Asteroids, Comets, Meteors 1991, pp. 137-140
Lunar and Planetary Institute, Houston, 1992

N93-19144
140835
P-4

RADIO SPECTROSCOPY OF COMETS: RECENT RESULTS AND FUTURE PROSPECTS.

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Abstract

We review the recent results of cometary radio spectroscopy (since 1988). Successful observations with several instruments yielded the detection of new molecular species, the simultaneous investigations of several rotational transitions of the same molecule, and mapping of the coma.

INTRODUCTION

Since the observations of comet Kohoutek in 1973 and several pioneering attempts before, cometary radio spectroscopy has been a long series of hopes and frustrations. Just after the P/Halley campaign (recently reviewed by Crovisier and Schloerb 1991), the only firm successes were the observations of the OH lines at 18 cm in many comets and the confirmed detection of HCN at 3 mm in comet Halley. However, since that time, significant new results were obtained with the detection of new molecules and new molecular transitions. This announces a new start of cometary radio spectroscopy, not only due to the recent apparition of bright targets (P/Brorsen-Metcalf 1989 X, Austin 1989c1, Levy 1990c), but also to the opening of higher-frequency windows to large instruments.

Spectroscopic radio observations performed on recent comets are listed in Table 1. OH observations at 18 cm were conducted at several places and a daily monitoring was made at the Nançay radio telescope. Centimeter observations were made at the VLA (P/Brorsen-Metcalf) and at Effelsberg (comet Austin). Millimeter observations were made at IRAM, FCRAO, Nobeyama and SEST. Submillimeter observations were conducted at CSO. Interferometric observations at millimeter wavelengths (HCN 1-0 line) were also attempted on comet Austin at BIMA and IRAM.

The OH observations provided a follow-up of the gas production rates for all comets (Bockelée-Morvan *et al.* 1990, 1991). For comet Levy 1990c, the observing conditions were exceptionally good: high inversion of the OH ground state Λ-doublet of OH from July to September, and at the beginning of September, the cometary OH maser amplified an enhanced continuum background due to the crossing of the galactic plane by the comet. At that moment, the OH radio lines reached the record value of 1.5 K in antenna temperature. The high signal-to-noise ratio permitted (i) the detection of Zeeman effect and the measurement of the cometary magnetic field; (ii) the observation of the OH satellite lines at 1721 and 1612 MHz, revealing hyperfine anomalies due to second-order effects in the excitation mechanism; (iii) the mapping of the OH coma and the probing of the OH distribution (Bockelée-Morvan *et al.* 1991).

NEW MOLECULAR LINES

The highlights of the millimeter and submillimeter observations were the detections of the rotational lines of several molecular species: new transitions for the already known species HCN and H_2CO, and the detection of the new species H_2S and CH_3OH. Since these results are presented at this conference by Colom *et al.* (1991) for the IRAM observations and by Schloerb and Ge (1991) for the CSO observations, we will only comment some points of general interest.

Formaldehyde was unambiguously detected with high signal-to-noise ratio in comets Austin and

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Table 1: Summary of spectroscopic radio observations of recent comets.

Comet Date	Telescope[a)]	Wave-length	Molecules [b)]	Investigators or reference[c)]
P/Brorsen-Metcalf 1989 X				
890804-891031	Nançay	18 cm	**OH**	Bockelée-Morvan *et al.* 1990
890901-890905	FCRAO	3 mm	HCN	Schloerb and Ge
890902-890907	IRAM 30-m	1-3 mm	**HCN, H_2CO**	Colom *et al.* 1991
890902-890911	VLA	6 cm	H_2CO, HC_3N	Snyder *et al.* 1990
890908-890909	Green Bank 140'	18 cm	OH	Schloerb
Okazaki-Levy-Rudenko 1989 XIX				
891003-891202	Nançay	18 cm	**OH**	Bockelée-Morvan et al. 1990
	Green Bank 140'	18 cm	**OH**	Schloerb
	FCRAO	3 mm	HCN	Schloerb and Ge
891105	IRAM 30-m	1 mm	H_2CO	Colom *et al.* 1991
Aarseth-Brewington 1989 XXII				
891208-891230	Nançay	18 cm	**OH**	Bockelée-Morvan *et al.* 1990
Austin 1989c1				
900215-900614	Nançay	18 cm	**OH**	Bockelée-Morvan *et al.* 1990
900401-900430	Nobeyama	3 mm	**HCN**, HC_3N, CH_3CN	Irvine, Kawaguchi
900402	IRAM 30-m	1-3 mm	HCN, H_2CO	Colom *et al.* 1991
900402-900403	FCRAO	3 mm	HCN	Schloerb and Ge
900404-900531	Dwingeloo 25-m	18 cm	**OH**	Tacconi-Garman 1990
900406-900520	Green Bank 140'	18 cm	**OH**	Schloerb
900411-900518	Effelsberg	1-6 cm	OH, H_2CO, NH_3, CH_3OH	Walmsley *et al*
900412-900414	Onsala	3 mm	HCN	Ekelund and Winnberg
900424-900430	FCRAO, BIMA	3 mm	HCN	Palmer *et al.* 1990
900521-900525	IRAM 30-m	1-3 mm	**HCN, H_2CO, H_2S, CH_3OH**	Colom *et al.* 1991
900525-900528	IRAM interfero.	3 mm	HCN	Delannoy and Wink
900528-900601	CSO	1 mm	**H_2CO ?**	Schloerb and Ge
Levy 1990c				
900616-900930	Nançay	18 cm	**OH**	Bockelée-Morvan *et al.* 1991
900826-900831	IRAM 30-m	1-3 mm	**HCN, H_2CO, H_2S, CH_3OH**	Colom *et al.* 1991
900829-900901	CSO	1 mm	**HCN, H_2CO, CH_3OH**	Schloerb and Ge 1991
900927	SEST	1 mm	**HCN**	Winnberg 1990

a) BIMA: Berkeley-Illinois-Maryland Array; CSO: Caltech Submillimeter Observatory; FCRAO: Five College Radio Astronomical Observatory; IRAM: Institut de Radio Astronomie Millimétrique; SEST: Swedish-ESO Submillimetre Telescope; VLA: Very Large Array.
b) Detections are indicated in boldface.
c) Private communication from the investigators when no year is given for the reference.

Levy through its 2_{12}-1_{11} transition. This is a firm confirmation of the presence of this molecule in comets, which was already observed at 3.56 μm in P/Halley (Combes *et al.* 1988) but could not be retrieved in other cometary infrared spectra, and for which the 6 cm line was observed in P/Halley at the VLA, but with a poor signal-to-noise ratio (Snyder *et al.* 1989). In addition, the 5_{15}-4_{14} line was observed at the CSO in comet Levy. The space distribution of H_2CO, from both CSO and IRAM observations, might not be that of a parent molecule, but rather that of a distributed source. This renders difficult the evaluation of the H_2CO abundance. For the recent comets, this abundance is in any case lower than 1%, which is smaller than what was dereived for comet P/Halley (4%). In a re-analysis of the VLA observation of H_2CO in P/Halley of Snyder *et al.* (1989), Bockelée-Morvan and Crovisier (1991) failed to reconcile the 6 cm line intensity with a believable formaldehyde production rate.

Hydrogen cyanide could be observed in several rotational transitions, some of the observations being simultaneous (or nearly simultaneous): J= 1-0 at IRAM and Nobeyama, 3-2 at IRAM, CSO and SEST, 4-3 at CSO. As anticipated by excitation models, the 3-2 line is very strong, so that reliable mapping of the line brightness distribution could be performed at the CSO. This line is apparently optically thick, and radiative transfer should be taken into account in the analysis. After the observations of this molecule in P/Halley, it was concluded that the HCN abundance could not totally explain the CN production rate, and that another source (dust grains or other parent molecules ?) should be present. The recent observations, which constrain the excitation models, and will lead to improved estimations of the HCN abundances, may help resolving this problem.

The methanol observations are very promising, because several rotational transitions could be measured simultaneously with the same instrumental beam. This gives unique information on the rotational distribution of the molecule. We are thus provided with a way to probe the excitation conditions of the inner coma. From first analysis, the apparent temperature is rather cold (about 30 K), suggesting a relaxed rotational distribution. The only other parent molecule for which such information was obtained, up to now, was the water molecule for which the relative intensities of the rovibrational lines in the 2.7 μm band were observed from the KAO. The CH_3OH abundance retrieved by radio observations is relatively high: 1% relative to water. This suggests that methanol should have detectable vibrational bands in the infrared. Indeed, the 3.52 μm emission feature observed in several comets could be attributed to the ν_3 band of CH_3OH (Hoban *et al.* 1991). The ν_2 and ν_9 bands should also contribute significantly the the 3.4 μm emission, as well as the ν_1 band to the 2.9 μm cometary emission.

The detection of hydrogen sulfide gives insights upon the nature of sulfur depositories in comets. The inferred abundance of H_2S is 0.2% relative to water. That of HCN is about 0.1%. This shows how radio spectroscopy may be sensitive to minor components of cometary atmospheres.

PROSPECTS

Despite many efforts, centimetric observations were less successful than the observations at shorter wavelengths. CH_3OH, conspicuous everywhere in the millimeter range, was undetected at cm wavelengths at Effelsberg. This is also the case for H_2CO at 6 cm, H_2O and NH_3 at 1 cm, OH at 5 cm. This is in agreement with our present knowledge of molecular excitation and abundances in comets.

The millimeter-submillimeter instruments now in use typically probe the first few thousand km of the coma. In this region, molecules are not yet at fluorescence equilibrium, but evolve between rotational relaxation, radiative excitation, and collisions. Excitation models are still fairly primitive and rely on several uncertain parameters such as kinetic temperatures and collision rates. It may be expected that important constraints on these models will be obtained from the derivations of molecular rotational distributions.

With the large millimeter and submillimeter antenna now in use, the beams may be as small as 10". In contrast with optical observations, there is no way to check the real position of the comet. Therefore, the radio observer must rely, more than ever, on accurate ephemeris and he is strongly dependent upon his astrometrist colleagues for the rapid diffusion of updated orbital elements.

The obvious advantage of radio spectroscopy is that it allows unambiguous identification of the detected features, in contrast with low-resolution infrared spectroscopy and *in situ* mass spectroscopy investigations. Recent observations proved its ability to detect minor species such as HCN or H_2S, and complex molecules such as the 6-atom methanol molecule. It is very likely that several other minor and/or complex constituents are still to be found in cometary atmospheres, and that radio spectroscopy will help us unravelling their nature.

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