FINAL REPORT

covering the period June 1965 - August 1974

NASA GRANT NGL 14-001-060

entitled

SPECTROPHOTOMETRY OF COMETS *

to

The University of Chicago

5801 Ellis Avenue

Chicago, Illinois 60637

Original Principal Investigator:

Dr. C. R. O'Dell

Principal Investigator at the time of termination:

Dr. Thomas F. Adams

* NASA Technical Officer for this grant is Maurice Dubin, NASA Headquarters.

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Nine years ago (March 1965), the proposal was submitted that led to this grant, which was extended through additional funds and no cost extensions to the present. The goals of the program were rather broad, as suited an area where little quantitative observation had been made. The original abstract reads:

> "It is proposed that the National Aeronautics Space Administration financially support in part a systematic program of photoelectric spectrophotometry of comet tails and nuclei. Such a study should enable us to greatly increase our knowledge of the nature of the solid particles and origin of the gases and to re-evaluate the theories of formation and decay. A major feature of this grant will be the construction of a high performance telescope-photoelectric spectrophotometer system capable of measuring the faint comets. It is shown that the design presented is optimum for such studies and should enable a new degree of understanding to be derived for the conditions in comets. Applications of this instrument to problems in the detection of faint lines in stellar spectra and nature of the interstellar medium are also described."

Examining these original goals and comparing them with the achievements during that time, as evidenced by published research papers, one can justifiably claim success for this grant.

This final report will first give a chronological account of the activities, list the papers that resulted, give their abstracts, and finally summarize what were the achievements of this activity.

The intent was to provide accurate quantitative data on the flux distribution in cometary spectra. To this end, at the beginning of the grant (June 1965) all effort was concentrated on construction of a unique research tool, the Photoelectric Nebular Spectrometer (PNS). Initially working alone, the original principal investigator was joined by Dr. Pavel Mayer of Charles University in Prague. Together the system was completed and the first successful comet observations were made in December, 1966, of Comet Rudnicki - 1966e(1). More extensive observations were then made by Mayer's successor, Wm. L. Gebel, of Comets 1967n, 1968b, and 1968c(2). Bright comets appear sporadically and have no regard for the scheduling needs of manpower or weather. Therefore, the success in observing came in spurts. Some unrelated scientific programs were conducted between apparitions. The most successful of these was conducted by Robert Brucato (3) who used the PNS for obtaining highly accurate line profiles of hot stars, a subject that later became his Ph.D. thesis topic.

By the end of 1969 it was felt that PNS had identified and established the principal problems that it could address. Although continued observations were worthwhile and attempted, it was felt that the main effort should evolve to the use of higher spectral resolution and extending the wavelength range. Therefore, by the winter of 1969-70, when two bright comets appeared, our efforts were concentrated in these areas. Comet Tago-Sato-Kosaka - 1969g was observed with an image tube equipped spectrograph on the Yerkes Observatory 41-inch reflector (4). This comet and Comet Bennett 1969i were both observed (with only upper limits) in the far infra-red from a Lear Jet research aircraft operated by the Ames Research Center — through the cooperation of Dr. Frank J. Low (5). This infra-red work was then brought together with the results of other studies for interpretation (6). Spectrographic observations of Comet 1969i were also made for determination of the scattered light characteristics (7). The results of these Comet 1969i programs were then subjected to a discussion in terms of particle size and composition (8).

The results of these investigations, both the molecular studies and those of the particles, were brought together in a new model for the cometary nucleus (9). Tied closely to this quantitative data, it produced a model physically similar to the now classic icy-conglomerate; but, with a very different origin.

In September, 1973, Dr. Thomas F. Adams assumed the role of principal investigator and a no-cost extension was granted to facilitate observations of Comet Kohoutek 1973f. Spectra of this comet were taken at Yerkes on eleven nights in January and February, 1974. The spectra generally covered the range 4700 - 8400Å at a dispersion of 180Å mm^{-1}. The first usable spectrogram was taken on January 15 UT. It shows marginal evidence for the H_2O^+ bands reported by other observers, although it is somewhat underexposed. The H_2O^+ bands are not readily apparent on later spectra, consistent with the reported rapid drop in the strength of these bands with increasing heliocentric distance. Because of the fainter than expected scattered light continuum in this comet and certain mechanical difficulties with the observing equipment, it was not possible to derive useful spectrophotometric data from these plates.

Publications Resulting From This Grant

1. Title: Emission-Band Ratios in Comet Rudnicki (1966e)

   Author: P. Mayer and C. R. O'Dell

   Reference: Ap. J., 153, 951-962, 1968.

   Abstract:

"A photoelectric spectrophotometric investigation of Comet Rudnicki (1966e) is described, with attention given to the specialized instrument developed for this program. Total band-sequence fluxes are determined for three sequences of C_2, two sequences of CN, and the λ4050 features of C_3. Although the vibrational Boltzmann temperature describing the relative population of the lower state of C_2 should be close to the color temperature of the Sun if depopulating transitions do not exist, these observations indicate a temperature of about 4000°K. The source of this discrepancy remains enigmatic after examination of the processes of spontaneous emission and collisional de-excitation, although the latter processes are very unlikely. It is inferred from these observations that depopulating transitions of some type do occur. The λ4050 feature is seen to vary more slowly in brightness than either the C_2 or CN emission, and the total absolute brightness of the comet is lower than that of previously investigated objects."

2. Title: Spectrophotometry of Comets 1967n, 1968b, and 1968c

   Author: William L. Gebel

   Reference: Ap. J., 161, 765-777, 1970.

   Abstract:

"Photoelectric spectrum scans of comets Ikeya-Seki (1967n), Thomas (1968b), and Honda (1968c) covering the range 3500 - 6300Å are presented. A previously reported intensity anomaly in the C_2 Swan Bands is shown to be independent of heliocentric distance, which thereby rules out depopulation by forbidden

magnetic-dipole vibrational transitions as an explanation of the anomaly. For future study of this problem, mean profiles of the principal band sequences have been determined. All of the comets exhibited a moderately strong continuum. The reflected or scattered light is found to be gray, in contrast to the reddening previously reported for dust tails."

3. Title: Hydrogen Line Profiles in Early-Type Stars

Author: R. J. Brucato

Reference: Pub. A.S.P., 80, 263-268, 1968.

Abstract:

"The line profiles of Hβ were photoelectrically measured for α Leo, η UMa, γ_oPeg, α Del, and δ Cas at a resolution of 0.5A. These observed profiles were then compared with profiles predicted by model-atmosphere calculations for rotating and nonrotating early-type stars."

4. Title: Spectrophotometry of Comet 1969g (Tago-Sato-Kosaka)

Author: C. R. O'Dell

Reference: Ap. J., 164, 511-519, 1971.

Abstract:

"The spectrum of Comet 1969g (Tago-Sato-Kosaka) was studied over the wavelength interval 3800 - 8500A. Composite spectra were formed, and the results are shown as relative absolute energy-distribution plots. Earlier (photoelectric data) conclusions of a disagreement of theory and observations of Swan Band intensities are confirmed, and it is suggested to be due to noninclusion of the Ballik-Ramsay bands in the calculations. The Phillips bands are seen in emission and enable a C_2 singlet/triplet population ratio to be derived. Both the red and the violet CN band sequences are observed and quantitatively compared with theory. NH_2 is quite strong and dominates the red spectral

region. An upper limit to the Hα surface brightness is consistent with the OAO observations and Biermann's chromospheric resonance fluorescence model, but does not allow discrimination between detailed models. A tentative identification of the λ5015 line of He I is made, possibly produced by the Biermann mechanism."

5. Title: Infrared Observations of Comets 1969g and 1969i

Author: D. E. Kleinmann, T. Lee, F. J. Low, and C. R. O'Dell

Reference: Ap. J., 165, 633-636, 1971.

Abstract:

"Ground-based and airborne infrared observations have been made over the wavelength range 1.25 - 70μ of Comets Tago-Sato-Kosaka (1969b) and Bennett (1969i). The flux distributions in wavelength and across the coma and tail at fixed wavelengths were determined. The observations are similar to previous work in that they show color temperatures higher than those of a blackbody. An outburst of infrared luminosity was seen in Comet Tago-Sato-Kosaka."

6. Title: Nature of Particulate Matter in Comets as Determined from Infrared Observations

Author: C. R. O'Dell

Reference: Ap. J., 166, 675-681, 1971.

Abstract:

"Infrared and optical wavelength photometry are combined to determine the albedo (0.3 ± 0.15) of particles in three bright comets. The infrared data also indicate that the 10-μ absorptivity is only about one-fourth that in optical wavelengths. Surface-brightness distributions give particle radii of about 0.1μ. The resulting particle models are similar in these aspects to the interstellar particles."

7. Title: The Scattered-Light Continuum of Comet Bennett 1969i

Author: Gerald M. Stokes

Reference: Ap. J., 177, 829-834, 1972.

Abstract:

"The scattered-light continuum of Comet Bennett has been observed in the region between 4500 and 8000Å. This continuum is found to be distinctly redder than sunlight, and analysis leads to a lower limit on mean particle size of 0.1μ. The contribution to the reddening due to the C_2 Phillips bands and blackbody thermal radiation is considered and found to be negligible."

8. Title: Particle Sizes in Comet Bennett (1970 II)

Author: C. R. O'Dell

Reference: Icarus, 21, 96-99, 1974

Abstract:

"The particle size distribution in the coma and tail of Comet Bennett has been determined by several methods, each sensitive to a particular size range. It is confirmed that a minimum value of the particle density (ρ), size (d), and radiation pressure efficiency (Q_{rp}) function ($\rho d/Q_{rp}$) exists at about 3 - $10 \times 10^{-5} g cm^{-2}$. The existence of such a cutoff is probably due to the decreasing radiation pressure efficiency for particles smaller than the wavelength of the light being scattered. An exact determination of this cutoff may allow identification of the particle type."

9. Title: A New Model for Cometary Nuclei

Author: C. R. O'Dell

Reference: Icarus, 19, 137-146, 1973.

Abstract:

"A new model for the nucleus of comets is presented, hypothesizing formation at large heliocentric distances from many independent solid bodies. It is shown that such a configuration would collapse to a single assemblage if it is to survive into the inner solar system. Prior to collapse, the bodies would be subject to coating by interstellar gas and particles, which would form the material lost into the coma at subsequent inner solar system perihelia. Quantitative estimates place an upper limit to the body sizes of 2.3m and a lower limit of the number as $3x10^{10}$ with sizes of a few tenths of a micron and numbers of 10^{33} most probable. The major structural and evolutionary features of such comet nuclei are consistent with the Whipple icy-conglomerate model."

Achievements of this Research Activity

The principal achievement of papers 1, 3, and 4 is to provide absolute flux distributions of the principal spectral features for five comets of different composition and heliocentric distance. The interpretation was centered about diatomic carbon (C_2). From study of the Swan Bands it was concluded that previous studies of the population distribution were incorrect. The breadth of the observational material allowed the search for the source of the discrepancy to be narrowed down to a radiative mechanism. It was then shown that the presence of the infra-red Ballik-Ramsey bands could account for the problem. The detection of the Phillips bands was an important first for it allows one to do diagnostics of both the singlet and triplet sequences. The greatest long-range impact lies in the fact that C_2 is the best molecule for determination of isotopic ratios — a powerful diagnostic tool for comet cosmogony. We believe that this work has significantly altered and improved our understanding of this, the most visible, molecule in comets.

The study of particles has not only provided basic observations but has developed fundamental diagnostic tools. It was shown that the particles have a characteristic elevation above black-bodies under the same illumination, thereby establishing their low infra-red emissivities. Comparison of visible (scattered light) and infra-red (thermal emission) brightnesses can allow calculation of the optical albedoes of the particles — an important first. This technique has now been adopted and applied to several other comets. A final major contribution was to show that in Comet Bennett - 1969i, there was a minimum value of $\rho d/Q_{rp} \simeq 3\text{-}10 \times 10^{-5} gcm^{-2}$ ($\rho \equiv$ density, $d \equiv$ diameter, $Q_{rp} \equiv$ radiation pressure scattering efficiency). This means that either there is a minimum particle size in that comet or (more likely) that the effects of diminishing Q_{rp} at small sizes causes $\rho d/Q_{rp}$ to be constant, causing an apparent cut-off. The point at which this cut-off occurs is different for various particle types and this can be used for diagnostics. Of the presently evaluated particles, only small iron and graphite spheres match the observations.