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UNIVERSITY OF CALIFORNIA

SAN DIEGO

La Jolla, California

Center for Astrophysics and Space Sciences

Final Report

"Infrared Astronomy Research /
High Altitude Observations."

1973 - 1983 Grant No. NGR 05-005-055

B. Jones,
Center for Astrophysics
and Space Sciences, C-011,
University of California, San Diego,
La Jolla, CA 92093.

Principal Investigators:

W. A. Stein / B. T. Soifer	12/15/73	-	8/31/78
S. P. Willner	9/ 1/78	-	10/31/80
B. Jones	11/ 1/80	-	4/30/83

The NASA Technical Officer for this grant is:

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NASA Ames Research Center,
University Affairs Office,
Mail Stop 241-25,
Moffett Field,
California 94035.

Table of Contents

1. Scientific Goals and Achievements

Because of the wide range of time covered by this investigation the scientific goals have undergone changes as our knowledge of both instrumental procedures and astronomy have expanded and matured. The overall motivation has been to understand the emission mechanisms in the 4 - 8 micron region of the spectrum, and to use this to study the properties of individual objects or classes of objects.

Initial work was directed towards the optimization of instrumentation including study of the atmospheric transmission at altitude and observing techniques. Subsequent studies have included

- spectroscopy of planets
- stellar atmospheres
- highly obscured objects in molecular clouds
- planetary nebulae
- HII regions
- extragalactic objects.

Abstracts are presented of all publications resulting from this research (section 5), so highlights rather than full scientific details are presented here.

Recent work (see publication #31) has included spectroscopy of protostellar sources, looking for correlations between absorption features at 2.8, 3.1, 3.4, 6.0, 6.8, and 10 microns. Evidence was found suggesting that the 6.0 micron feature originates in amorphous water ice, but the identification of the 6.8 micron feature remains uncertain. The study of absorptions in the spectra of protostellar sources in molecular clouds uses the sources as probes of the cloud material properties along the line of sight.

One continuing investigation has been the observation of the emission features ocurring at 3.3, 6.2, 7.7, 8.7, and 11.3 microns. The emission processes responsible for these features have not yet been completely explained, although it is certain that they result from some type of dust grain mantle material. Data on the 6.2 and 7.7 micron features can only be obtained from above the atmosphere. Publications #4, #11, #12, #13, #15, #18, #21 have all resulted from work on this problem.

Another project which has provided useful data has been the study of fine structure atomic emission lines from HII regions in our galaxy to study the abundance of these elements as a fuction of position in the galaxy. This is difficult to do at visible wavelengths because of the large amount of obscuration in the galactic plane. The IR lines studied include ArII at 6.99 microns from our data, SIII (18.71) (from other C141 data), and ArIII (8.99) ,SIV (10.54) and NeII (12.81) from ground based work. Publications #26, #29, #33, and #34 result from this project.

2. Instrumentation

The majority of the data was taken with the UCSD circular variable filter wheel spectrometer using an lead-tin-telluride (PbSnTe) photovoltaic detector operated at 63K initially and 4K finally. A schematic diagram of the dewar mounted on the photometer is shown. The filter wheel covered the range 4 - 8 microns with 1 - 1.5% spectral resolution. Several broad band filters were used to give the usual wide bandpass measurements for fainter sources and for comparison to ground based data which may have used a different beam size. The field of view was usually 17 arc-sec. Normal IR chopping and wobbling techniques were used and spectra were calibrated with respect to standard stars. The detector signal, after preamplification, was further processed in the PAR phase sensitive amplifier. Data aquisition, processing, display and storage were done with the "ADAMS" onboard computer system.

3. Personnel

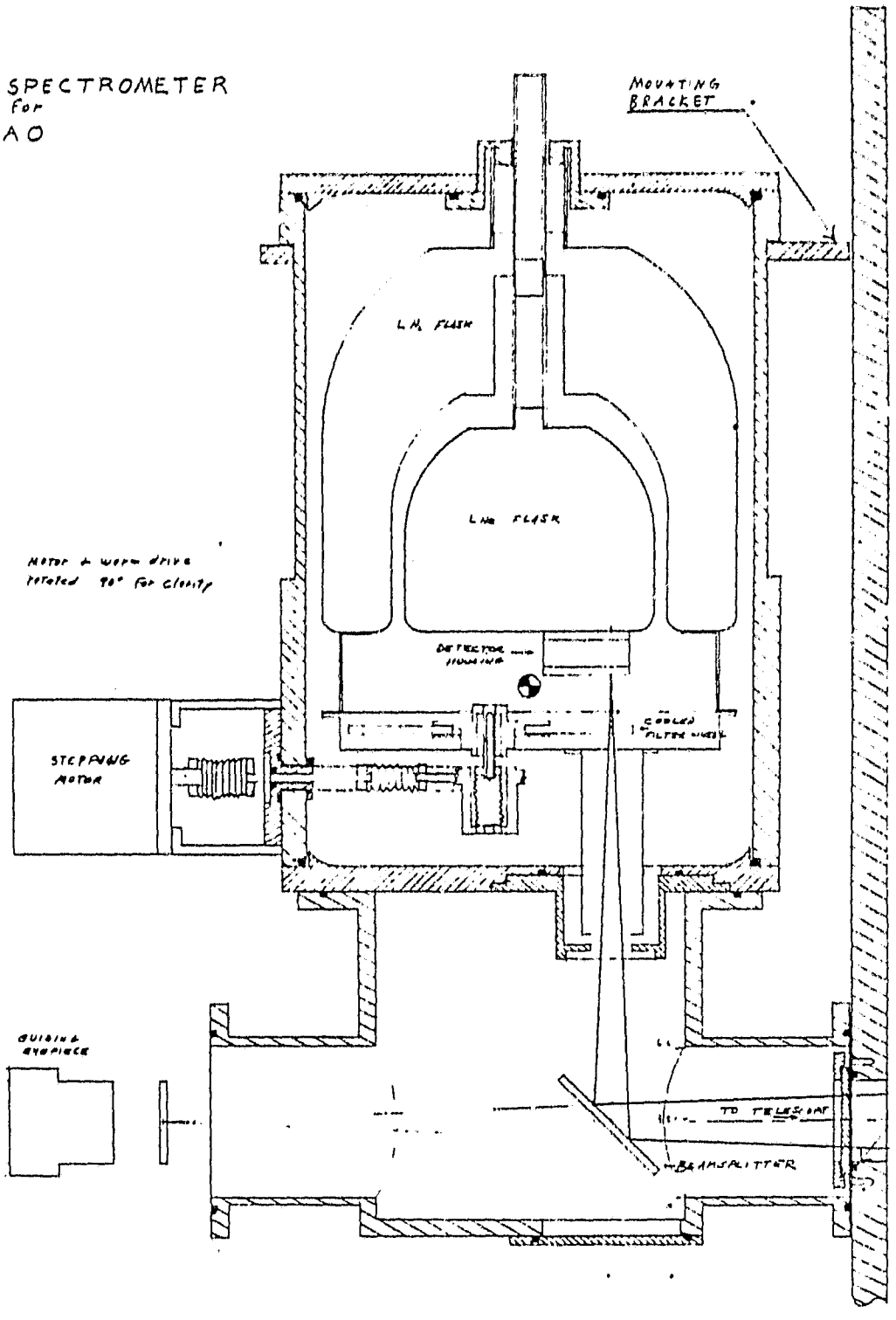
The program was started by B. T. Soifer in collaboration with W. A. Stein in 1973. WAS left UCSD for the University of Minnesota in 1976. BTS left UCSD for Caltech in 1977. Subsequently he remained involved with the program through subcontracts, while S. P. Willner became Principal Investigator at UCSD. SPW in turn left UCSD in 1980 when B. Jones became PI.

Many other scientific personnel at UCSD participated in the program, they are listed below with the approximate dates.

F. C. Gillett	1973 - 1975
R. W. Russell	1973 - 1979
W. J. Forrest	1973 - 1978
H. S. Hudson	1973 - 1978
R. C. Puetter	1976 - 1983
R. J. Rudy	1978 - 1980
J. J. Puschell	1981 - 1983

A long and fruitful collaboration was established with J. L. Pipher of the University of Rochester, and other scientists there who were "guest investigators" with the UCSD instrumentation.

UCSD SPECTROMETER
for
KAO



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7. "Observations of Jupiter and Saturn from 5-8 microns." Russell R. W. and Soifer B. T. 1977, Icarus 30, 282.

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9. "The 4 - 8 Micron Spectrum of the BNKL Source in Orion." Russell R. W., Soifer B. T. and Puetter R. C. 1977, Astr. Ap., 54, 959.

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16. "Infrared Spectra of HM Sagittae and V1016 Cygni." Puetter R. C., Russell R. W., Soifer B. T. and Willner S. P. 1978, Ap. J. 223, L93.

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1982

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34. "Abundances in Galactic HII Regions, III; G25.4-0.2, G45.5+0.06, M8, S159 and DR22." Pipher J. L., Helfer H. L., Herter T., Broitta Jr. D. A., Houck J. R., Willner S. P., and Jones B. 1984, Ap. J., 285.

5. Abstracts of Published Papers

1

24.09.04 4 μ - 8 μ Spectrophotometric Observations from the NASA Flying 36" Telescope. R. W. RUSSELL, B. T. SOIFER, & W. J. FORREST, Univ. of Calif., San Diego - Spectrophotometric observations from 4 μ - 8 μ with a liquid nitrogen cooled filter wheel having resolution $\Delta\lambda/\lambda \sim 0.012$ were obtained on αLyr, βPeg, μCeph, Jupiter, and the Moon, using the NASA flying 36" telescope on the Airborne Infrared Observatory. The lunar spectrum shows that it is not a black body emitter, with a depression between 6 μ and 8 μ.

The spectrum of μCeph, an M supergiant, shows no excess over the stellar continuum from 5 μ - 8 μ. This implies that the previously identified silicate grains are the only infrared active circumstellar material in this star. The implications of this will be discussed.

The Jovian spectrum shows a deep minimum at 6 μ, characteristic of ammonia in the atmosphere, as well as further spectral structure.

This work was supported by NASA grant NGR 05-005-055.

THE ASTROPHYSICAL JOURNAL, 198:L41–L43, 1975 May 15

2

SPECTROPHOTOMETRIC OBSERVATIONS OF MU CEPHEI AND THE MOON FROM 4 TO 8 MICRONS

R. W. RUSSELL, B. T. SOIFER, AND W. J. FORREST
Department of Physics, University of California, San Diego
Received 1974 December 11; revised 1975 February 14

ABSTRACT

We have obtained the first 4–8 μ spectrophotometric observations ($\Delta\lambda/\lambda \sim 0.01$) of μ Cep and the Moon, using the NASA Airborne Infrared Observatory. The lunar spectrum shows nongray behavior from 6.5 to 8 μ. The spectrum of μ Cep, an M2 Ia star with circumstellar emission, shows no evidence for circumstellar excess emission from 4 to 8 μ; we conclude that silicates provide the only infrared-active component of the circumstellar material.

Subject headings: circumstellar shells — Moon — spectra, infrared

THE ASTROPHYSICAL JOURNAL, 199:L181–L183, 1975 August 1

SPECTROPHOTOMETRY OF CRL 2688 FROM 2 TO 24 MICRONS

W. J. FORREST, K. M. MERRILL, R. W. RUSSELL, AND B. T. SOIFER
Department of Physics, University of California, San Diego
Received 1975 March 20

ABSTRACT

Medium-resolution spectrophotometry ($\Delta\lambda/\lambda \approx 0.01$) of CRL 2688 from 2 μ to 24 μ are reported. No significant features are found from 3 μ to 24 μ, although the spectral flux distribution is broader than that of a single-temperature blackbody.

Subject headings: infrared sources — nebulae — spectrophotometry

THE ASTROPHYSICAL JOURNAL, 196:179–189, 1975 February 15

THE PECULIAR OBJECT HD 44179 ("THE RED RECTANGLE")

MARTIN COHEN,[1] CHRISTOPHER M. ANDERSON,[2] ANNE COWLEY,[3] GEORGE V. COYNE,[4] WILLIAM M. FAWLEY,[1] T. R. GULL,[5] E. A. HARLAN,[6] G. H. HERBIG,[6] FRANK HOLDEN,[6] H. S. HUDSON,[7] ROGER O. JAKOUBEK,[2] HUGH M. JOHNSON,[6] K. M. MERRILL,[7] FRANCIS H. SCHIFFER III,[2] B. T. SOIFER,[7] AND BEN ZUCKERMAN[1,9]
Received 1974 July 22; revised 1974 September 3

ABSTRACT

A strong infrared source detected in the AFCRL sky survey is confirmed, and is identified with the binary star HD 44179, embedded in a peculiar nebula. *UBVRI* and broad-band photometry between 2.2 and 27 μ are combined with blue, red, and near-infrared spectra, polarimetry and spectrophotometry of the star, and a range of direct and image-tube photographs of the nebula, to suggest a composite model of the system. In this model, the infrared radiation derives from thermal emission by dust grains contained in a disklike geometry about the central object, which appears to be of spectral type B9–A0 III and which may be in pre-main-sequence evolution. Two infrared emission features are found, peaking at 8.7 and 11.3 μ, the latter corresponding to the feature seen in the spectrum of the planetary nebula NGC 7027. The complex nebular structure is discussed on the basis of photographs through narrow-band continuum and emission-line filters. The polarization data support the suggestion of a disk containing some large particles. No radio continuum emission is detected.

Subject headings: binaries — infrared sources — nebulae — stars, individual

THE ASTROPHYSICAL JOURNAL, 207:763–769, 1976 August 1

INFRARED OBSERVATIONS OF ICES AND SILICATES IN MOLECULAR CLOUDS

K. M. MERRILL, R. W. RUSSELL, AND B. T. SOIFER
Department of Physics, University of California, San Diego
Received 1975 October 20

ABSTRACT

Spectrophotometric observations from 2 to 4 μ and from 8 to 13 μ of several infrared sources associated with molecular clouds are reported. Narrow absorption features at 3.08 μ, attributed to interstellar ices, appear in all sources with a molecular cloud in the intervening line of sight. All sources showing ice absorptions also show broad absorption features, attributed to cold silicates, from 8 to 13 μ.

The observed ice absorption profiles are all quite similar; however, they do not fit in detail Mie theory predictions of extinction for pure H_2O or NH_3 ices. The ratio of ice to silicate optical depths is found to vary, with most sources showing $\tau_{ice}/\tau_{silicate}$ in the range 0.1–0.4. The ratio of visual extinction to ice absorption is found to increase rapidly from inside to outside the molecular cloud in NGC 2024.

Subject headings: infrared sources: general — interstellar: matter — interstellar: molecules

THE ASTROPHYSICAL JOURNAL, 208:L129–L132, 1976 September 15

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16–25 MICRON SPECTROSCOPY OF THE TRAPEZIUM AND BN-KL SOURCE IN ORION

W. J. FORREST
Cornell University
AND
B. T. SOIFER
Department of Physics, University of California, San Diego
Received 1976 April 26; revised July 2

ABSTRACT

Spectrophotometric observations from 16 to 25 μ of the Trapezium and BN–KL object in Orion are reported. These observations were obtained with a newly developed liquid-helium-cooled grating spectrometer. The observations of the Trapezium show a relatively flat 16–25 μ spectrum, consistent with a 20 μ emission peak similar to that previously found at 10 μ. The BN–KL source has a smooth 16–25 μ spectrum, showing little absorption such as characterizes the 10 μ spectrum of this source. This lack of a deep 20 μ absorption is attributed to complex radiation transfer processes within the molecular cloud.

Subject headings: infrared: spectra — nebulae: Orion Nebula

ICARUS 30, 282–285 (1977)

7

Observations of Jupiter and Saturn at 5–8 μm

R. W. RUSSELL AND B. T. SOIFER

Department of Physics, University of California, San Diego, La Jolla, California 92093

Received March 18, 1976; revised April 28, 1976

Moderate-resolution spectrophotometry ($\Delta\lambda/\lambda \sim 0.015$) has shown the effects of known atmospheric constituents (NH_3, CH_4, C_2H_6) on the 5–8 μm spectrum of Jupiter. Broadband observations of Saturn at 6.5 μm are also reported.

PUBLICATIONS OF THE ASTRONOMICAL SOCIETY OF THE PACIFIC
89:120–122, June 1977

SPECTRA OF LATE-TYPE STARS FROM 4–8μ

RICHARD C. PUETTER, RAY W. RUSSELL, KRISTEN SELLGREN,* AND BARUCH T. SOIFER
Department of Physics, University of California, San Diego

Received 1977 January 10

The 4–8μ spectra ($\Delta\lambda/\lambda \simeq 0.015$) of three late-type stars, obtained in October 1975 from the Kuiper Airborne Observatory, are reported. These spectra exhibit mainly stellar photospheric blackbody emission in the case of the M stars and thermal circumstellar dust emission in the C star. The only significant feature seen in this region is that attributed to CO from ~4.5μ to 5.2μ. This feature is observed in both types of stars.

Key words: late-type stars—infrared spectra

Astron. Astrophys. 54, 959—960 (1977)

ASTRONOMY
AND
ASTROPHYSICS

Research Note

The 4–8 μm Spectrum of the BNKL Source in Orion

R. W. Russell, B. T. Soifer and R. C. Puetter
Department of Physics C-011, University of California, San Diego, La Jolla, California 92093, USA

Received September 27, 1976

Summary. Observations of the 4.5–8 μm spectrum with a resolution $\Delta\lambda/\lambda \sim 0.015$ of the BNKL source in Orion are reported. No obvious spectral features are found. An upper limit on the abundance of carbonate grains in the line of sight to BNKL is determined.

Key words: infrared sources — Orion Nebula

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19.05.15 Infrared Spectra of Protostars R. C. PUETTER, R. W. RUSSELL, B. T. SOIFER, and S. P. WILLNER, Univ. of Calif., San Diego -- The 2 to 13 μm spectra of 5 compact infrared sources associated with molecular clouds have been measured with the Kuiper Airborne Observatory and ground-based telescopes. The sources -- OMC 2-IRS3, GL 989 = DAA 6, GL 2591 = UA 27, GL 2884, and NGC 7538E -- are spatially isolated from other sources of comparable strength. The spectra all show broad absorption features near 3.1 and 9.7 μm; the features are attributed to ice and silicates, respectively. Two new absorption features, shallower than the ice and silicate absorptions, are seen near 6.0 and 6.8 μm. The ratios of the depths of the various features are different from object to object. This research was supported by NASA grant NGR 05-005-055 and NSF grant AST 76-82890.

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19.05.07 The Infrared Spectrum of BD +30° 3639 and Possible Celestial Grain Constituents R. W. RUSSELL, R. C. PUETTER, B. T. SOIFER, and S. P. WILLNER, Univ. of Calif., San Diego -- Broad emission features at 6.2 and 7.7 μm, first seen in the spectrum of NGC 7027, characterize the 4-8 μm spectrum of the low excitation planetary nebula BD +30° 3639. These features, which are broader than the instrumental resolution ($\Delta\lambda/\lambda \sim 0.015$), have been attributed to peaks in the emissivity of the dust grains that produce the bulk of the infrared flux at these wavelengths. A comparison of the astronomical spectra with laboratory emissivity data for small (~ 2-5 μm) particles of $CaCO_3$ and $MgCO_3$ suggests that neither of these materials can be responsible for the peaks seen in the astronomical data. Alternative materials exhibiting some features similar to those seen in the planetary nebulae spectra have also been studied. However, these materials exhibit features that are not observed in the astronomical data. In addition to the broad features, BD +30° 3639 also possesses a strong [Ar II] line at 6.98 μm. From the strength of this line, argon is found to be over-abundant compared to cosmic abundances. Combined with the earlier report of an over-abundance of neon, this is evidence for significant nuclear processing and mixing in the central star. This research was supported by NASA under grant no. NGR 05-005-055.

THE ASTROPHYSICAL JOURNAL, 217:L121–L124, 1977 November 1

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2 TO 8 MICRON SPECTROPHOTOMETRY OF M82

S. P. WILLNER, B. T. SOIFER, AND RAY W. RUSSELL
Department of Physics, University of California at San Diego
AND
R. R. JOYCE AND F. C. GILLETT
Kitt Peak National Observatory*
Received 1977 June 13; accepted 1977 August 2

ABSTRACT

Observations of the central 30″ of the galaxy M82 with 1.5% spectral resolution from 2 to 8 μm are reported. Three emission features broader than the instrumental resolution are observed. Hydrogen recombination lines are also observed; they indicate an amount of thermal bremsstrahlung emission equivalent to 0.8 Jy of radio flux at 3.5 mm and provide an estimate of ~25 magnitudes for the extinction to the H II region. An upper limit on the 8.99 μm [Ar III] line intensity together with the measured [Ar II] intensity implies that the excitation of the H II region is extremely low. Comparison of fine-structure lines, including the 8 to 13 μm 1973 data of Gillett *et al.*, with the hydrogen lines shows that argon and neon have approximately their cosmic abundance.
Subject headings: infrared: spectra — galaxies: individual — abundances

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THE ASTROPHYSICAL JOURNAL, 217:L149–L153, 1977 November 1

THE 4 TO 8 MICRON SPECTRUM OF NGC 7027

RAY W. RUSSELL, B. T. SOIFER, AND S. P. WILLNER
Department of Physics, University of California, San Diego
Received 1977 May 26; accepted 1977 August 3

ABSTRACT

Spectrophotometric observations of NGC 7027 with $\Delta\lambda/\lambda \approx 0.015$ are reported. The continuum shows a strong, broad peak near 7.7 μm, but little or no evidence for the strong peak near 7.0 μm expected from previously postulated carbonate grains. A spectrally resolved feature at 6.2 μm is found and attributed to an increase in the emissivity of some as yet unidentified dust material.

Unresolved emission features are seen at 4.49 and 5.60 μm. These are attributed to [Mg IV] λ4.49, [Ar VI] λ4.52, and [Mg V] λ5.61. The flux in the [Mg V] line is used to derive a lower limit on the temperature of the central star of 1.3×10^5 K; a better estimate might be $T_* \approx 2 \times 10^5$ K. It is suggested that magnesium is overabundant.
Subject headings: infrared: spectra — nebulae: planetary

THE ASTROPHYSICAL JOURNAL, 219:114–120, 1978 January 1

14

SPECTROPHOTOMETRY OF OH 26.5+0.6 FROM 2 TO 40 MICRONS

W. J. FORREST,* F. C. GILLETT,† J. R. HOUCK,* J. F. MCCARTHY,* K. M. MERRILL,‡
J. L. PIPHER,§ R. C. PUETTER,‖ R. W. RUSSELL,‖ B. T. SOIFER,‖ AND S. P. WILLNER‖
Received 1977 April 22; accepted 1977 June 17

ABSTRACT

Airborne and ground-based observations show that OH 26.5+0.6 has strong 10 μm and weak 18 μm silicate absorptions superposed on an overall energy distribution much like a blackbody. The flux level, color temperature, and depth of the 10 μm absorption have varied during 2 years of observations. A model of the source as a late-type variable star that has ejected an optically thick dust shell is suggested; the mass-loss rate implied is greater than $\sim 10^{-5}\ M_\odot\ \text{year}^{-1}$. The fact that significant flux from the source is observed between 4 and 7 μm is evidence that oxygen-rich dust has significant opacity in that wavelength range.

Subject headings: infrared: sources — stars: circumstellar shells — stars: late-type — stars: mass loss

THE ASTROPHYSICAL JOURNAL, 220:568–572, 1978 March 1

15

THE INFRARED SPECTRA OF CRL 618 AND HD 44179 (CRL 915)

R. W. RUSSELL, B. T. SOIFER, AND S. P. WILLNER
Department of Physics, University of California, San Diego
Received 1977 August 15; accepted 1977 August 31

ABSTRACT

Spectrophotometry from 4 to 8 μm is reported for the infrared sources CRL 618 and HD 44179 (CRL 915). In addition, 2–4 μm spectrophotometry of CRL 618 is reported. Except for marginal detection of emission lines at 2.1 and 2.45 μm, the spectrum of CRL 618 is featureless, consistent with graphite being the major constituent of the circumstellar dust cloud. Strong emission bands at 6.2 μm and 7.7 μm are found in the spectrum of HD 44179. These bands have been observed previously in NGC 7027 and M82. No positive identification of these bands is made.

While both objects probably represent advanced stages of stellar evolution, the substantial differences between CRL 618 and HD 44179 suggest that they are members of different evolutionary sequences.

Subject headings: infrared: sources — infrared: spectra — stars: individual

THE ASTROPHYSICAL JOURNAL, 223:L93–L95, 1978 July 15
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INFRARED SPECTRA OF HM SAGITTAE AND V1016 CYGNI

R. C. PUETTER, R. W. RUSSELL, B. T. SOIFER, AND S. P. WILLNER
Department of Physics, University of California, San Diego
Received 1978 February 27; accepted 1978 April 21

ABSTRACT

Spectrophotometry of HM Sge from 2 to 13 μm is presented along with 2 to 4 μm spectrophotometry of V1016 Cyg. From 2.5 to 8 μm, the spectrum of HM Sge can be represented by a 950 K blackbody, and a strong silicate emission feature is seen from 8 to 13 μm. Both HM Sge and V1016 Cyg show evidence for CO absorption at 2.3 μm. It is suggested that the infrared radiation from these objects arises from a combination of emission by optically thin dust and by the reddened photosphere of a cool star.

Subject headings: infrared: spectra — stars: circumstellar shells

Ann. Rev. Astron. Astrophys. 1978. 16: 335-69

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INSTRUMENTATION FOR INFRARED ASTRONOMY

*2134

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INTRODUCTION

Over the last 10 years infrared astronomy from 2 μm to 1000 μm has blossomed into a major field of observational astrophysics. This development would have been impossible without two major technical advances. First, extremely sensitive detectors have been developed and become available for astronomical applications. As detector sensitivity increased, the new astrophysical problems that could be explored as a consequence spurred on concomitant instrument sophistication. Secondly, and also motivated by the first development, major groups have expended much effort in building and operating telescopes above most or all of the earth's atmosphere, in order to circumvent its opacity and emission throughout the range. As wavelengths longer than 30 μm became available to observers, it became clear (cf the review article by Neugebauer, Becklin & Hyland 1971) that many sources are unexpectedly bright in that previously inaccessible wavelength region. This also provided impetus to improve the selection of available instrumentation.

Many excellent papers describe specific aspects of infrared instrumentation in substantially more detail than is possible here. We name only a few; for example, Low & Rieke (1974) have given an excellent description of the techniques and equipment development of infrared photometry. Gillett, Dereniak & Joyce (1977) have given a comprehensive review of the current state of infrared detector development. Other detailed discussions of infrared astronomical instrumentation appear in the same volume as Gillett et al. In addition, several conferences have been devoted solely or partly to infrared instrumentation (e.g. Manno & Ring 1971, Rowan-Robinson 1976, Swift, Witteborn & Shipley 1974).

This review is an overview of the variety of the very sensitive instrumentation now or soon to be available to the infrared observer. We make no attempt to be comprehensive, and have, in fact, left out descriptions of the (now) more conventional instruments. Because efforts have been made in contemporary instrument development to minimize the effects of thermal backgrounds on observations, present instruments are generally limited in sensitivity by such fundamental factors as telescope/atmospheric emission and the solid angle of an observation. Of course each instrument has trade-offs as compared with a competing instrument, and we have attempted to provide enough detail (or appropriate references) to make these trade-offs apparent. Because the choice of the observing platform and the detectors plays as important a role as does the choice of instrument, we have preferred to describe each of the above categories under the broad heading of infrared astronomical instrumentation.

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UNIVERSITY OF CALIFORNIA

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An Analysis of Infrared Spectra of Some Gaseous Nebulae, with Emphasis on the Planetary Nebula NGC 7027

A dissertation submitted in partial satisfaction of the requirements for the degree Doctor of Philosophy in Physics

by

Ray William Russell

Committee in charge:

Professor Baruch T. Soifer, Chairman
Professor James R. Arnold
Professor E. Margaret Burbidge
Professor Robert J. Gould
Professor Barnaby J. Rickett

1978

ABSTRACT OF THE DISSERTATION

An Analysis of Infrared Spectra of Some Gaseous Nebulae,

with Emphasis on the Planetary Nebula NGC 7027

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University of California, San Diego, 1978

Professor Baruch T. Soifer, Chairman

Infrared spectra from 2 to 13 μm (with resolution $\Delta\lambda/\lambda \sim 0.015\text{-}0.02$) of a variety of objects (including the planetary nebulae NGC 7027, BD +30°3639, and IC 418; the galaxy M82; and CRL 915/HD 44179) are discussed. The inclusion of 4 to 8 μm spectrophotometry obtained from the Kuiper Airborne Observatory is stressed, although the entire 2 to 13 μm region is shown to be very useful in understanding the physical conditions and radiation mechanisms in these and other sources.

A basic summary of collisionally excited forbidden-line analysis is presented, and the equations and parameters developed to

permit the identification of such lines in the astronomical data and their subsequent use in ion abundance calculations. For both NGC 7027 and BD + 30°3639 evidence is found for enhancement of several products of the α process, indicating substantial nuclear processing and mixing has occurred in the central stars of these planetary nebulae.

A possible identification of [Mg V] at 5.6 μm in the spectrum of NGC 7027 is discussed. Assuming the identification is correct, one can argue not only that magnesium is overabundant, but also calculate a lower limit on the temperature of the central star of $1.3 \cdot 10^5$ K. When the absorption of ultraviolet photons by oxygen ions is considered, this limit is raised to $\sim 2 \cdot 10^5$ K.

The Br γ line in BD + 30°3639 is used in conjunction with existing optical observations to calculate the reddening to the source, which can be expressed as $\sim 1\overset{m}{.}5$ extinction at Hβ. When previous radio observations are also considered, this leads to the suggestion that a very compact (< 0.1"), or equivalently, a very high density ($n_e > 1 \cdot 10^6$ cm^{-3}) radio component exists in the BD + 30°3639 field.

Broad strong emission features at 6.2 μm and 7.7 μm are seen for the first time in the spectrum of NGC 7027. This brings to five the number of such features discovered in the spectrum of NGC 7027 and subsequently found in common in the other spectra discussed here. These features, unidentified at present, are seen at 3.28/3.4 μm, 6.2 μm, 7.7-7.8 μm, 8.6 μm, and 11.3 μm. Various possible emission

mechanisms for producing these features are considered, and that of structure in the emissivity curve of the material(s) emitting thermally at these wavelengths explored in some detail.

In line with that approach to the problem, emissivity measurements on collections of small (2-5 μm), isolated particles have been obtained and are presented for a number of materials either suggested in the literature or considered reasonable candidates based on abundance arguments and characteristic frequencies of vibration of molecular groups found in such materials. Although carbonates, sulfates, and nitrates all have spectral features similar in some respects to the astronomical data, they are sufficiently different that no identification can be made at this time. The 6.2 μm feature may be due to water of hydration in some host material, as an amorphous silicate with water of hydration exhibits a 6.2 μm feature quite similar to that seen in the data for NGC 7027. However, until the host material can also be identified, this must be considered a tentative identification. Other materials whose spectra disagree with the celestial data are discussed.

Some avenues of future research in trying to understand the emission mechanism which produces these features include variations on the method of sample preparation to more closely approximate the astrophysical grain condensation process, consideration of molecular forbidden transitions, emission from organic species associated with the celestial grains, and fluorescence mechanisms.

The ubiquity of the emitting material (evidenced by the presence of the features in the spectrum of the galaxy M82, as well as in the spectra of a large variety of galactic objects) and the importance of the emission mechanism (indicated by the relatively large amount of energy radiated in the features compared to that in the continuum at these wavelengths) point out the crucial nature of this problem.

THE ASTROPHYSICAL JOURNAL, 228:118–122, 1979 February 15

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SPECTROPHOTOMETRY OF COMPACT H II REGIONS FROM 4 TO 8 MICRONS

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ABSTRACT

Spectrophotometric observations from 4 to 8 μm of the compact H II regions W51–IRS 2 and K3-50 are reported. Two broad absorption features at $\sim$6.0 μm and 6.8 μm are observed in the spectra of W51–IRS 2, and the 6.0 μm feature is seen in K3-50. These features may be due to absorption by silicate grains. A more speculative identification is absorption by hydrocarbon molecules. The continuum flux from 2 to 13 μm is broader than emission from a single-temperature blackbody; this suggests a distribution of dust temperatures within the H II regions. Failure to detect hydrogen Pfund α in W51–IRS 2 indicates significant 7.5 μm extinction. Upper limits are placed on the abundance of Ar^+.

Subject headings: infrared: sources — infrared: spectra — nebulae: general

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THE ASTROPHYSICAL JOURNAL, 229:L65–L68, 1979 April 15

THE 4 TO 8 MICRON SPECTRUM OF THE GALACTIC CENTER

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ABSTRACT

Observations of the complex Sgr A W(N) with a 28″ beam and 1.5% spectral resolution are reported. Neither unidentified absorption features at 6.0 and 6.8 μm nor emission features at 6.2 and 7.7 μm were detected. The absence of the absorption features demonstrates that they are not characteristic of general interstellar extinction. The absence of emission features suggests that there is considerable distance between the ionized gas and the molecular clouds. The absence of 6.2 and 7.7 μm emission features also suggests that a feature previously seen at 3.3–3.4 μm is an absorption at 3.4 μm, and this absorption is apparently characteristic of interstellar extinction. The strength of the [Ar II] emission indicates an overabundance of argon. CO absorption seen at 4.67 μm indicates that saturation effects are not large, and there is evidently a large velocity dispersion in the line of sight to the infrared sources.

Subject headings: galaxies: Milky Way — galaxies: nuclei — infrared: spectra

Astrophysics and Space Science 65 (1979) 95–101. 0004-640X/79/0651-0095$01.05

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UNIDENTIFIED INFRARED SPECTRAL FEATURES*

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Abstract. The infrared spectra between 2 and 13 μm of a variety of objects have become available in the past few years. These spectra have shown many objects to have up to six emission features that are still unidentified. Other objects show absorptions due to ice, carbon monoxide, silicates, and two unidentified features. The observational characteristics of the unidentified features are discussed here, together with several possible identifications.

THE ASTROPHYSICAL JOURNAL, 232:L53-L57, 1979 August 15

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THE 4–8 MICRON SPECTRUM OF THE INFRARED SOURCE W33 A

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Received 1979 April 2; accepted 1979 May 15

ABSTRACT

Spectrophotometry with a resolution $\Delta\lambda/\lambda \sim 0.015$ of the highly obscured infrared source W33 A IR from 4.5 μm to 8 μm is reported. Three deep absorption bands, centered at 4.61 μm, 5.99 μm, and 6.78 μm, are observed. The band at 4.61 μm is most likely predominantly due to absorption in the fundamental vibration-rotation band of CO, although the wavelength of maximum absorption occurs slightly shortward of that expected for gaseous CO and could be affected by other absorbers. If no other absorber contributes to this band, then the minimum column density is 10% of the expected column density of carbon inferred from observed strength of the silicate absorption at 10 μm.

The absorption bands at 5.99 μm and 6.78 μm are extremely strong. Absorption processes in grains are needed to produce these bands, due to the large half-widths and equivalent widths of the absorptions. Observations of these bands in molecular cloud material, but not in the line of sight to the galactic center, strongly suggest that the formation process for these bands occurs within the molecular clouds. Arguments based on absorption strengths of these and the 10 μm silicate absorption require the 6.0 μm and 6.8 μm bands be caused by materials formed from cosmically abundant elements. The preponderance of available evidence suggests that these absorptions are due to hydrocarbon materials associated with interstellar dust. If this is the case, a substantial fraction of the carbon in the line of sight to W33 A IR is in the form of hydrocarbons.

Subject headings: infrared: sources — interstellar: matter

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THE ASTROPHYSICAL JOURNAL, 234:496–502, 1979 December 1

INFRARED SPECTRA OF IC 418 AND NGC 6572

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Received 1978 October 13; accepted 1979 May 21

ABSTRACT

Spectrophotometric observations from 2 to 4 and 8 to 13 μm of NGC 6572 and from 4 to 13 μm of IC 418 are reported. Also reported are observations of the size of IC 418 in the optical and at 1.65 and 2.2 μm. Both planetary nebulae emit more radiation than expected from recombination at wavelengths longer than ~4 μm; this radiation is attributed to heated dust. The spectra show a plateau from 10.5 to 13 μm, and this peak is tentatively attributed to emission from large silicon carbide particles. Fine-structure emission lines are also discussed; the presence of [Ar III] but not [Ne II] in NGC 6572 suggests that ions having the same ionization potential can nevertheless have different fractional abundances.

Subject headings: infrared: spectra — nebulae: planetary

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B. H. Andrew (ed.), Interstellar Molecules, 381–386.

INFRARED MOLECULAR ABSORPTION FEATURES

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Spectra of infrared sources associated with molecular clouds have shown absorption features at wavelengths of 6.0 and 6.8 μm. We suggest that the 6.0 μm feature can be identified with the stretching vibration of C=O and the 6.8 μm feature with the bending vibrations of CH_2 and CH_3. The amount of carbon in the form of hydrocarbon molecules may be comparable to the amount in CO. This abundance of hydrocarbons is probably too large to be consistent with radio observations if the molecules are gaseous, but large abundances of hydrocarbons on the surfaces of grains may explain the infrared features, yet be unobservable in the radio.

THE ASTROPHYSICAL JOURNAL, 235:104–113, 1980 January 1

THE INFRARED SPECTRUM OF THE CARBON STAR Y CANUM VENATICORUM BETWEEN 1.2 AND 30 MICRONS

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Received 1979 February 20; accepted 1979 July 19

ABSTRACT

The infrared spectrum of Y CVn (N3; C4, 5; SR*b* variable) is presented with essentially complete wavelength coverage from 1.2 to 30 μm and mostly at a resolution $\Delta\lambda/\lambda$ of 0.02. The previous identification of C_3 at 5.2 μm by Goebel *et al.* is confirmed. There is no clear evidence for the SiC_2 ν_3 fundamental absorption band at 5.7 μm; but the 11.5 μm SiC particulate emission band is seen. The 11.5 μm band shape is consistent with the laboratory measurements of crystalline SiC made by Dorschner *et al.* Thus both C_3 in the stellar photosphere and circumstellar SiC contribute to the violet opacity in Y CVn, although C_3 is dominant. The power radiated in the circumstellar SiC band is shown to be inadequate to account for the violet opacity in Y CVn, a result which supports the conclusion of Bregman and Bregman. A 7.5 μm absorption band is observed for the first time and attributed to a mixture of HCN and C_2H_2. Opacity between 2.4 and 2.7 μm is observed for the first time and is consistent with the $\Delta v = -1$ C_2 band. The molecules present in the infrared spectrum—CO, CN, C_2, C_3, HCN, and C_2H_2—are generally in agreement with the models of Tsuji, Scalo, Johnson, Beebe, and Sneden, and Querci and Querci. A possible emission feature is observed at 22.5 μm. Its significance and possible origin are discussed. The 1.6 μm H^- opacity minimum is seen, a requirement for detection of the photosphere. With the exception of the 11.5 μm SiC band and the emission feature at 22.5 μm, the photosphere is dominant over circumstellar emission out to 30 μm. This result should limit the amount of carbon-rich material (graphite) which early N type carbon stars similar to Y CVn could be capable of injecting into the interstellar medium.

Subject headings: infrared: spectra — line identifications — stars: carbon — stars: individual

THE ASTROPHYSICAL JOURNAL, 244: 511–516, 1981 March 1

MEASUREMENTS OF FORBIDDEN LINE RADIATION OF Ar II (6.99 μm) IN W3 IRS 1

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Received 1980 June 23; accepted 1980 September 10

ABSTRACT

Observations of the [Ar II] (6.99 μm) line flux in W3 IRS 1 are combined with previously obtained measurements of the [Ar III] (8.99 μm) line flux. The observed ratio of [Ar II]/[Ar III] is inconsistent with the calculated ratio for an H II region with the densities required by radio observations and with a central 40,000–45,000 K star with atmosphere as described by a Mihalas model. A softer effective UV radiation field is required; a dusty model we had previously invoked fits the observations. In addition we determine that the argon abundance is $n(\mathrm{Ar})/n(\mathrm{H}) \approx 8 \times 10^{-6}$, a value about twice that usually adopted for normal solar abundance; however, there are uncertainties in the extinction and the models which do not allow us to preclude solar abundance.

Subject headings: infrared: spectra — nebulae: abundances — nebulae: individual

ICARUS 45, 653–660 (1981)

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Observations of Saturn in the 5- to 8-μm Spectral Region

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Received August 18, 1980; revised January 29, 1981

A spectrum of Saturn obtained from the Kuiper Airborne Observatory exhibits an emission peak at 6.8 μm attributed to ethane, but is otherwise dominated by absorption from 5.3 to 7.2 μm. While the large absorption in this spectral region is consistent with the presence of ammonia gas or ammonia ice, or both, such an explanation is inconsistent with the lack of a major absorption near 3.0 μm.

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THE ASTROPHYSICAL JOURNAL, 246:455–463, 1981 June 1

IDENTIFICATION OF NEW INFRARED BANDS IN A CARBON-RICH MIRA VARIABLE

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Received 1980 May 5; accepted 1980 December 5

ABSTRACT

For the first time, we present complete 0.75–13 μm spectrometry of a carbon-rich, Mira-class variable star. Although the near-infrared is dominated by photospheric absorption bands of the CN red system, the infrared becomes progressively dominated by the bands of the polyatomic molecules HCN and C_2H_2. Since the band at 3.1 μm is known to be due to HCN and C_2H_2, we are able to associate bands at 1.04, 1.53, 1.85, 2.5, 2.7, 3.56, 3.85, 4.8, and 7.1 μm with HCN and C_2H_2. The spectrum indicates that radiative transfer in the carbon Mira class cannot be discussed quantitatively without the inclusion of HCN and C_2H_2 opacity. From a consideration of the carbon star models of Querci and Querci, it is deduced that the abundance ratio of HCN to C_2H_2, $A(\mathrm{HCN})/A(C_2H_2)$, can be used to indicate whether 3α-processed or CNO-processed material is in the outer atmosphere. $A(\mathrm{HCN})/A(C_2H_2) \gg 1 \Rightarrow$ CNO; $A(\mathrm{HCN})/A(C_2H_2) \leq 1 \Rightarrow 3\alpha$. An 11.3 μm SiC dust-emission feature is present, although it is significantly different from the 11.7 μm SiC feature in Y CVn. A featureless emission is present from 4 to 13 μm and can be ascribed to optically thin graphite grains with a temperature of 450 K.

Subject headings: infrared: spectra — line identification — molecular processes — stars: abundances — stars: carbon — stars: long-period variables

THE ASTROPHYSICAL JOURNAL, 250:186-199, 1981 November 1

ABUNDANCES OF ARGON, SULFUR, AND NEON IN SIX GALACTIC H II REGIONS FROM INFRARED FORBIDDEN LINES

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Received 1980 December 12; accepted 1981 May 7

ABSTRACT

Airborne measurements of the [Ar II] (6.99 μm) and [S III] (18.71 μm) lines for six compact H II regions are presented, as well as ground-based 2–4 μm and 8–13 μm spectroscopy if not already published. From these data and radio data, we deduce lower limits to the elemental abundances of Ar, Ne, and S. G29.9−0.0 at 5 kpc from the galactic center is overabundant in all these elements. The other five regions (at distances 6–13 kpc from the center) mainly appear to be consistent with standard abundances, with the exception of G75.84+0.4 at 10 kpc from the galactic center, which is overabundant in S. However, our preliminary results on G12.8−0.2 at 6 kpc from the galactic center suggest a possible underabundance. We feel that a large statistical sample of H II regions is required in order to determine if there is a radial gradient in the heavy element abundances in our Galaxy.

Subject headings: infrared: spectra — nebulae: abundances — nebulae: H II regions

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THE ASTROPHYSICAL JOURNAL, 250:631-635, 1981 November 15

4–8 MICRON SPECTROPHOTOMETRY OF OH 0739−14

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Received 1981 April 2; accepted 1981 May 19

ABSTRACT

Spectrophotometry of the dust-embedded late-type star OH 0739−14 shows an absorption feature at 6.0 μm characteristic of H_2O ice at temperatures significantly lower than 150 K, confirming the identification of H_2O ice in the circumstellar shell in this source. The differences in the infrared spectra of OH 0739−14 and embedded molecular cloud sources are attributed to the different cloud lifetimes and temperature regimes in which the molecules are formed. A lower limit to the mass loss rate of $10^{-4}\ M_\odot/\mathrm{yr}^{-1}$ is derived, based on the column density of ice and the size and the expansion velocity of the circumstellar cloud.

Subject headings: infrared: sources — infrared: spectra — masers — stars: individual

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THE ASTROPHYSICAL JOURNAL, 253:174–187, 1982 February 1

INFRARED SPECTRA OF PROTOSTARS: COMPOSITION OF THE DUST SHELLS

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Received 1981 July 17; accepted 1981 August 10

ABSTRACT

Nearly complete 2 to 13 μm spectra are presented for 13 compact infrared sources associated with molecular clouds, as well as partial spectra of six additional objects. The spectra resemble blackbodies with superposed absorption features from 2.8 to 3.5 μm, at 6.0 and 6.8 μm, and in the silicate band centered near 9.7 μm. Correlations among the features are studied in an attempt to confirm possible identifications. A good correlation between the deepest part of the absorption at 3.1 μm, its long wavelength wing, and the 6.0 μm features suggests that all may be due to large amorphous water ice particles. The relatively poor correlation between the 3.4 and 6.8 μm optical depths adds no evidence to support the suggestion that these bands may be due to CH bonds.

Subject headings: infrared: spectra — interstellar: matter — molecular processes — stars: pre-main-sequence

THE ASTROPHYSICAL JOURNAL, 260:141–146, 1982 September 1

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OBSERVATION OF INTERSTELLAR AMMONIA ICE

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Received 1981 December 14; accepted 1982 March 15

ABSTRACT

An absorption band probably due to solid ammonia on interstellar grains has been detected in the infrared spectrum at 2.97 μm of the Becklin-Neugebauer object and probably in NGC 2264-IR. An ammonia-water amorphous ice mixture can explain the structure of the new band and of the 3.07 μm interstellar absorption. Laboratory data suggest that a long wavelength wing extending to 3.5 μm in interstellar dust spectra may be absorption by $NH_3 \cdot H_2O$ complexes in the ices. In the molecular cloud obscuring the BN object, about 20 times as much NH_3 is frozen in grains as exists in the gas phase, suggesting that gas-grain interactions may be important in the ammonia chemistry of molecular clouds. Arguments are given that interstellar features at 6.0 and 6.8 μm are also ammonia-related absorptions.

Subject headings: infrared: spectra — interstellar: matter — interstellar: molecules — line identification — nebulae: Orion Nebula

THE ASTROPHYSICAL JOURNAL, 262:153-163, 1982 November 1

ABUNDANCES IN FIVE NEARBY GALACTIC H II REGIONS FROM INFRARED FORBIDDEN LINES

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Received 1982 March 1; accepted 1982 May 3

ABSTRACT

Airborne measurements of the [Ar II] (6.99 μm) and [S III] (18.71 μm) lines for five compact H II regions in the solar neighborhood are presented, as well as 2–4 μm and 8–13 μm spectroscopy where available. From these data and radio data we deduce lower limits to the elemental abundances of Ar, Ne, and S. Some of these H II regions suffer substantial nebular extinction, and some are extended. After correcting for beam size effects and extinction, we find that four of the objects are consistent with standard abundances, within the uncertainties of correcting for unobserved ionization states. A Perseus arm object, S156, is apparently overabundant in sulfur.

Subject headings: infrared: spectra — nebulae: abundances — nebulae: H II regions

ABUNDANCES IN GALACTIC HII REGIONS, III: G25.4-0.2, G45.5+0.06, M8, S159 and DR22

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Received 1983 August 8;

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ABSTRACT

Measurements of the [ArII](6.99μm), [ArIII](8.99μm), [NeII](12.81μm), [SIII](18.71μm), and [SIV](10.51μm) lines are presented for five compact HII regions along with continuum spectroscopy. From these data and radio data we deduce lower limits to the elemental abundances of Ar, S, and Ne. G25.4-0.2 is only 5.5 kpc from the galactic center, and is considerably overabundant in all these elements. G45.5+0.06 is at 7 kpc from the galactic center, and appears to be approximately consistent with solar abundance. S159 in the Perseus Arm, at 12 kpc from the galactic center, has solar abundance, while M8 in the solar neighorhood may be somewhat overabundant in Ar and Ne. DR22, at 10 kpc from the galactic center in the Cygnus arm, is overabundant in Ar. A summary of results from our series of papers to date on abundances is given.