Section 4 Radio Astronomy

Chapter 1. Radio Astronomy

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1.1 Galactic and Extragalactic Research

Sponsor

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1.2 Gravitational Lens Search

Two particularly interesting examples of the "Einstein ring" phenomenon were described in last year's *RLE Progress Report*. Both Einstein rings were discovered during the search program for gravitational lensed radio sources being carried out at MIT in collaboration with scientists at Princeton University and California Institute of Technology. We have established a data archive accessible to RLE students and visitors that includes the 4000 maps from this survey.

We have extended the MIT-Green Bank (MG) Survey, working with the National Radio Astronomy Observatory (NRAO) and using the Green Bank 300-foot telescope to cover a wider declination range beyond that of the original MG Survey. The results comprise Parts II, III and IV of the MG catalog. MG Part II has been published, Part III is in press, and Part IV has been submitted for

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publication. The survey had covered the entire band of sky between declinations 0.5 degrees and +3.9 degrees and approximately half of the band +37 degrees to +51 degrees when the Green Bank telescope collapsed in November 1988.

Currently, we are beginning a new survey, using the seven-feed NRAO cooled receiver at the Parkes 210-foot telescope in Australia. This new survey, known as the Parkes-MIT-Green Bank Survey (PMG Survey), will cover from 40 degrees declination to the South Celestial Pole.

Reduction of the 4000 VLA source maps, derived from MG I, is almost complete. The VLA has accepted our proposal to begin a program to search for more lenses, using the MG II and MG III survey results. We will map the first 1000 sources during the first six months of 1990.

1.2.1 Einstein Rings

We are continuing to study the two examples of the Einstein ring phenomenon that we discovered over the past two years: MG1131+0456 and MG1654+1346. The Einstein ring effect occurs when a distant object, usually a quasar, is aligned in a particular way with a foreground galaxy that acts as a gravitational lens. If the foreground object has spherical symmetry, the rays bend around it uniformly to form a ring-like image of a point source. Most lensing galaxies are ellipsoidal, so the result is an elliptical image that is not a perfect ring. The phenomenon is so striking that it can be recognized easily from radio data alone. Furthermore, optical data can provide complementary information on the redshifts of source and lens. This information can be used to define the total mass encircled by the ring and to deduce the degree of flattening of the ellipsoidal mass distribution.

The source MG1654+1346 is the first ring to be completely analyzed. Figure 1 gives a superposition of the radio and optical images. The distant quasar is labeled Q and the foreground galaxy is labeled G. The radio contours at A and C, on opposite sides of the quasar, are radio lobes driven by the central engine at Q, but the contours at C are distorted into a ring.

Figure 2 shows the model and the effect of an ellipsoidal lens on a set of three objects, labeled 1, 2, and 3. These are imaged as shown, with source 1 becoming A1 and B1, source 2 becoming A2 and B2, etc. The redshift of the lensing galaxy is 0.254, and the quasar redshift is 1.74, leading one to calculate a mass of $(2.97 \pm 0.32) \times 10^{11}h^{-1}$ for the galaxy, where h = 1 if the Hubble constant H degrees = 100 km/sec/Mpc. The mass-to-light ratio is 15.9 ± 2.3 h, probably the best determination of this ratio ever made for any galaxy.

The success of our work on MG1654+1346 has led us to conclude that similar determinations can be made for other systems. In our new survey, we expect to find additional lenses, which would make possible a wider search for dark matter. Several theories suggest that substantial quantities of nonluminous matter, possibly of exotic character, is present in galaxies and in the universe as a whole. Locating and analyzing gravitational lenses, especially in well-defined systems such as Einstein rings, is one of the best methods for measuring this important constituent of the universe.

1.2.2 VLBI Studies of 2016+112

Part I of the MIT-Green Bank survey and the associated VLA survey led to discovery of the 2016+112 gravitational lens system. Subsequent optical and radio observations have revealed a surprising number of components. There are three radio sources called A, B, and C respectively. We have found optical counterparts for all three radio sources. Components A and B appear to be gravitationally-lensed images of a single source as indicated by spectra with the same unusually narrow emission lines and identical redshifts of 2.273 within a given error of measurement. The light from the C component region is believed to come from a weak third image, C, in addition to the radio galaxy, C. There is a radio quiet galaxy, D, located between A, B, and C, which has a redshift of 1.010 ± 0.005. There are also two extended emission line objects to the west of A and B called A1 and B1, respec-

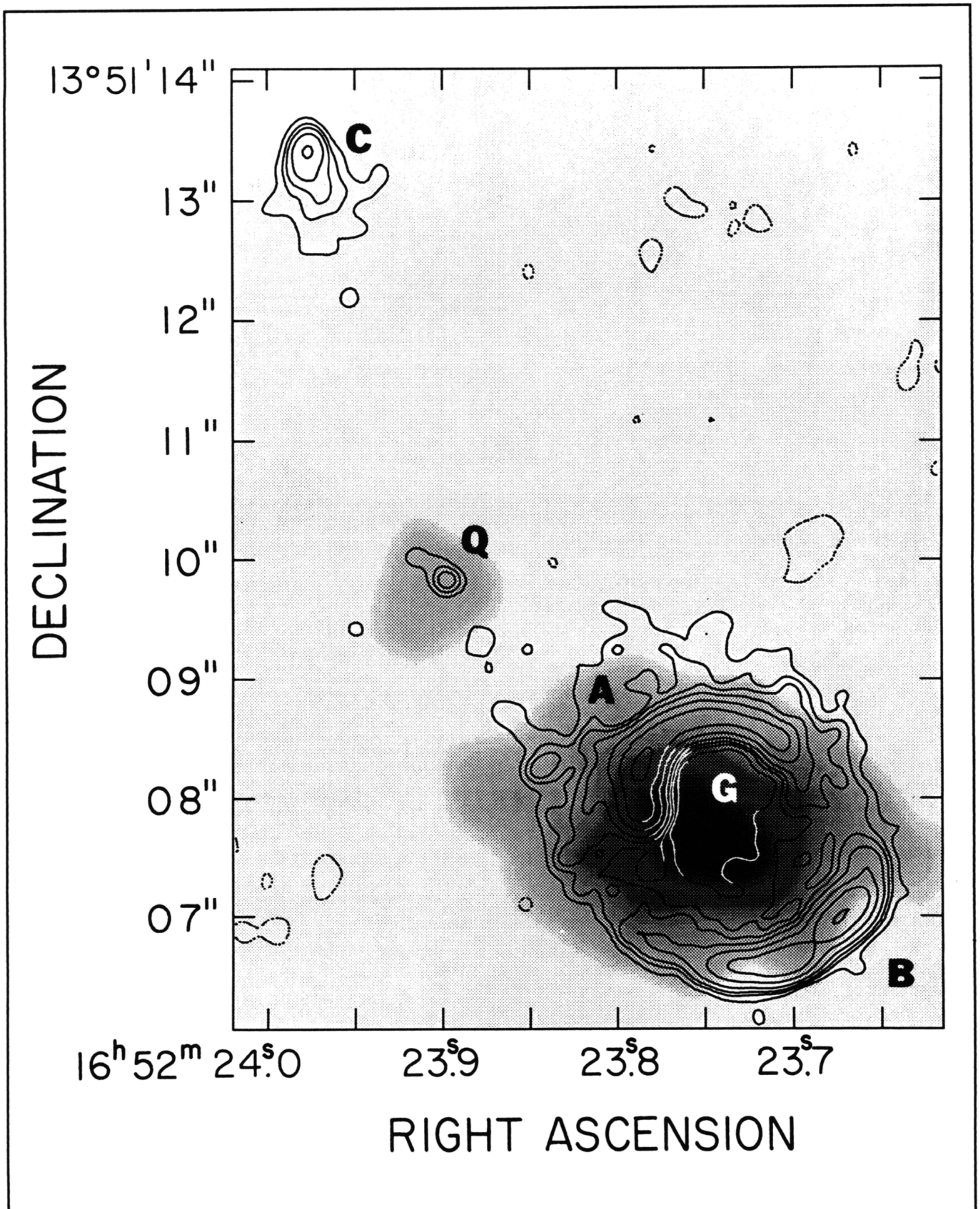

Figure 1. Superposition of optical image of MG1654+1346 on contours of VLA radio image.

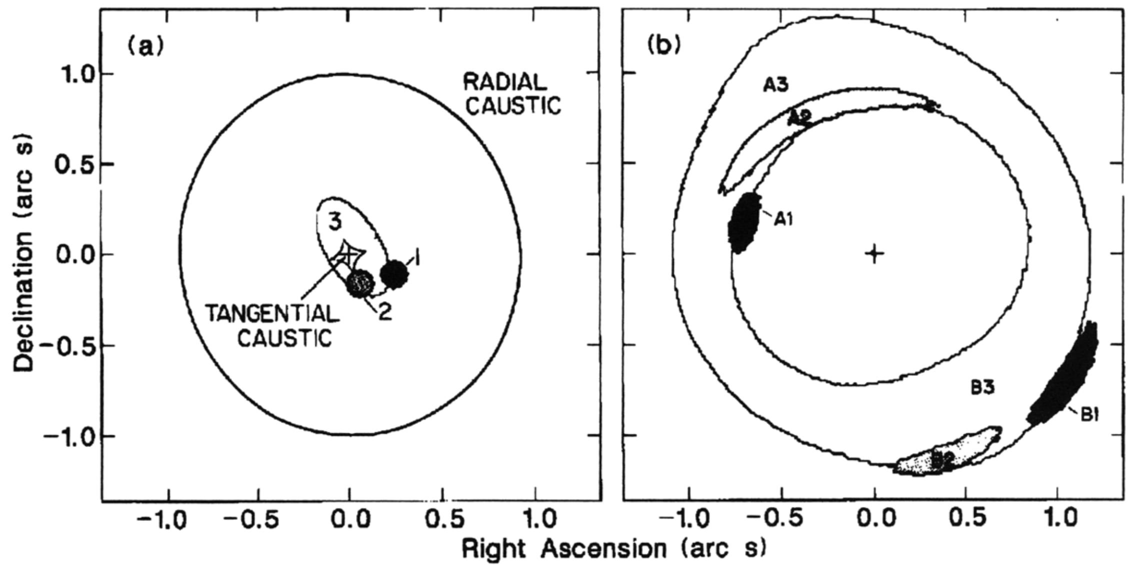

Figure 2. On the left, a 3-component source model with the model image shown on the right, to be compared with the radio image in figure 1.

tively, which may be two separate clouds of ionized gas that lie within a few kiloparsecs of the lensed source.

First epoch VLBI observations took place on June 1, 1984. Components A and B are both doubles at the milliarcsecond level. Models which allow A and B to be adjusted independently have a slightly better fit than those which constrain A and B to be related by a linear matrix, suggesting some source evolution on a time scale shorter than the unknown time delay. If a time delay of zero is assumed and the slightly degraded fit accepted, then the resulting model can be used for comparison with theoretical e lens models by predictions of the magnification matrix. Three lens models by Narasimha, Subramanian, and Chitre (1987) and one by Narasimha and Chitre (1989) predict magnification matrices. None of the predictions agree, but the dark halo model by Narasimha and Chitre (1989) works best. Final results are currently being submitted for publication. Second epoch observations were carried on November 9, 1989. Analysis should be complete by August of 1990.

1.2.3 Time Variations

The double quasar 0957+561, discovered by Walsh, Carswell and Weymann in 1979, was the first gravitational lens to be recognized. It has two compact radio components, A and B, separated by 6 arcseconds, which have optical counterparts with nearly identical spectra at a redshift of 1.4. We have also observed the principal lensing galaxy, about 1 arcsecond away from the B image, with a redshift of 0.36. The A and B components were observed to be variable in radio brightness by our group in 1980. According to models of this gravitational lens, there should be a time delay of about one year between variations observed in the A and B components. Measurement of the time delay would provide a further constraint to the lens models. Finally, Falco et al. showed in 1988 that the time delay could be applied to the lens models to estimate Hubble's constant.

In order to observe this time delay, we have been monitoring the radio flux of the two images for the past ten years. Both images decreased steadily in brightness by about 20 percent over the first five years of observation, leaving us without any features for time delay measurement. In 1984, however, the decline flattened out in the A image, and subsequently in the B component. The feature allowed us to roughly measure the time delay to be 500 $\pm$ 200 days (reported at the Cambridge Conference on Gravitational Lenses in 1988). Incidentally, applying the models of Falco et al., this measurement estimates Hubble's constant to lie between 50 and 100 km/s per Mpc.

Two factors prevented a more precise measurement: the feature was not very strong compared to our measurement error, and our time coverage was incomplete. The radio observations are made at the VLA roughly every month. The VLA alternates between four configurations, of which only the A and B arrays have sufficient angular resolution to clearly resolve the two images of 0957+561. Hence, for half of each year, we were unable to accurately measure the brightness of the two components. The annual 50 percent gaps made the measurement of a slight change in the light curves exceedingly difficult.

During the past year, we have been working on improving the quality of the time delay measurement by filling in the gaps in the light curves. We have applied a more complex reduction technique that enables us to extract the A and B image fluxes from the C array data that comprise about 80 percent of the missing time samples. We are also attempting to use the total source brightness of the D-array observations to fill the remaining gaps. With the C-array fluxes, the curve looks much better already.

We have also benefitted from a timely change in the radio source. During the spring of 1989, the A component increased sharply in flux, by a factor of about 15 percent. We have begun to observe the subsequent rise in the B component this spring. This much stronger feature, combined with our more complete time coverage, should allow us to improve the time delay measurement.

1.2.4 Lens Modeling

The derivation of cosmological information (such as H_0) from instances of gravitational lensing is dependent on accurate modeling of the mass of the lens. The model information is itself interesting since it gives the mass (and, with optical observations, the mass-to-light ratio) of the matter enclosed by the multiple images. In view of this, we are developing a ray-tracing/lens-modeling package.

The ray-tracing package is nearly complete. The package supports a wide variety of analytic mass profiles. In addition, arbitrary mass distributions on a grid are supported, permitting the use of optical images of the lens as mass models and the direct determination of M/L of the lens. The package permits the determination of image configuration for arbitrary source brightness distributions lensed by one or many galaxies at one or many redshifts. The modeling package permits the estimation of lens model parameters for a given configuration of images. At present, only point images are supported. The package will be upgraded to use arbitrary extended images (such as radio maps of the ring images).

In collaboration with an optical observer at MIT, the package in its present form will be used to model the gravitational lens system 1115+080 (for which the point image approximation is valid). The upgraded version (capable of dealing with extended images) will be used to model MG1654+1346 and extended image configurations which will be discovered in the upcoming VLA lens survey.

1.3 Orbiting VLBI

Sponsors

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Project Staff

Professor Bernard F. Burke, John W. Barrett, Samuel R. Conner, Michael B. Heflin

1.3.1 The Japanese VSOP Mission

The Japanese Institute for Science and Astronautics in Space (ISAS) has approved a mission to carry a VLBI radio telescope into space. The mission, which will have a 10-meter paraboloid with observing frequencies of 1.6, 6, and 22.3 Ghz, will be launched in early 1995. The United States will participate by providing the ground radio telescopes and the correlator of the National Radio Astronomy Observatory's Very Long Baseline Array (VLBA), now scheduled for completion in 1993. The Deep Space Net (DSN) of NASA will provide data acquisition, tracking, and orbital determination, and will serve as a participant in the mission management. Professor Bernard F. Burke, active in the Japanese advisory group for VSOP, is also chairman of the Science Consulting Group set up by NASA to coordinate U.S. participation in foreign VLBI missions.

Our group has been active in the preliminary TDRSS experiment (described in last year's *RLE Progress Report*). During the past year, we have been investigating the scientific aspects of the mission. We have also studied possible approaches to ground tracking and acquisition of information if the NASA Deep Space Net Program cannot fulfill that role.

1.3.2 The Soviet RADIOASTRON Mission

The Institute for Space Research (IKI) of the U.S.S.R. has approved deployment of a VLBI mission, designated RADIOASTRON. Complementary to the Japanese VSOP mission, RADIOASTRON will orbit much farther from the earth, giving baselines an order of magnitude larger than any achieved so far.

Recently, Vice President Quayle announced that the U.S. will join the Soviet mission as a memorial to academician Sakharov, who supported this effort. The roles of the United States and MIT will be similar to those established for the VSOP mission.

1.4 Development of an Undergraduate Laboratory

Sponsor

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Project Staff

Professor Bernard F. Burke, John W. Barrett, Jee Chung

The classical way of introducing undergraduate students to astronomy has been through optical results, i.e., using optical telescopes as part of the laboratory experience. In recent years, some of the most startling developments in astronomy have come from studying the radio domain: pulsars, quasars, and cosmic "big bang" radio background are outstanding examples. Although previously radio techniques had been considered too complex and too expensive, the rapid development of inexpensive digital systems and computers has changed the circumstances dramatically. We have been developing a new experiment for the MIT Junior Physics Laboratory to introduce students to the new science of radio astronomy.

In the experiment, we use an 8-foot telescope on the roof of our building that has a modern low noise L band amplifier. The receiver chain converts the incoming signal to baseband where the spectrum is analyzed by an autocorrelator. The local oscillator and filter frequencies are chosen so that the 21cm hydrogen line, coming from the interstellar medium, is in the middle of the analyzed band. The autocorrelator uses multichannel chips developed by the Netherlands Foundation for Radio Astronomy and incorporated into a working autocorrelator function to a spectrum by taking the Fourier transform. An IBM PC controls the telescope.

Not only does the experiment introduce the student to radio astronomy, it introduces modern techniques of noise analysis and the use of Fourier transform methods. Thus, there are practical benefits to the student's educational experience in addition to the exciting and intellectual adventure of directly measuring the large-scale motions of our galaxy.

1.5 Radio Interferometry of Nearby dMe Stars

Sponsor

Annie Jump Cannon Award

Project Staff

Jens-Ole Hansen, Professor Jacqueline N. Hewitt

dMe stars are dwarf M stars that show evidence of unusual surface activity. They have been known for some time to flare strongly at optical and radio wavelengths, and more recently it has been recognized that many dMe stars exhibit low level quiescent emission at centimeter wavelengths that is detectable with the Very Large Array radio telescope. In collaboration with colleagues at Haystack Observatory, Jet Propulsion Laboratory, and Bureau des Longitudes (France), we have shown that several nearby dMe stars are detectable with a Very Long Baseline Interferometry (VLBI) array. These measurements place limits on quantities of direct relevance to theories of the radio emission mechanism. In addition, detection of dMe stars on VLBI baselines makes possible measurement of the position of these stars with very high precision (≤ 0.5 milliseconds of arc). This high-precision astrometry would have several interesting applications, most notably in detecting planetary companions to the dMe stars. For example, the orbital motion of nearby dMe star about a companion of Jovian mass would be detectable in just a few years. We are currently working on more extensive VLBI measurements of the dMe star emission and undertaking a program aimed at identifying radio reference sources for use as positional standards in the astrometry.

1.6 Gravitational Lenses as Astrophysical Laboratories

Sponsor

Annie Jump Cannon Award

Project Staff

Alexandar Angelus, Professor Jacqueline N. Hewitt

Previous work (in collaboration with Professor Bernard F. Burke and colleagues at Princeton University and California Institute of Technology) has identified two gravitational lens systems, MG1131+0456 and MG0414+0534, that display a high degree of symmetry. As a consequence of this symmetry, these systems should be interesting astrophysical laboratories. They could provide new measurements of cosmological interest, such as Hubble's constant and the mass-to-light ratio of the matter forming the lens. After having carried out VLA observations of MG1131+0456, we are analyzing the data to determine whether the source is variable, a necessary condition to measure Hubble's constant. We have acquired VLBI and additional VLA data of the two lens systems so that we can model their gravitational fields.

1.7 Tiros-N Satellite Microwave Sounder

Sponsor

SM Systems and Research, Inc.

Project Staff

Professor David H. Staelin, Dr. Philip W. Rosenkranz, Charlene C. Kuo

This project scientifically supports the Advanced Microwave Sounding Unit (AMSU) scheduled for launch on polar-orbiting weather satellites in the mid-1990s. Support of this passive microwave spectrometer program emphasizes atmospheric transmittance spectra, retrieval methods, and instrumentation issues.

One issue we addressed this year concerned the strong nonlinearities in AMSU relative humidity retrievals; both the nature of the nonlinearities and the resulting limits to the altitude coverage and vertical resolution of AMSU were characterized. A manuscript describing the accuracy of such humidity retrievals is being prepared.

Studies of precipitation cell sizes observed in summer and winter aircraft flights of the MTS 118-GHz spectrometer suggest that AMSU-A will resolve perhaps one-third of such cells with 50-km resolution and that

AMSU-B should resolve perhaps two-thirds of these cells with its 15-km resolution; the implication is that AMSU-A and AMSU-B might have a useful role to play in estimation of global precipitation, which is an important parameter in understanding the global hydrological cycle and climate.

Further consideration of atmospheric transmittances in the 5-mm oxygen band resulted in improved expressions for the temperature dependence. In particular, the temperature dependence of the interference coefficient for each line was revised to be consistent with detailed balance and a tri-diagonal model for the relaxation matrix.

Study of AMSU has led to the conclusion that a simple circularly-polarized double-sideband spectrometer could be added to module A2, yielding temperature soundings to 75-km altitude using the 7+ and 9+ oxygen resonances. Polarization reversal between the sidebands and use of a 2-bit, 16-channel digital autocorrelator would efficiently yield approximately ten spectral channels with good altitude resolution for all magnetic field configurations.

1.8 Long-Baseline Astrometric Interferometer

Sponsor

U.S. Navy Office of Naval Research
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Project Staff

Professor David H. Staelin, John W. Barrett, Edward J. Kim, Howard R. Stuart

During 1989, our effort involved (1) completion of a study on dispersed-fringe, group-delay astrometry for the Mark-III optical interferometer and (2) initial development of infrared observing capabilities for the same instrument.

Fringe-tracking systems are typically limited to stars of ~9th magnitude, but dispersing the white fringe into a continuum of colors for which the interference pattern can be separately estimated permits integration over longer time periods and improved signal-to-noise ratio.[3] This technique was demonstrated using the Mark-III stellar interferometer at the Mount Wilson Observatory. For these tests the detectability limit (SNR ~1) was between 2 and 4 detected photons per 4-msec frame, using only 4000 frames. This represents an improvement of ~3 stellar magnitudes over the standard fringe-tracking mode which requires 40 photons per 4-msec interval. These results from four stars are believed to be the first stellar observations of dispersed-fringe group delays made with a visible-light stellar interferometer.

To facilitate infrared stellar diameter measurements, work began on modifying the interferometer to operate at ~2.2 microns. A preliminary system design was developed and work began on the electronics. Analyses predict that second magnitude stars could be observed with this system.

Previous progress in developing optical trusses for monitoring the positions of the siderostat mirrors was documented further.[4]

1.9 Nonthermal Radio Emission from the Jovian Planets

Sponsor

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The Planetary Radio Astronomy (PRA) experiment on the Voyager-2 spacecraft

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[3] E.J. Kim, *Dispersed Fringe Group Delay Astrometry Using the Mark III Stellar Interferometer,* S.M. thesis, Dept. of Electr. Eng. and Comput. Sci., MIT, 1989.

[4] B. Hines, M. Shao, M.M. Colavita, and D.H. Staelin, "Use of Laser Metrology Optical Truss for Monitoring Baseline Motion," paper presented at SPIE Conference 1237: Amplitude and Spatial Interferometry, February 14-16, 1990.

observed radio emission from five planets in 198 channels distributed over the band from 1.2 kHz to 40.5 MHz. The characterization of the observed Uranian radio emission was extended and documented in a draft manuscript, which is being prepared for publication.

During August 1989, Voyager 2 encountered Neptune. The PRA instrument again measured varied strong radio emission from the planet.[5] The types of emission observed included strong narrowband highly polarized bursts in the frequency range 0.1–1.3 MHz, episodes of smooth emission at 20–865 KHz, and excess emission during the ring plane crossing and the inbound crossing of the magnetospheric bowshock. Initial studies of the emission with high spectral resolution reveal frequency structures that evolve in a manner reminiscent of the emission seen on the other three Jovian planets. One unique feature is the presence of a very sharply defined and slowly drifting spectral region of no emission, bounded on both sides by emission that varies relatively smoothly with time and frequency. None of the other planets exhibited such a marked forbidden frequency band.

1.10 High-Resolution Passive Microwave Imaging of Atmospheric Structure

Sponsor

NASA/Goddard Space Flight Center
Grant NAG 5-10

Project Staff

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The scientific results obtained from the passive microwave observations of clear air and storms by an imaging microwave spectrometer on the NASA ER-2 high-altitude aircraft were documented for publication. The first paper[6] describes the instrument (MTS), which employed eight double-sideband channels centered around the 118.75-GHz O_2 resonance, in addition to describing the results from 32 aircraft flights during the Genesis of Atlantic Lows Experiment (GALE) and the Cooperative Huntsville Meteorological Experiment (COHMEX). Simultaneous observations were made with a single-beam 53.6-GHz radiometer and a video camera. It was shown that the response to clouds near 118.75 $\pm$ 1.47 GHz was $\sim$1.7 times greater than that near 53.65 GHz, a modest ratio considering that both frequencies sound tropospheric temperatures with approximately the same weighting functions.

Also prepared for publication were studies of the utility of these same 118-GHz O_2 observations for estimating parameters of precipitation cells imaged by the instrument.[7] It was shown that errors on the order of 1–2 km rms can be obtained for estimated altitudes

5 J.W. Warwick, D.R. Evans, G.R. Peltzer, R.G. Peltzer, J.H. Romig, C.B. Sawyer, A.C. Riddle, A.E. Schweitzer, M.D. Desch, M.L. Kaiser, W.M. Farrell, T.D. Carr, I. de Pater, D.H. Staelin, S. Gulkis, R.L. Poynter, A. Boischot, F. Genova, Y. Leblanc, A. Lecacheux, B.M. Pedersen, and P. Zarka, "Voyager Planetary Radio Astronomy at Neptune," *Science* 246:1498-1501 (1989).

6 A.J. Gasiewski, J. Barrett, P.G. Bonanni and D. Staelin, "Aircraft Based Radiometric Imaging of Tropospheric Profiles and Precipitation Using the 118.75 GHz Oxygen Resonance," accepted for publication *J. App. Meteor.* (1990).

7 A.J. Gasiewski and D.H. Staelin, "Statistical Precipitation Cell Parameter Estimation Using Passive 118-GHz O_2 Observations," *J. Geophys. Res.* 94:18367-18378 (1989).

of rain cell tops. The retrieval operator consisted of a Karhunen-Loeve transformation followed by a rank reduction, a nonlinear operator, and a linear mean-square-error estimator. Comparisons were made to celltop altitudes obtained by optical stereoscopy from the same high altitude aircraft flying near 65,000 feet.

Studies of the observability of temperatures in the upper stratosphere and mesosphere continued.[8] It was shown that ground-based observations near the 27-oxygen line can yield weighted temperatures near the stratopause (~1 mbar). Sensitivities would be ~1 K rms with 20 minutes of integration[9] for receiver noise temperatures of ~1000K. Observations from aircraft near 20 km altitude will be four times more sensitive since tropospheric attenuation will be eliminated.

In preparation for future experiments, improvements were made to the present MTS 53.6-GHz radiometer. Its local oscillator, calibration switch, and mixer preamplifier were replaced, and a 16-channel, 2-bit autocorrelation unit is being constructed for observations of oxygen lines.[10] The varactor-tuned Gunn-diode local oscillator can be rapidly tuned over the 52.8–54.94 GHz frequency range, thus permitting emulation of the Advanced Microwave Sounding Unit (AMSU) channels 4–7, which sound the lower troposphere. These improvements will make possible ground-based and airborne measurements of mesospheric temperatures and atmospheric transmittance microwave properties.

1.11 Characterization of Dolphin Whistles

Sponsor

Woods Hole Oceanographic Institution
Contract SC-28860

Project Staff

Professor David H. Staelin, Kevin G. Christian

Dolphin communication is characterized by a combination of repetitive whistles, not unlike bird song, and high speed clicks generally used for echo location. This project involves substantially compressing these signals and developing methods for organizing them in a database for rapid identification of repetitious song elements. One anticipated result of this research is improved understanding of how various songs are created and evolve in dolphin communities. The results of this research should also lead to signal analysis tools useful for acoustic diagnosis of machinery and other devices.

1.12 Rapid Precision Net-Form Manufacturing

Sponsor

Leaders for Manufacturing Program

Project Staff

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This project has three interrelated elements which include the development of (1) methods and apparatus for measuring the shape of arbitrary three-dimensional objects with sub-mil accuracy; (2) methods and apparatus for forming such objects in metal, ceramics, or plastics rapidly with sub-mil pre-

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8 P.W. Rosenkranz and D.H. Staelin, "Polarized Thermal Microwave Emission from Oxygen in the Mesosphere," *Radio Science* 23:721-729 (1990).

9 P.W. Rosenkranz, "Oxygen Line Emission as a Measure of Temperature in the Upper Stratosphere and Mesosphere," paper to be presented at the 1990 International Geoscience and Remote Sensing Symposium, University of Maryland, May 20-24, 1990.

10 M.C. Petro, *An Autocorrelator for Determining the Temperature of the Upper Atmosphere,* S.B. thesis, Dept. of Electr. Eng. and Comput. Sci., MIT, June 1989.

cision; and (3) new methods for adaptive experiment design that could facilitate process characterization and help achieve desired levels of precision by iteration of elements (1) and (2).

Most of the work involved development of a 4-axis stage with a scannable volume of ~ 20 cubic inches; its open loop accuracy is better than 25 microns. A 512^2 pixel CCD camera was linked to a telescope with an adjustable field of view down to 1-mm^2, and to a computer capable of receiving up to 30 frames per second. Holographically generated illumination patterns provide the signal which permits object shape to be measured at high data rates. Work on methods for adaptive experiment design and materials forming is still in the formative stages.