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STUDIES OF RADIATIVE TRANSFER IN PLANETARY ATMOSPHERES

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Current Research

Schloerb and post-doc M. Claussen completed their observational program to obtain a set of high signal-to-noise spectra of the 18-cm OH emission from comet P/Halley. They utilized the NRAO 140-foot antenna, which is equipped with the world's most sensitive 18-cm wavelength receiver. An example of the data obtained is shown in Figure 1, and in Figure 2 we show values of the OH production rate obtained. Results at heliocentric distances greater than 2 AU show the expected "turn on" of the comet between 2 and 3 AU as the ice in the nucleus begins to sublimate. Following this "turn on", the OH production rate derived from our radio observations initially showed an r_h^{-2} variation, like that expected naively from considerations of the solar energy available to sublimate ice. At times near perihelion, however, the apparent production rate flattens out. This effect could be due to a decrease in the intrinsic gas production by the comet, but in view of other observational data, a more likely explanation is that the cometary OH maser responsible for the radio

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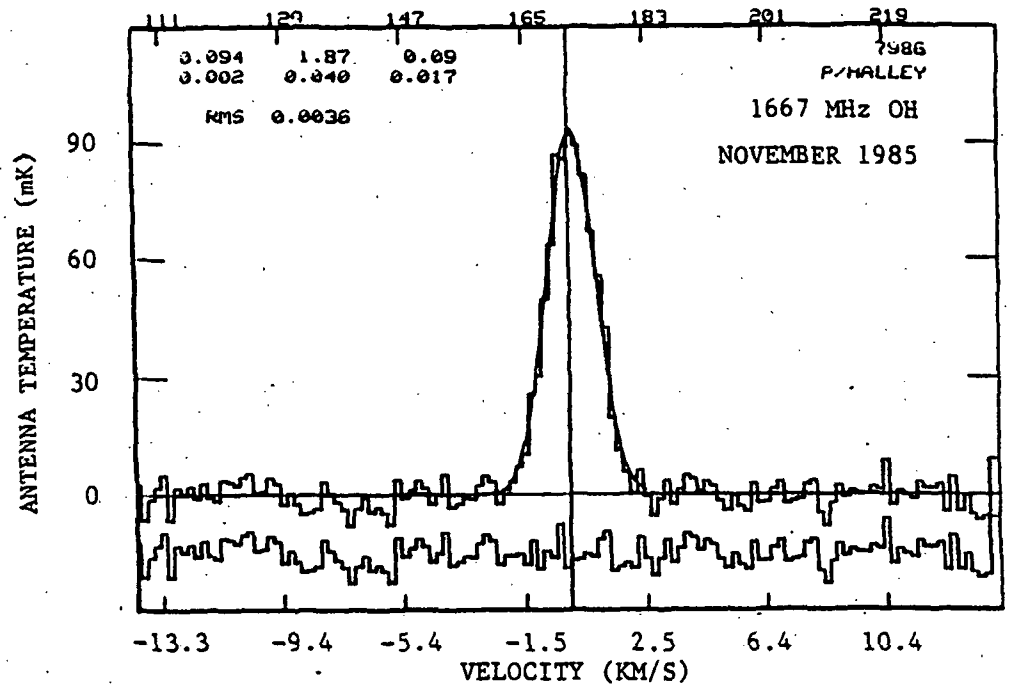

FIGURE 1 - 1667 MHz OH spectrum obtained at the NRAO 140-foot antenna by Schloerb and Claussen. A Gaussian fit to the line is shown; residuals to the fit are displayed below the spectrum.

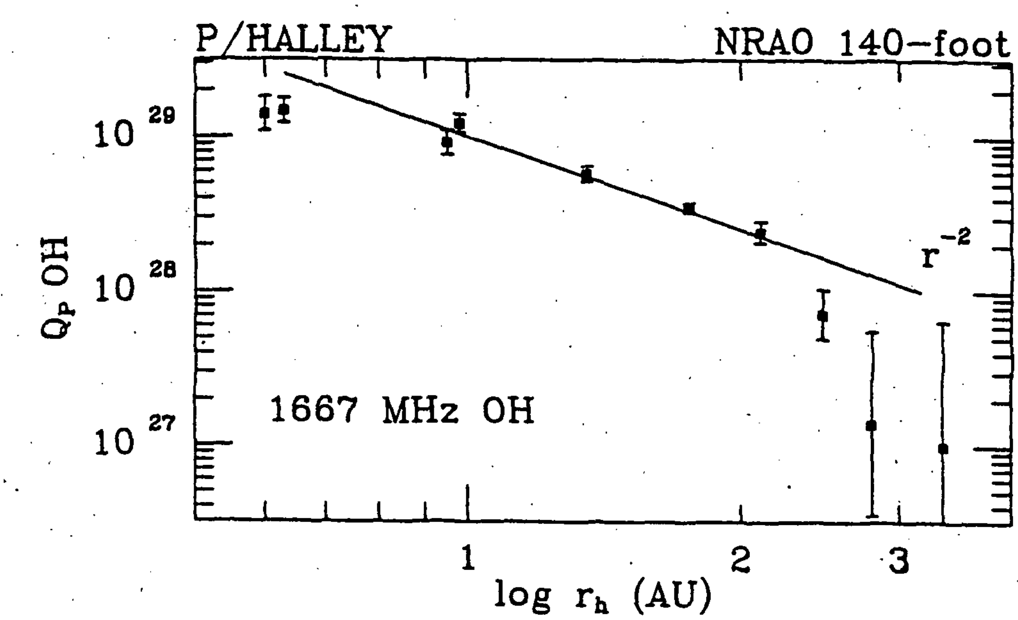

FIGURE 2 - OH Parent production rates inferred from 1667 MHz OH line observations.

emission is "quenched" to some extent by the presence of large gas densities when the comet is most active. We note that this quenching phenomenon has also now been observed directly in other radio and uv data obtained on Halley.

OH mapping results have shown interesting asymmetries even in the relatively large beam of the NRAO 140-foot antenna (18 arcmin). During October and November, Schloerb and Claussen found slight asymmetries to the north and south of the nucleus position. The latter observation was confirmed by a high resolution map of the OH emission obtained with the VLA by de Pater et al., and it is believed that this asymmetry is related to anisotropic outgassing from the nucleus. In maps obtained during December, January and March, however, the emission is stronger in the tailward direction from the comet. Such asymmetries are to be expected from the effects of solar radiation pressure on the OH molecule, and we shall be analyzing the maps to study these effects and directly determine the scale length of the OH radical.

During the course of the Halley OH campaign, Schloerb and Claussen were also able to obtain high signal-to-noise spectra on the comets P/Giacobini-Zinner, C/Thiele, and C/Hartley-Good. In addition to the obvious utility of the P/G-Z observations in the support of NASA's ICE mission, these data provide a much needed context in which to view the results of our Halley program. Previous OH observations of comets have typically been obtained with low spectral resolution and/or low signal-to-noise ratio. Thus, they are difficult to compare to the high resolution data obtained for Halley. One example of the utility of these additional observations concerns the line shape of cometary OH radio emission. Based on the behavior of these 4 comets, it appears that the "typical" radio OH line is well fit by a gaussian profile with a full width of 1.9 km/s. Since the OH line shape represents a convolution of the line profiles produced by the parent outflow velocity and the velocity gained by the daughter upon photodissociation of the parent, variations in the line shape are likely to be due to changes in the parent velocity distribution. At present, the only clear exceptions to the nominal 1.9 km/s gaussian profile occur in one spectrum of C/Hartley-Good and in spectra of Halley obtained at heliocentric radii less than 1 AU. In all these exceptional cases, the line is broadened, apparently as a result of increased activity by the nucleus. Thus, through comparison of the "typical" linewidth and that of lines broadened by activity, we expect to be able to place significant constraints on the parent outflow velocity distribution.

The HCN observations of Comet Halley were carried out by Schloerb, Irvine, and graduate students D. Swade and W. Kinzel at the Five College Radio Astronomy Observatory (FCRAO) during a total of 56 individual observing sessions between 18 November 1985 and 11 may 1986. These observations represent the largest monitoring program of HCN emission from any comet, and moreover, represent the first time that a cometary parent molecule has been so extensively observed. Significantly, this program could not have been carried out at any other facility in the world, since FCRAO is the only large millimeter-wave telescope with enough scheduling flexibility to cope with remarkable events like the variable HCN emission from Halley's comet.

In Figure 3, representative spectra are presented which were constructed in order to illustrate two important points about the HCN emission from Comet Halley. The first is that the total HCN flux from the comet is strongly time variable, as are the gas and dust production. In panel a, the results of averaging data obtained in February 1986 on days when the comet was clearly detected are shown. Interestingly enough, these days (Feb. 9, Feb. 12, and Feb. 26) also correspond to optical outbursts reported in the IAU circulars. In panel b, on the other hand, the average of many more days during February

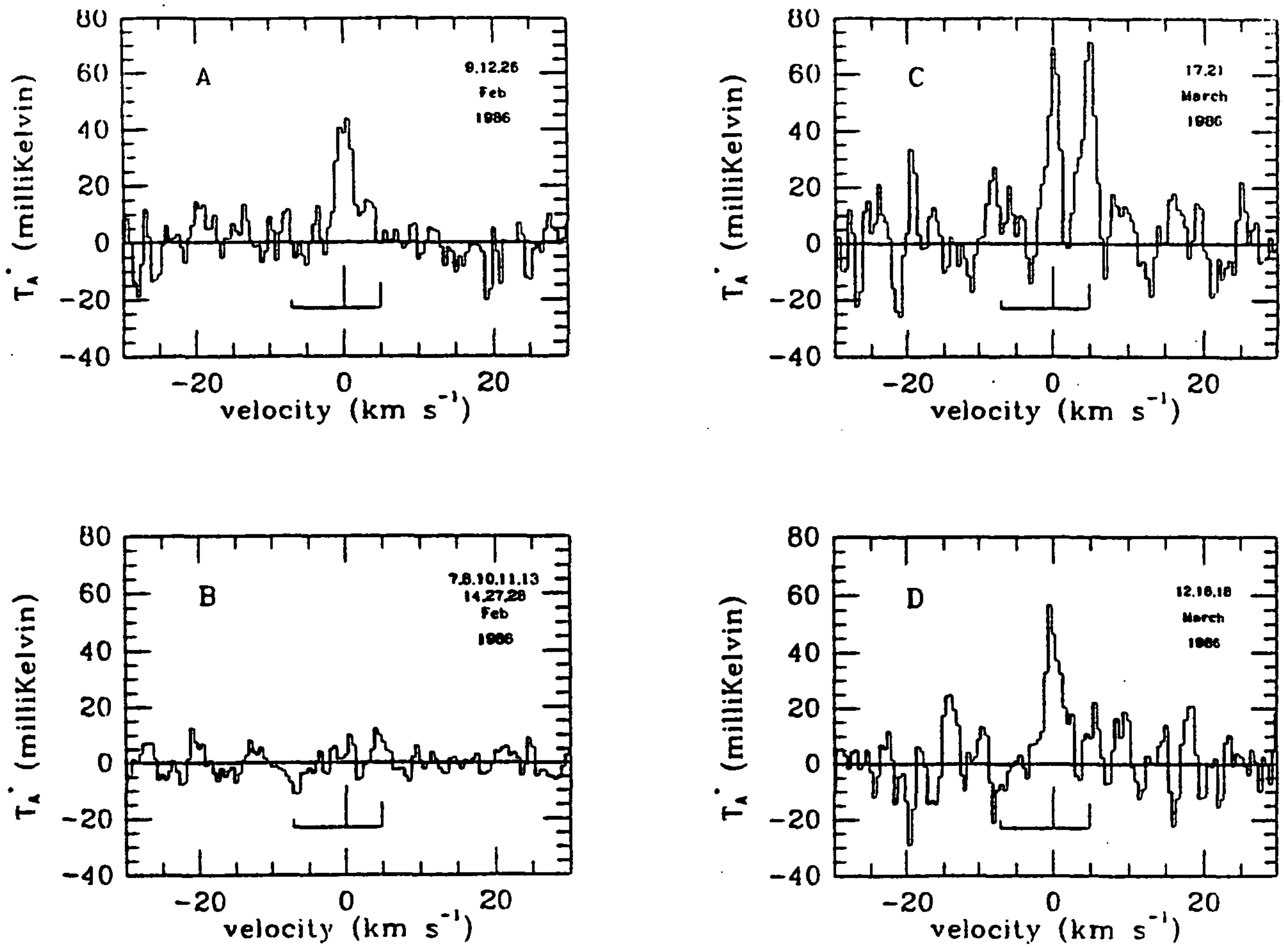

Figure 3 -- Selected FCRAO spectra of P/Halley obtained by averaging several days of observations together, as indicated. The individual days used in each spectrum were chosen to illustrate the behavior of HCN in comets. The spectra have been Hanning smoothed and sampled at 0.5 km/sec resolution. The bar beneath each spectrum indicates the location of the F=2-1, F=1-1, and F=0-1 hyperfine components and their LTE intensity ratio.

1986 when the comet was NOT clearly detected in a single day's observing are presented. As is evident from the figure, even averaging many such days fails to produce a detection of the comet. Thus, there are evidently large variations in the HCN production, which correlate well with the activity of the comet.

A second type of temporal variation of the HCN emission is also demonstrated in Figure 3. The ratio of the hyperfine components of the J=1-0 transition is not usually in accord with that expected from their statistical weights, and it is time variable as well. For example, the average of several days of observations in March where the F=1-1 hyperfine component was clearly detected is presented in Figure 3c, and Figure 3d shows the average of days when the F=1-1 line was not detected. The time intervals represented by the two spectra overlap, yet there is a large variation in the relative strengths of the F=2-1 and F=1-1 transitions. Existing theories for the excitation of HCN in comets do not explain either deviations from the 5:3:1 ratio expected from the statistical weights or their time variability. A new cometary phenomenon has been discovered!

The spectra shown in Figure 3 are averages of several days of observations which were selected in order to make specific points about the HCN emission from the comet. In order to discuss the longer term behavior, subsets of the data in which the individual daily averages were obtained within 4 days of each other have been averaged for our preliminary analysis. Since 4 day intervals are long compared to the HCN lifetime and the 2.2 day rotation period of the comet, this binning strategy clearly reflects only a mean behavior of the comet. In Figure 4 the measurements of the total HCN production rate of Halley's comet throughout the 1985-1986 apparition based on these averages at 18 epochs are shown along with measurements of the total visual

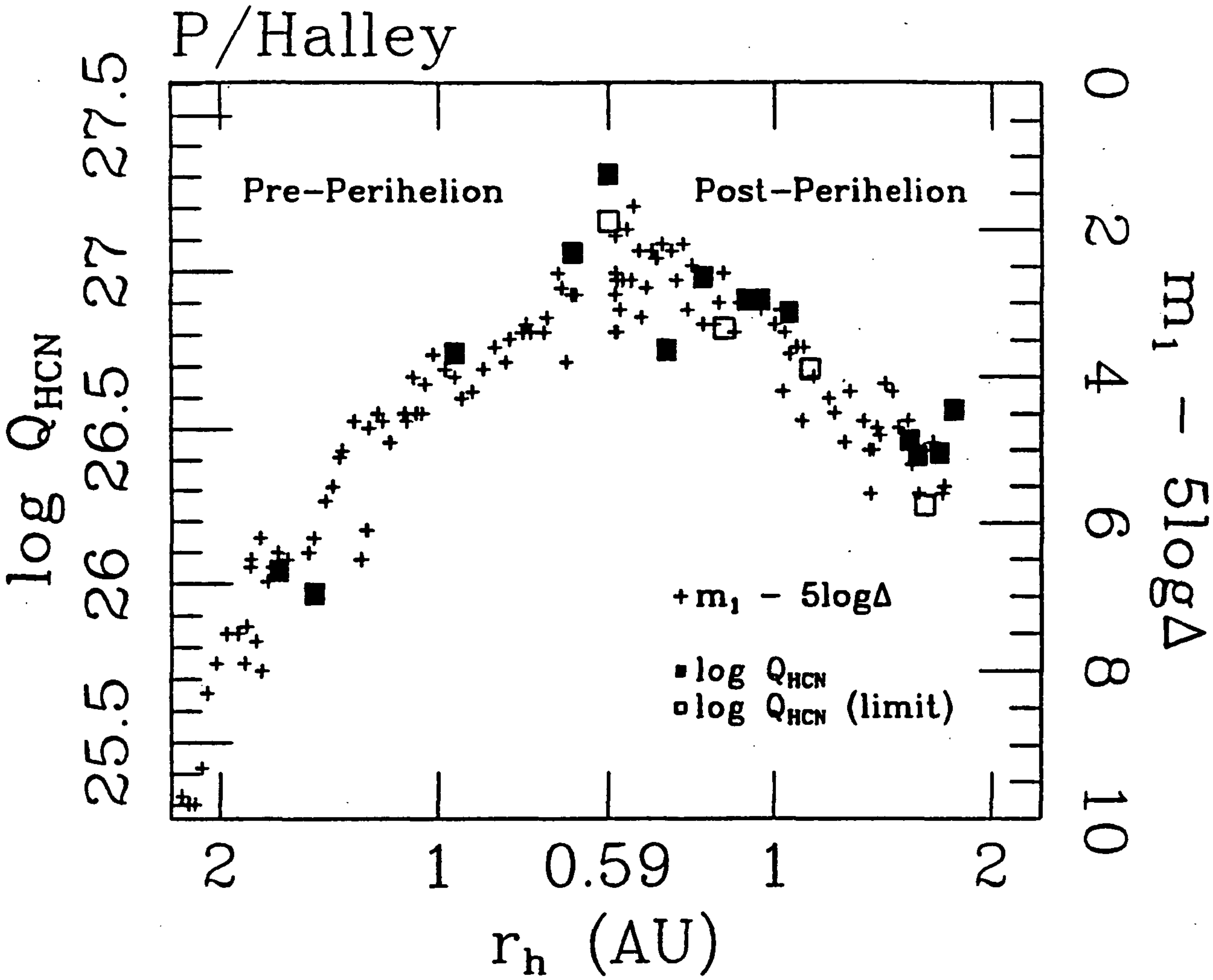

Figure 4 -- HCN production rates for P/Halley derived from the FCRAO observations using the IR excitation model of Bockelee-Morvan and Crovisier (1985) are plotted as a function of the heliocentric distance of the comet. Visual magnitudes of the comet derived from the IAU circulars and corrected for geocentric distance are also shown to illustrate the correspondence between HCN production and the visual magnitude of the comet.

magnitude (m_1) corrected for geocentric distance. Interestingly enough, there is an excellent correlation between the visual magnitude and the HCN production rate which is in accord with theories of the relationship between gas production and visual magnitude (c.f. Divine et al., preprint).

In addition to offering a direct means to monitor the production of a parent molecule from the nucleus, these data also provide fundamental information about the kinematics of parent molecules in the coma. Millimeter-wave spectroscopy allows the line profiles produced by outflowing gas to be resolved. Thus, it is possible to observe both the outflow velocity of the gas and the effects of anisotropic outgassing from the nucleus. It is interesting to note that the data show no significant trends in the observed HCN line width with heliocentric distance (r_h), although there is a slight tendency for the lines to be broader in March after perihelion when the comet was brighter and more active. Theoretical arguments and indirect observations have suggested that the outflow velocities should vary as $r_h^{-1/2}$ (c.f. Delsemme in Comets, U. Arizona Press, 1982). The HCN data are not consistent with such a variation and yield a single average linewidth of 1.74±0.12 km/s. Within the context of a pure radial outflow model, this result indicates an outflow velocity of 0.87±0.12 km/s, which is in excellent agreement with both recent theoretical calculations (0.8 km by J. Crovisier) and in situ observations by the Giotto spacecraft (0.9±0.2 km/s), as well as with the HCN linewidth independently observed in November 1985 by Despois et al. with the FRAM radio telescope.

Another trend in the observed HCN lines is the tendency of the line to be blue shifted with respect to the nuclear velocity. The average offset of all spectra is -0.18±0.05 km/s, and this tendency is in good agreement with spacecraft observations which show that the activity of the comet was largely restricted to its sunlit hemisphere. Since the phase angle of the comet was never above about 60 degrees during our observations, gas from the sunlit side of the nucleus moves primarily towards the observer in all cases, and the result is a general blue shift of the emission.

Finally, in addition to monitoring HCN from the comet, attempts were also made to detect other molecules via millimeter-wave spectroscopy. HC_3N, CH_3CN, HCO^+, and HNC were all sought several times during the apparition. No detections were made, and the upper limits imply that all are less abundant than HCN in cometary comae.

In an entirely separate program, Swade continued his study of the nearby cold, dark cloud L134N, which is typical of the regions in which solar-type stars are believed to form. The goal is to accurately determine both physical and chemical conditions throughout a cloud. The basic observational data have been otained, and statistical equilibrium models are now being applied to determine temperature, density, column density, and chemical abundances, particularly in the core region.

Schloerb resumed 3 millimeter observations of Mars in the J=1-0 transition of CO using the FCRAO 14 meter antenna. The data constrain the CO mixing ratio and the lapse rate in the Martian atmosphere.

Irvine and Professor K. Lumme from the University of Helsinki continued their research on radiative transfer in planetary, satellite, and cometary regoliths. The surface boundary is modeled as a multivariate normal distribution, which is explicitly defined once the autocorrelation function has been specified. Both a solid medium, which can be either opaque or translucent, and a particulate layer are being considered.

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

1) Ekelund, L., Ch. Andersson, A. Ekelund, W. Irvine, and A. Winnberg, "Cometary Observations at Onsala Space Observatory since 1980", in Asteroids, Comets, Meteors II, ed. C.I. Lagerkvist, B.A. Lindblad, H. Lundstedt, and H. Rickman, Uppsala Univ., pp. 283-288 (1986).

2) Swade, D.A., F.P. Schloerb, W.M. Irvine, and R.L. Snell, "Molecular Structure of L134N", in Masers, Molecules and Mass Outflows in Star-Forming Regions, ed. A. Haschick, NEROC, pp. 73-88 (1986).

3) Schloerb, F.P. "Millimeter-wave Spectroscopy of Solar System Objects: Present and Future", ESO-IRAM-ONSALA Workshop on (Sub)Millimeter Astronomy, ed. P.A. Shaver and K. Kjar, ESO Conf. Workshop Proc. No. 22, pp. 603-616 (1985).

4) Schloerb, F.P., and Claussen, M.J., "Radio Observations of OH in P/Halley and P/Giacobini-Zinner", Bull. Amer. Astron. Soc., 17, 920 (1986).

5) Schloerb, F.P., W. Kinzel, D. Swade and W. Irvine, "HCN in Comet Halley", IAU Circ. 4176, (1986).

6) Schloerb, F.P., W. Kinzel, D. Swade, and W. Irvine, "Further Detections of HCN in Comet Halley", IAU Circ. 4188, (1986)

Articles with grant support currently in press:

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

Future Plans

The OH observations of Halley and other comets obtained by Schloerb and Claussen provide some of the most sensitive data yet obtained on the cometary radio OH lines. The results provide a sensitive probe of the total gas production rate, coma kinematics, asymmetries of nuclear outgassing and, possibly, magnetic fields via the Zeaman effect on the 18-cm transitions. At this time, the data have been reduced and analyzed in terms of the standard radio models developed by Despois et al. and utilized by Schloerb and Gerard A.J., 90, 1117, 1985) to make predictions of the brightness of Halley's Comet. Comparison of our OH production rates derived from this standard model with those derived from UV observations has shown that there continue to be substantial disagreements in the rates derived by these different techniques. In fact, EVEN DIFFERENT RADIO TELESCOPES USING THE SAME MODEL DO NOT AGREE! Clearly, the simple models must be amended to include additional physical effects which may be significant, such as time-variable water production from the nucleus and quenching of the ground state OH inversion by collisions within the coma. We have begun this analysis using a monte carlo program to compute model radio spectra and maps. This computational technique was chosen because of the ease with which features such as asymmetric outgassing of the nucleus and the quenching of the OH maser may be added to the now standard vectorial model calculation.

One of the aims of cometary radio astronomy is to be able to directly observe the parent molecules sublimated from the nucleus and thereby to determine the composition of the cometary ices. The HCN observations of P/Halley obtained at the FCRAO and elsewhere show that this promise may be realized. At this time, we have completed the standard analysis using the traditional Haser model to derive molecular production rates and have analyzed the line profiles to obtain direct measurements of the gas outflow velocity of parent molecules. However, as in the case of our OH observations, it is already clear that both the standard coma models and our adopted scheme for the excitation of the HCN molecule will require some refinement. Given the steady state nature of the Haser model, one modification that will be necessary is a provision to allow for the observed time dependent behavior. One interesting aspect to be studied is the behavior of the spectral profile in a model including outbursts or jets of HCN from the nucleus. Simple versions of such models show that the shape of the HCN line should evolve during an outburst, and remarkably, we do have spectra which may be interpretable in terms of such a picture.

We also plan to undertake a more detailed study of the excitation of the HCN molecule in comets. A complete understanding of this excitation will not only permit us to maximize the amount of information gained from our observations, but it will also allow us to better understand and predict the behavior of other molecular species to assist searches in future bright comets. Indeed, the latter motivation was very strong before this Halley apparition and led previous workers to the realization that HCN was very probably the best bet for cometary radio observations. Previous excitation calculations have ranged from very simple LTE estimates to somewhat more complex calculations of the excitation achieved in radiative equilibrium with solar IR radiation, and these calculations have been used to derive HCN production rates which suggest that HCN is not the sole parent of the radical CN. However, since serious systematic errors may exist in the estimation of production rates due to uncertainties in the molecular excitation, we believe that this conclusion must remain tentative until the HCN excitation is better understood. Indeed, observations of anomalous hyperfine ratios in the HCN J=1-0 transition now show that refinements to these relatively simple models are required in order to match the data. Thus, we propose to improve upon previous work by considering a more detailed model which explicitly includes the hyperfine levels. Moreover, given the obvious variability of the HCN emission, it seems reasonable to perform the calculations within the context of a time dependent model such as has recently been used by Chin and Weaver (Ap.J. 285, 858, 1985) for the CO molecule.

Swade is continuing his analysis of observations of the nearby interstellar molecular cloud L134N. It is hoped that this study will shed light on the formation of solar type stars and conceivably of planets. The chemical composition will be compared to that of models of the solar nebula and to the observed composition of comets.

Theoretical studies of radiative transfer relevant to solar system objects will continue. Lumme and Irvine will give increased attention to scattering by dielectric materials such as ices, with a view to modeling thermal emission from a cometary nucleus.

The University of Massachusetts is negotiating an agreement with the University of Wyoming for guaranteed access to the Wyoming Infrared Observatory (WIRO) 2.3 m telescope, which is located on Mt. Jelm near Laramie. This site has extremely dry conditions on some winter days, making it an excellent location for sub-millimeter observations. The Five College Radio Astronomy Observatory, operated by the University of Massachusetts, is developing a sub-millimeter receiver system for use at WIRO. This has exciting potential for planetary science, including study of the CO J=4-3 transition to probe higher levels in the atmosphere of Venus and Mars than are monitored with the J=1-0 and 2-1 lines, and potentially the study of deuterated H_2O, NH_3, and CH_4 in planetary atmospheres.

Financial Report

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

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