HIGH VELOCITY OH IN BIPOLAR FLOWS

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ABSTRACT. High velocity OH was detected in absorption in several star forming regions. The supersonic OH shows similar bipolar geometry as the CO. The absorbing OH appears to trace the part of the outflows with the highest velocities and lower densities, and provides information on the structure of the outflows at large distances from the central source. At scales of 0.1 to 0.5 parsecs the outflows are elongated in the direction of the steepest density gradient in the ambient cloud. The transitions in the supersonic OH are markedly subthermal ($T_{ex} < 3.8$ K), since the radiation that is being absorbed is the cosmic background plus a small galactic contribution. We propose a cooling mechanism for the OH analogous to the adiabatic magnetic cooling of paramagnetic salts used in low temperature physics. Magnetic cooling is a potentially important mechanism for astrophysics.

1. INTRODUCTION

The OH radical has not been observed systematically in outflow regions. This molecule is known to be widespread in molecular clouds and to thermalize at densities lower than the CO. Thus, the OH is expected to give information on the possible presence of low-density gas in the outflow, difficult to detect even in CO.

Most of the research on molecular outflows that is being conducted at the moment aims to reveal the structure and physical processes at the central regions of the outflows. However, collimated outflows are known to reach distances of the order of 0.5 pc. from the central source. In this context, OH observations may be important to find the cause of this collimation in the large scale properties of the ambient cloud, as well as to understand the way in which star formation affects the structure of the environment in which it occurs.

The physics of the OH in supersonic molecular outflows is also interesting. Becouse the spin temperature of the molecules is lower than that of the cosmic background radiation, a cooling mechanism is needed. Magnetic cooling is proposed as a working hypothesis for more detailed models.

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2. OBSERVATIONS AND RESULTS

The 1612, 1665, 1667 and 1720 MHz lines of OH were surveyed using the 305-m antenna of the Arecibo Observatory. At the observing frequencies, the main beam has a full width at half power of 2.9 arc minutes. The receiver was an 18-22 cm GaAsFET, which has a system temperature of 40 K. Two circular polarizations were observed, with an 1008 channels autocorrelation spectrometer split into banks of 2.5 MHz each, obtaining a channel width of 1.76 km s^{-1} and a velocity coverage of 440 km s^{-1} per bank.

23 sources with previously known CO outflows were surveyed. Most of the star forming regions were selected from the catalogue by Bally and Lada (1983). 20 of the observed sources are located in directions of the outer Galaxy, where problems arising from confusion with background and foreground gas are minimized. 3 sources in the inner Galaxy that are at galactic latitudes greater than 3° were also surveyed.

In figure 1 are shown the 1665 and 1667 MHz lines in the direction of the infrared source IRS1 in the star forming region Sharples 255. The sharp emission at low velocities arises in the ambient cloud. One of the most striking features of these profiles is the broad absorption extending over a range of velocities of up to 150 km s^{-1}.

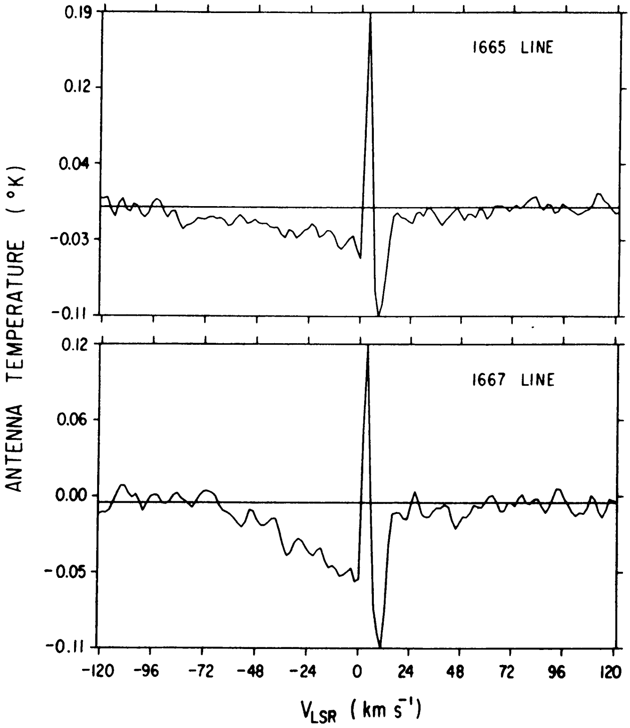

Figure 1. 1665 and 1667 MHz transitions of OH in the direction of the infrared source IRS1 in the star forming region Sharples 255. The broad absorption arises in the molecular outflow.

TABLE I. STAR FORMING REGIONS WITH DETECTED OH OUTFLOWS

SOURCE	ΔV_{OH} (km s^{-1})	ΔV_{CO} (km s^{-1})	$\frac{T_A\ \Delta V_{OH}\ (1667)}{T_A\ \Delta V_{OH}\ (1665)}$
NGC 1333	85	40	1.55
L 1551	50	30	1.50
NGC 2071	100	75	1.90
S 255	112	26	1.00
CRL 961	17	30	1.50
NGC 2264	24	28	--
SERPENS	28	28	1.80
L 723	50	20	1.40
B 335	30	30	1.70

High velocity OH was detected in absorption in the 9 sources listed in table I. The velocity widths of the OH absorption at the -0.01 K level and the widths of the high velocity CO emission from Bally and Lada(1983) are given. The ratio of the integrated high velocity flux absorbed in the 1665 and 1667 MHz lines is also indicated.

In the following we present maps of three regions that are resolved by the 2.9 arc minutes telescope beam and show relatively strong absorption signals.

L 1551: The detection of high velocity OH in L 1551, the archetype and best studied bipolar outflow, was reported by Mirabel et al. (1985). Figure 2 shows a superposition of the aproximate extents of the CS (Kaifu et al. 1984), NH_3 (Torrelles et al. 1983), CO (Snell, Loren and Plambeck 1980), and OH (Mirabel et al. 1985) line emission (or absorption). The transitions from these molecules trace the gas at different densities, from the high densities signaled by the CS $\{n(H_2)\simeq 10^5\ cm^{-3}\}$, to the low densities indicated by the OH $\{n(H_2)\simeq 10^2\ cm^{-3}\}$. The CS toroid may be focusing the outflow. The elongated NH_3 structure observed by Torrelles et al.(1983) shows a small velocity gradient in the direction of the outflow and may be constituted by dense gas. The CO traces the intermediate velocity gas, and the absorbing OH seems to be coming from regions more extended than the CO.

In figure 3 we show the integrated high velocity absorption superimposed on the contours of the corrected antenna temperature of the OH emission. The OH emission traces the density of the ambient cloud and has a very good similarity with the H_2CO absorption at λ6 cm, which was measured by Sandqvist and Bernes (1980). Figure 3 shows that for scales larger than 0.1 pc. the high velocity flows of OH and CO are collimated along the directions of the steepest density gradients in the ambient cloud. In figure 3 we have superimposed on the density contours the vectors obtained by Vrba, Strom and Strom (1976) for the direction and magnitude of the linear polarization of light from stars background to the perisphery of L 1551. The field seems to be aligned along directions that in general form angles smaller than 30°with the axis of the outflow.

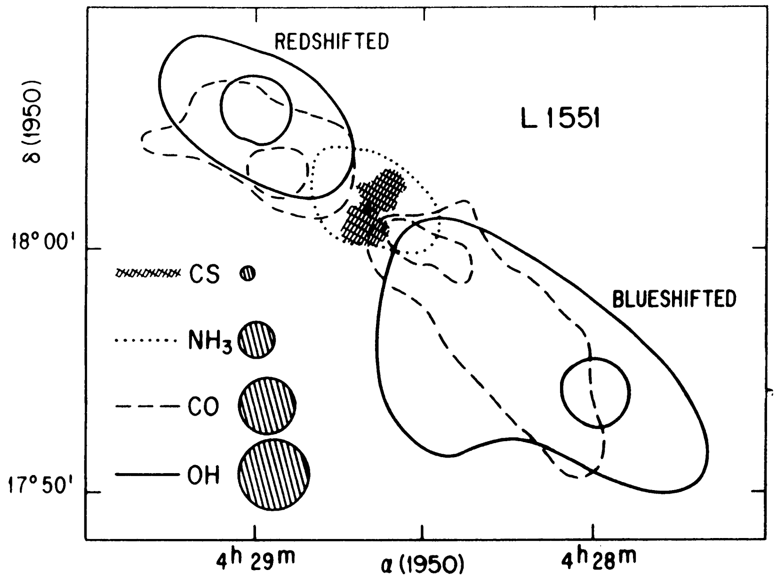

Figure 2. Superposition of the approximate extents of the CS (Kaifu et al. 1984), NH_3 (Torrelles et al. 1983), CO (Snell et al. 1980), and OH (Mirabel et al. 1985) line emission (or absorption) regions in L 1551. The OH absorption apparently represents the most extended, tenuous and high-velocity part of the bipolar flow.

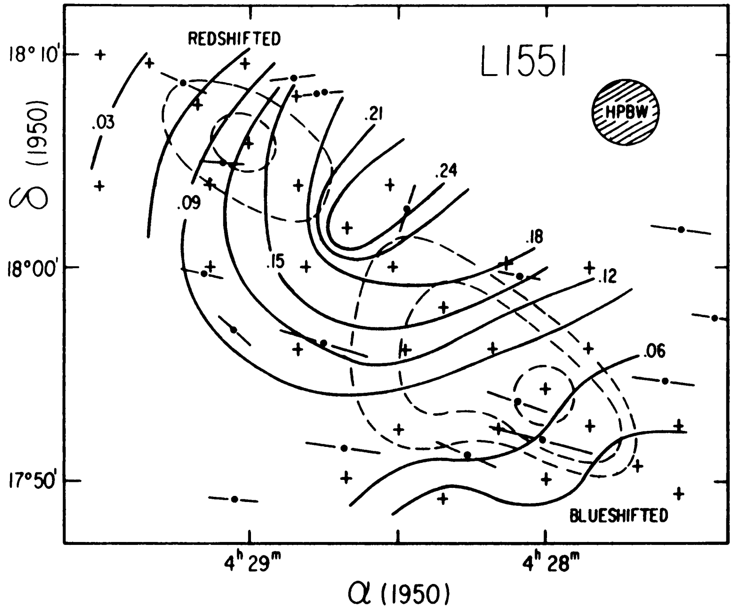

Figure 3. The high velocity OH (broken lines) is collimated in the direction of the steepest density (continuous lines) gradient of the ambient cloud. The direction and magnitude of the linear polarization from stars (Vrba et al. 1976) are also shown.

NGC 1333: South of the reflection nebula NGC 1333 lies the group of Herbig-Haro objects HH7-11. Associated to these objects Edwards and Snell (1983) found a CO outflow. A 1667 MHz map of the high velocity OH absorption is shown in the left panel of figue 4. The redshifted and blueshifted outflows partially overlap, having as the CO two distinct maxima displaced one from the other. However, a detailed comparison shows that the OH is detected at greater distances from the center of the outflow than it is the CO. The blueshifted OH extends several arc minutes to the southwest into a region of low density in the ambient cloud. The right panel of figure 4 shows a map of the peak temperature emission in the 1667 MHz line which is a tracer of the density in the ambient cloud. A comparison between the left and right panels shows that the axis of the blueshifted lobe coincides with the direction of a gradient in the density of the ambient cloud. Furthermore, there is a striking coincidence between the northwest borders of the outflow and the highest densities of the environment.

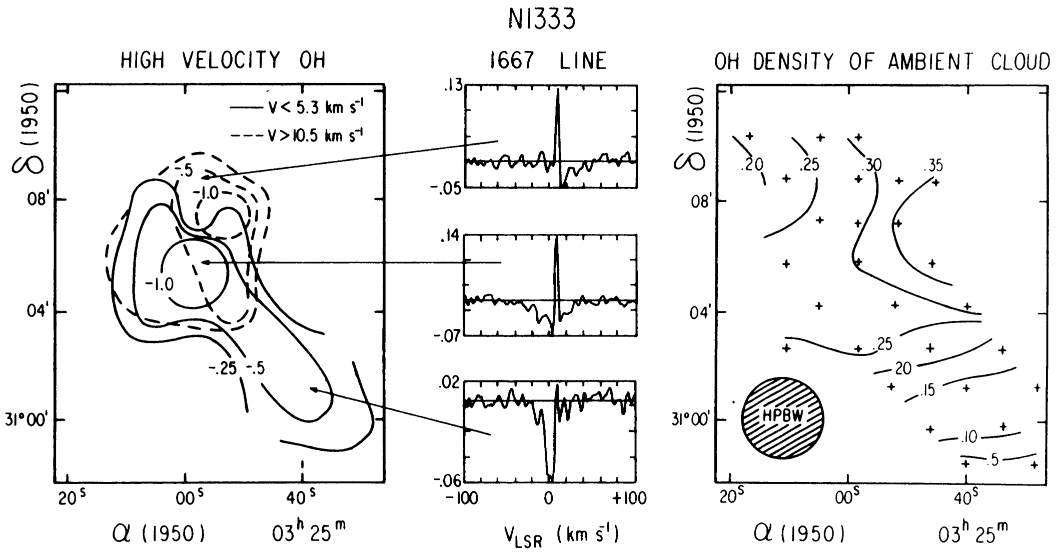

Figure 4. OH in the star forming region NGC 1333. The panel at the left shows the integrated high velocity absorption at 1667 MHz in units of K km s^{-1}. The redshifted and blueshifted OH show an anisotropic distribution. The panel at the right represents the peak temperature of the emission in the 1667 MHz line which is proportional to the gas density in the ambient cloud. The blueshifted high velocity OH is collimated by the density gradient in the ambient cloud.

L 723: High velocity OH in this dark cloud was first detected as a weak signal at the 140 foot radiotelescope of NRAO. An Arecibo map of the integrated intensities of the OH absorption at high velocities is shown in figure 5. It shows an E-W symmetric displacement of the blueshifted and redshifted OH in good agreement with the CO map by Goldsmith et al. (1984). The symmetry of the high velocity OH suggests two outflows with a common source on the far infrared object. The higher contours of the OH absorption and the CO emission do not coincide exactly.

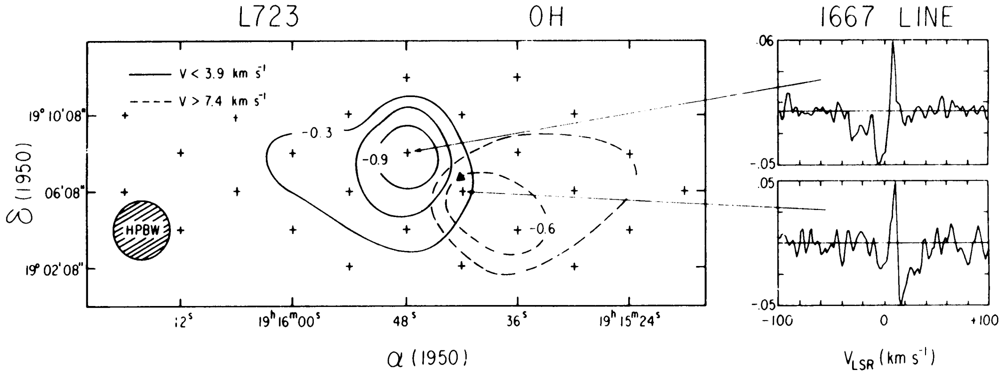

Figure 5. Integrated high velocity OH absorption at 1667 MHz in L 723. Units are K km s^{-1}. The outflow seems to be centered in the infrared source represented by the dark triangle.

We can summarize our results on high velocity OH as follows:

1. High velocity OH has been detected in absorption in 9 out of 23 star forming regions with previously known CO outflows.
2. The column density ratio of the high velocity absorption in the 1667 and 1665 MHz transitions is always in the range of 1.0 to 1.9.
3. No circular polarization is detected in the main transitions of the high velocity OH. For the stronger signals it is found an upper limit of 10% for the circularly polarized absorption.
4. In the 1612 and 1720 MHz satellite lines the OH outflow was detected marginally and only in absorption. The high velocity flux being absorbed in the satellite lines is less than 20% the flux absorbed in the 1667 MHz line.
5. In more than 50% of the sources the OH is detected up to higher velocit than the CO.
6. The geometry of the molecular outflows first seen in CO is also evident in the OH. However, the high velocity gas traced by the OH

usually is more extended than that traced by the CO. Furthermore, the position of the maximum OH absorption column density often does not coincide with the position of maximum column density of the high velocity CO.

7. In regions with lower density in the ambient cloud, it is more evident the larger extension of the OH outflow.

8. The OH observations of L1551 and NGC 1333 show that the molecular outflows are collimated in the direction of the steepest density gradient in the ambient cloud.

3. DISCUSSION

3.1. The excitation temperature of OH

In most of the sources the absorption spectra show the 1667 line deeper than the 1665 line. This behavior is consistent with optical thin transitions that share a common excitation temperature since then one expects $T_A(1667)/T_A(1665)=1.8$. Assuming that this is the case and that the source fills the beam, the line antenna temperature will be given by

$$T_L \simeq \eta_B(T_S-T_r)\zeta_\circ$$

where η_B is the beam efficiency, T_S the spin temperature, T_r is the total background temperature, and $\zeta_\circ$ is the optical depth at the center of the line.

To estimate the excitation conditions of the absorbing OH in the outflows we must know the total background temperature T_r. Continuum observations at λ=18 cm across L 1551, NGC 1333 and NGC 2071 show that in these regions there are no discrete sources with corrected antenna temperature greater than 0.2 K. This implies that the total background temperature is formed mainly by the cosmic background plus a small contribution from the large-scale nonthermal galactic background. Thus

$$T_r = 2.8\ \mathrm{K} + T_g$$

with typically $T_g \simeq 1.0$ K at the latitudes of the observed sources (Reich 1982). Since the high velocity OH is seen in absorption we can conclude that

$$T_s < T_r = 3.8\ \mathrm{K}$$

Assuming that $(H_2/OH)>10^6$ (Turner and Heiles 1974) and that the OH lines are not thermalized for densities $n(H_2)<10^2\ \mathrm{cm}^{-3}$ (Goss 1968), Mirabel et al.(1985) derived a more stringent limit of

$$T_s < 0.6\ \mathrm{K} \tag{1}$$

for the OH in bipolar outflows.

3.2. The cooling mechanism

Mirabel, Blum and Nieves (1985) have shown that in the absence of any other mechanism for transitions except the interaction with the background radiation, after a short time compared with the age of the outflow the gas must be in equilibrium with the radiation. Since the high velocity OH is seen in absorption rather than in emission, a nonthermal mechanism that brings the excitation temperature to values below that of the cosmic background is required.

The cooling mechanism proposed by Mirabel, Blum and Nieves (1985) can be easily understood in a thermodynamic context. The magnetic moments of the paramagnetic OH are initially aligned by a relativelly intense magnetic field. If after thermal relaxation takes place, the OH moves along a negative gradient of magnetic field, it is excerting magnetic work, and therefore, must cool down. In essence, This mechanism is analogous to the adiabatic nuclear cooling of paramagnetic salts used by low temperature physicists (Reif 1965).

In order to explain the absorption by this mechanism we must assume the following: (i) The OH streams from a region where the density of the gas and the intensity of the magnetic field are relativelly high, to a region where the density as well as the intensity of the magnetic field are relativelly small. For the known conditions in star forming regions it is possible that the initial (B_i) and final (B_f) magnetic field intensities are related by

$$B_i/B_f > 6 \qquad (2)$$

(ii) We must also assume that due to collisions between the OH molecules and other molecules and atoms in the densest region, the spin and angular momentum oscilations produced by the magnetic field are damped.

The final spin temperature $(T_s)_f$ can be calculated as follows (Reif 1965). At the densities under consideration, the mutual interaction between the magnetic moments of the molecules can be considered negligeable, so the entropy is a function only of B/T_s. Conservation of entropy then yelds

$$(T_s)_f = T_r(B_f/B_i) \qquad (3)$$

Assuming T_r=3.8 K, which results from the addition of the cosmic background plus a small galactic contribution (1.0 K), and introducing (2) in (3), we obtain $(T_s)_f < 0.6$ K, the stringent limit found from observations (Mirabel et al. 1985).

Magnetic cooling may be an important physical mechanism for astrophysics. Supersonic OH at subthermal temperatures has been found not only in star forming regions but also in accelerated clouds in supernovae remnants. Detailed models that will account for the specific pumping mechanism of the OH radical in the context of concrete astronomical scenarios are needed.

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PUDRITZ: Have you estimated the field strengths required for your mechanism to occur?

MIRABEL: With relatively low field strengths this mechanism could explain the phenomenon. The cooling depends essentially on the existence of a gradient of field intensity rather than on its absolute value.

WILSON: Must T_{ex} of OH be < 2.7 K, from your data? What is the time scale for the OH coming into equilibrium with the 2.7 K background radiation?

MIRABEL: The OH we detect in absorption must have excitation temperature smaller than 2.7 K. Our calculations show that in a few years the OH would come into equilibrium with the cosmic radiation, unless continuous cooling competes successfully with the background photons.

KUTNER: Can you rule out infrared pumping of the OH?

MIRABEL: Since OH is detected in absorption at distances of 0.5 pc from the energy source, it is unlikely that infrared pumping would be efficient.

HOLLENBACH: Why did you assume that the H_2 density was smaller than 100 cm^{-3} in the OH region?

MIRABEL: Because it is known that the OH thermalizes at densities greater than 100 cm^{-3}.