POLARIZATION OF OH RADIATION

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ABSTRACT

The ground $^2\pi_{3/2}$ state of OH consists of 2 Λ-doubled levels which are separated by about 1666 MHz. The upper (parity = +1) and lower (parity = -1) levels each have eight hyperfine sublevels which consist of a three-fold degenerate F=1 and five-fold degenerate F=2 energy state, and transitions between these levels give rise to the OH-18-cm radiowave spectrum. Of the four possible transitions the F=2 → 2 and F=1 → 1 transitions are most intense and are the source of the 1667 MHz and 1665 MHz signals observed from comet Kohoutek (Biraud, *et al* (1973), Turner (1973)). The peak antenna temperature $\Delta T_b/T_b$ for these lines are approximately proportional to the ratio $i = (N^+ - N^-)/(N^+ + N^-)$ where $N^{\pm}$ are the total concentrations of $^2\pi_{3/2}$, J = 3/2 molecules in the indicated parity state. In the optically thin, collisionless atmosphere of a comet these populations are determined predominantly by the fluorescent scattering of solar u.v. radiation by 12 absorption lines of the $OH(A^2\Sigma^+ \leftarrow X^2\pi)$ transition. The steady state distribution is only a function of the *relative* solar flux at these 12 absorption wavelengths. The molecules are pumped into a large set of $^2\pi$ states, which then rapidly cascade by infrared transitions back to either the + or - levels of the ground state. Because of the Doppler shift of the absorption spectrum relative to the solar Franhaufer spectrum, the ratio i is a sensitive function of the heliocentric velocity V_h of the comet, and the radio signals can be seen either in absorption or stimulated emission relative to the galactic background temperature T_b, depending on whether the levels are anti-inverted, $i < o$, or inverted, $i > o$.

Biraud, Bourgois, Crovisier, Fillit, Gerard, and Kazes (1974) have published a beautiful paper in which they propose this mechanism, calculate i as a function of V_h, and indeed find excellent agreement with their observations of comet Kohoutek. Similar calculations were made by Mies (1974) for $V_h = \pm 41$ Km/sec. and both studies are in quantitative agreement. There is little doubt that optical pumping is predominantly responsible for the OH-18-cm signal. However, both sets of calculations have ignored the effects of the hyperfine levels by using averaged rate constants for the parity states. We shall study the role of the hyperfine levels in this paper. As we shall see their dominant effect is to produce a small degree of linear polarization of both the radio wave and the fluorescent signals, and otherwise they have very little influence on the resultant spectra.

The incident solar radiation is unidirectional and defines a useful axis of quantization for the magnetic quantum number $-F \leqslant M_F \leqslant +F$ associated with a given parity and F. The fluorescent pumping rate out of the 16 hyperfine levels of the ground state is dependent on these quantum numbers, and a total of 576 $^2\pi$ vibrational-rotational-hyperfine levels are either pumped directly, or reached by intermediate cascade. However, if the incident solar radiation is *unpolarized* then the pumping rates only depend on the *magnitude* of M_F, and not the sign of M_F, and the resultant ground state probability distribution $p^{\pm}(F,M_F)$ generally will be aligned, but cannot be oriented. Thus any radiation processes observed at an angle Θ_f relative to the incident axis may be linearly polarized in the sun-comet-earth plane, but, since $p^{\pm}(F,M_F) = p^{\pm}(F,-M_F)$, the radiation cannot be circularly polarized.

The ultimate determination of $p^{\pm}(F,M_F)$ can be reduced to a simple seven-fold multiplication of a (164x164) stochastic matrix. The resultant distributions for $V_h = \pm 41$ Km/sec.

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are summarized in Table 1. Also tabulated is the average of the quantity $3M_F$ - F(F+1) for each parity and F state. This is proportional to the induced magnetic quadrupole moment and is a measure of the degree of alignment. (For a microcanonical distribution of M_F-states, this quantity is zero and the radiowave signal is unpolarized.) The ratio i is calculated to be -0.463 and +0.451 for V_h = -41 and +41 Km/sec. respectively. This is almost identical to the values -0.465 and -0.453 obtained in previous calculations using absorption rates averaged and summed over initial and final hyperfine states.

The calculated properties of the OH-18-cm signals from comet Kohoutek on 29 November 1973 and 25 January 1974 are presented in Table 2. As predicted, the signals were observed (Biraud, et al (1974)) first in absorption and then in emission on these respective dates. Unsuccessful attempts were made to observe circular polarization of the radiation, which is consistent with our theoretical predictions that only linear polarization should be present. However, the measurements are only accurate to about 20 per cent and we cannot be sure that circular polarization is completely absent.

The maximum linear polarization P_{max} of the radiowave signals occurs at the angle $\Theta_f = 90° \cdot P_{max}$ for the absorption of the 2 → 2 and 1 → 1 lines on 29 November 1973 is -15 per cent and -10 per cent respectively while the comparable emission lines in January 1974 only have maximum polarizations of -3.5 per cent and -0.9 per cent. However, the actual angle of observation from the earth was 135.5° in November and 112.1° in January and the expected polarizations are reduced to -6.7 per cent and -4.7 per cent in November and -3.0 per centand -0.8 per cent in January. Obviously such small polarizations are beyond present detection techniques, and we must conclude that the influence of the non-equilibrium hyperfine distributions predicted in Table 1 cannot easily be observed.

The ratio of the 1667 to 1665 MHz total line intensities is also influenced by the non-equilibrium distribution of hyperfine populations, but the values 1.854 and 1.805 for November and January respectively deviate only slightly from the maximum theoretical ratio of 1.802 predicted for an equilibrium population, and are certainly beyond detectability. This is also true of the polarization of the u.v. fluorescence spectrum. The largest degree of polarization is about 5.0 per cent, which could conceivably be detected. However, even an equilibrated, unaligned distribution of hyperfine levels will result in linearly polarized scattered light, and the non-equilibrium effects only <u>change</u> the degree of polarization by at most about 1.5 per cent.

The calculations we have made of the fluorescent pumping model are based on the following four assumptions:

(1) The fluorescent pumping rate, and the infrared cascading rates are fast compared to any other processes such as collisions or infrared pumping which can influence the population of the -doubled levels of the ground state.

(2) The incident u.v. radiation is unpolarized.

(3) The OH gas is optically thin to the solar radiation.

(4) The OH gas is not exposed to any magnetic or electronic fields. The observations pretty well substantiate assumption (1) since any other mechanism for the inversion or anti-inversion of the -doubled levels would not be dependent on the heliocentric velocity of the comet. The quantitative agreement we have obtained previously with the observed fluorescent spectrum of OH from comet Kohoutek (Mies (1974)) suggests that assumption (3) is satisfied. However, a valid quantitative test of all

the assumptions could best be obtained by accurate measurement of the polarization of the radiowave signals. Substantial deviations from the predictions are expected if any of the assumptions are violated.

References

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Table 1

Calculated Distribution of Hyperfine Levels

STATE				V_h = -41 Km/sec		V_h = +41 Km/sec	
Energy (MHz)	Parity	F	$\vert M_F \vert$[a]	Relative[a] Population	$\langle 3M_F\text{-}F(F+1)\rangle$[b]	Relative Population	$\langle 3M_F\text{-}F(F+1)\rangle$
	+	2	2	0.03470		0.08548	
	+	2	1	0.03294		0.09356	
	+	2	0	0.03234		0.09635	
1720.53	+	2	sum	0.16763	+0.1465	0.45441	-0.2501
	+	1	1	0.03520		0.08944	
	+	1	0	0.03049		0.09199	
1665.40	+	1	sum	0.10089	+0.0933	0. 7087	-0.0189
	+	Total		0.26853[c]	+0.1265	0.72528[d]	-0.1638
	-	2	2	0.07758		0.03272	
	-	2	1	0.09863		0.03527	
	-	2	0	0.10683	-0.6573	0.03611	
53.17	-	2	sum	0.45925		0.17210	-0.2069
	-	1	1	0.08495		0.03403	
0.00	-	1	0	0.10232		0.03456	
	-	1	sum	0.27223	-0.1276	0.10262	-0.0104
	-	Total		0.73147[c]	-0.4602	0.27472[d]	-0.1335

(a) Populations are the same for both F, $+M_F$ and F, $-M_F$ levels.

(b) The averaged value of this quantity is proportional to the induced magnetic quadrupole moment, and is a measure of the degree of alignment in the particular state.

(c) The ratio i = -0.4629 and indicates an anti-inversion of the Λ-doubled levels.

(d) The ratio i = +0.4506 and indicates an inversion of the Λ-doubled levels.

Table 2

Predicted Properties of OH-18-cm Radiation from Comet Kohoutek

		29 November 1973 (V_h = -41 Km/sec)		25 January 1974 (V_h = +41 Km/sec)	
		$F^+ = 2$	$F^+ = 1$	$F^+ = 2$	$F^+ = 1$
$F^- = 2$	$\Delta T_1/C$[(a)]	-0.28693	-0.02652	+0.25994	+0.02825
	β[(b)]	-0.1280	+0.1467	-0.0338	-0.0169
	P_{max}[(c)]	-0.1468	+0.1280	-0.0350	-0.0172
	P_{obs}[(d)]	-0.0671	+0.0672	-0.0299	-0.0148
	ν_o (MHz)	1667.36	1612.23	1667.36	1612.23
$F^- = 1$	$\Delta T_1/C$	-0.02811	-0.15197	+0.02740	+0.14105
	β	+0.0264	-0.0908	+0.0514	-0.0090
	P_{max}	+0.0257	-0.0998	+0.0489	-0.0090
	P_{obs}	+0.0128	-0.0467	+0.0423	-0.0078
	ν_o (MHz)	1720.53	1665.40	1720.53	1665.40

(a) ΔT_1 is the change in antenna temperature for radiation polarized perpendicular to the sun-comet-earth plane. The quantity C is equal to the following: $C = 1.127 \times 10^{-9} (\nu_o/1667) N_c\, g(\nu)\, T_b$ (°K), where N_c is the total column density (cm^{-2}) of ground state OH, $g(\nu)$ is a normalized shape function such that $\int g(\nu) d\nu = 1$, and T_b is the background blackbody temperature which is assumed to be large compared to the fine structure splitting, i.e., $T_b \gg 0.08$°K.

(b) ΔT_{11} for radiation polarized parallel to the sun-comet-earth plane is dependent of the angle of observation Θ_f relative to the axis of the incident solar radiation, $\Delta T_{11} = \Delta T_1 (1+2\beta \sin^2 \Theta_f)$. The degree of polarization, $P = (\Delta T_{11} - \Delta T_1)/(\Delta T_{11} + \Delta T_1)$, is then related to the parameter β as follows: $P(\Theta_f) = \beta \sin^2 \Theta_f / (1+\beta \sin^2 \Theta_f)$.

(c) The maximum polarization occurs as $\Theta_f = 90°$, where $P_{max} = \beta/(1+\beta)$.

(d) P_{obs} is the degree of polarization expected on the date of observation. The observation angle $\Theta_f = 135.5°$ on 29 November 1973 and Θ_f 112.1° on 25 January 1974.