HIGH VELOCITY GAS IN THE ORION NEBULA

Nicholas Z. Scoville
Department of Physics and Astronomy
University of Massachusetts

ABSTRACT

Observations at both millimeter and infrared wavelengths reveal energetic activity within the core of the Orion molecular cloud in the vicinity of the KL-BN cluster. New observations of the high velocity CO emission at 2.6-mm with improved angular resolution (HPBW = 44") show that the source diameter averages 4×10^{17} cm and the center of mass is displaced 10-12" north of the Kleinmann-Low nebula to a position close to the Becklin-Neugebauer object. The total mass of high velocity gas in the core region is $\sim 10\ M_{\odot}$ (assuming 10% of the carbon is in CO); the present kinetic energy is 4×10^{47} ergs. Further evidence that BN may be the ultimate source of this energy is provided by high resolution infrared spectra which show both ionized and high temperature ($T_k \gtrsim 3000$ K) neutral gas in this source. CO bandhead emission ($v = 2 \rightarrow 0$, $3 \rightarrow 1$, and $4 \rightarrow 2$) seen in BN is thought to arise from collisional excitation at high temperatures in a very dense ($n_H > 10^{10}$ cm^{-3}) region only 1 AU in size. And high spectral resolution profiles of the Br α and γ recombination lines show that the HII region previously detected in BN apparently has motions over 100 km s^{-1}.

Over the last few years our impression of the evolutionary status of the Kleinmann-Low nebula at the core of the Orion cloud has radically changed as a result of several entirely independent observational discoveries. Taken together, these new observations suggest that the core region is evolving on timescales as short as a few thousand years rather than 10^4 to 10^5 years as previously contemplated. Observations of millimeter wavelength rotational transitions of carbon monoxide reveal emission far out in the line wings at ±50 km s^{-1} relative to the cloud center of mass at $V_{LSR} = 9$ km s^{-1} (Zuckerman, Kuiper, and Kuiper 1976; Kwan and Scoville 1976, Phillips et al. 1977). In the near infrared, high spectral resolution observations by Gautier et al. (1976) detect several lines at 2μ identified with decay from the v = 1 state of H_2 at the equivalent energy $h\nu/k$ of 6800 K (reviewed here by Beckwith). In the immediate vicinity of the strongest near infrared source (BN), there is also now evidence of both ionized gas (Grasdalen 1976)

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and hot, high density neutral gas (Scoville, Hall, Kleinmann, and Ridgway 1979).

For several years observers of millimeter wavelength molecular lines in the Orion nebula have recognized that the emission profiles show two distant components: a spike feature at 9 km s^{-1} of width $\Delta V \simeq 5$ km s^{-1} and a "plateau" component centered at about the same velocity but with much larger width $\Delta V \simeq 40$ to 100 km s^{-1}. The narrow component is spatially extended and is therefore emitted from the large Orion cloud; the broad feature is seen only at the infrared nebula. Our most recent millimeter wavelength observations (Solomon, Huguenin, and Scoville 1979) are designed to better define the spatial characteristics of the $J = 1 \rightarrow 0$ CO line. We chose this line for the best possible indication of the mass distribution since the excitation requirements of CO are very modest, CO is least likely to suffer abundance gradients due to shock chemistry, and choosing from amongst the low rotational transitions of CO, the $1 \rightarrow 0$ line is the most optically thin. For these observations the highest possible angular resolution (44") was provided by the 45-foot FCRAO telescope at the University of Massachusetts. Figure 1 shows data taken along a declination strip which crosses both KL (at $\Delta\delta = 0$) and BN (at $\Delta\delta = 0'.2$). The apparent half-power size of 57" for the high velocity emission (measured at 20 km s^{-1} from line center) translates into a true radius of $\sim 2 \times 10^{17}$ cm when corrected for the 44" primary beam of the FCRAO telescope.

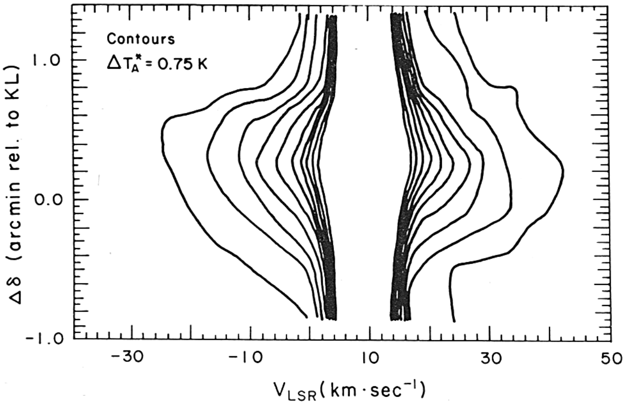

Figure 1. Map of the $J = 1 \rightarrow 0$ CO emission along a declination strip crossing KL at $\Delta\delta = 0'$ and BN at $\Delta\delta = 0'.2$. Data was taken with the 45-foot FCRAO telescope for which the HPBW = 44".

For the declination strip shown in Figure 1, a careful comparison of the source size measured at different velocities reveals evidence that the size increases somewhat for greater velocities further out in the line wings (e.g. compare 10 km s^{-1} with 25 km s^{-1} from line center). If verified for the right ascension direction, this behavior would provide strong support of kinematic models in which the largest velocities occur at greatest radius in the source (e.g. $v \propto r$).

The smoothness of the CO and ^{13}CO profiles strongly favors dynamical models with large scale motions such as rotation, collapse, or expansion to account for the line width. The alternatives, that the broadband emission arises from a superposition of narrow lines from randomly moving clumps of gas each unresolved in the beam, would produce a "spikey" appearance in CO and ^{13}CO profiles unless there were a very large number of such clumps. The absence of observable velocity gradients across source and the high degree of symmetry in all the line profiles make rotation models unlikely. Moreover, if high velocity rotation is to be stabilized gravitationally by the mass of the region itself, then an interior mass of 10^4 $M_\odot$ is required. Such a high mass, if it is contained in the gas, would be expected to produce very optically thick CO lines ($\tau > 400$) and cause the ^{13}CO to be equally bright. The same argument also rules against gravitational collapse models. Collapse and expansion models where the radial motion is all at a constant velocity may also be ruled out from the profile shapes.

For a differentially collapsing or expanding envelope the velocity can be either a decreasing or increasing function of radius. The argument against the first case is provided by the observational result that the size of the emission at larger velocities is at least equal to that at the lower velocities. A final argument favoring an expansion model over collapse is the discontinuous change in chemical abundances between the outer cloud, the "spike" feature, and the "plateau" source. If the high-velocity gas is merely a collapsed core pulled in from the larger cloud, then why are the chemical abundances so radically different? On the other hand, if the high-velocity gas is ejected from some condensed core where the chemistry is different, an abrupt change in abundances is entirely expected at the interface between the outflowing material and the ambient medium. Indeed the relatively high abundance of SiO in the high-velocity gas is perhaps indicative that the temperature of the core where this gas was chemically processed was much higher than the outer Orion cloud (e.g. Lada, Oppenheimer, and Hartquist 1978).

The total mass of the high velocity gas may be estimated assuming that the CO is optically thin and has a mean excitation temperature of 150 K throughout the envelope. For a $[CO/H_2]$ abundance ratio of 1.2×10^{-4} (10% of C in CO), the mass estimate is about 10 $M_\odot$. The kinetic energy of the high velocity gas is 4×10^{47} ergs at present but would of course have to have been much greater ($\sim 10^{50}$ ergs) in the past if most of the 10 $M_\odot$ is swept up material rather than original ejecta. If the high velocity gas has been accelerated by radiation pressure over the expansion time scale (R/v = 1000 yrs), the rate of momentum transfer must be 3×10^7 $L_\odot/c$. Since the required luminosity is 300 times greater than what is observed in the far infrared from the Kleinmann-Low nebula (Werner et al. 1976), it appears unlikely that the envelope is driven by radiation pressure.

In the above model which was originally proposed by Kwan and Scoville (1977) for the CO emission, a shock heated gas layer must naturally occur where the expanding gas confronts the stationary molecular cloud. High gas temperatures, possibly giving rise to the observed 2μ H_2 emission, should be expected in a shell with angular extent on the sky equivalent to the ≳40" size of the high velocity CO. The hot shell would be thin ($\Delta r \leqslant 10^{14}$ cm) due to the fast cooling of the gas (reviewed here by Hollenbach). In view of this proposed connection between the H_2 emission and the plateau source, it is significant that the diameter measured here for the mm CO emission is nearly equal to that of the 2μ H_2 emission, and the 60-90 km s^{-1} widths of the H_2 lines measured at high resolution (Nadeau and Geballe 1979, Hall <u>et al</u>. 1979) are comparable with the millimeter line widths.

A second goal of the recent millimeter CO observations was to identify the source of origin of the energetic phenomena in the infrared cluster. From the data of Figure 1 it is clear that the center of mass is shifted about 10-12" north of the KL position to a point close to BN; similar data in right ascension shows no significant displacement from $\Delta\alpha = 0\overset{s}{.}0$. Frequent pointing on planets at the time of these observations indicates an absolute position accuracy of ±5"; moreover three repetitions of this experiment at FCRAO and one at the 36-foot NRAO telescope all gave consistent displacements north of KL. (The 5" accuracy of this central position determination does not decisively rule out the source IRc2 which was shown by VLBI between FCRAO and NEROC to be the source of SiO maser emission (Genzel <u>et al</u>. 1979)).

Other evidence of the very special nature of the BN object has been contributed by high resolution infrared spectroscopy recently made possible by a Fourier-Transform-Spectrometer on the 4-m KPNO telescope. The IR absorption lines seen in the continuum of BN sample the entire line-of-sight down to radius $r \leqslant 10^{15}$ cm. At 4.6μ Hall <u>et al</u>. (1978) have reported two CO absorption systems at V_{LSR} = +9 and −20 km s^{-1} which they ascribe to the large Orion molecular cloud and to the foreground half of the plateau source respectively. More recently a third CO system (in emission!) has been seen at V_{LSR} = +20 km s^{-1} (Kleinmann <u>et al</u>. 1979).

Perhaps even closer to BN is the ionized gas responsible for the near IR recombination lines (Grasdalen 1976; Joyce, Simon, and Simon 1978). The doppler widths of these lines are up to 100 km s^{-1} (Hall <u>et al</u>. 1978). Finally there now exists data on the neutral gas close to the surface of BN. At 2.3μ we recently detected the CO overtone bandheads ($v = 2 \rightarrow 0$, $3 \rightarrow 1$, and $4 \rightarrow 2$), the last of which arises from a level at E/k = 19000 K (Scoville <u>et al</u>. 1979). Analysis of the latter observations indicates that the overtones must arise from an ultrahigh density ($n_H > 10^{10}$ cm^{-3}), compact region (~1 AU) near BN. The temperature here must be > 3000 K.

I have described here only a part of the observational data at both millimeter and infrared wavelengths which seem to be converging towards a very exciting picture of the Orion nebula. We find consistent evidence from both sets of observations suggesting the occurrence of very energetic phenomena within the young star cluster. The total kinetic energy estimated to exist in the core at present is 4×10^{47} ergs or about 0.1% the energy of a supernova. The original energy must have been much greater as much of the kinetic energy could have been liberated earlier as heat. At present BN (as opposed to IRc 2) appears as a prime candidate for the origin of this energy due to the near-IR detection of an HII region and high temperature neutral gas in close proximity. Future near IR observations at high sensitivity will be important to clarify the nature of IRc 2.

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DISCUSSION FOLLOWING SCOVILLE

Elitzur: If the shock velocity is ~ 50 km s^{-1}, the post-shock temperature is $\sim 10^5$K. So far there is no evidence for such high temperatures. Do you have any idea how this can be resolved?

Scoville: Perhaps the highest velocity gas is accelerated in clumps so that the bulk of the material can be maintained at low temperature. I should point out that the rotational lines at millimeter wavelengths are not sensitive indicators of the very hot shocked gas, since the column length of hot gas behind the shock is only 10^{13}-10^{14}cm.

T. Wilson: The maps of NH_3, made with the Bonn 100-m telescope, and of HCN, made with the Onsala 20-m dish, both with angular resolution

∿40", indicate that the peak of the plateau appears to be south of your peak position. The angular size of the NH_3 plateau is consistent with a region of size <20".

Scoville: There are other molecules in the plateau source which peak to the north of our position (e.g. HCO^+). It is now becoming evident that different molecules peak at different locations in the Orion core. The reasons may lie in the varying excitation requirements of different molecules, or in the occurrence of shock-chemistry which can cause differential gradients in molecular abundance across the source. In my own opinion the CO emission gives the best estimate of the true center of mass because CO is most easily excited and is rather insensitive to shock processing. Among the various CO lines ($J = 3 \rightarrow 2$, $2 \rightarrow 1$, and $1 \rightarrow 0$), the $1 \rightarrow 0$ line is preferable due to its lower optical depth, $\tau < 1$ for this region.

Zuckerman: In distinguishing between stellar-wind models and explosive models, the dependence of the source size on velocity is important. You said your observations suggest that the source size is increasing at the larger velocities. Would Dr. Phillips be willing to comment on source-size measurements he may have made of the $2 \rightarrow 1$ line of CO, and indicate whether his measurements agree with yours?

Phillips: CO($2 \rightarrow 1$) observations from the Owens Valley 10-m telescope have 25 arcsec resolution. We do not find evidence that the size of the plateau source increases as velocity shifts from the central velocity. In fact, there may be some evidence for a decrease, at least in right ascension.

Scoville: Our measurements of the putative increase are in declination only. Other possible discrepancies between our $J=1 \rightarrow 0$ and your $2 \rightarrow 1$ observations might be ascribed to the higher opacity of the $2 \rightarrow 1$ line (assuming no observational errors!).

Staude: Your sketch of the immediate surroundings of BN suggests axial symmetry, maybe the presence of a dense disk around the central star. Is there any specific evidence for that? In describing the IR polarization data of BN we assumed scattering in an unresolved bipolar distribution of dust (Elsasser and Staude, 1978, Astron. Astrophys. 70, 43) similar to that observed in the spatially resolved case of S106 (Eiroa et al., 1979, Astron. Astrophys. 74, 89).

Scoville: We have no direct evidence of a disk surrounding BN, only indirect evidence that there is both dense neutral gas and ionized gas near BN. The former is implied by the CO $\Delta\nu = 2$ bandhead observations, the latter by the near-IR Brackett α and γ lines. One possible geometry in which both may occur is that of a neutral disk, with ionized gas above and below the disk but still in view of the central UV source.

Elmegreen: The temperature, density, and size of the source, and the fact that neutral gas occurs close to the BN star (as derived from your CO bandhead observations), all suggest that there is a protoplanetary type of disk surrounding the star.

Scoville: That is the model presented in my sketch. I should emphasize again that there is no direct evidence of a disk, only indirect evidence. The precise geometry is not clear.