DISCOVERY OF AN EXPANDING MOLECULAR BUBBLE IN ORION BN/KL

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ABSTRACT

During their infancy, stars are well known to expel matter violently in the form of well-defined, collimated outflows. A fairly unique exception is found in the Orion Becklin–Neugebauer/Kleinmann–Low star-forming region where a poorly collimated and somewhat disordered outflow composed of numerous elongated “finger-like” structures was discovered more than 30 years ago. In this Letter, we report the discovery in the same region of an even more atypical outflow phenomenon. Using 13CO(2–1) line observations made with the Submillimeter Array, we have identified there a 500–1000 year old, expanding, roughly spherically symmetric bubble whose characteristics are entirely different from those of known outflows associated with young stellar objects. The center of the bubble coincides with the initial position of a now defunct massive multiple stellar system suspected to have disintegrated 500 years ago and with the center of symmetry of the system of molecular fingers surrounding the Kleinmann–Low nebula. We hypothesize that the bubble is made up of gas and dust that used to be part of the circumstellar material associated with the decayed multiple system. The Orion hot core, recently proposed to be the result of the impact of a shock wave onto a massive dense core, is located toward the southeast quadrant of the bubble. The supersonic expansion of the bubble and/or the impact of some low-velocity filaments provide a natural explanation for its origin.

Key words: ISM: individual objects (Orion BN/KL) – ISM: jets and outflows – ISM: molecules – stars: pre-main sequence – techniques: spectroscopic

Online-only material: color figures

1. INTRODUCTION

During more than 40 years ago, the Becklin–Neugebauer/Kleinmann–Low (BN/KL) region in Orion (Becklin & Neugebauer 1967; Kleinmann & Low 1967) remains quite enigmatic. It is at the center of a fast (30–100 km s⁻¹) and massive (∼10 M☉) outflow particularly prominent in molecular hydrogen emission at near-infrared wavelengths (Kwan & Scoville 1976; Allen & Burton 1993; Taylor et al. 1984). Composed of numerous elongated “finger-like” structures, this outflow has a very peculiar morphology suggestive of an explosive origin. A strong and turbulent hot molecular core (Wright et al. 1996; Blake et al. 1996; Liu et al. 2002) associated with intense maser emission from several molecular species (Gaume et al. 1998; Cohen et al. 2006; Zapata et al. 2009a) also lies in the BN/KL region, but the very nature of this hot core and its relation to the outflow remain debated. Three massive young stars (BN, I, and n) are known to be moving away from the KL nebula (Plambeck et al. 1995; Gómez et al. 2005, 2008) at a few tens of km s⁻¹. Their velocity vectors point away from a common point of origin where the three stars must have been located about 500 years ago. This suggests that they were originally members of a multiple system that dynamically decayed very recently (Rodríguez et al. 2005; Gómez et al. 2005, 2008). Remarkably, our recent molecular observations of the outflow associated with BN/KL (Zapata et al. 2009b) showed that the elongated fingers forming that flow also point exactly away from the position where the initial multiple stellar system was located. Moreover, in this study, we found that the dynamical age of the outflow is consistent with about 500 years. It is, therefore, very likely that the same energetic phenomenon that led to the acceleration of the stellar sources BN, I, and n was also responsible for the explosion that gave birth to the peculiar gaseous outflow in the BN/KL region of Orion.

2. OBSERVATIONS

In order to further explore the interrelation between the various energetic phenomena occurring in Orion BN/KL, we have carried out interferometric observations of the region in the optically thin 2→1 line of 13CO at ν = 220.3 GHz using the Submillimeter Array (SMA; Ho et al. 2004). This transition is a reliable indicator of the kinematics and mass of the region observed. The observations were collected in 2007 January and 2009 February while the SMA was in its compact and sub-compact configurations, with baselines ranging in projected length from 6 to 58 m; this provides an angular resolution of about 4″. The digital correlator was configured to provide a spectral resolution of 0.40 MHz, corresponding to a resolution in velocity of 1.05 km s⁻¹. The zenith opacity (τ_{220GHz}) was ∼0.1–0.3, indicating reasonable weather conditions. Observations of Uranus and Titan provided the absolute scale for the flux density calibration. The gain calibrators were the quasars 0530+135, 0541−056, and 0607−085. The data were calibrated using the IDL superset MIR, originally developed for the Owens Valley Radio Observatory (Scoville et al. 1993) and adapted for the SMA. The calibrated data were imaged and analyzed in a standard manner using the MIRIAD, GILDAS, and AIPS packages. We used the ROBUST parameter set to 2 to obtain a slightly better sensitivity sacrificing...
some angular resolution. The line image rms noise was around 100 mJy beam$^{-1}$ for each channel.

3. RESULTS AND DISCUSSION

The $^{13}$CO(2–1) line detected in our observations is broad, extending from about $-30$ km s$^{-1}$ to $+40$ km s$^{-1}$ in radial velocity. The structure of the emitting region is shown in Figure 1, where we present separately the blueshifted (from $-31$ to $-18$ km s$^{-1}$; upper panel) and redshifted (+23 to +33 km s$^{-1}$; lower panel) integrated intensity maps. In Figure 1, we also show (as contours) the integrated intensity of the high-velocity fingers (from $-130$ to $-35$ km s$^{-1}$ for the approaching velocities, and from +35 to +120 km s$^{-1}$ for the receding velocities) traced by $^{12}$CO(2–1) emission (Zapata et al. 2009b) and the positions and proper motions of the runaway sources (BN, I, and n). The

Figure 1. Color and contour images of the blueshifted (upper panel) and redshifted (lower panel) integrated $^{13}$CO(2–1) line emission from the molecular bubble overlaid with the $^{12}$CO(2–1) filaments. Upper panel: the white contours represent the blueshifted $^{13}$CO(2–1) emission and are at $-2, 2, 3,$ and $4$ times $2.5$ Jy beam$^{-1}$ km s$^{-1}$. The blue contours represent blueshifted $^{12}$CO(2–1) emission and are at $-4, 4, 8, 16, 24, 32, 38, 42,$ and $52$ times $2$ Jy beam$^{-1}$ km s$^{-1}$. Lower panel: the yellow contours represent the redshifted $^{13}$CO(2–1) emission and are at $-2, 2, 3, 4,$ and $5$ times $13$ Jy beam$^{-1}$ km s$^{-1}$. The orange contours represent redshifted $^{12}$CO(2–1) emission and are at $-4, 4, 8, 16, 24, 32, 38, 42,$ and $52$ times $2.7$ Jy beam$^{-1}$ km s$^{-1}$. In both panels the blue and red points represent the position of the $^{12}$CO(2–1) emission peaks in every velocity channel. The synthesized beam of the line image is $4.2'' \times 3.2''$ with a P.A. of $-4.0^\circ$. The wedge indicates the line emission in mJy beam$^{-1}$ km s$^{-1}$. The red and green filled dots mark the positions of the runaway sources BN, I, and n (Gómez et al. 2005). The vectors on these sources represent the direction of their proper motion (Rodríguez et al. 2005; Gómez et al. 2005, 2008). The red and green cross-hair circles mark the zone from where the three sources were ejected some 500 years ago (Gómez et al. 2005) and the origin of the explosive flow (Zapata et al. 2009b). The dashed lines in the top panel mark the position and orientation of the position–velocity diagrams presented in Figure 2 were computed.

(A color version of this figure is available in the online journal.)

Figure 2. $^{13}$CO(2–1) position–velocity diagrams of the molecular ring computed at a position angle of $+210^\circ$ (upper panel) and $+300^\circ$ (lower panel). The contours in both panels are from $26\%, 27\%, 29\%, 30\%, 40\%, 50\%, 60\%, 70\%, 80\%,$ and $90\%$ of the peak of the line emission. The systemic LSR radial velocity of the ambient molecular cloud is about $9$ km s$^{-1}$. The synthesized beam of the line image is $4.3'' \times 3.2''$ with a P.A. of $-4.0^\circ$. The pink star marks the position and LSR velocity of the center of the explosive outflow (Zapata et al. 2009b). The emission at ambient velocities is clearly extended and poorly sampled with the SMA. In the right bottom corner of the upper panel, we show an intensity–velocity cut of the ring at a P.A. = $+90^\circ$ (see the white line) which reveals that expansion velocity of bubble is approximately $15$ km s$^{-1}$. In the bottom panel, we mark the position of the Orion Hot Core.

(A color version of this figure is available in the online journal.)
position of the multiple stellar system which contained these sources before it decayed is shown as a crossed-haired circle, and we shall henceforth refer to this point as “O.”

The $^{13}$CO(2–1) emission clearly traces a roundish structure curling around position “O.” The emission at position “O” itself is weak so the structure must be hollow: it is either a ring or a shell. In Figure 2, we show the $^{13}$CO(2–1) position–velocity diagrams of that structure computed along strips centered on “O” along position angles of +210° and +300°. The morphology seen in these diagrams is characteristic of a bubble: redshifted and blueshifted emission are simultaneously present toward the center of the structure, corresponding to the two sides of the bubble. It is impossible from its morphology and kinematics alone to decide whether the bubble is expanding or contracting. The fact that the three stars (BN, $I$, and $n$) known to be moving away from point “O” are projected exactly on top of the bubble, however, almost certainly indicates that it is expanding. The expansion velocity of the bubble is of order 15 km s$^{-1}$ (Figure 2) and, given the distance to Orion (414 pc; Menten et al. 2007), its radius is about 2000 AU. This yields a dynamical age for the bubble of about 600 years, with an uncertainty of a few hundred years.

The C$^{18}$O(2–1) line was also included in our SMA observations. The bubble is marginally seen in these data, with a typical intensity six to eight times weaker than in the $^{13}$CO(2–1) line. This indicates that the $^{13}$CO(2–1) line is optically thin, and can be used to estimate the mass of the expanding bubble. Assuming an excitation temperature of 50 K, and an abundance ratio between $H_2$ and $^{13}$CO of 5 × $10^5$, we obtain a mass of about 5 $M_\odot$ for the entire bubble. The corresponding kinetic energy (assuming an expansion velocity of 15 km s$^{-1}$) is about $1 \times 10^{46}$ erg, roughly one order of magnitude smaller than the kinetic energy of the outflow (Kwan & Scoville 1976).

The bubble is centered on point “O,” which decidedly appears to be a very special position within the Orion BN/KL region. This, combined with the remarkably similar timescales of all three phenomena, clearly indicates that the acceleration of the massive young stars BN, $I$, and $n$, and the births of both the fast outflow and the bubble most certainly occurred as a consequence of a single energetic event. Indeed, a natural scenario explaining the creation of the bubble follows from the interpretation of the large velocities of BN, $I$, and $n$ in terms of a dynamical disintegration. Young stars are well known to be surrounded by circumstellar disks and envelopes. If a multiple system disintegrates because of a chaotic few-body encounter, the circumstellar material initially in those structures will clearly be affected. The gas most strongly bound to the young stars may be ejected together with the stars themselves, and some of the material may even be independently ejected to high speed by a sling-shot effect. The least strongly bound material, however, will likely remain nearly stationary at first. However, since the stars that provided most of the gravitational binding energy of the young system are now gone, this material will find itself with an excess of kinetic energy, and will start to expand at a speed typical of the velocity dispersion of the material ($\approx 15$ km s$^{-1}$ as we will see momentarily). Moreover, since it was initially distributed among several disk/envelope structures with randomly oriented angular velocities, this material would be expected to expand fairly isotropically rather than as a highly flattened system. Finally, because of conservation of angular momentum, the system will progressively lose any original flattening it might have had.

As mentioned earlier, the kinetic energy of the bubble is about $1 \times 10^{46}$ erg, a factor of 100–1000 times less than the disruptive energy of $I$, and $n$ and BN 500 years ago (Bally & Zinnecker 2005). Its gravitational energy, on the other hand, is about $-\frac{GM_n}{R} \approx -2 \times 10^{44}$ erg. Thus, the bubble is clearly not currently in virial equilibrium, and must be expanding—in agreement with our previous considerations. Before the disintegration, however, BN, $I$, and $n$ as well as the 15 $M_\odot$ in the outflow and bubble were all part of a common system. The combined mass of BN, $I$, and $n$ must be of order 35 $M_\odot$, so the total mass of the system would have been about 50 $M_\odot$. For such a system to be in virial equilibrium, it must be confined to a radius of about 200 AU. Interestingly, this is approximately the size of the region (1") where the sources BN, $I$, and $n$ were located about 500 years ago (Gómez et al. 2005). Moreover, the typical speed of the gas in such a virialized structure would be $v = \sqrt{\frac{GM}{R}} \approx 15$ km s$^{-1}$, in excellent agreement with the measured expansion velocity of the bubble.

The expansion velocity of the bubble is clearly supersonic, so shocks should be created where it encounters dense gaseous clumps during its expansion. Interestingly, our SMA observations do reveal the presence of typical shock tracers (e.g., SiO, SO, and SO$_2$) in the bubble. The Orion hot core mentioned earlier is located toward the southeast quadrant of the bubble (see Figure 2), and was recently suggested to be caused by the impact of a shock wave related to the dynamical decay of BN, $I$, and $n$ onto a dense pre-existing core called the “Extended Ridge” (Zapata et al. 2010). To explain the near systemic mean velocity of the hot core, the authors of that suggestion argued that the shock wave must be fairly slow, and interact with a particularly dense and massive material. Zapata et al. (2010) proposed that the required shock wave might be due to the impact of low-velocity filaments. However, the supersonic expansion of the bubble reported here might provide a more natural explanation of the shocks required to explain the Orion Hot Core. For a more complete discussion of the nature of the Orion Hot Core, we refer the readers to Zapata et al. (2010).

4. CONCLUSIONS

In this Letter, we reported the discovery of an entirely new type of outflow phenomenon in the BN/KL region of Orion. Using $^{13}$CO(2–1) SMA observations, we identified a 500–1000 year old, roughly spherically symmetric bubble, expanding at about 15 km s$^{-1}$. The center of the bubble coincides with the initial position of a now defunct massive multiple stellar system suspected to have disintegrated 500 years ago and with the center of symmetry of the system of molecular fingers surrounding the Kleinmann–Low nebula. We propose that the material in that bubble was originally associated with the young stars in the now defunct multiple system.

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REFERENCES

Allen, D. A., & Burton, M. G. 1993, Nature, 363, 54
Bally, J., & Zinnecker, H. 2005, AJ, 129, 2281
Becklin, E. E., & Neugebauer, G. 1967, \textit{ApJ}, 147, 799
Blake, G. A., Mundy, L. G., Carlstrom, J. E., Padin, S., Scott, S. L., Scoville, N. Z., & Woody, D. P. 1996, \textit{ApJ}, 472, L49
Cohen, R. J., Gasiprong, N., Meaburn, J., & Graham, M. F. 2006, \textit{MNRAS}, 367, 541
Gaume, R. A., Wilson, T. L., Vrba, F. J., Johnston, K. J., & Schmid-Burgk, J. 1998, \textit{ApJ}, 493, 940
Gómez, L., Rodríguez, L. F., Loinard, L., Lizano, S., Allen, C., Poveda, A., & Menten, K. M. 2008, \textit{ApJ}, 685, 333
Gómez, L., Rodríguez, L. F., Loinard, L., Lizano, S., Poveda, A., & Allen, C. 2005, \textit{ApJ}, 635, 1166
Ho, P. T. P., Moran, J. M., & Lo, K. Y. 2004, \textit{ApJ}, 616, L1
Liu, S.-Y., Girart, J. M., Remijan, A., & Snyder, L. E. 2002, \textit{ApJ}, 576, 255
Kleinmann, D. E., & Low, F. J. 1967, \textit{ApJ}, 149, L1

Kwan, J., & Scoville, N. 1976, \textit{ApJ}, 210, L39
Menten, K. M., Reid, M. J., Forbrich, J., & Brunthaler, A. 2007, \textit{A&A}, 474, 515
Plambeck, R. L., Wright, M. C. H., Mundy, L. G., & Looney, L. W. 1995, \textit{ApJ}, 455, L189
Rodríguez, L. F., Poveda, A., Lizano, S., & Allen, C. 2005, \textit{ApJ}, 627, L65
Scoville, N. Z., Carlstrom, J. E., Chandler, C. J., Phillips, J. A., Scott, S. L., Tilanus, R. P. J., & Wang, Z. 1993, \textit{PASP}, 105, 1482
Taylor, K. N. R., Storey, J. W. V., Sandell, G., Williams, P. M., & Zealey, W. J. 1984, \textit{Nature}, 311, 236
Wright, M. C. H., Plambeck, R. L., & Wilner, D. J. 1996, \textit{ApJ}, 469, 216
Zapata, L. A., Menten, K., & Beuther, H. 2009a, \textit{ApJ}, 691, 332
Zapata, L. A., Schmid-Burgk, J., Ho, P. T. P., Rodríguez, L. F., & Menten, K. M. 2009b, \textit{ApJ}, 704, L45
Zapata, L. A., Schmid-Burgk, J., & Menten, K. M. 2010, arXiv:1009.1426