ARECIBO OBSERVATIONS OF THE 18CM OH LINES OF SIX COMETS

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ABSTRACT

Using the 300m Arecibo telescope, we have obtained observations of 18cm OH emission in six comets since May 2000: C/1999 S4 LINEAR, C/1999 T1 McNaught-Hartley, C/2001 A2-B LINEAR, C/2002 C1 Ikeya-Zhang, C/2000 WM1 LINEAR, and C/2002 F1 Utsunomiya. The Arecibo telescope is well suited to mapping observations that resolve cometary comae with high sensitivity and spectral resolution. These comets are detected with production rates between 10^{28} and 10^{29}mol/s. We find strong OH emission from C/2001 A2-B in July, 2001, which was likely enhanced by the breakup of the nucleus a few weeks prior to the observations. Asymmetric OH spectra may thus occur either as a result of physical jet structures or of differing line excitation across the coma, or both. Both comets C/2000 WM1 and C/Ikeya-Zhang show unusual line shapes, which indicate complex outflow behavior and excitation characteristics.

1. INTRODUCTION

The 18-cm lines of OH are a valuable diagnostic of conditions in the comae of comets. The brightness of the OH lines is related to the total production of OH in the coma, and the spectral line shape contains information on the velocity of the outflowing gas, the distribution of gas production from the nucleus. In this paper, we present new observations of the 18 cm OH emission in six comets to explore these effects and to attempt to measure the effect of “quenching” of the OH radio emission in the inner coma.

The excitation of the ground state Λ-doublet transitions responsible for the 18 cm emission is complicated. These levels are excited by a process in which OH molecules are promoted from the ground state by the solar UV and subsequently decay radiatively back to the ground state. This process may cause the Λ-doublet levels to be either inverted or anti-inverted depending on the details of the UV excitation. Since the solar UV spectrum contains a forest of strong absorption lines, the exact behavior of the Λ-doublet depends on the position of the comet’s UV OH lines with respect to the solar spectrum. Thus, the inversion of the Λ-doublet depends strongly on the the heliocentric radial velocity of the comet, and this process leads to complex behavior. OH lines appear as emission lines amplifying the cosmic background when the levels are inverted and as absorption lines against the cosmic background when the levels are anti-inverted. Moreover, variations in the excitation of the OH molecule across the coma, due to differences in heliocentric velocity for molecules moving toward and away from the Sun, may also lead to a distortion of the line shape (Greenstein Effect) which must be accounted for in models of the emission.

In extremely high-production comets, such as Hale-Bopp, the inversion of the Λ-doublet may also be affected by collisional excitations between the levels. Collisions have the effect of re-balancing the population and thereby quenching the inversion produced by the UV excitation scheme described above. This effect has been easily observed in bright comets, but in more typical comets, with low production rate, the degree of quenching has not been well measured, though it is thought to decrease with the square-root of the production rate (Schloerb , 1988). Coma-resolving mapping observations of OH emission from comets offer a means to characterize the degree of collisional quenching, as well as other characteristics of the OH coma, such as its outflow velocity or asymmetry. The Arecibo 300m telescope is well suited to resolving the coma with mapping observations at high sensitivity and high spectral resolution.

2. OBSERVATIONS AND ANALYSIS

We have obtained OH observations of six comets since May 2000: C/1999 S4 LINEAR, C/1999 T1 McNaught-Hartley, C/2001 A2-B LINEAR, C/2002 C1 Ikeya-Zhang, C/2000 WM1 LINEAR, and C/2002 F1 Utsunomiya. Ephemerides were obtained using the Horizons system at JPL. Spectra were obtained using the L-wide receiver on the Arecibo 300m telescope, using a spectral resolution of 68.6 m/s. Simultaneous LCP and RCP observations were made at 1612, 1665, and 1667 MHz, together with calibrated noise diode measurements after each set of 4 or 5 minute integrations. In general, the telescope gain is a function of the pointing direction,

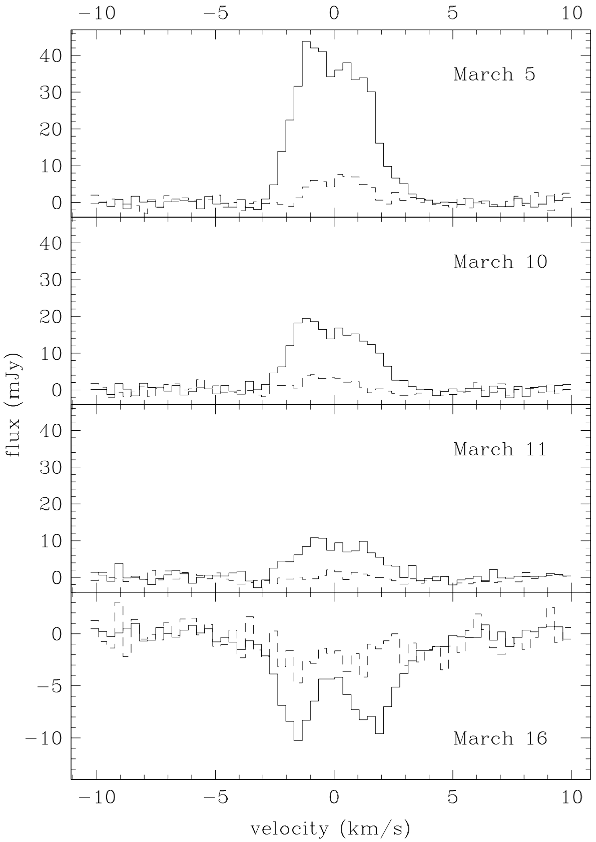

Figure 1. Observed 1667 MHz OH spectra for Comet C/2002 C1 Ikeya-Zhang maps in March, 2002. Solid lines represent nucleus-centered spectra, while dashed lines represent an average of the 6 offset points in the maps. Note that the flux scale (vertical axis) is the same for March 5-11, and different for March 16, when the line appears in absorption.

and is modeled using many known sources at declinations distributed throughout the Arecibo sky. Before September 2001, the main reflector was being adjusted to improve the gain, so sources of known flux were observed at the same declination as the comet (within 2 degrees) to better determine the gain correction. Since that time, the telescope has been stable physically, so a gain curve correction has been used to convert antenna temperature to flux.

Whenever the observed nucleus-centered lines were strong, maps were also made. These contain 7 positions: the nuclear position, and a hexagonal pattern of points, aligned to the sun-tail axis, offset by the width of one beam (3.62 arcminutes for C/1999 S4 LINEAR, 4.1 arcminutes for all others). The Arecibo telescope is restricted to observing objects with declinations between -1° and 38°. Selection of dates and times for 18 cm OH observations are further complicated by the characteristics of OH line excitation in the coma. Ideally, the inversion factor would be strong while the comet is observable in the Arecibo beam, but this is not always the case. As a result, some comets must be observed at times when the lines are not expected to be very strong. Such is the case with C/2000 WM_1 LINEAR, which was observed in late November 2001 at a time when the heliocentric velocity led to small values for the predicted inversion. However, the resulting spectra are quite interesting and serve as a valuable constraint on inversion models.

A summary of the observational circumstances, line characteristics, model outflow velocities and OH production rates are given for each observation in Table 1. In this table, time indicates the on-nucleus integration time, and r_h and Δ are heliocentric and geocentric distances. For each secure detection, the observed line peak and integrated intensity (area) are given. This peak and area may be either positive or negative, depending on the characteristics of the inversion of the Λ-doublet during the observation. A typical RMS in the line area is ± 0.1 mJy km s^{-1}. The full width of the line, indicated as ΔV, is estimated by dividing the area by the peak of the line. This line width can be an important constraint on the outflow velocity in the coma. The average velocity, $V_{\rm mean}$ is an indication of line asymmetry, for if the emission is significantly asymmetric, the average velocity will not be zero with respect to the comet. Mapping observations for Comet C/Ikeya-Zhang are shown in Fig. 1.

Monte Carlo models are run for both dayside and nightside emission over a range of OH parent velocities and quenching radii. Two different models for the inversion are employed: Despois et al. (1981), and Schleicher & A'Hearn (1988). The model having the lowest χ^2, and thus the best fit to the observed spectra, is used to estimate the OH production rate for that date ((Tacconi-Garman et al. , 1990); (Schloerb & Gerard , 1985)). Spectra best fit by the Despois et al. inversion are noted (†). Production rates (Q) and best-fit OH parent velocities ($v_{\rm parent}$) are also included in Table 1, except for C/Ikeya-Zhang on 16-23 Mar (indicated **), when neither model converges. Best-fit models and spectra are illustrated for Comets C/McNaught-Hartley, C/A2-B, and C/Utsunomiya in Fig. 2.

3. RESULTS

On dates when maps were made, our results are consistent with a small quenching radius for these low-production rate (10^{28} to 10^{29} mol s^{-1}) comets. Our mapping observations are summarized in Table 2, with statistics given for the average of all six offset spectra as in Table 1, along with the ratio of the offset-to-nucleus integrated line intensity. Best-fit models for C/Ikeya-Zhang on 16 Mar 2002 are consistent with a quenching radius of 50,000 km. All other mapping observations are consistent with quenching radii less than 10,000 km. A quenching radius is not estimated for dates which are not mapped.

For every observation of comet C/2000 WM_1 (LINEAR) and for comet C/2002 C1 (Ikeya-Zhang) on 23 March 2002, transitional spectra of unusual shapes were seen. These spectra likely represent the transition from anti-inversion to inversion of the Λ-doublet. Gases in different portions of the coma are moving at different velocities with respect to the Sun, so the radio OH excitation is different at different positions in the coma. Since the two inversion models predict the zero amplification phase

Table 1. Arecibo 1667 MHz Observations of Comets 2000-2002

UT date	time min	r_h AU	Δ AU	peak mJy	area mJy km s^{-1}	ΔV km s^{-1}	V_{mean} km s^{-1}	V_{parent} km s^{-1}	Q $\times 10^{28}$ mol s^{-1}
C/1999 S4 (LINEAR)									
2000 Jun 04.6	160	1.231	1.871	4.49	6.56	1.46	0.15	0.7	1.35±0.21
C/2001 A2-B (LINEAR)									
2001 Jul 05.388	30	0.253	1.107	18.97	41.46	2.19	-0.09	0.6	†0.80±0.8
C/1999 T1 (McNaught-Hartley)									
2001 Jan 16.516	55	1.289	1.340	-10.40	-19.94	1.92	-0.08	0.6	0.81±0.13
2001 Jan 21.507	30	1.323	1.315	-13.36	-28.80	2.16	0.00	0.6	0.80±0.14
2001 Jan 22.517	40	1.330	1.310	-12.88	-28.99	2.25	0.27	0.8	0.99±0.12
C/2000 WM_1 (LINEAR)									
2001 Nov 20.140	75	1.405	0.431	4.44	10.70	2.41	0.13	0.7	0.45±0.06
2001 Nov 26.083	105	1.310	0.350	-6.67	-14.79	2.22	-0.08	0.7	0.70±0.07
2001 Nov 27.075	105	1.294	0.340	-6.52	-12.48	1.92	-0.34	0.6	0.57±0.06
2001 Nov 28.075	95	1.277	0.332	-4.96	-8.89	1.79	-0.55	0.8	0.49±0.06
C/2002 F1 (Utsunomiya)									
2002 Apr 13.637	80	0.499	1.185	26.43	75.85	2.87	0.04	1.3	19.51±1.44
2002 Apr 14.643	50	0.487	1.182	31.76	107.21	3.38	-0.02	1.6	29.89±1.58
2002 Apr 21.693	55	0.439	1.190	-3.59	-8.34	2.32	-0.44	1.7	9.00±2.19
C/2002 C1 (Ikeya-Zhang)									
2002 Mar 05.767	50	0.596	1.077	42.33	152.84	3.61	0.02	1.7	20.40±0.90
2002 Mar 10.781	70	0.544	0.980	18.76	70.44	3.75	-0.09	1.9	28.43±0.88
2002 Mar 11.784	50	0.536	0.960	9.95	35.50	3.57	-0.05	1.8	†23.89±2.11
2002 Mar 16.748	110	0.510	0.861	-9.00	-43.76	4.86	0.19	2.6	†41.64±3.90
2002 Mar 17.770	45	0.508	0.841	-3.56	-7.60	2.13	0.87	**	2.06±0.03
2002 Mar 23.713	70	0.520	0.730	-7.08	-15.63	2.21	-0.78	**	3.29±0.02
2002 May 30.159	140	1.548	0.649	-11.26	-23.95	2.13	-0.02	0.6	0.38±0.02
2002 Jun 01.139	120	1.580	0.679	-9.18	-18.28	1.99	-0.02	0.7	0.33±0.02
2002 Jun 03.135	130	1.611	0.711	-8.94	-18.99	2.12	-0.02	0.7	0.34±0.02

**neither inversion model converges, so Q estimated as in (Tacconi-Garman et al. , 1990)

Table 2. 1667 MHz Mapping Observations of Comets

year	UT date	r_h AU	Δ AU	peak mJy	area mJy km s^{-1}	ΔV km s^{-1}	V_{mean} km s^{-1}	ratio[1]
C/1999 T1 (McNaught-Hartley)								
2001	Jan 21.507	1.323	1.315	-2.12	5.25	2.48	0.04	0.17
2001	Jan 22.517	1.330	1.310	-3.40	8.03	2.36	0.26	0.26
C/2001 A2-B (LINEAR)								
2001	Jul 5.388	1.107	0.253	10.58	27.28	2.58	0.02	0.66
C/2002 C1 (Ikeya-Zhang)								
2002	Mar 5.767	0.596	1.077	7.22	17.69	2.45	0.23	0.12
2002	Mar 10.781	0.544	0.980	3.69	8.12	2.20	-0.37	0.12
2002	Mar 16.748	0.510	0.861	-3.41	9.88	2.90	-0.11	0.23
2002	Mar 17.770	0.508	0.841	-1.84	3.08	1.68	-0.10	0.41
C/2002 F1 (Utsunomiya)								
2002	Apr 13.637	0.499	1.185	3.20	4.17	1.30	-0.02	0.06
2002	Apr 14.643	0.487	1.182	4.61	11.54	2.50	0.14	0.11

[1] ratio of line areas in the nucleus and offset positions (see Table 1)

to occur at slightly different heliocentric radial velocities, simulations of such transitional spectra provide an opportunity to discriminate between the inversion models. All transitional spectra treated here (for LINEAR WM_1 with heliocentric velocities around -28 km/s) are only consistent with the Schleicher & A'Hearn (1988) inversion model. Representative spectra are shown in Fig. 3, along with the best-fit Monte Carlo models.

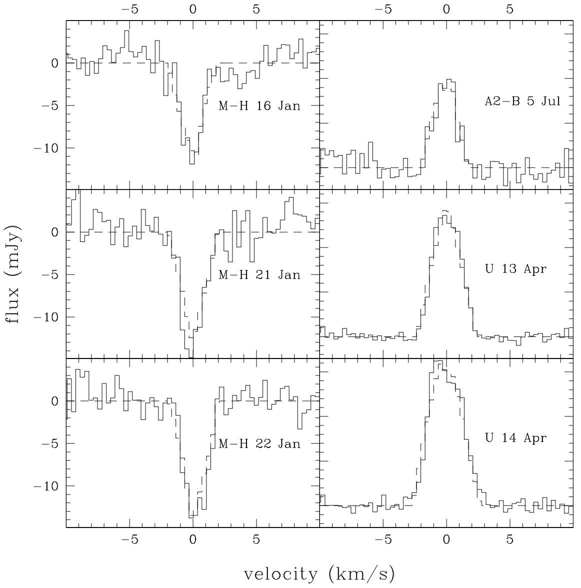

Figure 2. 1667 MHz OH nucleus-centered spectra for Comet C/1999 T1 McNaught-Hartley (M-H), C/A2-B LINEAR, and C/Utsunomiya (U). Solid lines represent observed spectra, while dashed lines represent the best-fit models.

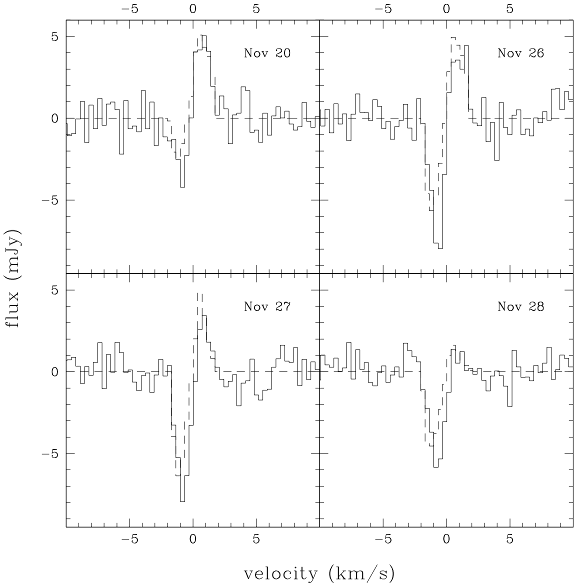

Figure 3. Observed OH 1667 MHz spectra as calibrated flux versus cometocentric velocity (solid line) for Comet WM_1 LINEAR in November, 2001. The best-fit Monte Carlo simulation (dashed line) employing the (Schleicher & A'Hearn , 1988) inversion, with a zero quenching radius and a parent outflow velocity of 0.6 km/s is also shown for comparison.

4. CONCLUSIONS

High-resolution high-sensitivity 18 cm OH mapping observations, made with the Arecibo 300m telescope, can provide useful constraints on the line excitation and quenching conditions in the coma of comets. We find that quenching radii are low, generally less than 10,000 km, for comets with production rates equal to or less than 10^{29} mol s^{-1}, consistent with past predictions of collisional quenching in cometary comae. Transitional spectra, revealing simultaneous inversion and anti-inversion characteristics at different positions across the coma were observed for two comets, and are consistent with model predictions for such transitions.

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