetary Rings: 3 July 1989 28 SGR
Occultation by Saturn***

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Strategy

To reduce and synthesize near infrared observations of the 3 July 1989 occultation of 28 Sagittarii by Saturn and its rings made from 7 different telescopes spread around the world (2 in Chile, 1 in Hawaii, 1 in Mexico, and 3 in Tucson); and to combine these observations with Voyager data to study the dynamical state of Saturn's rings. This unique event, which occurred 8 years after the Voyager flybys, provides a temporal baseline over which kinematical and dynamical phenomena within the rings may be examined in detail.

Progress and Accomplishments

Observations were successfully made at all 7 sites. Standard aperture photometry was used at 4 of them; rapid, 2-dimensional imaging was used at the remaining 3. The aperture data have all been reduced. The radial positions of roughly 20 sharp-edged ring features, believed to be circular at the 2 km level, have been determined in these data sets. These measurements have been used to refine the event astrometry to the point where ring features may be absolutely located to an accuracy of several kilometers. A paper on the astrometry from this event and its implications for the ring radius scale and Saturn's pole position is now in the final stages of preparation (Hubbard *et al.* 1991). We have already begun to refine the kinematics of Saturn's major eccentric rings by combining previous Voyager imaging and occultation measurements with our ground-based data. A DPS presentation (Turtle *et al.* 1990) has been given on this work.

Substantial progress has been made in reducing the 2-dimensional array imaging data sets. Software for batch-processing (i.e., cleaning, background subtraction, and integration of total stellar flux) of these data have already been accomplished on one data set and will eventually be applied to the remaining two.

Projected Accomplishments

In the following year, I expect to: i) Continue the batch-processing of the remaining 2-dimensional imaging data sets; ii) Continue my work in re-examining the dynamics of Saturn's eccentric features (Porco *et al.*, 1984a, 1984b; Porco 1990; Turtle *et al.*, 1990); search gap edges for edge waves indicative of shepherding satellites; fill out the particle size

distribution; refine our knowledge of Saturn's gravitational harmonics by improving tenfold the precision of ringlet kinematics (Nicholson and Porco, 1988; Turtle *et al.* 1990).

Publications

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Observational Studies of the Exospheres of the Moon and Mercury

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Strategy

The sodium and potassium atmospheres of Mercury and the Moon are mapped using spectroscopic measurements of resonance scattered sunlight. The objective is to define the sources and sinks for these atmospheric constituents, and in so doing, provide a better understanding of atmospheric processes on these bodies, which are unique in that their atmospheres consist solely of an exosphere with the planetary surface at its base.

Progress and Accomplishments

We published images of sodium D₂ emission for Mercury, and interpreted the non-uniform and changeable distribution of sodium as the result of magnetospheric processes driven by solar activity.

We continued observations of Mercury, and obtained data during three runs in 1990. The December 1990 run was outstanding in quality and duration (6 days), and for the first time, we observed both sodium and potassium distributions on the same day. We expect to learn more about the mechanisms controlling the Mercury atmosphere from comparison of the sodium and potassium distributions.

We completed the analysis of lunar sodium distribution from three observing runs in 1989 and 1990. We found sodium emission up to an altitude of 1500 km. over the sunlit equator. The apparent temperature of the sodium above the equator was 950-1150°K. Above the north pole, the temperature dropped to about 450°K. An extensive (6 night) lunar observing run was completed in December 1990, which covered the range from full moon past third quarter.

Projected Accomplishments

We will complete the analysis and interpretation of the same-day sodium and potassium distributions on Mercury that were obtained in December 1990. Our explanation of the variable distribution of sodium on Mercury is that solar activity influences the magnetosphere of Mercury, which in turn influences the sodium distribution. We have initiated a synoptic program of Mercury sodium observations at the McMath telescope, which will generate a substantial body of new data to test this hypothesis.

We will complete the analysis of the December 1990 body of lunar sodium data, and will continue lunar measurements as observing time is available. We also plan to explore techniques for mapping the entire sodium exosphere of the Moon, using coronagraphic techniques.

Publications

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Ground-Based Observations of Comets, the Jupiter Plasma Torus, and Io

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Strategy

We have been investigating aspects of cometary and magnetospheric physics by means of ground-based astronomical spectroscopy. We have used high-throughput, dual-etalon Fabry-Perot spectrometers (usually at the McMath solar telescope on Kitt Peak) to obtain very high resolution spectra of atomic, molecular, and ionic emission lines from the diffuse gases and plasmas associated with comets and the Jupiter plasma torus. The Fabry-Perot spectrometers were also used with a CCD camera to obtain images of these extended emission sources in individual spectral lines at high spectral resolution.

We also recently began a new program using the McMath solar-stellar spectrograph to observe emission lines from Io. The McMath spectrograph has a high-resolution mode ($\lambda/\Delta\lambda \approx 10^5$) which allows the detection of narrow, relatively faint emission lines superposed on Io's reflected solar spectrum.

Progress and Accomplishments

1) Ground-based observations of cometary ions can be used to help constrain models of the solar wind-cometary plasma interaction and photochemical models of ion reactions in the inner coma. Our goal in Fabry-Perot observations of cometary H_2O^+ emissions is to determine the outflow velocities of plasma in the coma and tail directly by measuring the Doppler shifts of the emission lines. Displacements of features in cometary plasma tails, obtained from photographs and CCD images, have been used to infer plasma motions with tailward velocities in the range of 20 to 250 km s^{-1} (Celnik and Schmidt-Kaler 1987, Jockers 1981, 1985). The question of whether these apparent motions represent propagating disturbances such as MHD waves moving down the tail or actual mass motions of the cometary ions or a combination of both can be resolved with Doppler measurements of H_2O^+ .

High-resolution spectra of Comet Halley H_2O^+ emissions, primarily the 6158.64, 6158.85 Å spin doublet, were obtained in 1985 and 1986 using a 150 mm Fabry-Perot scanning spectrometer at the McMath west auxiliary solar telescope on Kitt Peak. On each night of observations, spectra were obtained at several distances in the range of 0 to 2×10^6 km from the comet head along the anti-Sunward direction. The outflow velocities of the cometary plasma were determined from the Doppler shifts of the emissions. The results usually but not always were consistent with constant acceleration of the plasma along the anti-Sunward

direction, but the acceleration varied from night to night over a range of about 30-300 cm sec⁻² (Scherb et al. 1990).

These accelerations do not seem to be consistent with the smaller values obtained by Celnik and Schmidt-Kaler (1987), using time-lapse photography of the plasma tail. This apparent discrepancy deserves further study, but for now we note that our 150 mm Fabry-Perot spectrometers are 10-25 times more sensitive to spatially diffuse emission than photographic techniques. Thus, one possibility is that the bright condensations recorded photographically were relatively massive, which could account for their smaller accelerations.

2) For our Comet Halley observations, the Fabry-Perot spectrometer provided effective isolation of cometary [OI]6300 emission from nearby cometary NH₂ lines, as well as terrestrial OH and [OI]6300 emissions. Our high resolution spectra of the 6300 Å region showed conclusively that there was no other cometary emission line of measurable strength within 0.5 Å of the cometary [OI]6300 emission line. Since the cometary [OI]6300 line was free of contamination, we were able to obtain values of the production rate of O(¹D) atoms by measuring the total amount of [OI]6300 emission within the field of view and correcting for the amount of emission outside the field of view. These production rates are nearly model-independent when the field of view is large enough to include most of the [OI]6300 flux. This condition can usually be met over a large range of cometary heliocentric distances with the large field of view of a Fabry-Perot spectrometer. The O(¹D) production rates were then used to obtain production rates for H₂O, using an appropriate model for the photodissociation of H₂O (Magee-Sauer et al. 1990).

3) Comet Austin (1989c1) presented a new opportunity for our group to carry out important studies of the comet and its interaction with the solar wind in interplanetary space. We observed Comet Austin in April and May 1990 with the Fabry-Perot spectrometer at the West Auxiliary of the McMath Solar Telescope. The spectrometer had two modes of operation: (1) a high spectral resolution mode with a Doppler velocity resolution of 1.2 km s⁻¹ and (2) a mode with medium spectral resolution of 10 km s⁻¹. Spectral line profile data were obtained by photon counting with a photomultiplier as the Fabry-Perot scanned over an emission feature, and imaging data were obtained with a Photometrics CCD camera using a TK516 Ford chip. The field of view on the sky was 10'.5; the CCD images had a spatial resolution of 7".6.

The program included observations of both ions and neutral species in the cometary atmosphere and tail. Although Comet Austin was about one hundred times fainter in April and May than predicted in January 1990, the techniques we used were still able to obtain data of good quality (Schultz, et al. 1990).

The cometary [OI]6300 and NH₂ 6298.6 emission lines were observed, both in high and medium resolution modes. Since the high resolution mode was able to resolve the emission profiles the observed widths of the lines provide information on outflow velocities of the comet's atmosphere. The medium resolution [OI]6300 observations provide production rates

for O(¹D). These production rates can then be used to obtain production rates for H₂O, with the same basic procedure as was used to obtain H₂O production rates for Comet Halley.

The H₂O⁺ emission doublets at 6159 Å and 6147 Å were observed with medium spectral resolution scans and images. Velocity resolved sequences of images (data cubes) were obtained on nine nights. Each data cube consisted of a sequence of four to eight images, with the central wavelength of the spectrometer stepped 0.2 Å (10 km s⁻¹) between each image in the sequence. Each image took from five to fifteen minutes to acquire.

4) On the basis of a proposal we submitted to the National Solar Observatory (NSO), in February 1990 the staff of NSO used the McMath solar telescope high-resolution echelle stellar spectrograph to search for "auroral" [OI]6300 emission from Io's atmosphere. Six spectra of Io and two spectra of Europa were obtained at a spectral resolving power of about 120,000, with excellent signal/noise. An examination of the observations indicates that [OI]6300 emission from Io was detected, and the emission was not present in the Europa spectra. The [OI]6300 emission, which was superposed on Io's bright, reflected solar spectrum, had an intensity of about 30 kiloRayleighs, assuming that it was produced in a thin atmospheric layer near Io.

Since the [OI]6300 emission is probably time variable, the NSO staff carried out a new set of observations of Io and Europa in February 1991, and a third set of observations is planned for May 1991.

This type of observation appears to open up a new method of studying the Jupiter plasma torus/Io system.

Projected Accomplishments

1) Interesting variations in the structure of the Comet Austin (1989c1) ion tail were seen at different wavelengths in all the Fabry-Perot H₂O⁺ data cubes. A major effort in data analysis will involve treating the time variability of the comet plasma, since the morphology of the H₂O⁺ emission changed significantly from the first to the last image of each data cube. The Joint Observatory for Cometary Research (JOCR) obtained interference filter H₂O⁺ images of the comet on four nights when data cubes were obtained by the Wisconsin group. The JOCR images, which were taken about every ten minutes, can be used to monitor temporal changes in the morphology of the H₂O⁺ emission, thus allowing us to treat the time variability separately from velocity structure within the H₂O⁺ emission. We plan to carry out an extensive analysis of the Wisconsin data cubes and JOCR images in order to investigate the dynamics of the solar wind-cometary plasma interaction.

2) The new data from the February 1991 observing program at the McMath telescope to search for [OI]6300 emission from Io will be analyzed as soon as it is received from NSO. If further data is obtained in May 1991, we will promptly analyze it, also. It may be possible to obtain some information on the spatial distribution of the emission around Io, using the

McMath stellar spectrograph image slicer, but seeing/guiding problems may preclude this possibility.

3) The analysis of our 1988 Jupiter plasma torus observations will be completed and the results will be submitted for publication. We will also compare these results with our earlier work on the torus in 1981, 1982, 1984, and 1987.

Publications

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Groundbased Cometary Studies

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Strategy

In this grant we seek to understand the physical properties of comets by applying a wide variety of observational techniques. We particularly emphasize simultaneous or coordinated observations in different spectral regions (e.g. visible and thermal I.R. or visible and far U.V.) or with different instrumentation (imaging, spectroscopy, photometry). We aim to (1) measure the basic properties of cometary nuclei by studying comets whose comae are so anemic that the signal from the nucleus can be extracted, (2) investigate the group characteristics of comets by narrowband photometry applied uniformly to a large sample of comets, (3) understand the detailed physics and chemistry occurring in cometary comae through wide-field CCD imaging using narrow filters and through long-slit CCD spectroscopy, and (4) investigate the rotational states of comets through time-resolution photometry.

Progress and Accomplishments

In the past year (under our previous grant "Planetary Research at the Lowell Observatory") we have conducted three major observing campaigns, along with several other investigations. Photometric observations of Comet Levy (1990c) began in early July 1990 and continue into 1991. Strong asymmetry about perihelion was observed for all species. Time-resolution monitoring of Levy in late August revealed periodic variations with a 19 hr period. Levy is the first long-period comet in which rotational variations have been observed using photometric techniques. In May and June 1990, an extensive set of coordinated observations of Comet Austin (1989c1) were acquired using a conventional photometer on the Lowell 42-inch telescope, a long-slit CCD spectrograph on the Perkins 72-inch telescope, and a Texas Instruments 800 by 800 CCD on a Takahashi ϵ -200 f/4 telescope. Observations of Comet P/Encke were obtained in October in order to better understand the apparent decoupling of OH from other species seen in earlier apparitions of this comet at small heliocentric distances. We have performed an analysis of photographic photometry of Comet P/Halley from the 1910 apparition. Based on these old observations, we have been able to present strong evidence that Halley exhibited the same 7.4-day brightness variations in 1910 that we discovered during the recent apparition.

Projected Accomplishments

In the next year, emphasis in this research program will be given to analysis and publication of our data sets on Comets Levy and P/Halley, and of our total database of comet photometry (now numbering 80 comets). Coordinated visible and infrared observations of Comet P/Faye are planned which, if successful, will yield the dimensions, albedo, color, and rotational period of this comet's nucleus. Finally, observations of newly discovered comets will be undertaken as circumstances warrant.

Publications

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Radiative Transfer in Planetary Atmospheres

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Strategy

This research effort covers a wide range of topics including: (1) the observational study of cometary comae via millimeter and radio spectroscopy; (2) observational and theoretical studies of planetary atmospheres at millimeter wavelengths; (3) application of theoretical models of the reflection of light from solid surfaces to the study of planetary regoliths and planetary rings.

Progress and Accomplishments

The focus of last year's effort was to take advantage of observational opportunities for cometary work as a part of our continuing effort to use the radio spectral region to probe the physics and chemistry of the coma. Our most exciting results of 1990 were obtained at the Caltech Submillimeter Observatory (CSO) on Mauna Kea. Observations of both C/Austin and C/Levy were obtained, and in C/Levy we made several good detections of cometary molecules, including the first detections of submillimeter transitions of HCN, formaldehyde and methanol. In addition, the emission was so strong that, for the first time, it was possible to map these parent molecules in the coma. The HCN map revealed an asymmetric distribution of this molecule in the coma, with the strongest emission from the sunward side of the nucleus. Observations of the formaldehyde emission showed evidence of extended emission in our 20" beam. If real, this emission indicates that formaldehyde may be produced directly from a source in the coma, rather than from the nucleus alone. In a second project, observations of the 18-cm OH transitions were made at the NRAO 140-foot telescope in P/Brorsen-Metcalf, C/Okazaki-Levy-Rudenko, and C/Austin. All comets were detected and the OH line shapes are now being analyzed to deduce coma outflow speeds. Finally, we participated in a coordinated campaign to observe C/Austin in the HCN 1-0 line with the Five College Radio Astronomy Observatory (FCRAO) 14m telescope and the Berkeley-Illinois-Maryland millimeter array (BIMA) simultaneously. Unfortunately, no detections were made, but the experience obtained combining the data from these two instruments has prepared the collaboration partners to make sensitive use of these observatories when the next bright comet appears.

Projected Accomplishments

The work on the study of comets via their radio/millimeter emission will continue. We will complete reduction and analysis of data obtained during the last year and continue our theoretical investigations of the cometary coma, using the data provided by this effort over the last several years. When bright comets provide the opportunity to do radio work, new observations will be pursued, especially at the CSO facility in the submillimeter portion of the spectrum where we have arranged a commitment for observing time for cometary work. In addition, our continuing collaboration with K. Lumme on the study of radiative transfer in planetary and satellite regoliths will continue.

Publications

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Radar Studies in the Solar System

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Strategy

We are engaged in a study of the solar system by means of ground-based radar. We have concentrated on (i) developing the ephemerides needed to acquire radar data at Arecibo Observatory and (ii) analyzing the resultant data to: test fundamental laws of gravitation; determine the size, shape, topography, and spin vectors of the targets; and study the surface properties of these objects, through their scattering law and polarization characteristics.

Progress and Accomplishments

We have actively engaged in radar observations of asteroids and comets, both as systematically planned targets and as "targets of opportunity." During the past year, we attempted observations of four newly-discovered asteroids within a few weeks of discovery as well as three planned asteroids and two planned comets. Both attempts at comets failed, one because of a transmitter failure at Arecibo and the other because the target's radar cross-section was too low. The same two causes also prevented one asteroid attempt each, but two other attempts at observing new targets were highly successful. These observations took advantage of daily ephemeris refinements based on the available optical data beforehand and on the preliminary radar data during the observing run. The results are still being analyzed. The observing program also covered two of the four Galilean satellites of Jupiter and the satellites of Mars. In addition, progress was made in our ongoing effort to obtain "closure point" observations of Mercury, both at Arecibo and at the Goldstone radar operated by JPL. Finally, we have continued the analysis of radar data and prepared articles for publication in collaboration with our colleagues. Three papers were published, and analysis was begun on newly-acquired Venus radar data. Another paper, on 1986 DA, is in press.

Projected Accomplishments

We plan to continue our activities in this field, both by obtaining radar observations of asteroids, comets, planets, and satellites and by analyzing the data. We plan to refine the spin vector of Venus on the basis of recently acquired data; the result could be important in the interpretation of results from the Magellan mission.

Publications

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Planetary Astronomy

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Strategy

Lunar-based astronomy offers major prospects for solar system research in the coming century. Because such developments typically require decades to implement, now is the time for efforts to begin. During a partial leave of absence from the University of Texas at Austin, H. Smith is at the Lunar and Planetary Institute organizing workshops on the various issues associated with astronomy from the Moon. Several articles on the subject are being prepared.

Progress and Accomplishments

A workshop and conference on astronomy from the Moon was organized and carried out last year (with M. Mumma at GSFCA).

Projected Accomplishments

In addition to active advocacy of both ground-based and Lunar-based astronomy, a workshop on the value of asteroids as a resource for man is being organized.

Publications

"Astrophysics from the Moon - Composition and Structure of Planetary Atmospheres," L. Trafton, in *Astrophysics from the Moon* (M.J. Mumma and H.J. Smith, eds.), AIP Conference Proceedings **207**, 41-44.

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Radar Interferometric Studies of Comets

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Strategy

Our objectives are to use radio interferometry to study the composition, velocity distribution, maser excitation, and plasma interactions of cometary gas. In previous studies, we demonstrated that the VLA can be used to make radio images of 18 cm wavelength cometary OH emission with a resolution of $\approx 1'$ which show previously unknown and unexpected small scale structure close to the nucleus. We used similar techniques with the VLA to detect the 6 cm transition of H_2CO in comets Halley, Machholz, and Brorsen-Metcalf. We discovered that the Comet Halley H_2CO emission was produced from an extended source in the coma as well as directly from the nucleus; this was later confirmed by Krankowsky's analysis of the H_2CO channel in the NMS data. The centimeter wavelength detections place important constraints on the partition function and excitation of cometary H_2CO ; these constraints are essential for interpreting observations at shorter wavelengths and, in particular, for deriving the correct gas production rate from radiative transfer models.

Two new cometary chemistry programs have been started with radio interferometers. First, the VLA has been used to search for HC_3N emission from Comet Brorsen-Metcalf at 3.3 cm wavelength, and it was demonstrated that for this molecule the VLA can be expected to reach significant levels of sensitivity in many comets. Second, the BIMA millimeter array was used to observe Comet Austin in HCN while our colleagues observed HCN simultaneously with the FCRAO 14-m radio telescope and the Flagstaff 42-inch optical telescope. The primary goal was to map the distribution of cometary HCN, compare the radio data with the simultaneous, high resolution optical CN images, and solve the long-standing problem of whether HCN is the parent molecule of optical CN. The secondary goal was to test the feasibility of detecting the 3 mm continuum emission from comets. Both programs have had a modest amount of success, which demonstrates some important directions for future radio interferometric studies of cometary chemistry.

Publications

Snyder, L. E., Palmer, P., and de Pater, I., 1990, "Observations of Formaldehyde in Comet Machholz (1988j)", *Icarus*, **86**, 289-298.

Palmer, P., A'Hearn, M. F., de Pater, I., Klavetter, J. L., Mehringer, D., Schloerb, F. P., Snyder, L. E., and Wilner, D., 1990, "Simultaneous Imaging of Optical CN Lines and Radio HCN Lines in Comet Austin", in *Workshop on Observations of Recent Comets (1990)*, eds. W. F. Huebner, J. Rahe, P. A. Wehinger, and I. Konno (Southwest Research Institute), p. 40-43.

Snyder, L. E., Palmer, P., and de Pater, I., 1990, "VLA Searches for Formaldehyde and Cyanoacetylene Emission from Comet P/Brorsen-Metcalf (1989o)", in *Workshop on Observations of Recent Comets (1990)*, eds. W. F. Huebner, J. Rahe, P. A. Wehinger, and I. Konno (Southwest Research Institute), p. 86-91.

de Pater, I., Palmer, P., and Snyder, L. E., 1990, "A Review of Radio Interferometric Imaging of Comets", in *Comets in the Post-Halley Era*, eds. R. L. Newburn, M. Neugebauer, and J. Rahe (Dordrecht:Kluwer), in press.

Snyder, L. E., Palmer, P., and de Pater, I., 1990, "Comet Halley and Interstellar Chemistry", in *Proceedings of Pacificchem '89 Symposium No. 228, Chemistry and Spectroscopy of Interstellar Molecules*, ed. N. Kaifu (University of Tokyo Press), in press.

Spatially Resolved Quantitative Spectroscopy of Comets

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Strategy

The objectives of my cometary research are to gain indirect knowledge of the chemical composition of cometary nuclei and the velocity field of the ejected daughter species. This can be done through conventional, high-resolution spectroscopy and indirectly by imaging the dissociation radicals in the outflowing cometary comae.

Progress and Accomplishments

Two-dimensional CCD images of Comet Austin (1989c1) were obtained with Newburn, Brown, and Dickinson using the Lick 1-m reflector on three nights in May 1990. The images were obtained using optical interference filters to isolate CN, C₂ and a good continuum wavelength. The goal of this subproject will be to continue studies of the gas production rates, comae asymmetries, and to eventually model the coma outflow mechanisms. We also obtained echellograms of comet Austin, using the conventional (multi-order) mode of the Hamilton Echelle at the Lick 3-m, and also we obtained several high spectral/spatial 2-D images using an interference filter to isolate the cometary H α line. The circumstances for Austin placed solar-directed outflows into the sky plane with no geocentric radial velocity component.

Cometary H α emissions arise from the photo-dissociation of H₂O and OH (plus excitation of fluorescence from the solar Ly Beta line). The velocity distribution of the H atoms near the cometary nucleus could give clues to possible heavier parent molecules. Some fraction of the H atoms are apparently thermalized to low speeds by collisions with neutral water molecules close in. Our Austin spectra show an amazingly (spatially) compact low-velocity H α line (it is as spatially nucleated or more so than the dust component). On our one good H α long-split echellogram of Comet Levy (1990c) we see an unusually strong blue-wing to the H α profile. This feature, which causes a strong asymmetry on part of the cometary H α velocity profile, is a likely jet of H gas directed from the solar-illuminated hemisphere (roughly) toward the Sun and the Earth. It does not appear to be an instrumental artifact or a likely consequence of the exciting solar LyBeta line. In this case we note, after the fact, that the geometry was favorable to detect collimated jets ejecting gas towards the Sun.

Projected Accomplishments

Analysis of the cometary CCD images (with Newburn) will continue; we also are in the midst of a detailed search of the chemical literature to help with the identification of the approximately 3,000 unidentified emission lines in our echellograms of Comets P/Brorsen-Metcalf, Austin, and Levy. The unidentified and nucleated band near $\lambda 4838$ still has us baffled; it is not due to CO and probably not HCO. In any future bright comet opportunity, we also intend to measure the H_2O^+ ionic velocities in the "near-tail" with long-slit echellograms, if the geometry is suitable.

The Evolution of Young Stellar Object Disks and Their Environment

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Progress and Accomplishments

Our main efforts have been directed toward determining the frequency of disk occurrence and the timescales for disk evolution for solar-type and intermediate mass stars. Results to date indicate that:

- Optically thick disks ($\tau > 1$ in regions sampled by excess emission $\lambda \leq 10\mu\text{m}$) are found around 30% to 50% of young ($\tau < 3$ Myr) stars of all masses $M < 3 M_{\odot}$. Optically thick disks are found around PMS stars of higher mass, but with unknown frequency. For the relatively limited sample of objects for which sub-mm and mm-continuum measurements are available, nearly all stars with $\tau > 1$ show disk masses $M_d > 0.01 M_{\odot}$ ($\equiv M_{\text{mm}}$). Disk sizes range from ~ 10 AU to ~ 1000 AU. Hence *disks of solar system sizes, and of masses comparable to or greater than the minimum mass solar nebula appear to form around a large fraction of stars with $M < 3 M_{\odot}$.*
- Nearly all optically thick disks show evidence of (1) boundary layer emission diagnosed by "spectral veiling" at all optical wavelengths, and indicative of accretion of material onto the stellar surface; and (2) strong, broad H α emission and forbidden line emission arising in energetic winds whose mechanical luminosity is proportional to the disk accretion luminosity. We conclude that *optically thick disks are accretion disks* with typical accretion rates $M_{\text{acc}} > 10^{-8} M_{\odot}/\text{yr}$.
- Disks survive as massive, optically thick structures extending nearly to the stellar surface for times ranging from $t \ll 3$ Myr to $t \sim 10$ Myr around solar-type PMS stars. No optically thick disks have been identified around solar-type stars with ages $t \geq 30$ Myr. The survival time for disks around more massive stars are not well established, particularly for stars $M > 3M_{\odot}$. However, the limited data available suggests that the disk survival times for such massive stars may be considerably shorter ($t < 1$ Myr) than those for solar-type stars.
- The descendants of massive, optically thick disks are disks containing masses of distributed micron-size dust grains $M < 10^{-4} M_{\odot}$; such disks are optically thin, and perhaps analogous to the structures observed to surround the intermediate mass stars Vega and β Pic.

Evidence of infrared excess emission consistent with emission arising in optically thin disks is found for stars of all masses. Stars surrounded by optically thin disks show none of the signatures associated with disk accretion (strong boundary layer emission; emission from spectral features arising in energetic winds). Hence, when disks become optically thin, disk accretion ceases.

- The presence of micron-size grains in optically thin circumstellar disks at distances $r < 1$ AU from the surface of solar-type stars, requires that such grains be continuously supplied to these disk regions; Poynting-Robertson or aerodynamic drag would otherwise deplete the grains on timescales short compared to the age of stars surrounded by optically thin disks. Small grains can be supplied either by collisions among larger grains or planetesimals; by evaporation of cometesimals gravitationally scattered into the inner disk regions; or by grains spiraling in from cold, outer disk regions ($r \gg 1$ AU). Millimeter continuum observations currently underway can place stringent limits on the amount of distributed cold dust.
- Disks with apparent "inner holes" have been discovered. These are most likely structures in transition between disks that extend inward to the stellar surface and are optically thick throughout, and those that are optically thin. The presence of an "inner hole" may require that the inner regions of a disk be isolated from the exterior, optically thick disk regions. If so, the formation of a giant planet provides an attractive mechanism for tidally isolating the outer and inner disk regions. In this picture, the formation of a giant planet creates a gap in the disk. Gas and small grains located inward of the gap accrete onto the parent star; small grains, and possibly gas exterior to the gap survive for times $t > 0.1$ Myr.
- Our assessment of disk properties to date rests entirely on observations of emission arising from *dust* contained within the disk. Interferometric observations reveal CO mm-line emission arising in disk gas surrounding two extremely young solar-type PMS stars (HL Tau and L1551, IRS 5). The estimated gas mass for these systems lies in the range 0.1 to $1M_{\odot}$ (consistent with the masses determined from mm-continuum emission, "standard" dust emissivities, and an interstellar gas/dust ratio). Systematic searches for disk gas associated with stars of differing ages and masses are critical to determining characteristic times for the evolution of the gas component. However, no such searches are yet available, primarily because the sensitivity required demands extensive time on large mm-wave telescopes. We have searched for CO emission associated with G and K main sequence stars in the nearby Ursa Major cluster ($d=25$ pc; $t\sim 200-300$ Myr). We find no evidence of CO emission associated with these stars, despite the fact that our measurements are sensitive enough to permit detection of $M \sim 10^{-4} M_{\odot}$ of gaseous material with a CO/H₂ ratio comparable to interstellar values. If CO survives in the circumstellar environment, then these observations suggest a gas survival time $t < 200-300$ Myr.

Projected Accomplishments

We plan to complete program of precise near- and mid-infrared measurements aimed at probing the distribution of dust located within the inner regions ($r < 1$ AU) of circumstellar disks surrounding solar-type stars. Our goal is to establish the magnitude of excess (above

photospheric levels) near-infrared emission for a large (150) sample of stars with ages ranging from 30 Myr to 300 Myr, and to determine thereby the timescale(s) over which dust emission arising from inner disk regions becomes undetectable. Because dust in the inner regions of optically thin disks must be replenished continuously, we believe that this program will provide a strong astronomical constraint on the timescale(s) for assembling earth-mass bodies from planetesimals by monitoring the rate at which small grains are produced via collisions between planetesimals as a function of stellar age.

We also plan to carry out a program of sensitive mm-continuum observations aimed at:

- *Determining for solar-type stars with ages $t > 10$ Myr, the fraction, as a function of parent star age, that are still surrounded by circumstellar disks containing a significant ($M > 0.001 M_{\odot}$) amount of material in the Giant Planet Region ($3 < r < 30$ AU). These observations will provide an important astronomical constraint on the timescale available for building giant planets, and will complement recent infrared and mm-continuum surveys of much younger ($t \ll 10$ Myr) solar-type stars.*
- Identifying solar-type stars in which planet-building may already have taken place at $r < 1$ AU. Such stars should be surrounded by disks which produce strong mm-continuum excess, but no near- and mid-IR excesses. This spectral signature is indicative of a star surrounded by a significant mass of cold dust located at distances of $r \gg 1$ AU, but little or no warm, micron-size dust located within ~ 1 AU of the stellar surface. The development of such "inner holes" may signify that agglomeration of dust into planetesimals has begun in the terrestrial planet region.

Finally, we will pursue efforts to detect CO emission from disks surrounding young ($t < 100$ Myr) solar-type stars using the IRAM antenna.

Publications

Evolutionary Timescales for Circumstellar Disks Associated with Solar-Type Pre-Main Sequence Stars, 1989, *Sixth Conference on Cool Stars, Stellar Systems, and the Sun*, Astronomical Society of the Pacific Conference Series Volume 9, ed. G. Wallerstein -- with S. Edwards and M. Skrutskie.

Forbidden Lines in T Tauri Star Spectra: A Clue to the Origin of T Tauri Winds? July 1989, *ESO Workshop on Low Mass Star Formation and Pre-Main Sequence Objects*, in Garching, F.R.G. -- with S. Edwards, S. Cabrit, and L.O. Ghandour.

Lithium Abundances Among Solar-Type Pre-Main Sequence Stars, 1989, *A.J.* **98**, 1444 -- with K.M. Strom, F.P. Wilkin, and R.L. Seaman.

Further Evidence for Differential Rotation in V1057 Cygni, 1990, *Ap. J.* **349**, 328 -- with A.D. Welty, K.M. Strom, L.W. Hartmann, S.J. Kenyon, G.L. Grasdalen, and J.R. Stauffer.

An IRAS Survey of the Taurus-Auriga Molecular Cloud, 1990, *A.J.* **99**, 869 -- with S. Kenyon, L. Hartmann, and K.M. Strom.

Evolutionary Timescales for Circumstellar Disks Associated with Solar-Type Pre-Main Sequence Stars, 1990, in *Protostars and Planets III*, (ed. E. H. Levy and J. Lunine, University of Arizona Press: Tucson) -- with S. Edwards and M. Skrutskie.

A Sensitive 10 μ Search for Emission Arising from Circumstellar Dust Associated with Solar-Type Pre-Main Sequence Stars, 1990, *A.J.* **99**, 1187 -- with M.F. Skrutskie, D. Dutkevitch, S. Edwards, K.M. Strom, and M.A. Shure.

Correlation of Optical and Infrared Excesses in T Tauri Stars, 1990, *Ap.J.Lett.* **354**, L25 -- with P. Hartigan, L. Hartmann, S.J. Kenyon, and M.F. Skrutskie.

Forbidden Line Emission and IR Excesses in T Tauri Stars: Evidence for Accretion-Driven Mass-Loss? 1990, *Ap.J.* **354**, 687 -- with S. Cabrit, S. Edwards, and K.M. Strom.

Disks Associated with Intermediate Mass Stars, 1990, in *NATO Advanced Research Workshop: Angular Momentum Evolution of Young Stars* 17-21 Sept. 1990, NOTO, Italy (to appear in conference proceedings: Kluwer Academic Publishers; Dordrecht, The Netherlands) -- with J. Keene, S. Edwards, L.A. Hillenbrand, K.M. Strom, L. Gauvin, and G. Condon.

Visual and Infrared Studies of Asteroids and the Pluto-Charon System

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Strategy

1. To analyze lightcurves of Pluto-Charon mutual eclipse event lightcurves to derive models of the Pluto-Charon system. 2. To use these results in planning and reducing Hubble Space Telescope observations tentatively scheduled to be obtained in August 1991 to determine the Pluto-Charon mass ratio. 3. To obtain visual and infrared photometry of selected asteroids to help determine their albedos, sizes, shapes, pole orientations, taxonomic classes, and phase functions.

Progress and Accomplishments

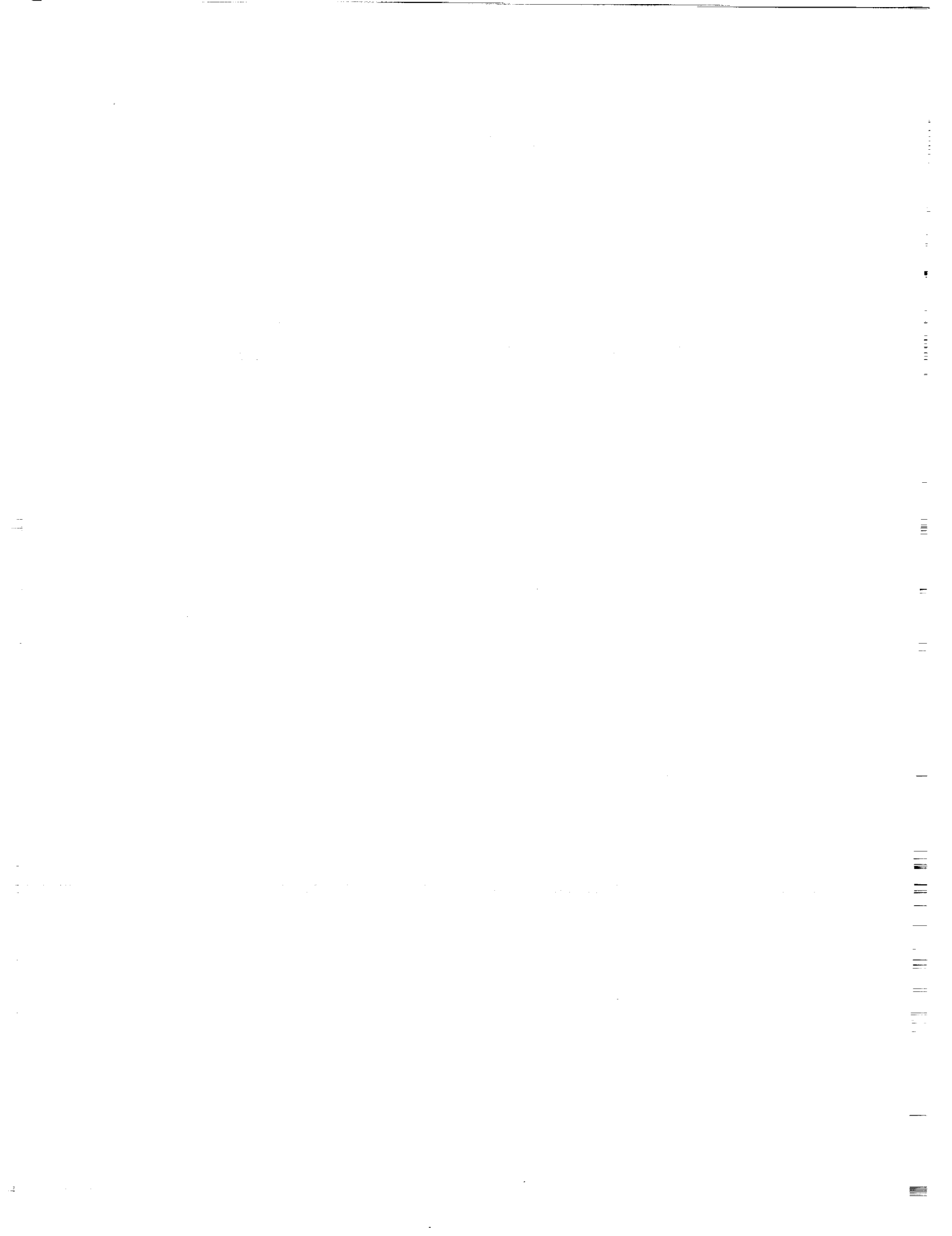
During 1990 we completed reduction of Pluto-Charon mutual event light-curves obtained with the Palomar 1.5-meter telescope and submitted for publication a synthesis of simultaneous observations, spanning 0.44 to 2.4 μm , of the 03 March 1987 total event. We completed the IRTF infrared mutual event lightcurve program by successfully observing three of four scheduled events. Production of a master data base of four decades of asteroid UBV photometry and a listing of asteroid absolute magnitudes and slope parameters, to appear in the 1992 *Ephemeris of Minor Planets* were completed.

Projected Accomplishments

During 1991 we will publish the Palomar CCD Pluto-Charon mutual event lightcurves, the UBV color indices and absolute magnitude listings, and thermal infrared lightcurves of the near-Earth asteroid 1580 Betulia.

Publications

Tedesco, E.F. (1990). Magnitude parameters for the numbered minor planets. *Minor Planet Circulars* 17256-17273.



Planetary Optical and Infrared Imaging

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Strategy

The purpose of this investigation is to obtain and analyze high spatial resolution CCD coronagraphic images of extra-solar planetary material and solar system objects. These data will provide information on the distribution of planetary and proto-planetary material around nearby stars leading to a better understanding of the origin and evolution of the solar system. Tests of high efficiency coronagraph designs on ground-based telescopes will support the Astrometric Imaging Telescope (AIT). Observations using a membrane mirror will test imaging improvements possible by adaptively compensating for atmospheric seeing. Imaging within our solar system will provide information on the current cloud configurations on the outer planets, search for new objects around the outer planets, and provide direct support for Voyager, Galileo, and CRAF by imaging material around asteroids.

Progress and Accomplishments

Over the last year an analysis of multispectral and polarization images of the disk of material around the nearby star Beta Pictoris suggests that the material is very low albedo and similar to dark outer solar system carbon rich material. This material is believed to be associated with the formation of planets and provides a first look at a planetary system much younger than our own. A coronagraphic search for other systems has already examined over 120 nearby stars and an image processing data system has been set up to evaluate these data and to establish limits for circumstellar material. Initial coronagraphic observations were taken with a tilt-tip adaptive optics system as a precursor to a membrane mirror.

Projected Accomplishments

A survey of the nearby stars will be completed and data will be examined more deeply to provide limits on the probability of circumstellar material around stars and to understand the morphology of young planetary systems. Observations made by combining a coronagraph with a membrane mirror adaptive optics system will allow more sensitive searches and provide test data for more advanced applications of seeing compensation. Tests will be made of components of a higher efficiency coronagraph on ground-based telescopes using graded occulting masks. Further analysis of the Beta Pictoris polarization data as a function of color will be used to model the particle size distribution of dust in the disk. Coronagraphic

imaging of the outer planets, asteroids and star forming regions will continue to provide support for ongoing missions such as Voyager, Galileo, CRAF, Cassini and AIT.

Publications

1 paper and 6 abstracts published.

Richard J. Terrile:

Hansen, C. J., McEwen, A., Ingersoll, A. P. and Terrile, R. J. (1990) "Surface and Airborne Evidence for Plumes and Winds on Triton." *Science*, **250**, 421.

Studies of Triton and the Pluto-Charon System

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Strategy

This project is designed to take advantage of the six-year-long series of mutual occultation and eclipse events involving Pluto and its satellite Charon during one of its rare edge-on orbital alignments. High-precision, high-time-resolution photometry of these events, each of which displays a unique geometry of the system, can be utilized to extract several important physical parameters, including the relative sizes of the two bodies, the orientation of the orbit of the satellite, and the surface albedo distribution on one hemisphere of each object. An important derived parameter is the mean density of the system, which constrains the bulk composition of the two bodies.

Progress and Accomplishments

1990 was the final year of events, with the last event occurring on 1990 October 15 UT. Prior to opposition, grazing geometry involving only the shadows of the two objects produced very shallow events of less than five percent in maximum depth, decreasing as Pluto approached opposition. Following opposition, parallax produced overlap of the two projected disks, and the events reached a maximum depth of nine percent (in blue light) near the time of postopposition quadrature. Opposition represented a time of last contact for the events involving shadows and first contact for events involving disks and thus offered an opportunity to perform very sensitive edge detection observations. During 1990, six events were well observed with the 2.24-m telescope on Mauna Kea, and two additional events, partially damaged by adverse weather conditions, contain some useful data. In particular, a five-hour-long observation near opposition yielded photometric resolution of 0.0025 magnitudes per 72 second integration, thereby providing a significant constraint on the sizes of the two bodies.

Projected Accomplishments

Work in 1991 will be devoted primarily to establishing photometric baselines at the two rotational phases corresponding to the events, thus enabling interpolation to be used to determine the expected unocculted or uneclipsed brightness of the system that can be differenced with the measured brightness during an event, which in turn goes into the surface albedo mapping effort. Also, a systematic rereduction of the data obtained throughout the mutual event season will begin with an analysis of the long term photometric behavior of the comparison stars used for the last nine years. Our goal is to produce a network of comparison stars whose brightnesses and colors have an internal consistency approaching

0.001 magnitudes, thereby minimizing any degradation of the Pluto data from systematic errors in the comparison star magnitudes.

No new work on Triton was performed during 1990, nor is any anticipated for 1991. Prior observations were obtained primarily to support the Voyager 2 encounter with the Neptune system, which occurred in 1989.

Publications

No new papers were published in scientific journals during calendar year 1990, although a popular level summary article was published.

Tholen, D. J. 1990. Pluto. *McGraw-Hill Yearbook of Science & Technology 1991*, pp. 334-336. McGraw-Hill, New York.

Visible and Infrared Investigations of Planet-Crossing Asteroids and Outer Solar System Objects

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Strategy

This project is supporting lightcurve photometry, colorimetry, thermal radiometry, and astrometry of selected asteroids. Targets include the planet-crossing population, particularly Earth approachers, which are believed to be the immediate source of terrestrial meteorites, future spacecraft targets, and those objects in the outer belt, primarily the Hilda and Trojan populations, that are dynamically isolated from the main asteroid belt. Goals of this work include the determination of population statistics for the planet-crossing objects, which were poorly sampled in earlier surveys, the characterization of spacecraft targets to assist in encounter planning and subsequent interpretation of the data, a comparison of the collisional evolution of the dynamically isolated Hilda and Trojan populations with the main belt, and the determination of the mechanism driving the activity of the distant object 2060 Chiron.

Progress and Accomplishments

Earth approaching asteroids that were observed during 1990 include 1951 Lick, 1927 TC, 1989 WM, 1990 DA, 1990 HA, 1990 OA, 1990 SA, 1990 SB, 1990 SM, and 1990 SQ. The most unusual of these objects are 1951 Lick and 1990 SQ, whose colors, based on preliminary reductions, indicate rare A-type and Q-type classifications, respectively. Astrometry was obtained of several of these newly discovered objects to assist in the determination of their orbits. Due to relatively short observational windows for many of these objects, most of these observations were essential to permit future recovery of these asteroids.

During 1990, special attention was given to 951 Gaspra, the asteroid that the Galileo spacecraft will encounter on 1991 October 29. Observations were obtained to characterize this object's rotation state, shape, surface scattering properties, surface variegation, and orbit, all to assist the planning of the encounter and to maximize the science return. The rotational period was found to be just over 7 hours, and the data suggest that the obliquity of the rotation axis is not low. The lightcurve implies a non-symmetric shape, with axis ratios $a_1:a_2:b_3$ of approximately 1.7:1.5:1.1:1. The phase function could not be uniquely determined due to the changing sub-Earth latitude (and cross-sectional area), but appears to be typical of asteroids with its spectral classification. Very subtle variations in color over the surface may exist, but appear in the data at only the one standard deviation significance level. Six astrometric observations of Gaspra were obtained during the 1990 opposition to help navigate the Galileo spacecraft to the asteroid.

The lightcurves of eight additional Hilda and Trojan asteroids were observed during 1990, thereby augmenting our sample of objects. Analysis of these data are continuing.

Monitoring of the brightness of asteroid-turned-comet 2060 Chiron continued during 1990. The data show a reduced level of activity from the peak in early 1989, but appears to have leveled off, rather than continuing to decrease. Another successful detection of the thermal emission from this object was made at 20 microns, though this time the significance was only at the two standard deviation level.

Portions of the work described here are being done in collaboration with Dr. D. P. Cruikshank of NASA Ames Research Center and Dr. W. K. Hartmann of the Planetary Science Institute.

Publications

Cruikshank, D. P., D. J. Tholen, W. K. Hartmann, J. F. Bell, and R. H. Brown 1991. Three basaltic Earth-approaching asteroids and the source of the basaltic meteorites. *Icarus* **89**, 1-13.

Hartmann, W. K., and D. J. Tholen 1990. Comet nuclei and Trojan asteroids: A new link and a possible mechanism for comet splittings. *Icarus* **86**, 448-454.

Hartmann, W. K., D. J. Tholen, K. J. Meech, and D. P. Cruikshank 1990. 2060 Chiron: Colorimetry and cometary behavior. *Icarus* **83**, 1-15.

Astrometry of minor planets has been published in the following *Minor Planet Circulars*:

MPC 17522 (1991)	MPC 16669 (1990)
MPC 17492 (1991)	MPC 16331 (1990)
MPC 17105 (1990)	MPC 15967 (1990)
MPC 16956 (1990)	MPC 15948 (1990)
MPC 16801 (1990)	MPC 15810 (1990)

Related Publication

Schleicher, D. G., R. L. Millis, D. T. Thompson, P. V. Birch, R. Martin, D. J. Tholen, J. R. Piscitelli, N. Lark, and H. B. Hammel 1990. Periodic variations in the activity of comet P/Halley during the 1985/1986 apparition. *Astron. J.* **100**, 896-912.

*A Continued Program of Planetary Study at the University of Texas
McDonald Observatory*

University of Texas at Austin

L. Trafton

Strategy

The program conducts solar system research in support of NASA missions and of general astronomical interest. Investigations of composition, physical characteristics and changes in solar system bodies are conducted primarily using the facilities of McDonald Observatory.

Progress and Accomplishments

We have monitored Io's 2.1253 μm feature, which we discovered last year, as a function of time and of subearth longitude on Io. We have also explored the rest of Io's K-band in search of other unidentified absorptions. None were found. In sharp contrast to Io's other known absorptions, the feature has not been observed to vary with time (over a 1.5 year interval) or with longitude on Io. Therefore, it can only indirectly be associated with Io's volcanos. With our collaborators at NASA-Ames, we have ruled out sources which are overtones or combinations of any of the molecular vibrations associated with species already identified on Io (SO_2 , H_2S , H_2O) or from chemical complexes of these molecules. Laboratory experiments show that the most likely candidate is a multimer or "cluster" of CO_2 molecules. Our collected data show that very unusual periods of global scale auroral activity occurred during September and November of 1988. This would suggest that unusual periods of widespread magnetospheric dumping occur. This contrasts with the very weak activity seen a year later. There are long-term time scales for the Jovian auroral activity, and these are different for the H_2 and H_3^+ emissions. There have been times, as in 1986, when the H_3^+ was not detectable while the H_2 emission was clearly visible. During the global scale events, the H_2 and H_3^+ emissions remained confined to their unusual auroral zones but strong, unidentified emissions appeared in the vicinity of the H_2 quadrupole lines.

Projected Accomplishments

We will take advantage of the eclipses and occultations of Io to locate the source region on Io of the 2.1253 μm feature. We will also obtain high resolution FTS spectra at Kitt Peak of this feature to establish whether it is of gaseous or solid origin, and to enable more discriminating matches with laboratory spectra (useful for composition and state studies). We will also observe the eclipses of Galilean satellites by Io to study the Na atmosphere of Io. We will continue our spectroscopic study of the Jovian auroral emissions in an attempt to understand the excitation processes and connection with the plasma torus and Io volcanic activity. Pluto's post-perihelion changes will be monitored.

Publications

Published Papers:

1. "A Two-Component Volatile Atmosphere for Pluto I. The Bulk Hydrodynamic Escape Regime", L. Trafton, *Ap. J.* **359**, 512-523.
2. "Astrophysics from the Moon -- Composition and Structure of Planetary Atmospheres", L. Trafton in *Astrophysics from the Moon*, (M. J. Mumma and H. J. Smith, eds.), AIP Conference Proceedings **207**, 41-44.
3. "Origin and Evolution of Planetary and Satellite Atmospheres (S. K. Atreya, J. B. Pollack, and M. S. Matthews, Eds.), -- book review by L. Trafton, *Icarus* **86**, 574-575.

Submitted Papers:

1. "A New Class of Absorption Feature in Io's Near-Infrared Spectrum", L. M. Trafton, D. F. Lester, T. F. Ramseyer, F. Salama, S. A. Sandford, and L. J. Allamandola, *Icarus* **89**, 264-276, in press.
2. "Laboratory Studies of the Newly Discovered Infrared Band at 4705.2 cm^{-1} ($2.1253\text{ }\mu\text{m}$) in the Spectrum of Io: The Tentative Identification of CO_2 ", F. Salama, S. A. Sandford, L. J. Allamandola, L. M. Trafton, D. F. Lester, and T. F. Ramseyer, *Icarus*, in press.

Compositional Studies of Primitive Asteroids

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Strategy

The aqueous alteration history in the solar system will be studied through acquiring additional CCD reflectance spectra in the blue-UV through near-infrared (0.4 - 1.0 μm) spectral region and analyzing these spectra for information about iron oxides in phyllosilicates identified in the CM and CI carbonaceous chondrites. Emphasis will be on the main-belt and Cybele primitive asteroids, as these asteroids show spectral diversity and are also spectral analogues for known meteorite samples. The porphyrin bands found in organics near 0.4 μm will also be sought.

Progress and Accomplishments

During 1990, additional CCD reflectance spectra of main-belt C-class asteroids and some outer-belt asteroids were acquired. Spectra already acquired have been examined for changes in absorption strength and shape which occur with heliocentric distance. Sources of error which may affect broadband photometry but which can be delineated in narrowband spectrophotometry have also been studied. Spectra of Martian satellites Phobos and Deimos have been acquired and are being analyzed.

Projected Accomplishments

The data base of CCD spectra of primitive asteroids will continue to be enlarged, shifting the emphasis to the main-belt and Cybele primitive asteroids, and extending the spectral coverage to shorter wavelengths. Detail in the spectra of these asteroids will reveal more of the history of aqueous alteration in the solar system. An observational search for the porphyrin bands near 0.4 μm will be conducted.

Publications

Vilas, F. and Gaffey, M. J. (1989) "Phyllosilicate Absorption Features in Main-Belt and Outer-Belt Asteroid Reflectance Spectra", Science, 246, 790.

Vilas, F., and McFadden, L. A. (1990) "CCD Reflectance Spectra of Selected Asteroids", LPSC XXI, 1272.

Vilas, F. and Larson, S. M. (1990) "The Continued Search for Aqueous Alteration Products Among the Primitive Asteroids", BAAS, 22, 1125.

Astrometric Observations of Comets and Minor Planets

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J. G. Williams and J. Gibson

Strategy

Comets and planet crossing asteroids are observed so that accurate positions can be determined. The observations are made with the Palomar 1.5m telescope equipped with a CCD array. This combination of telescope and detector is quite efficient at recording faint comets and minor planets. This proves quite useful for early acquisition of comets and asteroids returning for a new opposition. The resulting positions permit accurate orbits to be determined and allow the properties of the comets and asteroids to be measured by other observers using a variety of techniques. Recoveries and other notable observations of comets and planet crossing asteroids observed during the past year are discussed below.

Progress and Accomplishments

Of the comets observed during the past year, two were recoveries of periodic comets. The first recovery, P/Honda-Mrkos-Pajdusakova (1990f), was shared with another observatory. The second recovery was P/Johnson (1990h). The periodic comet P/Arend-Rigaux (1984 XXI) and other comets were also observed.

Projected Accomplishments

Asteroids which can come close to the earth (Apollos) are another high priority target. The Apollo 1988 EG was recovered at its second opposition. For the Apollos 4486=1987 SB and 4581=1989 FC observations at the second opposition were shared with another observatory. Both were permanently numbered as a consequence of the observations. 1989 FC is the small asteroid which passed very close to the earth in the spring of 1989. A fourth Apollo 4450=1987 SY was permanently numbered as a consequence of recovery and observations at both second and third oppositions.

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Physical Studies of Small Asteroids and Cometary Nuclei

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Strategy

This work comprises photoelectric and CCD photometry of small asteroids in the 0.5-25 km diameter range and cometary cores. It is to reconcile the observed physical properties of those bodies with models and laboratory experiments. As there is an inevitable spread between the laboratory scale and the real asteroid scale, the observations of smaller bodies offer us a natural laboratory to serve as an intermediate link between experimental sizes and real ones. Whenever possible, UBVMX colors are obtained to define taxonomic classes.

Progress and Accomplishments

Over 100 nights have been scheduled in support of this work. The observations are made mainly on the 60" and 90" telescopes of the University of Arizona Observatories on Mt. Lemmon and Kitt Peak. Approximately 30 small asteroids were observed. Nine of them were Earth-approaching ones, observed within days after discovery. Ten lightcurves were obtained for Galileo target 951 Gaspra covering the time span 1989 Dec - 1990 Apr.

Projected Accomplishments

I propose to continue physical observations (taxonomy and lightcurves) of small asteroids. Last year the impressive increase of discoveries of Earth-Approaching objects by PCAS and Spacewatch calls for particular attention, because smaller and smaller bodies are being discovered. The observability windows are very short -- quite often just a few days after discovery.

Since the Galileo spacecraft is on its way to fly by asteroids 951 Gaspra and 243 Ida, extensive ground-based coverage should be conducted to define the physical characteristics such as shape, taxonomy, albedo variegation and pole orientation before the encounters.

Publications

The rotation poles and shapes of 1580 Betulia and 3909 (1980 PA) from one apparition (J. Drummond and W. Z. Wisniewski 1990 Icarus 83, 349).

Rotation of Comet P/Tempel 2 from CCD and Photoelectric Photometry: W. Wisniewski 1990, Icarus 85.

Highly Variable Objects in the Solar System: W. Wisniewski 1991 Proceedings of the AAVSO meeting. Belgium 1990. In press.

Physical Studies of Small Asteroids. W. Wisniewski. 1991, Icarus 90.

Spectroscopy of Comets

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Susan Wyckoff

Strategy

Observations of NH_2 , $[\text{OI}]$, CH , CO^+ , CO_2^+ , H_2O^+ , and N_2^+ in optical spectra of comets represent ionization and dissociation products of virtually all of the volatile fraction of a comet nucleus, and can provide abundances of N_2 , NH_3 , H_2O , CH_4 , CO_2 and CO . The primary objectives are to determine: 1) accurate production rates for the observed species, and 2) accurate relative abundances of condensates in a sample of comet nuclei. The ultimate goal is to constrain models of comet formation and chemical processing in the outer primordial solar nebula.

Progress and Accomplishments

Monte Carlo models of comet comae have been developed which include effects of multiple-step photodissociation, asymmetric gas flow, radiation pressure, and time-dependent outflow. Improved methods for extracting surface brightness profiles of NH_2 were developed and used to demonstrate that ammonia production rates can be determined from NH_2 spectra with relatively insignificant model dependence except in cases of highly active comets. A study of NH_2 in a diverse sample of comets indicated that the mean ammonia/water abundance ratio was ~ 0.1 , with no significant variation among the comets. The apparent uniformity of the ammonia abundances among comets attests to a remarkable degree of chemical homogeneity over large scales ($>1\text{AU}$) in the comet forming region of the primordial solar nebula. A fluorescence model for the CN B-X band has been developed for determining the $^{12}\text{C}/^{13}\text{C}$ ratio in a sample of comets.

Projected Accomplishments

Calculation of photoabsorption rates of a set of cosmically abundant molecules relevant to comets has been completed using cross sectional data complete to Jan 1991, and a relatively high resolution solar EUV spectrum. The solar rates together with a bibliography will be published. A list of unidentified molecular ion features in the optical region of comet spectra is being compiled. The program to determine the NH_3 abundances from NH_2 spectra in an enlarged sample of comets continues. Abundances and the structure of the comet ionosphere are being studied both spectroscopically and with narrow-band images. The N_2^+/CO^+ ratio is being used to derive N_2/CO abundance ratios in a sample of comets. Both spectroscopic and narrow-band images of comet Austin are presently being analyzed. The carbon isotope ratios are under study in several comets.

Publications

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4. Wehinger, P. 1990, **Carbon Isotopes in Comets**, in *Workshop on Observations of Recent Comets (1990)*, eds. W. Huebner, P. Wehinger, J. Rahe and I. Konno, (San Antonio: Southwest Research Institute), p. 103.
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Comet and Asteroid Dynamics

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Strategy

In order to provide the ground-based observing community and NASA flight projects with accurate comet and asteroid ephemerides, improvements are being made to the existing dynamic models and new data types are being investigated. For active comets, nongravitational forces must be taken into account; these forces are assumed due to the rocket-like thrusting of outgassing cometary ices.

Progress and Accomplishments

New orbital solutions were computed for the dozen well observed near-Earth asteroids suspected of being inactive comets. For ten of these objects, the orbital improvements included the use of radar observations. For 1862 Apollo and 1566 Icarus, the existing optical and radar data could not be fit without the use of the outgassing acceleration model that is usually employed only for active comets. For asteroid 1566 Icarus in particular, the RMS orbit residuals and predictive capability of the computed orbits improved with the use of these nongravitational effects.

During 1990-1991, radar ephemeris predictions were provided for asteroids 1580 Betulia, 1989 JA, 1989 PB, 1917 Cuyo, comet 1989 c1 Austin, as well as for Mercury, Venus, Mars, Saturn, Titan, and Iapetus. Ephemeris information for approximately two dozen comets and asteroids were provided to observers both outside of, and within, the NASA community.

Simplified procedures were developed to allow the coordinate conversions of astrometric observations, ephemeris positions, and orbital elements between the B1950 and J2000 coordinate systems. These procedures involve only simple matrix manipulations and are symmetric in the sense that a conversion from B1950 to J2000 and from J2000 back to B1950 will reproduce the original initial conditions. These procedures will be adopted by IAU Commission 20 for use after January 1, 1992 -- when the community of comet and asteroid researchers will switch from the currently employed B1950 coordinate system to the J2000 system.

Projected Accomplishments

Because radar data has been shown to dramatically improve the orbits of many comets and asteroids, new orbital solutions will be performed for all comets and asteroids for which radar and optical astrometric data exist. Accurate comet and asteroid ephemeris information will continue to be provided to the community of observers (ground-based, Earth-orbital, and NASA flight projects).

Publications

1990 "Radar Images of Asteroid 1989 PB", *Science*, 248:1523-1528. (S.J. Ostro, J.F. Chandler, A.A. Hine, K.D. Rosema, I.I. Shapiro, and D.K. Yeomans).

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HIGHLIGHTS
OF
RECENT ACCOMPLISHMENTS
IN PLANETARY ASTRONOMY



Halley's Spin State Determined M. J. S. Belton

Since the VEGA and GIOTTO flybys of comet Halley in 1986 there has been a rising controversy over the nature of the spin state of its nucleus. So far, some 8 different models have been published but none as yet has been shown to simultaneously satisfy both spacecraft and ground-based data. Resolution of this problem is important because the future interpretation of much of the data archived by the *International Halley Watch* will depend on the existence of an accurate spin ephemeris.

The problem has now been resolved by M.J.S. Belton, W.H. Julian, A. Jay Anderson and B.E.A. Mueller who have found a spin state that simultaneously satisfies the VEGA and GIOTTO imaging data and a wide range of ground-based data. The latter includes photometric time-series taken both pre- and post-perihelion passage, time-series images of CN-jets emanating from the nucleus, and an extended episode of production of CN-shells that were seen to propagate through the coma. The total spin vector is not fixed in the nucleus but is inclined to the total angular momentum vector at an average angle of 21.4 degrees and precesses around it with an average period of 3.69 days. The average period associated with the total spin vector is 2.84 days, but neither this period or the inclination is constant in time. This spin state results in the return of the Sun to a position over particular areas of the nucleus every 7.4 days as required by the ground-based observations.

This solution has also allowed the first reasonably accurate maps of the locations of active areas on the nucleus to be drawn. There are five important areas of activity and one of these appears to have either chemical or physical properties that are different from the rest. This area appears to be active at very large heliocentric distances and to be solely responsible for the production of CN-shells. A further consequence of the model is that the interior density distribution in the nucleus is constrained to emulate that of a roughly homogeneous distribution.

The reason why it has taken so long to achieve a satisfactory model is that the direction of the long-axis of the nucleus in the original interpretation of the VEGA 1 pictures was assumed to be the reverse from what is actually the case.

Io's Atmosphere Detected by Ground-Based Microwave Spectroscopy

M. J. S. Belton

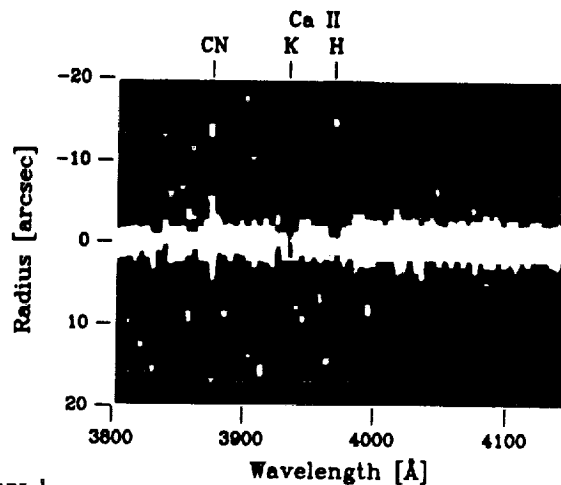
Io's corona and extended atmosphere, i.e. the plasma torus and neutral sodium and potassium clouds, have for a long time been the subject of intensive ground-based studies. However our understanding of the mechanisms by which S, O, Na, K and presumably other atoms reach the extended atmosphere has been poorly constrained by lack of knowledge of Io's neutral atmosphere and its relationship to the properties of the surface. SO₂ in some sort of vapor pressure equilibrium (determined by the microphysics of the boundary layer) with surface frost has been a prime candidate for the major constituent, but the presence of much more volatile species, e.g. H₂S and O₂, have also been considered as possibilities. These gases have been searched for, particularly in the UV region of the spectrum, ever since the discovery of active volcanism on Io by Voyager in 1979, but none of them have ever been detected.

E. Lellouch, M.J.S. Belton, I. de Pater, S. Gulkis, and Th. Encrenaz, have now, not only detected but also fully resolved the profiles of two pure rotational lines of SO₂ using the 30-m microwave dish located in southern Spain. The lines (near 222 and 143 GHz) were found in emission showing that early theoretical predictions for a thermally inverted atmospheric structure (i.e. temperature increasing with height from the surface) were correct. The profiles have the character of thermally broadened, but heavily saturated, lines with central brightness temperatures that indicate that only a fraction of the disk is sheathed in SO₂. Lines with effectively identical properties were observed on both leading and trailing hemispheres and at times separated by almost one year. These are characteristics to be expected of a pure SO₂ atmosphere in equilibrium with frost distributed over most of the surface of Io. One of the fascinating aspects of the data obtained so far is that, for a short period of time, the character of the spectrum was observed to rapidly change. The width of one of the lines narrowed while its central intensity increased. A preliminary analysis indicates that for a very short time the total amount of SO₂ on Io must have tripled. It is presumed that a major, but short-lived, volcanic event was responsible for this behavior. Further observations are scheduled.

Detection of CN Emission From (2060) Chiron E. Bowell

Spectrophotometric observations of (2060) Chiron were obtained in January 1990 using the Ohio State University Longslit CCD Spectrograph on the 1.8-m Perkins reflector at Lowell Observatory. The primary goal of these observations was to look for subtle differences in color between Chiron and its surrounding coma, and to search for possible absorption or emission features in Chiron's spectrum. Chiron started to exhibit comet-like behavior in late 1987, when, at a heliocentric distance of 13 AU, it slowly brightened more than expected for an asteroid approaching the Sun. According to Meech and Belton (*Astron. J.* **100**, 1323-1338, 1990), this activity peaked in January 1989, and has since been slowly declining. They, along with Luu and Jewitt (*Astron. J.* **100**, 913-932, 1990), and West (*The Messenger* No. 60, 57-59, 1990) all noted a substantial coma around Chiron, but did not report gaseous emission.

Fig. 1. A portion of the two-dimensional spectral image of Chiron resulting from the average of seven individually reduced exposures from which Chiron's reflected solar continuum has not been subtracted. The spatial scale along the slit is 0.75 arc sec per pixel, and the dispersion is 4.555 Å per pixel. A 3 by 1 pixel smoothing function, equivalent in extent to the characteristic seeing of 2 arc sec and weighted in the form [0.25, 0.50, 0.25], has been applied to the image in the direction parallel to the slit, reducing the apparent level of background noise while not affecting the spectral resolution. Visible are the Ca II H and K absorption lines in the solar continuum, and the extended CN (0-0) band centered at 3875 Å.



Our observations were obtained on 1990 January 29 and 30 UT, when Chiron was at a heliocentric distance of 11.3 AU. They consisted of several 20-minute exposures taken in each of three overlapping spectral regions, giving complete coverage from 3300 to 10000 Å, with a dispersion of 4.5 Å per pixel. We identified the presence of the CN (0-0) emission band, centered near 3875 Å at the 5- σ level (see the figure above). This faint feature can be traced about 7 arcsec (50,000 km) on both sides of Chiron along the E-W orientation of the slit. Our detection of CN proves Chiron's cometary nature and breaks the record heliocentric distance for cometary gaseous emission.

The presence of CN in Chiron's spectrum can be interpreted either as the result of continuous outgassing or of a recent outburst. Photometric observations by Luu and Jewitt (*op. cit.*) show that an outburst of dust was occurring at the time of our January observations.

Spectroscopic observations of Chiron at other times have failed to show any emission features, supporting the idea that gaseous emission is linked directly to cometary outbursts on Chiron. Our observations suggest that the outgassing seen in Chiron is primarily being driven by isolated outbursts of a volatile species such as CO₂ or CO from a rather small fraction of Chiron's surface.

Reference: Detection of CN Emission from (2060) Chiron. S. J. Bus, M. F. A'Hearn, D. G. Schleicher and E. Bowell. (1991). *Science* **251**, 774-777.

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Asteroid 1990 MB was discovered by D. H. Levy and H. E. Holt on 20 June 1990 during the course of the Mars and Earth-Crossing Asteroid and Comet Survey conducted by E. M. and C. S. Shoemaker. An orbit based on a 9-day arc and the asteroid's location near Mars' L5 (trailing Lagrangean) longitude led E. Bowell to speculate that it might be in 1:1 resonance with Mars, analogous to the Trojan asteroids of Jupiter. Subsequent observations strengthened the possibility (IAUC 5067), and later calculations by M. Yoshikawa and B. G. Marsden (IAUC 5075) confirmed it. Thus 1990 MB is the first known asteroid in 1:1 resonance with a planet other than Jupiter. Subsequently, E. Helin found images of the asteroid on plates taken in 1979 (*Minor Planet Circ.* No. 17333), allowing further orbit improvement. The most recent orbit, from the observations in 1979 and 1990, shows that the asteroid's semimajor axis (1.5235591 ± 0.0000003 AU, epoch 10 December 1991) is very similar to that of Mars (1.5235830 AU, same epoch).

The existence of 1990 MB--a small body most likely between 2 and 4 km in diameter--provides remarkable confirmation of computer simulations performed by S. Mikkola and K.A. Innanen (IAU Colloquium 123, in press). Their self-consistent n-body simulations have demonstrated just this sort of stability for Trojans of all the terrestrial planets over at least a 2-million-year time base. In the case of Mars Trojans, it was initially thought that stable-looking orbits must have semimajor axes that depart from Mars' by less than $da/a = 0.003$ and angular excursions from L5 that are less than 2 deg. Such a small region of stability led Bowell *et al.* (*Bull. Amer. Astron. Soc.* **22**, 1357, 1990) to speculate that 1990 MB was captured from a free orbit fairly late in solar system history, since it appeared unlikely to have survived the heavy bombardment known to have occurred in the region of the terrestrial planets. Additional evidence came from the existence of (3800) 1984 AB, an asteroid having a semimajor axis of 1.578 AU, which suggests that multiple encounters with Mars could lead to orbits rather close to the 1:1 resonance. However, more recent integrations of the motion of 1990 MB by Mikkola and Innanen show that stable excursions about L5 as large as 80° occur on timescales of millions of years. Thus, the question of whether 1990 MB is a primeval Mars Trojan remains open.

The discovery of 1990 MB suggests that others of similar or smaller diameter may be found. A systematic search of Mars' L4 and L5 libration regions is planned, as are more detailed studies of the regions of planetary Trojan stability.

Research supported, in part, by NASA grant NAGW-1470.

*The Last Disconnection Events in Comet Halley
in April 1986*

J. C. Brandt

Perhaps the most spectacular event in cometary plasma physics is the regular loss of the entire plasma tail and the growth of a new one. This is called a disconnection event or DE. Understanding the cause of DEs would be a most important step in our knowledge of cometary plasmas and the interaction with the solar wind.

Analysis of a sequence of DEs that occurred from 13-18 April 1986 shows that they correlate well with a magnetic, sector-boundary crossing and a complex magnetic structure in the solar wind with polarity reversals that occurred about one day later. These events are entirely consistent with sunward, magnetic reconnection as the DE mechanism.

If this mechanism is assumed, the fact that these DEs were the last ones in Comet Halley can be explained. By the time the sector boundary or the magnetic structures associated with them would encounter the comet on the next solar rotation, the plasma tail had disappeared (on 3 May) and no DE was possible.

Many asteroids are known to be non-spherical, as revealed by changes in their brightness as they rotate (lightcurves) and present varying cross-sections to view. Models of collisional evolution of the asteroid belt suggest that many of the larger asteroids are shattered "rubble piles," consisting of fragments bound together by gravity. If these assemblages are sufficiently weak, they should relax to equilibrium shapes that depend only on their spin periods and densities. Thus, if the shape of an asteroid is known, one might infer its density (constraining its composition) and internal structure.

Asteroids are too small for their shapes to be resolved directly by ground-based telescopes. The goal of our program is to use their brightness variations to derive shapes indirectly. This can be done by fitting mathematical models to a series of lightcurves obtained at different viewing geometries, i.e., at different points in their orbits. Over an eight-year period, we obtained hundreds of lightcurves for a selected sample of 26 asteroids. Model-fitting procedures allow us to derive their shapes; other information, e.g., pole orientations, spin directions, and phase functions are also obtained. Our observing program also included many "targets of opportunity"; we were able to derive rotation periods for 16 of these.

The derived shapes indicate some plausible candidates for equilibrium figures, but it is also clear that a majority of asteroids show large deviations from these idealized shapes. Analysis of the probable stresses within these asteroids shows that they require strengths of the order of 1 bar, which is quite weak compared with most geological materials. Their shapes can be explained if "rubble piles" do not consist only of small fragments, but include some large chunks as well.



*Physical Observations of Comets: Their Composition,
Origin and Evolution*

A. L. Cochran (P.I.)
E. S. Barker
W. D. Cochran

The Active Comet P/Schwassmann-Wachmann 1

Comet P/Schwassmann-Wachmann 1 (SW1) is an enigmatical comet. Its orbit is virtually circular with perihelion at 5.77 au and aphelion at 6.4 au. Thus, it should have relatively constant solar insolation and should not display much activity. However, SW1 is known to undergo tremendous outbursts of as much as 8 magnitudes at random intervals. In 1978, we discovered that in addition to producing dust during the outbursts, the comet sometimes produces CO⁺ gas. There appears to be no correlation between the gas and dust activity however.

We have observed SW1 during one observing run each in 1989 and 1990 and these observations have yielded significant new information. The spectra of December 1989 show the most well developed CO⁺ coma ever observed for SW1. Our spectra showed that the fluorescence efficiency calculations of Magnani and A'Hearn are reasonably consistent with the data. We demonstrated that there was an asymmetry in the gas distribution along the solar/anti-solar direction. In addition, we detected for the first time emissions due to CN and also due to an unknown molecule. No evidence of OH was detected.

The December 1990 observations were obtained at a time when the comet was less bright than the December 1989 observations discussed above. On the first night of observation in December 1990, the CO⁺ gas was barely visible. However, by the second night, the CO⁺ emissions were quite noticeable and substantially stronger. We were able to determine a maximum rise time for the gas of 1.2 days. These observations represent the first detection ever of the turn-on of the gas. The CO⁺ gas also showed signs of not being in equilibrium. We did not detect any CN emissions this observing run, although our upper limit for these observations is lower than our actual detection from the year before. Once more, OH was not detected.

At the distance from the sun of SW1, photoionization cannot be responsible for the creation of the observed CO⁺. We have explored various creation mechanisms but have not been able to identify the process by which the CO⁺ is ionized.

Near-Ultraviolet Observations of Comets

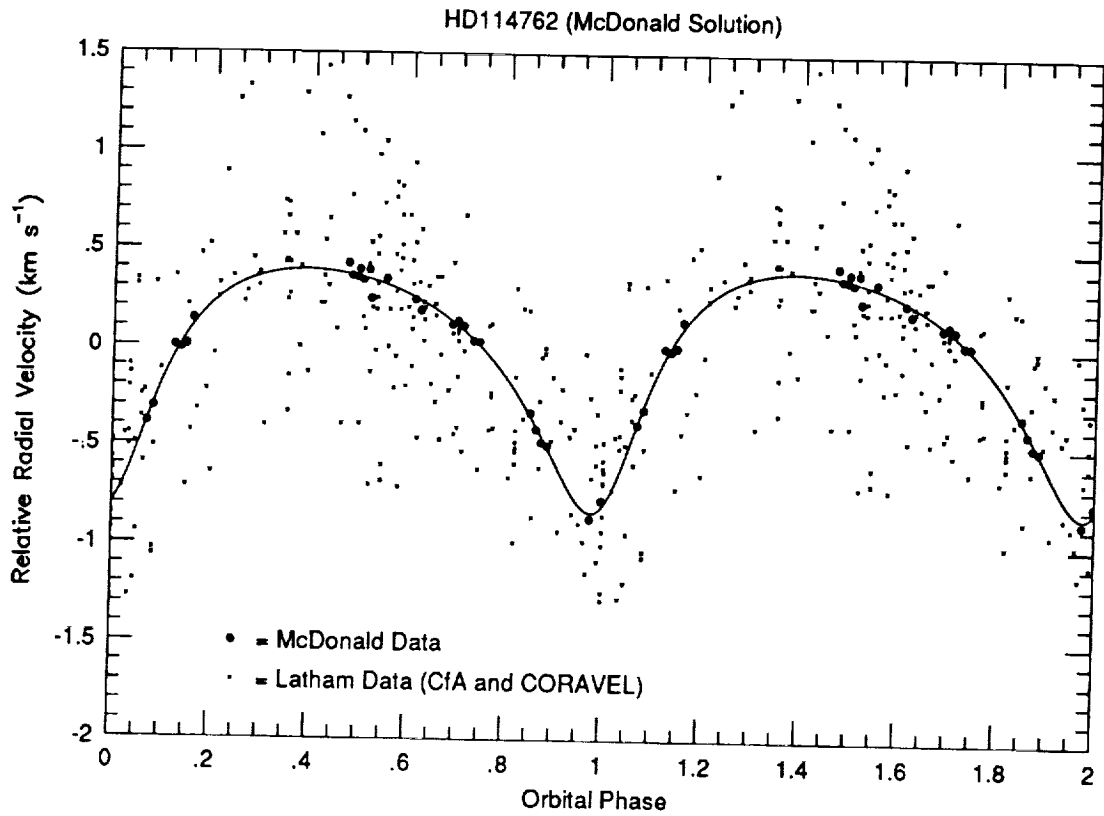
The near-UV (3000-3500Å) is a mostly unexplored spectral region for comets since it is not visible to spacecraft such as IUE and most ground-based detectors and spectrographs are not sensitive in the near-UV. We have a spectrograph at McDonald Observatory (the Large Cass Spectrograph or LCS) which is sensitive all the way down to the atmospheric cut-off at

3000Å. Recently, we used the LCS to observe two relatively bright comets, Austin and Brorsen-Metcalf, at 1Å resolution from 3000-3600Å. These observations have been carried on in collaboration with C. R. O'Dell and his graduate students from Rice and with C. Opal of McDonald Observatory.

With these spectra, we were able to confirm some previous barely detected features, to confirm the presence of features such as the CN $\Delta v=1$ and OH (0-1) bands which were expected but never before detected, and to observe for the first time in the optical such features as H₂CO. These detections point to the near-UV as a powerful new spectral region in which to study comets.

The Companion Object to HD114762 W. D. Cochran

The most interesting results obtained so far in the McDonald Observatory Planetary search concern the star HD114762. Lower precision radial velocity variation results by David Latham of Harvard indicated that this star might have a companion object, with an orbital period of about 84 days. We have obtained 28 independent radial velocity measurements on this star, and we are now able to derive our own orbit solution. We confirm the existence of a companion object in an orbit with a semimajor axis about 0.4 au. Our new orbit solution is shown in the figure below. The solid line is the radial velocity curve from our orbit solution. The large dots are our radial velocity observations, and the small markers are the discovery observations of Latham, phased to our orbit solution. The mass function indicates that the companion has $M \sin i = 0.011 M_{\odot}$. If we are viewing the system nearly equator-on, then the companion object could easily be a planet. A year ago we tested for the case of an exactly equator-on orientation by searching unsuccessfully for transits of the secondary object across the disk of the star (Robinson *et al.* 1990, *A. J.* **99** 672-674). We have since taken our observed spectra which were used to calculate the radial velocity variations, and we have analyzed the stellar spectral line profile shapes. In the profile of a stellar photospheric absorption line, there are two dominant line broadening processes. These are macroturbulence, which results from Doppler shifts due to photospheric convection patterns, and rotational broadening due to the component of the stellar rotation along the line of sight. For a given star, the macroturbulence will be independent of the viewing geometry, while the rotational broadening will depend on the sine of the inclination angle. When the stellar photospheric line profiles are analyzed in the Fourier domain, the two types of broadening can be separated. We have modeled the photospheric line profiles in HD114762, and have concluded that the best fit is with a macroturbulent broadening of 4.7 km s^{-1} (which is well within the range of what is to be expected for this type of star), and a rotational broadening of 0.0 km s^{-1} . Our upper limit on the projected rotational velocity $V \sin i$ is 1.0 km s^{-1} . This very low value of the projected rotational velocity is quite significant. There is a very tight observed relationship between stellar mass and true equatorial rotational velocity. An F9V star such as HD114762 should have a true rotational velocity of about 13 km s^{-1} . Therefore, we are able to place an upper limit on $\sin i$, the sine of the stellar inclination angle, of 0.08. However, in our solar system the solar equator is inclined by 7.25 degrees to the ecliptic. If we allow a similar misalignment between the stellar rotational angular momentum vector and the orbital angular momentum of the companion object in HD114762, then our constraint becomes $\sin i < 0.20$ for the companion object. Since we had determined from our high precision radial velocity measurements that the companion object had $M \sin i = 11$ Jupiter masses, we can now determine that the companion object mass is at least 55 Jupiter masses, or $0.055 M_{\odot}$. This would mean that the companion is not a planet, but instead is a brown dwarf or a low mass star in a system viewed nearly pole-on. We have determined that this system is a "false alarm" for planet detection!



Radial velocity curve for HD114762. The McDonald Data are shown as the large dots, and the original discovery data of Latham *et al.* (1989) are shown as the small markers. The solid line is the radial velocity curve derived from the McDonald data orbital solution.

Detection of Solid C≡N Bearing Materials on Solar System Bodies D. P. Cruikshank

The occurrence of solid matter of very low albedo on many small bodies of the Solar System is now widely acknowledged. To date a few hundred asteroids of very low albedo have been identified, and taxonomic schemes including subtypes defined by details of the spectral reflectance have been established. The surfaces of the nuclei of at least several comets are also of very low albedo. It is generally accepted, though not proven, that the cause of the low albedo of these bodies is the presence of macromolecular carbon-bearing compounds, elemental carbon, and opaque minerals. The dark asteroids are thought to be the source(s) of the carbonaceous meteorites, which contain complex organic solids of various kinds, elemental carbon, and organic-rich cosmic dust grains. Among the many low-albedo planetary satellites, the most striking example is the hemispheric covering on Saturn's satellite Iapetus which is centered on the apex of orbital motion (the "leading" hemisphere). The particles comprising the rings of Uranus appear to be similarly dark.

What, if anything, links chemically the meteorites, asteroids, comets, planetary rings and satellites, and possibly the interstellar medium, and what might this link tell us about the origins of the organic solids that they contain? In search of answers to this and related questions, we have pursued for several years a program of telescopic observations of small bodies in the Solar System.

In a new study we have found observational evidence for the presence of C≡N-bearing solid material on four classes of Solar System bodies: comets, asteroids, the rings of Uranus, and Saturn's satellite Iapetus. Gaseous CN has long been known in comet spectra, and the infrared spectra of Comet P/Halley obtained with the Vega spacecraft shows emission of the C≡N fundamental at 4.5 μm interpreted as solids containing the -C≡N group in the grains of the inner coma¹⁵. The data presented here offer the first evidence for chemically related material on the other objects.

We find a spectral absorption band seen in diffuse reflectance at 2.2-2.3 μm in spectra we have obtained of several D-type asteroids, and in published spectra of two "new" comets, the dark hemisphere of Iapetus, and the rings of Uranus. This band is the first overtone of the -C≡N fundamental at wavelengths between 4.5 and 4.8 μm, depending on the chemical environment of the group. This work suggests that those objects bearing the -C≡N signature have not been altered by liquid water, indicating either the absence of water or a thermal history in which water was never in a liquid or vapor phase. By implication, the surface materials of the D-type asteroids are the least chemically altered material in the middle regions of the Solar System.

This work was conducted jointly with W.K. Hartmann, D.J. Tholen, L.J. Allamandola, R.H. Brown, C.N. Matthews, and J.F. Bell.

*Studies of Thermal Wave Phenomena on the
Jovian Planets*

D. Deming

Ground-based and Voyager observations of Jupiter have provided evidence that the tropospheric temperature shows global-scale longitudinal variations which are often wavelike in character. Voyager data were reported to exhibit the presence of "slowly-moving thermal features" (Magalhaes et al., 1989 *Nature* **337**, 444), wherein the jovian tropospheric temperature patterns are not advected by the equatorial zonal winds, but are found to rotate at the System III (interior) rate. Ground-based data in a broad infrared band (8-13 μm) show a wavelike structure (Deming et al. 1989, *Ap.J.* **343**, 456) whose amplitude and spatial scale are similar to the reported properties of the slowly moving thermal features. This investigation is directed toward obtaining additional ground-based data in infrared spectral bands whose contribution functions are optimized for specific atmospheric regions (tropospheric at 20 μm , and stratospheric at 7.8 μm), in order to confirm the previous results, and to identify the nature and physical significance of wavelike longitudinal temperature fluctuations on the jovian planets. A 2-D infrared array detector and low resolution cryogenic grating spectrometer is being adapted to obtain maps in $\sim 2 \text{ cm}^{-1}$ bandpasses.

Subsequent to our initial exploratory observations in 1987, we obtained additional 8-13 μm data in 1989, and extended the observations to include 7.8 μm data. Additional observations have been hampered by relatively poor weather over Mauna Kea, and by instrumental problems in 1991. Nevertheless, significant additional data have been obtained at 7.8 and 20 μm , and all of the data are currently being analyzed. It is anticipated that the recent data should help to clarify the nature of longitudinal temperature variations on Jupiter.

In FY92, the cryogenic grating spectrometer will be made fully operational, and the spectral bands will be extended to include the strong stratospheric ethane emission near 12 μm . Exploratory observations will be made of possible longitudinal temperature variations on Saturn.

Discovery of Near-Earth Asteroids by CCD Scanning T. Gehrels

T. Gehrels, R. S. McMillan, M. L. Perry, D. L. Rabinowitz, J. V. Scotti

After years of preparation and computer programming, fund raising for advanced CCD and computer equipment, and waiting for the delivery of a 2048 x 2048 CCD, in order to make finding near-Earth asteroids possible even with our old 91-cm Spacewatch Telescope . . . we now discover them! The Table shows the results to date. They are all such different objects, with peculiar orbits. With our new technique of CCD scanning we have entered the domain of discovery that was not possible before, namely of the smallest, the fastest and the closest near-Earth asteroids. 1991 BA has a diameter of 9 meters, moved 24°/d when it was discovered, near magnitude-per-pixel of V = 23.0, and it came to about 170,000 km from Earth when it passed closest, at 18 hours UT of 18 January 1991.

Spacewatch Discoveries, to date *

Identification	Perihelion distance (AU)	Aphelion distance (AU)	Inclination (deg)	Diameter (km)	Date of Discovery	Remarks
1989 UP	0.98	2.7	3.9	0.3	27 Oct., 1989	elongated; perihelion at Earth orbit
1990 SS	0.89	2.5	19.4	0.9	25 Sep., 1990	
1990 TG1	0.77	4.2	9.1	4.6	14 Oct., 1990	
1990 UN	0.81	2.6	3.7	0.09	22 Oct., 1990	H=23.5
1990 UO	0.30	2.2	29.3	0.4	22 Oct., 1990	perihelion at Mercury orbit
1990 UP	1.10	1.5	28.1	0.4	24 Oct., 1990	Amor; slow rotation
1990 VA	0.71	1.3	14.2	0.6	9 Nov., 1990	Aten; perihelion at Venus orbit
1991 AM	0.51	2.8	29.7	2.3	14 Jan., 1991	crosses Venus orbit
1991 BA	0.71	3.8	2.0	0.009	18 Jan., 1991	smallest object found so far
1991 BN	0.87	2.0	3.4	0.5	19 Jan., 1991	
1991 CB1	0.64	2.7	15.8	1.3	15 Feb., 1991	Discovered at 2.54 AU from Sun
1991 EE	0.85	3.7	9.8	1.5	13 Mar., 1991	
1991 FA	1.08	3.0	3.2	1.5	17 Mar., 1991	Amor
1991 FE	1.08	3.5	8.6	5.8	18 Mar., 1991	Amor

*Automatic operation began in September 1990. We "rediscovered" 1990 UP (twice), (1865) Cerberus, P/Kopff, P/Taylor, P/Helin-Roman-Alu 2, and P/Hartley 1. We followed a few asteroids that turned out to be in the main belt after all, while one was a geosynchronous object.

Palomar Planet-Crossing Asteroid Survey (PCAS)

1/1990 - 2/1991 E. F. Helin

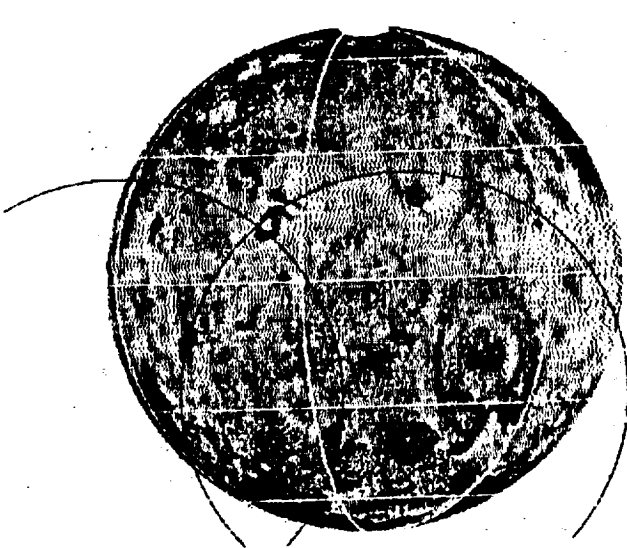
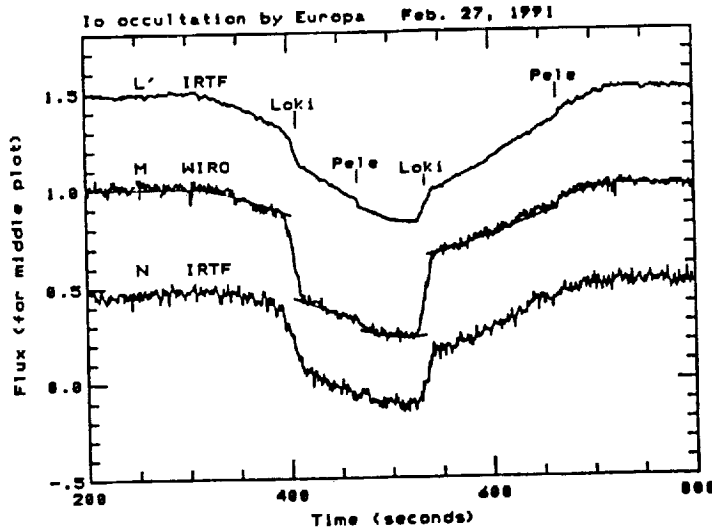
PCAS continues to make major gains in the discovery of Near-Earth Asteroids (NEA'S) as well as other classes of asteroids related to the evolution of objects into planet-crossers. Fourteen NEA's (5 Apollos and 9 Amors) have been found during the period of January, 1990 through February, 1991. Also, 43 special high inclination asteroids were discovered. Thirteen asteroids have been recovered which has led to their permanent numbering. Of these, two are NEA's. Our best observed mission candidate, 1982 DB was recovered in September, 1990 and subsequently numbered (4660). With it's well-determined orbit, it offers many opportunities for missions in the next 15 years.

Several of our NEA discoveries (1990 MF, 1990 OS, and 1991 AQ) made relatively close approaches to the Earth allowing successful radar observations to be made. S. Ostro's (JPL) detection of echos from these asteroids provides otherwise unavailable information about their physical properties. Also, our role in alerting radar astronomers about new candidate asteroids (in real time) makes it possible for them to acquire critical astrometry which dramatically improves the orbital elements of the new discovery. Earth-crossing Amor asteroid, 1990 SQ, has proven to be the brightest asteroid amongst the Earth-crossers at a very bright absolute magnitude, $H=12.5$, about 10km in diameter. This indicates that the entire known population of NEA's (including the brightest) is not yet complete.

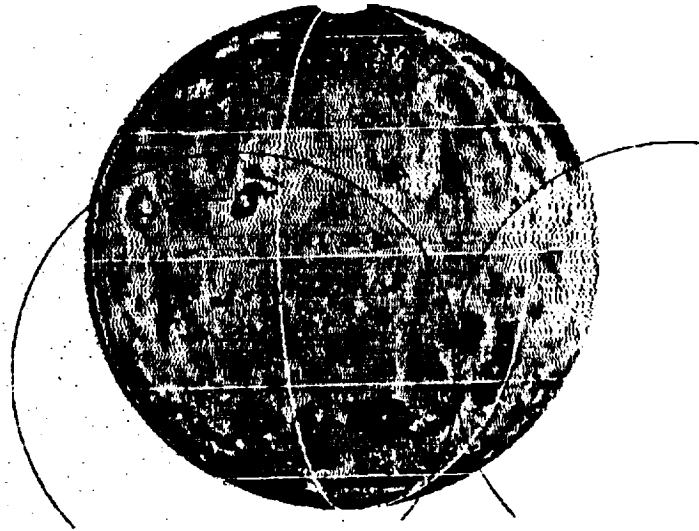
Our rate of discovery increased to one per month in 1990 which exceeds any other previous record.

*Infrared Speckle Interferometry and Spectroscopy
of Io*

R. R. Howell



LOKI



PELE

Observations of a series of "mutual events" of the Galilean satellites occurring in early 1991 are providing high resolution information concerning the volcanic hot spots on Jupiter's moon Io. In the first figure the brightness of Io is plotted as a function of time, as it is occulted by Europa. The top and bottom curves are shifted vertically by 0.5 for clarity. The sharp jumps in the curves are caused by volcanic hotspots being covered and uncovered. The L' and N (i.e. 3.8 and 10 micron) data were obtained by Jay Goguen and coworkers at IRTF, while the

M (5 micron) data were obtained by Robert Howell at the Wyoming 92" telescope. Both are supported by the NASA Planetary Astronomy program: Goguen -- "1991 Io Occultations by Europa", and Howell -- "Speckle Interferometry and Spectroscopy of Io."

The lower figures are Voyager derived globes of Io, with the positions of Europa at the time of the lightcurve jumps shown by dark circles. The intersections of the circles give the locations of the hot spots. The bright hotspot is located at the dark feature "Loki", while the fainter hotspot is located at "Pele". Loki has been active since the time of Voyager. Pele seems to erupt intermittently.

The sizes and temperatures of the hot spots can also be derived from the lightcurves. Loki takes roughly 13 seconds to disappear and reappear, indicating a diameter of 150 km. Pele is brighter at shorter wavelengths while Loki is brighter at longer wavelengths, therefore Pele is hotter. Analysis of other mutual events in the 1991 series will allow us study the structure in the Loki hot spot, and to check for variability of Pele.

Probing Titan's Atmosphere With a Stellar Occultation

W. B. Hubbard

The 3 July 1989 occultation of 28 Sgr by Titan was observed from two stations in Israel: the Wise Observatory 1m telescope and a portable 0.36m telescope at Kibbutz Ein Harod. It was also observed from Italy at the Vatican Observatory 0.6m telescope at Castel Gandolfo. Excellent data with signal/background of about 30/1 were obtained. The star was readily detectable *throughout* the occultation, reaching a minimum normalized flux ϕ of about 0.05. The occultation probed Titan's atmosphere in a region which was not studied by the Voyager spacecraft, i.e. from an altitude range of about 250 km to about 450 km. This region is important for aerobraking of Titan entry probes, and direct information about its properties is important for the Cassini mission. Fig. 1 shows occultation data (normalized stellar flux ϕ vs universal time) for the NASA-supported stations, along with data from the collaborating group at the Wise Observatory in Israel. Clouds prevented observation of immersion at the Vatican Observatory (Vatican data have been shifted earlier in time by 100 sec for ease in plotting).

Strong scintillation of the star is noticeable in the data records, and provides information on waves/turbulence in Titan's high atmosphere. The Titan data have been analyzed in a preliminary way (W.B. Hubbard *et al.*, *Nature* **343**, 353-355, 1990), and yield a temperature and pressure of about 183 K and 5 μ bar respectively, at an altitude of about 456 km. These results validate engineering models being used to design a Titan entry probe.

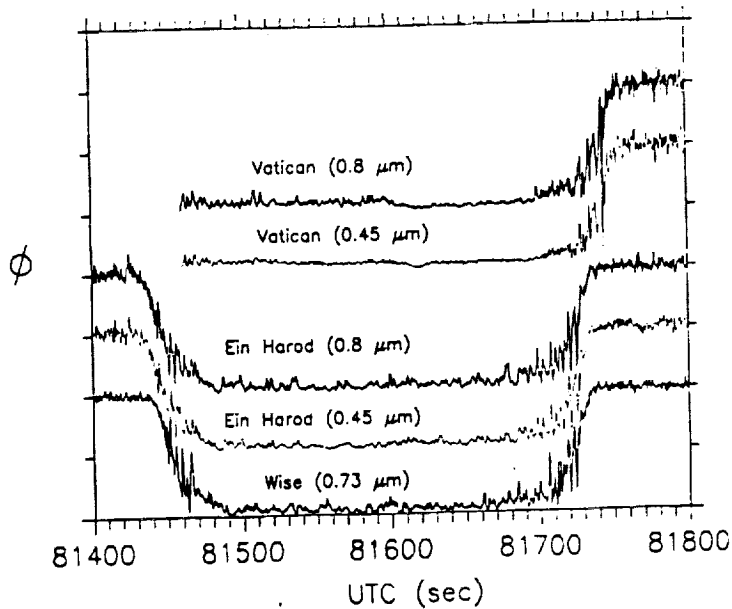


Fig. 1: The Titan occultation observed at several wavelengths and stations.

*Laboratory Simulation of the Surface of Halley's
Comet*

W. M. Jackson

In the past year we have developed a model for the photodissociation of icy grains in comets. In general this model does not predict the radical yield that is observed in the jets of comets. To reproduce these yields, the concentrations of the radicals precursors will have to be too high to be consistent with the abundance that we expect in comets. We have also constructed a theoretical model for the formation of ions on icy cometary grains. That model shows that only a small number of the cometary ions could be produced as ions in icy grains if the particle has only positively charged ions. If it contains both positive and negative ions then it could have a higher concentration of ions without violating charge neutrality. When such a particle evaporates it can release ions with both charges into the gas phase. These ions could produce radicals via dissociative recombination with electrons if they are positive ions or by photodetachment of electrons if they are negative ions. Finally an avalanche process involving the acceleration of electrons towards charged particles is evaluated. It is shown that this will not lead directly to gas phase ions, but it might lead to additional ionization, and dissociation on the grain.

Publications:

1. 1990 W.M. Jackson and Charles Hendricks. **On the Formation of Ions and Free Radicals in Comets from Small Ice Grains.** Proceedings of the 15th Annual National Conference of the National Organization of Black Chemists and Chemical Engineers, Philadelphia, PA, Anthony L. Dent, Ed. ISSN 0896-2367, Volume 15.

Caltech/JPL radar astronomers made use of the Very Large Array (VLA), Socorro, NM, during February 1990, to receive radar echoes from the planet Venus. The transmitter was the 70 meter antenna at the Goldstone complex northwest of Barstow, CA. These observations made use of the 27 antennas to provide the resolution of a much larger telescope with size equivalent to the area over which the antennas are spread. These observations contain new information about the roughness of Venus at cm to decimeter scales and are complimentary to information being obtained by the Magellan spacecraft. Some of the more elevated regions on Venus appear especially bright at the radar's 4 cm wavelength. Moreover, as the altitude increases in these regions, the radar brightness also increases. One possible interpretation is that radar-bright material, perhaps from volcanic sources, is more common at higher elevations.

The VLA/Goldstone Titan radar experiment of June 1989 was repeated on 3 consecutive days in July 1990, with somewhat reduced sensitivity due to the 1990 VLA configuration. The 1990 experiment differed significantly from the 1989 experiment by measuring both circularly polarized modes of reflection. This second year's results were very similar to those of 1989: no echo was detected on the first day and a very strong echo was measured on the second. Only 2 hours were obtained on the third day due to VLA equipment problems. These limited data suggest that a very weak echo was building on this third day. The echoes for the middle day were equally strong in both polarizations and nearly identical to the strong echo in the 1989 single polarization experiment. These results are best interpreted as echoes from a highly reflecting, multiple-scattering structure such as ice. These new observations strengthen the similarity of Titan to the radar-reflective properties of Jupiter's giant satellites. Tidal theory arguments predict that Titan is rotating synchronously about Saturn, presenting a fixed face to its primary. However, the two days with strong echoes from 1989 and 1990 fail to line up in longitude by about 30 degrees! The straightforward but premature interpretation of these results is that Titan has significant nutations about the synchronous-locked rotation state. More radar observations of this enigmatic satellite are imperative with as much transmitted power as possible, in particular to provide valuable data for design of the instruments for the Cassini spacecraft mission to the Saturn system. The Titan VLA experiment team consisted of D. Muhleman, B. Butler, and A. Grossman of Caltech and M. Slade of JPL. The Venus VLA team added K. Tryka of Caltech.

1990 was a busy year for observing asteroids with the Goldstone radar. Two close Earth-approaching asteroids -- 1990 MF and 1990 OS -- were observed in July and August. The ranging to 1990 MF provided the highest precision radar measurement to a solar system target (0.375 microseconds), and, at a round-trip light-time of 33 seconds, the smallest fractional precision radar ranging ever done (1 part in 10^6). The Doppler frequency shift observations of 1990 OS from Goldstone ensured that the orbital parameters for this object are known well enough to predict its future close Earth passages. The mainbelt asteroid Prokne was observed from Goldstone in early August 1990. Prokne is the first mainbelt

asteroid to be observed at Goldstone, and became the first object in the 200 km size category to have its radar reflection properties measured at 4 cm. The principal investigator for the asteroid radar observations is S. Ostro of JPL.

***Time-Lapse CCD Imagery of Plasma-Tail Motions
in Comet Austin***

D. A. KlingleSmith III
M. B. Niedner, Jr.
R. J. Oliverson
D. Westpfahl

Introduction. The appearance of bright comet Austin 1989c1 in April-May of 1990 allowed us to test a new imaging instrument at the Joint Observatory for Cometary Research (JOCR): a 300mm lens/CCD system with interference filters appropriate for cometary emissions. This system lacks the spatial resolution of JOCR's "Comet Schmidt" (using 4"x5" glass plates as detector), but has the advantage that the data are in digital form and, being filtered, are much less susceptible to moonlight and bright sky. In addition, the ability to monitor activity in real time means that a night's observing sequence can truly be tailored to the comet's behavior. These factors came together on the night of May 21, 1990 with the observation of impressive activity in the plasma tail/ray system of comet Austin.

Instrumentation. Our optical system consists of the 300mm f/2.8 Nikon lens used by Parker, Gull, and Kirschner (1979) to conduct emission-line sky surveys. A set of interference filters is available for cometary work at JOCR, and has been described by KlingleSmith *et al.* (1990). The detector is a cooled Tektronics 512 times 512 CCD camera system built by Princeton Scientific Instruments, the entire system being mounted piggy-back on the JOCR 16-in Newt./Cass. telescope. The CCD field of view is 1.9 degrees square (good for inner plasma tail), and each pixel is of width 13.6 arcsec. The installation of this system at JOCR was largely the work of D. A. KlingleSmith during a sabbatical year at JOCR/NMIMT.

Observations of comet Austin. KlingleSmith and M. B. Niedner were on the mountain on May 21, and intended to obtain CCD imagery through the entire set of four available filters (H_2O^+ , C_2 , red and blue cont.) during a 2.5 hour run. However, the first H_2O^+ ($\lambda 6205$, FWHM=50A) exposure suggested to one of the authors (MBN) that a period of high plasma-tail activity, possibly disconnection of the entire tail, was beginning. We decided to dedicate the entire morning's run to H_2O^+ exposures, in the hope of resolving any event(s) in time. A series of 13 exposures was obtained; cf. KlingleSmith *et al.* (1990) for details.

Data Description, Generation of Movie. The 13 frames have been made into a time-lapse movie showing the evolution of the plasma tail. Specifically, we were able to follow at least two large-scale waves out through the main tail structure. During the sequence we saw two new tail rays form and undergo similar wave motion. Several condensations, possibly representing disconnected material, were seen to develop and move out along the tail ray with a velocity of about 60 km s^{-1} . It remains to be determined what solar-wind agents were associated with this activity, but it seems clear that the bending or "flapping" of the tail was caused by sharp changes in the solar-wind flow direction. We are continuing to work with this sequence as well as with several others generated on other nights.

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Parker, R., Gull, T. R., and Kirschner, R. P. 1979, NASA Publication SP--434, "An Emission--Line Survey of the Milky Way".

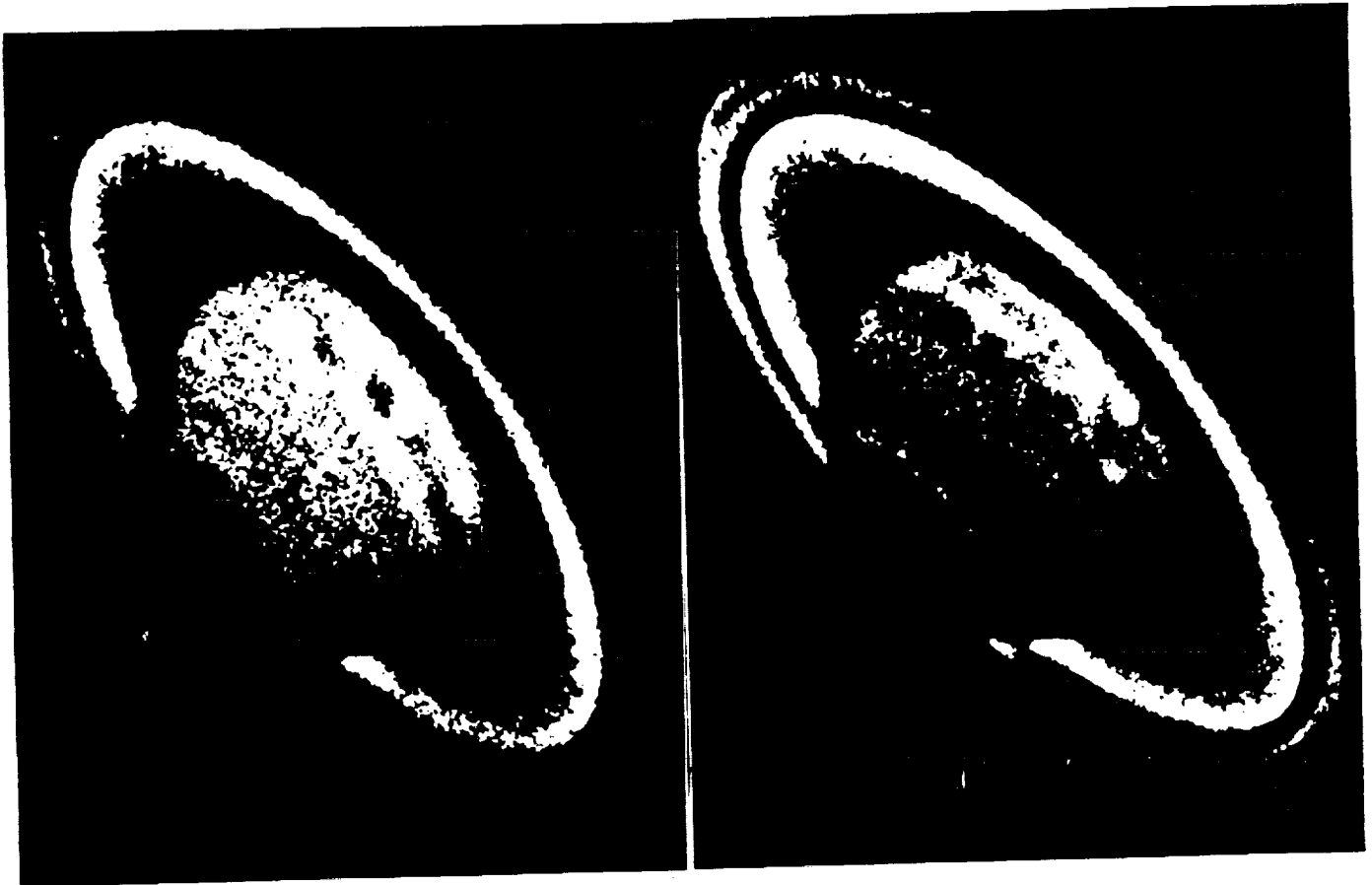
***Ground Based Infrared Measurements of the Global
Distribution of Ozone in the Atmosphere of Mars T. Kostiuk***

F. Espenak, M. J. Mumma, T. Kostiuk, (GSFC) and D. Zipoy (U. MD)

The global distribution of ozone in the atmosphere of Mars was determined from Doppler-limited infrared heterodyne spectroscopy measurements at the NASA IRTF during June 3-7, 1988. Mars spectra near two O₃ lines arising from the ν_3 band near 1031.45 cm⁻¹ were used. The lines were Doppler-shifted out of the strong terrestrial ozone absorption spectrum and its effect was removed. Ozone measurements were obtained at eight beam positions over a range of latitudes (80° S to 20° N) and local solar zenith angles (-0.5^h to +5.5^h). The beam size on the planet (~12 arcsec diameter) was 1.4 arcsec. A Martian CO₂ line appeared in the spectra and was inverted to retrieve local temperature profiles. Using these temperature profiles, the total ozone column abundance at each position was retrieved by fitting the measured line with synthetic spectra generated by a radiative transfer program. The only previous measurement of ozone at this season (L_s~204) was made above the South polar cap by Mariner 7 and revealed an abundance of 10 $\mu\text{m-atm}$. However, the retrieved O₃ column abundances from this investigation are less than 2.2 $\mu\text{m-atm}$ at all positions sampled. These results are consistent with mid-spring abundances predicted by photochemical models of Liu and Donahue, and Shimazaki and Shimizu.

T. Kostiuk, F. Espenak (NASA/GSFC); P. Romani (SSAI) and J. Goldstein (LA/NASM)

A significant enhancement in infrared emission from hydrocarbon constituents of Jupiter's stratosphere has been observed at a north polar hot spot (60° latitude, 180° longitude). A unique probe of this phenomena is ethylene (C₂H₄) which has not been observed previously from the ground. The profile of the emission line from ethylene at 951.742 cm⁻¹, measured near the north pole of Jupiter, was analyzed to determine the morphology of the enhancement, the increase in C₂H₄ abundance and local temperature, as well as possible information on the altitude (pressure regions) where the increased emission is formed. Measurements were made using infrared heterodyne spectroscopy at the NASA Infrared Telescope Facility on Mauna Kea, Hawaii in December 1989. The spectral resolution was 0.00083 cm⁻¹ and the instantaneous spatial resolution was ~1 arcsec (Jupiter diameter ~46 arcsec). Measurements at 60° north latitude away from the hot spot over longitudes 260°-355° showed no strong line emission and the retrieved C₂H₄ abundance was representative of quiescent values. At 181° longitude a very strong emission line was seen, which corresponds to a 13-fold increase in C₂H₄ abundance or a 115K increase in temperature in the upper stratosphere, compared to values outside the hot spot. The hot spot was found to be localized to ~10° in longitude and the line shape (width) implied that the enhanced emission originated very high in the stratosphere, near the 10 μbar pressure region.



In September 1990, a white spot appeared on Saturn's atmosphere, which later spread over the entire equatorial region. The accompanying images were obtained as a part of an effort to refine techniques for obtaining high resolution groundbased CCD images of the planets, and show the turbulent disturbance in Saturn's atmosphere. These broad red-band CCD images were obtained on 1990 November 11.1 (upper) and 12.1 UT (lower) with the Catalina 1.5 m telescope. The planet was low in the sky at sunset, but the seeing was good enough to show detail in the equatorial region over all longitudes. Visibility of the features is enhanced by digital spatial filtering techniques. A storm of this magnitude has not been seen on Saturn since 1933.

Visual and Near-IR Spectrophotometry of Asteroids L. A. Lebofsky

We have been continuing our studies of the spectral properties of dark asteroids in the solar system. From these studies we expect to learn about the distribution of volatile materials, such as water in clay minerals (water of hydration) and how the asteroids may relate to the comets. Our previous work has shown that dark asteroids in the middle of the main belt generally have water of hydration, but that the outer belt asteroids and Trojans do not. This appears to imply that these asteroids were originally composed of anhydrous silicates and ice and that the main belt asteroids have been heated in early solar phase, melting the ice and hydrating the silicates, while the outer asteroids have never been heated.

Our most recent work has been concentrating on simultaneous visual and near IR photometry near earth, main belt, and trojan asteroids. This preliminary work is shown in Figure 1. We have also made observations of some unusual "asteroids" such as Chiron which is in an orbit between Saturn and Uranus and has recently shown cometary activity, and 944 Hidalgo which has a cometary-like orbit. We have also begun studies of the small dark satellites of Mars and Jupiter in order to understand better how they may relate to the asteroids: could they actually be captured asteroids or comets?

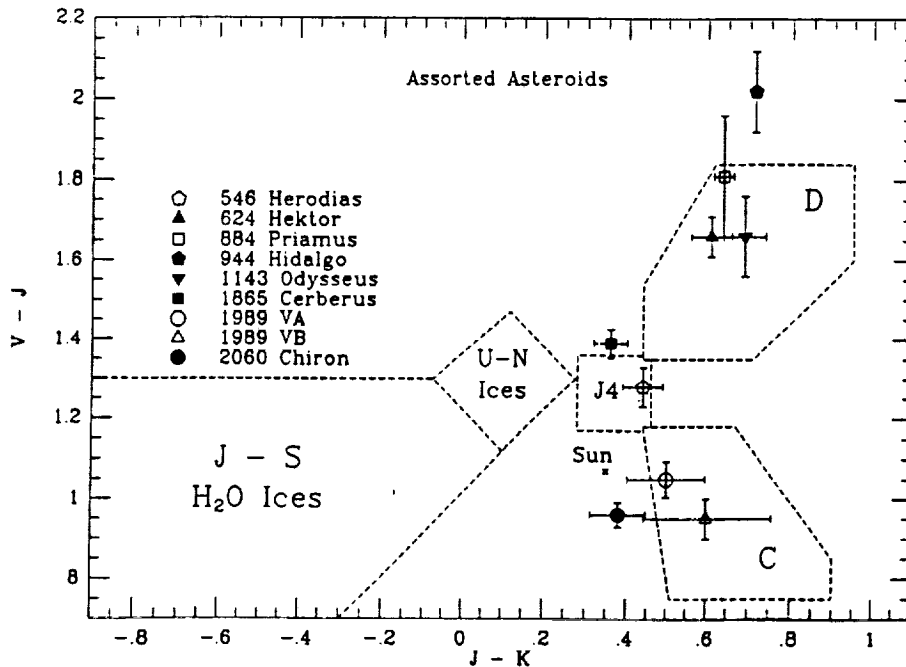


Figure 1. Color-color plot of selected outer solar system and Earth-crossing asteroids together with fields occupied by other solar system satellites and asteroids.

Deuterium on Venus: Observations from Earth B. L. Lutz
 C. de Bergh
 B. Bézard
 T. Owen
 D. Crisp
 J.-P. Maillard

The amount of deuterium relative to hydrogen in the atmosphere of Venus is a fundamental constraint on models for the evolution of its atmosphere. For example, a large enrichment of deuterium, compared to the protosolar value, would support arguments of a wet Venus in its early history, although its present-day atmosphere is water-deficient by 4 to 5 orders of magnitude. The deuterium-to-hydrogen ratio has been a controversial topic, with *in situ* observations by the Pioneer Venus Orbiter, suggesting a hundredfold enhancement of the deuterium-to-hydrogen ratio compared to that ratio on Earth. Yet ultraviolet spectra recorded by the International Ultraviolet Explorer provided an upper limit significantly less.

In view of the importance of the deuterium-to-hydrogen ratio in understanding the evolutionary scenario of planetary atmospheres and its relationship to understanding the evolution of our own on Earth, we undertook a series of observations designed to resolve the previous observational conflicts. We observed the dark side of Venus in the 2.3 μm spectral region in search of both H_2O and HDO , which would provide us with the D/H ratio in Venus' atmosphere. We identified a large number of molecular lines in the region, belonging to both molecules, and, using synthetic spectral techniques, obtained mixing ratios of 34 ± 10 ppm and 1.3 ± 0.2 ppm for H_2O and HDO , respectively. These mixing ratios yield a D/H ratio for Venus of $\text{D/H} = 1.9 \pm 0.6 \times 10^{-2}$ and 120 ± 40 , times the telluric ratio. Although the detailed interpretation is difficult, our observations confirm the Pioneer Venus Orbiter results and establishes that indeed Venus had a period in its early history in which it was very wet -- perhaps not unlike the early wet period that seems to have also been present on Mars -- and that, in contrast to Earth, lost much of its water over geologic time.

In the last year we have continued our program of near infrared imaging of the outer planets of the solar system. Images of the giant planets in the near infrared, particularly near $2.3 \mu\text{m}$, are exceedingly sensitive to the presence of miniscule quantities of aerosols in the very highest (lowest pressure) portions of the atmospheres because the strong methane absorption of the scattered sunlight strongly suppresses light scattered from lower down in the atmosphere. This feature also permits us to search for very faint objects close to the planetary disk, objects that would not be visible otherwise because of the strong scattered light component from the nearby planet.

Uranus is virtually invisible at $2.3 \mu\text{m}$, showing that the methane is an effective absorber of the incident sunlight and that there is very little aerosol content in the upper atmosphere. On the other hand, Neptune shows a haze present over the entire northern hemisphere at $2.3 \mu\text{m}$. This leads to the inference that there is an aerosol layer at a high altitude.

We have recovered the Neptune satellite 1989 N1, which was first discovered in Voyager images. The satellite is exceedingly faint in the near infrared, and was detectable only because the planet itself was comparatively faint at this wavelength. Observations of this satellite, coupled with the Voyager images, permit us to substantially refine the satellite's orbit, and hence carefully probe the gravitational field of Neptune.

*Asteroid 1986 DA: Radar Evidence for a Metallic
Composition*

S. J. Ostro

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Radar observations of this near-Earth asteroid were carried out at the Arecibo Observatory in April 1986, two months after its discovery. Resolution of the echoes in frequency (radial velocity) and, on one date, in time delay (distance) show this object to be about 2 km in size and to have an extremely irregular, nonconvex, and possibly bifurcated shape. However, the echo polarization implies that the asteroid's surface is very smooth at cm-to-m scales. The measured radar cross section, when combined with all available constraints on the object's dimensions, yields a radar reflectivity at least twice as large as that estimated for any of the several dozen other radar-detected asteroids and about ten times the lunar value. The most plausible interpretation of this radar signature is that 1986 DA's composition is very rich in metal, and that there is little coverage of the surface by a porous regolith thicker than a few centimeters. The radar results are consistent with the hypothesis that 1986 DA is a piece of NiFe metal derived from the interior of a much larger object that melted, differentiated, cooled and subsequently was disrupted in a catastrophic collision.

This 2-km asteroid might be (or have been a part of) the parent body of some iron meteorites. Or, 1986 DA might share the parentage and/or part of the dynamical history of some meteorites without ever having contributed any of its own ejecta to our meteorite sample. Analysis of samples returned from 1986 DA's surface via spacecraft would elucidate this asteroid's history and its meteoritic kinship.

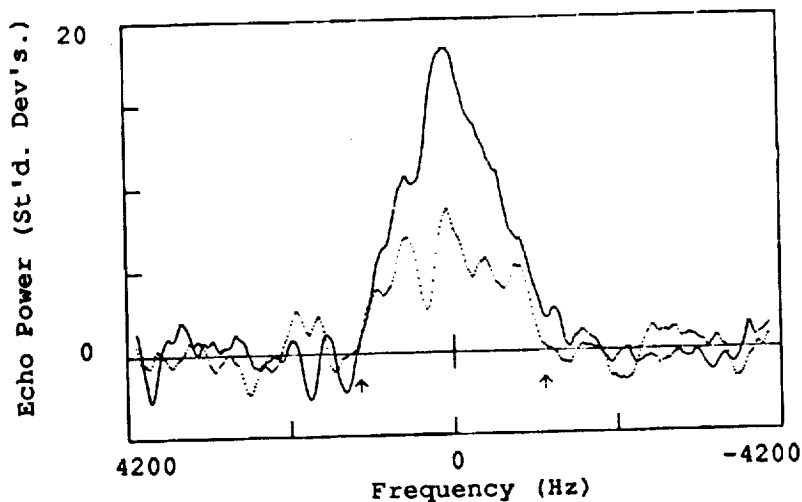
Motivations leading to spacecraft missions to 1986 DA might ultimately involve economic considerations. Meteoritic metal is mostly iron with about 8% nickel, but also contains substantial concentrations of precious and strategic metals, including ~1 ppm of gold and ~10 ppm of platinum-group elements. If these abundances apply to 1986 DA, it contains some 10^{16} g of iron, 10^{15} g of nickel, 10^{11} g of platinum-group metals, and 10^{10} g of gold.

Outburst of Comet Halley at 14.3 AU K. J. Meech

Observations of comet Halley on 1991 February 15 showed that the comet had undergone a tremendous outburst in brightness sometime before the past month. At the time of the observation, the comet was at a heliocentric distance, R of 14.3 AU, and the expected nuclear magnitude was near 25.4 in the m_R bandpass. The comet was observed to have an extensive dust coma, extending at least 300,000 km in diameter towards a position angle of 135 degrees. The anti-solar direction was at a position angle of 27 degrees. The brightness of the comet within a 5 arcsec aperture was approximately 20.2, and the total brightness of the nucleus and coma is estimated near 17. An effective exposure of 4.75 hours shows that the coma is well defined with a brightness enhancement at the outer edge. The last observations of the comet were obtained during 1990 April with the Cerro Tololo 4m telescope when the comet was at a distance, R of 12.75 AU. At that time the comet had reached its expected nuclear brightness of 24.9 and there was no evidence of activity. This new episode of activity in the comet is most likely caused by sublimation of a more volatile species than water, for example CO or CO₂, which had built up sufficient pressure beneath the dust mantle to initiate an outburst. Continued monitoring of the comet is planned to observe the evolution of the dust coma. Measurements of the expansion velocity may suggest which volatile was responsible for the activity.

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Arecibo 13-cm-wavelength radar observations during 1987-90 have yielded echoes from Io on each of 11 dates. Whereas Voyager imaged parts of the satellite at resolutions of several km and various visible/infrared measurements have probed the surface's microscale properties, the radar data yield new information about the nature of the surface at cm-to-km scales. Our observations provide fairly thorough longitude coverage and reveal significant heterogeneity in Io's radar properties.



The figure shows sums of echo spectra from the 11 dates, obtained in the same circular polarization as transmitted (SC, dotted curve) and in the opposite circular (OC, solid curve). The frequency resolution is 240 Hz, or 10% of the limb-to-limb bandwidth; arrows indicate expected positions of the spectral edges. The OC spectrum, which includes echoes due to single back-reflections from large, smooth surface elements, is much broader than lunar OC spectra. Io's average SC/OC ratio is about 0.5, an order of magnitude larger than the corresponding value for the Moon. Io's 13-cm, total-power geometric albedo averages about 0.06, three times the lunar value. These results show Io's surface to be much rougher than the Moon's at virtually all scales from a few centimeters up to the resolution of Voyager images.

The discovery that sodium and potassium vapor can be observed in the lunar atmosphere using ground-based telescopes has opened up a field of investigation that was closed after the last Apollo mission to the Moon. The Apollo measurements showed that the Moon does have a detectable atmosphere, but left a number of questions unanswered. During the Apollo missions, surface measurements were possible only during nighttime when outgassing from the nearby manned vehicle was negligible. Orbital measurements using spectroscopy gave negative results, apparently because the spectral range of the instrument was not wide enough to include all possible species in the atmosphere. The ground-based measurements of sodium and potassium vapor show that the lunar atmosphere extends to great heights. Sodium has been detected at altitudes up to 1500 km above the surface. This implies a high effective temperature for the sodium, of the order of 1000° K. However, there is some evidence for two populations of sodium and potassium, one at temperatures corresponding to the surface, and another corresponding to high temperatures, as quoted above. The sources for the lunar atmosphere are not understood. Meteoric bombardment of the surface, solar wind sputtering of the surface, and photo-sputtering of the surface have all been suggested as possible sources for the lunar atmosphere. One of the objectives of current research is to test different hypotheses by measurements of the atmosphere under different conditions of solar illumination and shielding from the solar wind by the earth.

Radiative Transfer in Planetary Atmospheres F. P. Schloerb

Submillimeter-wave Spectroscopy of Comets

Knowledge of the molecular composition of comets has long been a goal of planetary scientists. However, the realization of this goal has been frustrated by the fact that cometary spectral lines in the optical and uv portions of the spectrum are generally due to fragments of the molecules that actually make up the nucleus. For many years, astronomers have had to be content with solving a complicated molecular "jigsaw" puzzle to learn about the composition of comets, even though a better strategy would clearly be to observe the primary constituents of the nucleus directly as the cometary ices sublime. Radio astronomers have sought to achieve this through the use of the low energy radio and millimeter wavelength rotational transitions of candidate cometary molecules, but unfortunately, this work has been difficult since the cometary spectral lines are intrinsically very weak. As the technology of radio astronomy at millimeter and submillimeter wavelengths continues to improve, however, these observations should become increasingly important as a means to probe the chemistry of the coma.

During 1990, a significant step was made in this pursuit by our Planetary Astronomy group at the University of Massachusetts. We obtained several exciting new detections of submillimeter-wave spectral lines from molecules in the coma of Comet Levy (1990c) using the 10m telescope of the Caltech Submillimeter Observatory, located on Mauna Kea. The molecules HCN, formaldehyde, and methanol were all detected in abundances that make them important minor constituents of the nucleus. Moreover, the emission was so strong that, for the first time, it was possible to map the distribution of these species in the coma and study their behavior as they flow outwards from the nucleus. It is clear that, with sensitive submillimeter-wave systems like the CSO, the study of the molecular composition of the cometary nucleus has finally come within the reach of the ground based astronomer. We eagerly look forward to the opportunity to continue this work on a future bright comet.

Radar Studies in the Solar System I. I. Shapiro

We have actively engaged in observations of asteroids and comets, both as systematically planned targets and as "targets of opportunity." The most recent example of the latter is asteroid 1991 AQ, which was discovered optically on 1991 January 14 and found to be rapidly nearing the Earth. Due, in part, to our previous success in obtaining useful radar data on short notice, we and our colleagues were able to schedule time on the Arecibo radar on January 28-31, when the asteroid was within the Arecibo declination window. Each day during that period, a fresh ephemeris was made including all available data, both optical and (after the first day) radar. The first two of these were transmitted electronically to Arecibo for use on subsequent observations, but including even a single radar datum along with the optical data proved to be sufficient for predicting ephemerides for the rest of the observing run. Each day yielded a strong detection of the asteroid. With further processing, the results of the observations are expected to include detailed two-dimensional images of the asteroid, and information on its surface properties, size, shape, and spin.

The observing program also covered two other asteroids besides 1991 AQ, two of the four Galilean satellites of Jupiter, the satellites of Mars, and the planet Mercury. We are gaining understanding of the surfaces of both rocky and icy bodies from analysis of these results. Also, analysis of newly available radar observations of Venus has led to a refinement of the spin vector of that planet and has thereby provided a coordinate basis for the Magellan spacecraft mapping mission.

*Observations of Formaldehyde and Search for
Cyanoacetylene in Comet Brorsen-Metcalf (1989o)* L. E. Snyder

P. Palmer

I. de Pater

The VLA was used in 1989 September to search Comet P/Brorsen-Metcalf (1989o) for the $1_{11}-1_{10}$ transition of formaldehyde (H_2CO) at 4,829.659 MHz (6.2 cm λ) and for the $J=1-0$, $F=2-1$ rotational transition of cyanoacetylene (HC_3N) at 9098.3321 MHz (3.3 cm λ).

An emission line of H_2CO was detected from Brorsen-Metcalf which was approximately as strong as the H_2CO emission from comets Halley and Machholz that we observed earlier (Snyder, Palmer, and de Pater, 1989, *A. J.*, **97**, 246; 1990, *Icarus*, **86**, 289). For Comet Brorsen-Metcalf, we used a new technique for reducing the data. Data blocks which were either 3x3 pixels, 5x5 pixels, or 9x9 pixels were examined for a signal from H_2CO . Using this approach, different pixel clusters within the field of view can be sampled to optimize the coupling of the synthesized beam to the gas distribution. This illustrates one of the strengths of using arrays which is particularly important in the case of comets: small pointing errors caused by an inaccurate ephemeris can be corrected after the array observations have been made -- a feat which is impossible with single dish radio observations. In general, the centimeter wavelength H_2CO detections place important constraints on the partition function and excitation of cometary H_2CO ; these constraints are essential for interpreting observations at shorter wavelengths and, in particular, for deriving the correct H_2CO production rate from radiative transfer models.

HC_3N is of immediate interest as a cometary molecule because it may be a reservoir of carbon and a source of cometary CN. Our search for HC_3N emission at 3.3 cm wavelength demonstrated that for this molecule the VLA can be expected to reach significant levels of sensitivity in many comets.

Asteroid Absolute Magnitudes and Slope Parameters E. F. Tedesco

One of the most fundamental observational parameters for asteroids is their absolute magnitudes. Their most common use is in predicting apparent brightness but they are also used in computing the albedo and diameter given observations of the thermal flux, and in deducing bias-correction factors.

A new listing of absolute magnitudes (H) and slope parameters (G) has been created and published in the Minor Planet Circulars; this same listing will appear in the 1992 Ephemerides of Minor Planets. Unlike previous listings, the values in the current list were derived from fits to data at the V band. Approximately 5,200 photoelectric observations (obtained from about 200 papers published between 1949 and 1990) and 34,000 reliable photographic observations (obtained from B. Marsden and based on observations made between 1934 and 1990) were used in the analysis.

All observations were reduced in the same fashion using, where appropriate, a single basic default value of 0.15 for the slope parameter. Distances and phase angles were computed for each observation. The data for 113 asteroids were of sufficiently high quality to permit derivation of their H and G.

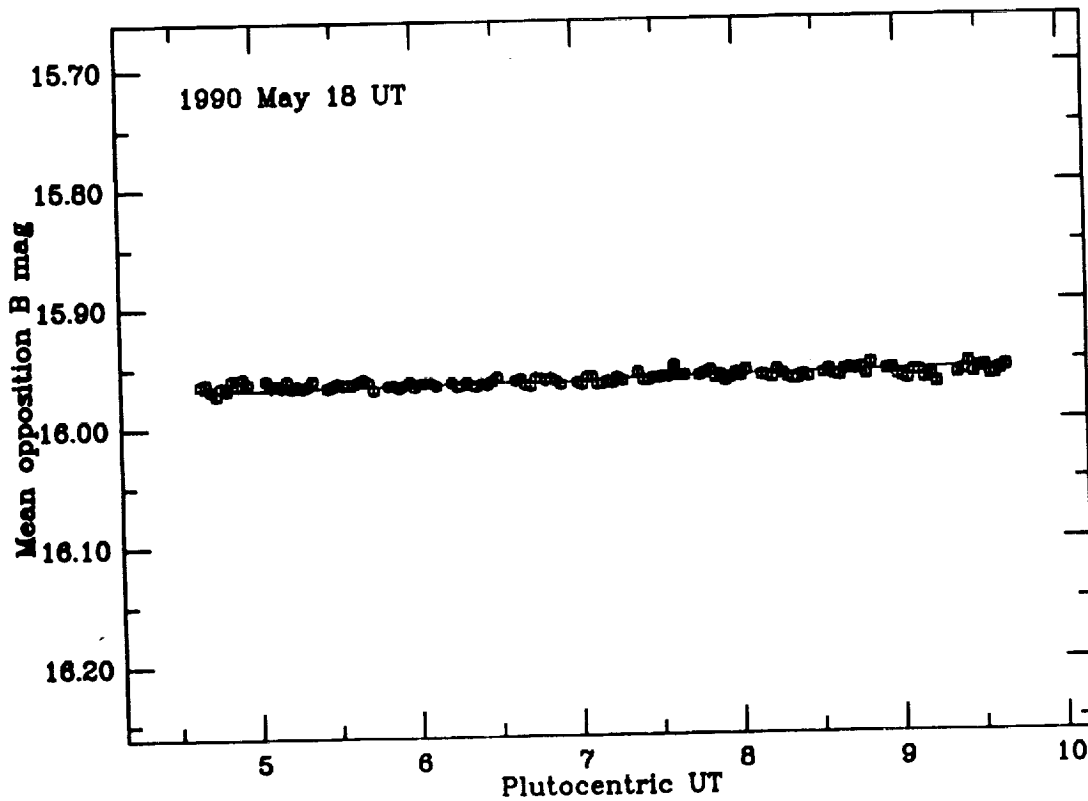
These improved absolute magnitudes and slope parameters will be used to deduce the most reliable bias-corrected asteroid size-frequency distribution yet made.

1990 Marks End of Pluto-Charon Mutual Event Season D. J. Tholen

From late 1984 until late 1990, the orbit of Pluto's satellite Charon was sufficiently close to an edge-on configuration, as seen from Earth, to produce transit, occultation, and eclipse events involving the two objects. The systematic observation of these events, each of which offers a unique geometry of Pluto, Charon, and shadow, has been used to directly measure several parameters of the system.

With data now available from the entire mutual event season, reliable values for the radii of Pluto and Charon can be derived. Pluto's radius is 0.05860 ± 0.00031 , in units of Charon's mean orbital radius, and Charon's radius is 0.03019 ± 0.00066 , in the same units. The best available orbital radius for Charon is 19,640 km, thus the values above become 1151 ± 6 km and 593 ± 13 km, respectively, although Charon's orbital radius is uncertain by about 1.6 percent, which raises the uncertainty in the objects' true radii to about 20 km in both cases. The mean density of the system is 2.029 ± 0.032 grams per cubic centimeter, implying a bulk composition of about 70 percent rock and 30 percent water ice.

The figure below shows data obtained close to Pluto's opposition in 1990. On this night, the shadow of Charon was extremely close to last contact with Pluto's disk, while the disk of Charon was also extremely close to first contact with Pluto for the 1990 opposition. These data therefore represent an extremely sensitive edge detection experiment. If either Pluto or Charon are slightly larger than indicated by the values given above, a detectable dip in overall system brightness would have occurred. The photometric resolution for these data is highest



yet achieved (0.0025 magnitudes per 72 second integration), limited entirely by photon counting statistics. The data were obtained with the University of Hawaii 2.24-m telescope on Mauna Kea.

With the observations on 1990 September 23 representing the last made during this mutual event season, no more such events will occur for almost 120 years. At that time, Pluto will be near aphelion and almost ten times fainter than it is now.

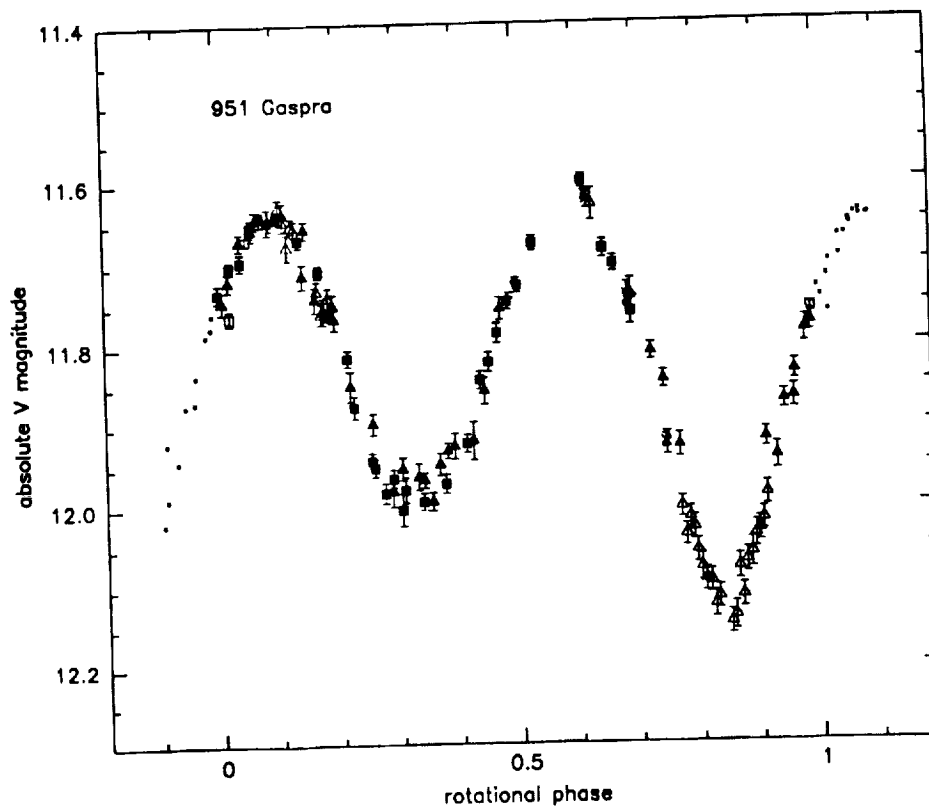
First Spacecraft Encounter with an Asteroid Approaches D. J. Tholen

During the course of the Galileo spacecraft's journey to Jupiter, it will make two excursions through the main asteroid belt, which is situated between Mars and Jupiter. The first excursion occurs between the two Earth gravity assists being used to direct the spacecraft to its ultimate destination and involves a close encounter with the asteroid 951 Gaspra; the second excursion occurs two years later during the final approach to Jupiter and will likely involve yet another asteroid flyby, this time with 243 Ida.

The first of these asteroid flybys will take place on 1991 October 29. In preparation for this encounter, ground-based astronomers have been studying the target asteroid with a variety of techniques to characterize this object, thereby complementing the spacecraft observations and enhancing the overall scientific return from this mission.

Below is a figure showing the brightness of the asteroid as a function of time. Data from several nights between January and April of 1990 have been folded with a period of 7.04246 ± 0.00006 hours, which represents the synodic rotational period of the asteroid. Colorimetry obtained concurrently with the lightcurve shows subtle variations in color, but only at the one standard deviation level of significance. The evolution in the rotationally averaged brightness of the object during the opposition suggests that the sub-Earth latitude was changing significantly, a situation that could not occur if the obliquity of the rotation axis were low, thus a moderate to high obliquity is inferred. The overall shape of the lightcurve implies an asymmetrical shape for the asteroid, with axis ratios of about 1.6 to 1.1 to 1.

Gaspra is a small (about 15 km diameter) asteroid near the inner edge of the main asteroid belt. It's spectral classification is S, suggesting a composition similar to those of stony-iron meteorites.



1990 1/83

Global Scale Auroral Emissions on Jupiter L. Trafton

Jupiter's aurora are normally confined to limited regions around the magnetic poles. Our collected spectra show that very unusual periods of global scale auroral activity occurred during September and November of 1988. During the global scale events, the H_2 and H_3^+ emissions remained confined to their unusual auroral zones but strong, unidentified emissions appeared in the vicinity of the H_2 quadrupole lines. This would suggest that unusual periods of widespread magnetospheric dumping occur. This activity contrasts with the very weak auroral emission seen only a year later. In addition, long-term time scales have been observed for Jovian auroral activity within the normal auroral zones. For example, the relative strengths of the H_2 and H_3^+ emissions are observed to change. There even have been times, as in 1986, when the H_3^+ was not detectable while the H_2 emission was clearly visible. Jupiter's magnetosphere, which powers the aurorae, is thought to be populated largely by Io's volcanic activity. Further monitoring is continuing to test the validity of this linkage.

*Tentative Identification of a Newly Discovered
Class of Material on Io* L. Trafton

Io has a thin atmosphere which is supported by volatile ices on the surface, concentrated near active volcanos and the warmer subsolar latitudes. The newly discovered absorption feature in Io's spectrum at 2.1253 μm contrasts with the other known features from SO_2 , H_2S and H_2O in that it has not been observed to vary in strength over the 1.5 year interval since its discovery. Moreover, it appears to be uniformly distributed in longitude. Therefore, it represents a new class of absorption for Io and promises to reveal significant insights in the nature of the interaction among Io's surface, atmosphere, and volcanos. Volcanic activity is thought to explain the variability of the other absorptions, and to populate the plasma torus and Jovian magnetosphere. The uniformity of this feature suggests that it is widespread, at least in longitude. Laboratory experiments of various ice mixtures at Io's temperature rule out an origin from the known constituents, including various mixtures of the volatile ices. The most likely candidate appears to be clusters of CO_2 molecules. Observations are underway of the current series of occultations and eclipses of Io by other Galilean satellites (which occur only every six years, as the earth passes through the plane of the Galilean satellites) in order to locate the source of this newly discovered material on Io, which should provide further clues to its origin.

Primitive asteroids in the solar system (C, P, D class and associated subclasses) are believed to have undergone less thermal processing compared with the differential (S class) asteroids. The S-class asteroids comprise the majority of the main-belt and near-Earth asteroid population. The C-class asteroids become the dominant class of the main-belt asteroids beginning at a heliocentric distance of 2.5 AU. The transition of the dominant class of asteroid from the Cs to the P class occurs near 4.0 AU, with the D-class asteroids being the dominant class at the distance of Jupiter's orbit, 5.2 AU. Telescopic spectra of C-class asteroids show effects of aqueous alteration products, produced when heating of the asteroids was sufficient to melt surface water, but not strong enough to produce differentiation. These features include a sharp blue-UV turnover beginning at wavelengths shorter than 0.55 μm ; the edge of a sharp UV charge transfer absorption seen in phyllosilicates (clay silicates having a sheet-like texture); absorption features attributed to Fe^{2+} - Fe^{3+} charge transfers in iron oxides present in phyllosilicates located in the visible/near infrared spectral region; and a deep absorption feature located from 2.6-4.0 μm attributed to structural hydroxyl (OH) and interlayer and absorbed water (H_2O) in phyllosilicates.

Absorption features in telescopic spectra of main-belt asteroids 1, 102, 368 and 877 and Cybele asteroid 1467 show similarities to absorptions seen in laboratory spectra of terrestrial serpentines and chlorites, and laboratory spectra of CM2 carbonaceous chondrite meteorites. Absorption features have also been identified in C- and P-class asteroids in the Cybeles ($a=3.4$ AU) and some of the Hildas ($a=4.0$ AU); however, no analogues exist for these spectra among spectra of the known meteorites. Spectra of 10 additional asteroids, all located in the outer belt, show no indication of these absorption features. These 10 objects include all of the Trojan asteroids (asteroids at the greatest heliocentric distance in this study) and all of the D-class asteroids (asteroids generally considered to have the most primitive composition) studied. These spectra suggest that aqueous alteration terminated in the outer belt and did not operate at the distance of Jupiter's orbit (1). These studies are consistent with observations of the presence or absence of the 3.5- μm water of hydration absorption in the infrared spectra of outer-belt asteroids (2).

(1) F. Vilas and M.J. Gaffey (1989). Phyllosilicate absorption features in main-belt and outer-belt asteroid reflectance spectra. Science 246, 790-792.

(2) L.A. Lebofsky, T.D. Jones, P.D. Owensby, M.A. Feierberg, G.J. Consolmagno (1990). Icarus 83, 16-26.

Astrometric Observations of Comets and Minor Planets

J. G. Williams and J. Gibson

Comets and planet crossing asteroids are observed so that accurate positions can be determined. The observations are made with the Palomar 1.5m telescope equipped with a CCD array. This combination of telescope and detector is quite efficient at recording faint comets and minor planets. This proves quite useful for early acquisition of comets and asteroids returning for a new opposition. The resulting positions permit accurate orbits to be determined and allow the properties of the comets and asteroids to be measured by other observers using a variety of techniques. Recoveries and other notable observations of comets and planet crossing asteroids observed during the past year are discussed below.

Of the comets observed during the past year, two were recoveries of periodic comets. The first recovery, P/Honda-Mrkos-Pajdusakova (1990f), was shared with another observatory. The second recovery was P/Johnson (1990h). The periodic comet P/Arend-Rigaux (1984 XXI) and other comets were also observed.

Asteroids which can come close to the earth (Apollos) are another high priority target. The Apollo 1988 EG was recovered at its second opposition. For the Apollos 4486=1987 SB and 4581=1989 FC observations at the second opposition were shared with another observatory. Both were permanently numbered as a consequence of the observations. 1989 FC is the small asteroid which passed very close to the earth in the spring of 1989. A fourth Apollo 4450=1987 SY was permanently numbered as a consequence of recovery and observations at both second and third oppositions.

Minor Planet 1566 Icarus - Asteroid or Comet? D.K. Yeomans

Of the dozen well-observed, near-Earth asteroids that are suspects for inactive comets, only 1862 Apollo and 1566 Icarus show any indication that their orbital motions are affected by nongravitational perturbations -- effects that are normally associated only with active comets. By employing a cometary nongravitational force model, based upon the outgassing of a water ice nucleus, the orbital fits to the optical and radar astrometric data are improved for both Apollo and Icarus. A reliable value for the magnitude of these nongravitational effects can be determined for Icarus, but not Apollo. Because Icarus is less than a kilometer in extent, the small amount of outgassing required to explain its anomalous orbital behavior would probably not be sufficient to create an easily visible coma. While these results do not prove that 1566 Icarus is an active comet masquerading as an asteroid, this object certainly deserves future scrutiny to determine its true identity.

A near-Earth asteroid showing cometary activity must represent only the tip of a much larger cometary iceberg. For such an object whose aphelion is well inside Jupiter's orbit, the time scale for losing its volatiles is much shorter than the time scale for evolving out of the inner solar system. Thus for each active member of the near-Earth asteroid population, there must be many more that are temporarily or permanently inactive.





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