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STUDIES OF RADIATIVE TRANSFER IN PLANETARY ATMOSPHERES

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Current Research

Irvine and Schloerb organized what is to our knowledge the first ever Workshop on Cometary Radio Astronomy, which was hosted by the National Radio Astronomy Observatory at Green Bank, West Virginia, on September 24-26. Virtually all the types of radio science studies by which Comet Halley was investigated were indeed represented at the Workshop, which included scientists from Germany, Brazil, France, Argentina, South Africa, Canada, and Sweden, as well as the USA. The papers presented will be published by NRAO, and this publication should be a very valuable resource for future cometary studies. One day was set aside for informal discussions and intercomparison of data obtained as part of the International Halley Watch. These discussions resulted in a new agreed-upon Radio Model, (1986a), for the interpretation of observations of the OH radical in cometary comae.

Schloerb and Claussen continued their analysis of the very high quality data set obtained on the 18 centimeter OH line from Comet P/Halley with the

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NRAO 43 meter antenna. The new Radio Model 1986a (see previous paragraph) has been adopted, as well as the formalism of Schloerb and Gerard (AJ 90, 1117, 1985) and the inversion curve of Schleicher (Ph.D. dissertation, University of Maryland, 1983). The OH parent production rate so derived as a function of heliocentric distance removes some of the traditional discrepancy between the radio and ultraviolet production rates, but there is still approximately a factor of two difference between the radio and UV data for Halley, although the general behavior is in reasonable agreement. Possible reasons for the difference are being investigated. Moreover, the present radio data do not appear to show the strong pre- and post-perihelion asymmetry in production rates found in the UV and by other observers. The radio data are well fit by an inverse square law for the range in heliocentric distance $0.6<r_h<2.1$ AU. The OH production rate is well correlated with the total visual magnitude of the Comet, and the slope of this correlation suggests that the visual magnitude is proportional to the OH-parent production rate, $Q_p^2(OH)$, which would be the case if C_2 emission dominates the visual pass band (N. Devine, *et al.*, *Space Science Reviews*, 1986, in press).

The high spectral resolution (0.22 km/sec) and high signal-to-noise of the OH spectra make them ideal for the study of kinematics in the coma. In general, the lines are well fit by a Gaussian profile. The line full width at half maximum increases significantly with decreasing heliocentric distance. In addition, the OH data show an asymmetry in the linewidth between pre-perihelion and post-perihelion at the same heliocentric distance, with the post-perihelion width being about 40% greater. The mean OH velocity has been determined by correcting for the Greenstein effect, with the result that the observed mean velocity is generally blueshifted by about 0.2 km/sec from the predicted nuclear velocity, consistent with anisotropic outgassing predominately from the sunward side of the nucleus.

In order to fully interpret the OH line profiles, graduate student L. Tacconi-Garman has begun to construct synthetic profiles for comparison with the data. A vectorial model has been developed using the Monte Carlo techniques originated by Combi and Delsemme. The model can easily include the OH Greenstein effect, anisotropic outgassing, and the effects of beam resolution of the coma by the antenna. Initial results are consistent with a significant increase in parent outflow velocities when the comet is nearer the sun, consistent with the direct observations of HCN (see below). The Greenstein effect is clearly present in the data.

Schloerb, Irvine and graduate students D. Swade and W. Kinzel continued analysis of the millimeter wavelength observations of HCN emission from P/Halley obtained throughout much of the recent apparition, using the University of Massachusetts 14 m millimeter-wavelength (FCRAO) antenna. These data represent the first time that a cometary parent molecule has been so extensively monitored. The HCN production rate is well correlated with the total visual magnitude of the comet, indicating that HCN follows the overall gas and dust production. A detailed comparison with the rate of water production as determined by the Vega and Giotto spacecraft shows that at the time of the encounter the HCN production rate was approximately 10^{-3} that of the total gas production, so that HCN is only a minor constituent of the cometary nucleus. Since HCN is a probable parent of the CN radical, it is of interest to compare its production rate with that of CN. During the Spacecraft encounters the IHW photometery net reported that the CN production rate was $2x10^{27}$/sec, which exceeds our HCN production rate at the same time by a factor of 2. Taken at face value, the results seem to indicate that HCN cannot be the only parent of CN. However, since both the CN and HCN production rates vary by factors of 2 to 3 from day to day in this time interval, and since both productions rates are model dependent, it seems prudent to defer final judgement on this question until additional data is available and a more detailed analysis can be carried out.

The evidence for time variability in the HCN production is illustrated in Figure 1. Gaussian lineshapes have been fit to all three hyperfine components of the J=1-0 transition, in the nominal 5:3:1 ratio of statistical weights. This procedure improves the signal-to-noise ratio by about a factor of two over that discussed in our previous semi-annual report. Some striking day-to-day variations are apparent, for example during the few days around perihelion. As more data becomes available on optical outbursts, it will be extremely interesting to investigate the detailed correlation between the HCN results and such information from other wavelength intervals. In addition, we find evidence for time variations in the ratios of the hyperfine lines. For a sample period in mid-March, a Chi-square test of the data shows less than a one percent chance that such variations are due solely to statistical errors. Since existing theories for the excitation of HCN predict the lines always to be in the LTE ratio of 5:3:1, this interesting phenomenon deserves further study.

A detailed analysis of the HCN lineshapes has been carried out over the last six months. Contrary to our initial impression, it appears that the linewidth, and hence the outflow velocity from the nucleus, varies consistently with heliocentric distance, approximately as the inverse 1/2 power. This agrees with earlier results deduced from observations of the CN radical. However, the magnitude of the outflow velocity is approximately 50% greater then that derived from CN in previous comets. Note that the HCN results provide a direct measurement of the outflow velocity of parent molecules in the coma. Curiously, the HCN velocities derived for P/Halley are larger than the CN velocities derived in previous comets. Since the velocity spread for a

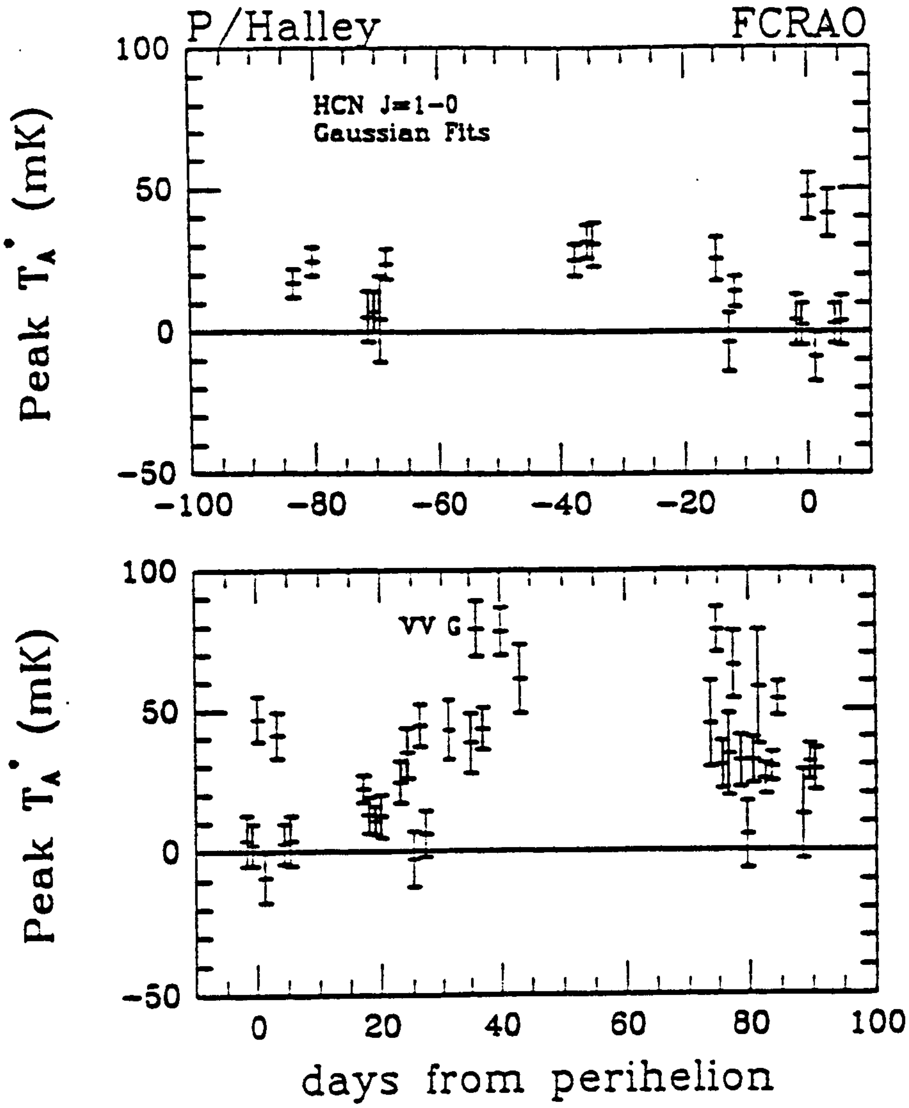

Figure 1 - The results of gaussian fits to the spectra obtained on individual days. There is evidence of significant time variability which is probably related to activity of the comet.

daughter molecule should be greater than that for its parent, this suggests a kinematic problem with HCN as the sole parent for CN. The results could be reconciled if substantial amounts of CN were produced directly from dust in the coma, which travels with somewhat lower velocities than the gas. Such a deduction will be consistent with the suggestions that CHON particles may be an important source of the CN radical, at least in Comet Halley (A'Hearn et al., Symposium on the Exploration of Halley's Comet, Heidelberg, October, 1986).

Graduate student W. Ge has been studying the excitation of HCN in the coma to try to obtain a detailed match to the observed spectra. Given the time variability of the HCN emission, the model is being developed to include time dependence. As a result, the shape of the HCN line should evolve during an outburst from the nucleus, and there is evidence in the spectra to support such a picture. The excitation calculations will explicitly include the hyperfine levels, in an effort to investigate possible sources of hyperfine anomalies.

D. Swade is continuing his studies of the relatively nearby, cold, dark interstellar cloud L134N, which is a possible formation site for solar type stars. He has developed statistical equilibrium models of the excitation for the many molecular transitions observed, and is applying these results to determine temperature, density, and chemical abundances in the core region of the cloud. A comparison will be made to the observed chemical composition of comets, and to models of the solar nebula.

Schloerb has been studing the use of passive millimeter wave radiometers to probe the physical and chemical nature of comets from spacecraft. Millimeter waves have the advantage for the exploration of the cometary nucleus that they penetrate the surface and provide constraints on subsurface physical proper-ies. Millimeter wavelength spectroscopy with heterodyne systems allows very high spectral resolution, for example of the 1(1,0)-1(0,1) line of water vapor, which may be used to measure directly the outflow velocity of gas in the coma, the gas kinetic temperature, and (beyond 1,000 kilometers from the nucleus) the gas density.

Irvine and K. Lumme (University of Helsinki) continue to work on an improved theory of radiative transfer for rough and porous surfaces, such as the regoliths of satellites, asteroids, and comets. The surface is defined by a multivariate normal distribution function. For a medium which is solid (as opposed to particulate), the formulation of the problem leads to two simultaneous integro-differential equations with specified boundary conditions. Explicit results are obtained for the case when the reflection/refraction coefficient of a surface element can be given by a linear combination of diffuse and specular reflection.

During the period of this report Irvine, Schloerb, Swade, and Tacconi-Garman attended the Workshop on Cometary Radio Astronomy in Green Bank, West Virginia, in September; Irvine and Schloerb attended the Symposium on Cometary Exploration in Heidelberg in October; and Irvine, Schloerb, and Swade attended the annual meeting of the Division for Planetary Sciences of the American Astronomical Society in Paris. Four papers describing research supported by this grant were presented in Green Bank, two in Heidelberg, and three in Paris.

Articles with grant support published during the period of this report:

1) Schloerb, F.P., Kinzel, W.M., Swade, D.A., and Irvine, W.M., "HCN Production from Comet Halley", Astrophys. J. (Letters), 310, L55.

2) Lumme, K. and Irvine, W.M., "Radiative Transfer in a Medium with a Statistically Rough Boundary. I. Scattering of Light by a Homogeneous Solid Medium", Bull. Amer. Astron. Soc. 18, 801 (1986).

3) Irvine, W.M., Swade, D.A., Schloerb, F.P., and Kinzel, W.M., "Time Variable HCN Emission and the Expansion Velocity of Parent Molecules in the Coma of Comet P/Halley", Bull Amer. Astron. Soc. 18, 805 (1986).

4) Swade, D.A., Schloerb, F.P., Kinzel, W.M., and Irvine, W.M., "HCN Production and a Search for Other Parent Molecules in the Coma of Comet P.Halley", Bull Amer. Astron. Soc. 18, 805 (1986).

5) Schloerb, F.P., Claussen, M.J., and Tacconi-Garman, L., "Radio OH Observations of Comet P/Halley", Bull Amer. Astron. Soc. 18, 812 (1986).

6) Schloerb, F.P., Kinzel, W.M., Swade, D.A., and Irvine, W.M., "HCN Production from Comet Halley", in Exploration of Halley's Comet, ESA SP-250, 244.

7) Schloerb, F.P., Claussen, M.J., and Tacconi-Garman, L., "OH Radio Observations of Comet Halley", in Exploration of Halley's Comet, ESA SP-250, 245.

Articles with grant support currently in press:

1) Schloerb, F.P., Kinzel, W.M., Swade, D.A., and Irvine, W.M., "Observations of HCN in Comet Halley", Workshop on Cometary Radio Astronomy, ed. Irvine, W.M., Schloerb, F.P., and Tacconi-Garman, L. (NRAO, Green Bank, West Virginia), in press.

2) Swade, D.A., Schloerb, F.P., Kinzel, W.M., and Irvine, W.M., "Search for Parent Molecules in Comet Halley at Millimeter Wavelength", Workshop on Cometary Radio Astronomy, ed. Irvine, W.M., Schloerb, F.P., and Tacconi-Garman, L. (NRAO, Green Bank, West Virginia), in press.

3) Claussen, M. and Schloerb, F.P., "Radio OH Observations of P/Halley with the NRAO 43-m Telescope", Workshop on Cometary Radio Astronomy, ed. Irvine, W.M., Schloerb, F.P., and Tacconi-Garman, L. (NRAO Green Bank, West Virginia), in press.

4) Tacconi-Garman, L. and Schloerb, F.P., "Models of the OH 18-cm Line Profiles of Comet Halley", Workshop on Cometary Radio Astronomy, ed. Irvine, W.M., Schloerb, F.P., and Tacconi-Garman, L. (NRAO Green Bank, West Virginia), in press.

5) Schloerb, F.P., "Millimeter-wave Instrumentation for Cometary Missions", Proc. Workshop on Multi-Comet Mission, ed. S. Maran, in press.

6) Schloerb, F.P., Claussen, M., Irvine, W.M., Kinzel, W.M., Tacconi-Garman, L., "Radio Observations of Comet Halley", Bull. Amer. Astron. Soc., in press.

7) Tacconi-Garman, L. and Schloerb, F.P., "Models of the OH 18-cm Line Profiles of Comet Halley", Bull. Amer. Astron. Soc., in press.

Future Plans

The OH observations of Comet P/Halley, P/Giacobini-Zinner, C/Thiele, and C/Hartley-Good provide some of the most sensitive data yet obtained on the cometary 18 centimeter OH lines. Reduction will continue in order to investigate such questions as the ratio of the hyperfine components as a function of heliocentric distance, solar radiation field, outburst events, etc., in order to determine the physical mechanisms responsible for deviations from the equilibrium ratio; detailed analysis of the polarimetric information available for both the 1667 and 1665 MHz lines, which will provide information on the magnetic fields in the coma via the Zeeman Effect; analysis of the mapping data to study the distribution of emission in the coma; and a more detailed analysis of the time dependence of the OH production rate. Model calculations for comparison with the theory will form the Ph.D. dissertation for graduate student L. Tacconi-Garman.

As a result of the Workshop on Cometary Radio Astronomy, we have developed a collaboration with Dr. M. Gaylard of the Hartebeesthoek Observatory in South Africa. The South African data provide very high time resolution observations of the OH ground state lambda doublet at a time when P/Halley was (1) crossing the galactic plane and (2) transiting the strong extragalactic source Cen A. Tacconi-Garman is comparing his model calculations for the relevant dates with the observational results.

Work is continuing on models of the HCN thermodynamics and excitation, for comparison with the 3 millimeter observations of the J=1-0 transition obtained at the University of Massachusetts. We hope to be able to model in detail outbursts from the nucleus and ultimately to gain insite into the question of what fraction of the observed HCN is sublimated directly from the nucleus, and what fraction may be released from grains in the coma. These calculations will explicitly include the hyperfine levels, in an effort to determine the causes of the observed hyperfine anomalies.

Swade is continuing his analysis of observations of molecular emission in the nearby interstellar cloud L134N, in an effort to shed light on the formation of solar type stars and conceivably of planets. Detailed statistical equilibrium calculations are under way to determine the excitation of the transitions observed, in order to deduce both physical parameters and chemical abundances.

Irvine and Lumme are continuing their study of radiative transfer in planetary and satellite regoliths, which is also relevant to asteroids and cometary nuclei. Lumme has been named a Co-Investigator, and Irvine a collaborator, on the USSR Phobos Mission to Mars and its satellites. They will be responsible for light scattering calculations of reflection from the surface of Phobos.

Personnel

University of Massachusetts graduate student L. Tacconi-Garman joined the project as a Research Assistant in June. Post-doctoral Research Associate M. Claussen is supported 1/4 time by the present grant. Graduate student J. Alonso will be joining the research effort in January, 1987, with support from the Graduate Student Researchers Program (Under-Represented Minority Focus).

Financial Report

A detailed financial report will be submitted by the Office of the Treasurer, University of Massachusetts.

William M. Irvine
Principal Investigator

F. Peter Schloerb
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