A SWEPT-UP MOLECULAR BUBBLE IN L1551

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1. Introduction

The environment of the young stellar object IRS5 in L1551 dark cloud is a representative of the "protostellar disk and outflow" systems found in star forming regions. The bipolar molecular outflow there was discovered as the first of its kind a decade ago (Snell, Loren, and Plambeck 1980). Its location in the sky, that is, its proximity (160 pc), isolation, and its almost edge-on inclination have favored the observation in great detail. IRS5 is thought to have the spectral type G – K (Mundt *et al.* 1985) similar to the Sun, with its dominant activity in the stellar wind, and not in the UV radiation as in massive protostars. The blueshifted and redshifted outflow lobes are clearly resolved into a pair of shell structures. The successive studies, mostly in CO lines, have led to a model of the outflow in which the molecular material is accelerated at the edge of a cavity evacuated by the protostellar wind (*e.g.* Uchida *et al.* 1987, Rainey *et al.* 1987, Moriarty-Schieven and Snell 1988).

Meanwhile, another set of molecular lines were used to identify the central protostellar core, the presumed agent for energizing and collimating the outflow. The intensity of CS J=1-0 and J=2-1 transitions peaks at two bright spots, to the north and south of IRS5. The origin of the outflow spatially coincides with the CS depression and the axis of the outflow is orthogonal to the elongation of the CS emission (*e.g.* Kaifu *et al.* 1984). The J=2-1 transition of CS peaks closer to the center than the distribution of the J=1-0 emission, a clear evidence of the density gradiant increasing toward the protostar. The map of NH_3 shows an elongated structure along the outflow in addition to an elongation similar to that present in the CS distribution, indicating the vigorous interaction between the outflow and the ambient dense disk (*e.g.* Menten and Walmsley 1985). FIR continuum emission from the dust core also shows an elongation both along and perpendicular to the molecular outflow (Cohen *et al.* 1985).

2. Description of the current approach

A hole in the molecular emission was found in the south-west of IRS5, via recent sensitive ^{13}CO observations (Bally and Hayashi 1989; also noticeable in Moriarty-Schieven and Snell 1988). In order to locate this ^{13}CO structure with respect to other features, especially the outflow and the disk, we have carried out a higher spatial resolution observation with Nobeyama 45-m radio telescope. An area of $\sim 15' \times 10'$ along and across the outflow axis (position angle of $\sim 45^o$) has been covered in ^{13}CO J=1-0 emission line at 110.201 GHz.

The emission from the rare isotope CO is moderately thin ($\tau = 0.5 - 1$) even in the line velocity at $V_{\rm LSR} = 6.5\ km\ s^{-1}$. Because of this opacity, the ^{13}CO distribution shows enhanced features against the quiescent cloud, in contrast to the distribution of the low velocity ^{12}CO emission. The current data presents the following characteristics :

- A tuning-fork like structure to the south-west of IRS5 – reminiscent of the blueshifted ^{12}CO emission.
- A broken symmetry of the structure in the south-west and the north-east – unlike in the ^{12}CO bipolar distribution.
- Spatial relation with the optical/IR compact sources – indicating interaction with other young stellar objects.

The most conspicuous feature, the tuning-fork like ridge in ^{13}CO emission, is limited to the narrow velocity range. Its dimension is most clearly measured in the intensity distribution integrated between $V_{\rm LSR}$ = 5 and 8 $km\ s^{-1}$. The length of both north and southern "legs" is approximately $4'$, separated by a similar distance and with a thickness 20 – $40''$. The ridge of this enhanced ^{13}CO emission consists of clumps of less than $1'$ scale size. This characteristic tuning-fork shape can be traced in the individual velocity maps at $V_{\rm LSR} = 5-6$ and $6-7$ $km\ s^{-1}$, namely in the line core and in the slightly blueshifted velocity. The ^{13}CO intensity, integrated over a wide range of blueshifted velocity, does show a visible mixing with the outflow; a series of high velocity ^{12}CO emission. The northern "leg" is brighter than the southern one, and has some (anti-)correlation with the intricated optical nebulosity HH102. The prominent ^{13}CO ridge is situated to the north of HH102, and there is another faint ridge of ^{13}CO between the two streaks of this Herbig-Haro object.

As a natural expectation, one may look for a counterpart of this southern arch. At first glance, there is no significant arch nor shell toward the north and east of IRS5, where the redshifted lobe of ^{12}CO is situated. However, one can pick up a depression of ^{13}CO to the east, as a bay like structure opening to the east. This depression zone does not make a perfect pair with the south-west tuning-fork; it is detached from IRS5, its scale is smaller and its axis is offset from the extention of the south-east arch, and not aligned with the ^{12}CO redshifted lobe either. The location of ^{13}CO with respect to the redshifted lobe of ^{12}CO ridge falls into the ^{13}CO bay, and the northern ridge of ^{12}CO also encounters the lower ^{13}CO emission. The area between HL & XZ Tau and the bay is strong in ^{13}CO emission.

A spur, a short and bright ridge of ^{13}CO of $\sim 2'$ extends form IRS5 to the north-east. It is aligned to the radio continuum jet (*e.g.* Bieging *et al.* 1984), and located opposite to the optical jet present in the south-west of IRS5 (*e.g.* Mundt and Fried 1983). The south of this spur delineates the edge of the newly identified IR source L1551 NE (Emerson *et al.* 1984). Also there is some correlation between ^{12}CO and L1551 NE; the curved ridge of blueshifted ^{12}CO and a peak of redshifted ^{12}CO are seen in the east of L1551 NE. The spatial coincidence of L1551 NE and those molecular features strongly suggests the activity form this infrared source interacting with the ambient cloud. The ^{13}CO distribution exhibits a correlation (or anticorrelation, rather) with other optical/IR sources as well. HL and XZ Tau, and HH30, which are to the north of the redshifted ^{12}CO, and the compact knot HH29 in the south, are accompanied by small clumps of ^{13}CO. HL & XZ Tau themselves are in the depression.

3. Implication

The current data have evoked two arguments on the outflow structure. So far, the model based mainly on ^{12}CO outflow data is qualitatively sufficient to reproduce the morphology of the outflow phenomena, although it has severe deficit in the momentum supply. The present ^{13}CO measurement requires a significant amount of energy and momentum deposit into the molecular material, which further exaggerates the quantitative difficulty of the outflow models.

The most striking result is that the south-west arch of ^{13}CO is located immediately outside the blueshifted ^{12}CO emission arch, as shown in figure 1. The distance between the two legs of

^{12}CO tuning-fork feature is 2.5$'$ to 3$'$ (0.11 – 0.13 pc) while the ^{13}CO is 4$'$ (0.18pc) further out. Even the low velocity ^{12}CO shell is surrounded by the arch of ^{13}CO. The clear offset between these two archs implies that ^{13}CO is not merely a limb brightening of the ^{12}CO outflow shell. This ^{13}CO structure is most likely a shell, not just filaments, sitting outside the ^{12}CO "shell", namely, the ^{13}CO emission arises from the region surrounding the outflow in a 3 dimensional sense. In order to discriminate between the ^{12}CO and ^{13}CO molecular archs, they are here called ^{12}CO shell and ^{13}CO bubble, respectively. The name bubble is meant to show preference to the hypothetical expanding structure which surrounds the stellar wind cavity. This is reminiscent of the bubble created by the stellar wind from a massive star, phenomena which has been throughly studies before protostars (*e.g.* Weaver *et al.* 1977). We suppose that this bubble is ambient material swept-up by the stellar wind (*e.g.* Moriarty-Schiven and Snell 1988), rather than the material directly blown out from the protostellar disk. The emission in the higher velocity range could arise from the clumps entrained in the outflow, which are abrases from the cavity wall.

The expansion timescale in the case of L1551 IRS5 is estimated to be $\sim 10^5$ years, if one assumes an outward velocity of the order of 1 $km\ s^{-1}$, and a distance of 0.09 pc. The mass of the ^{13}CO bubble is estimated to be $3 - 7M_{\odot}$, derived from the column density of ^{13}CO with the adopted excitation temperature ranging between 10 K for the dark cloud and 25 K for the outflow. In order to sweep up the ambient material into this bubble, the energy budget for the outflow mechanism is significantly increased, not to mention the difficulty with the momentum deficit. The mass of ^{13}CO bubble is comparable to that of the entire outflow, 3.5 $M_{\odot}$ (Moriarty-Schieven and Snell 1988), and to that of the protostellar disk of IRS5 (Kaifu *et al.* 1984).

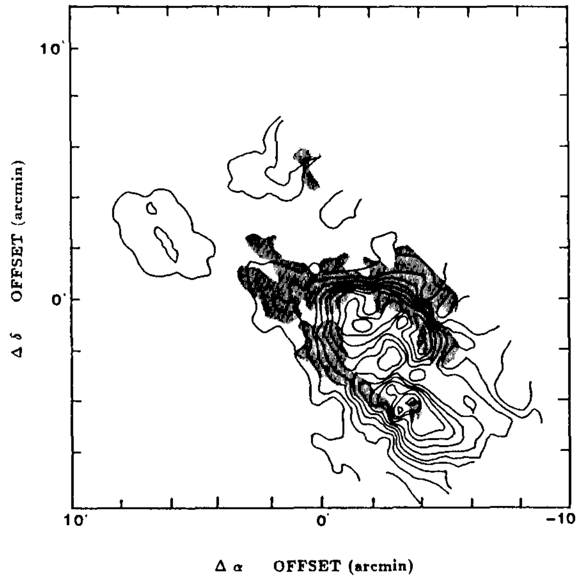

Figure 1.
Molecular bubble surrounding the outflow from L1551 IRS5

shaded area : ^{13}CO J=1-0 (total intensity above 5 K km/s)

contours : ^{12}CO J=1-0 (intensity for -5 to 5.5 km/s min. 1.5, step 1.5 K km/s)

The second issue is on the bipolarity, or the symmetry of the distribution with respect to the driving source L1551 IRS5. The ^{12}CO structure has been described as a pair of shells, similar in shape to each other. The blueshifted shell is in the south-west of IRS5, and the redshifted shell is to the north-east of it, respectively. The ^{13}CO bubble could be still bipolar in nature, but not in appearance. The bubble structure is seen in the south-west of IRS5, while there is no counterpart in the north-east. This asymmetry in ^{13}CO could be due to the large scale asymmetry of the dark cloud structure as well as to the influence of the activity from other young stellar objects.

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The bipolar nature of the ^{13}CO bubble is shown in relation to the ^{12}CO distribution. There is a remarkable coincidence between the ^{12}CO peaks in the ^{13}CO bay. The blueshifted ^{12}CO emission peaks at the north-east bay, while the redshifted ^{12}CO delineates the northern edge of it. The ^{13}CO looks like a basin of the ^{12}CO water fall. However, the presence of ^{13}CO ridge in the middle of the ^{12}CO redshifted "lobe" brought some conflict when interpretating that lobe as a "shell". Perhaps the outflow to the redshifted velocity range goes more eastward, particularly at the distance of the bay area. This is in accordance with the ^{13}CO spur, as well as optical and radio continuum jets (e.g. Mundt and Fried 1983, Bieging *et al.* 1984). In addition to this shift, other protostars (HL & XZ Tau, L1551 NE) seem to disturb this area.

Summary

The observations toward L1551 dark cloud exhibited a vivid image of the star formation site where the placental cloud is dissipating. Mapping in ^{13}CO emission resolved a bubble to the south-west of L1551 IRS5, which surrounds the ^{12}CO shell blueshifted outflow. We interpret this feature as material swept up by the protostellar wind. There are some other indications of the interaction between the ambient cloud and other yound stellar objects to the north-east of IRS5. The discovery of the massive swept-up bubble doubled (at least) the estimate of the energy and momentum budget of the driving mechanism.

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Discussion

PALOUS: The snow-plough model can be applied in the case of the strong shock, when the thickness of the shock is much less than the radius of the cavity. In our case $0.03/0.1 = 0.3$, which means that probably the weak shock approach would be more appropriate.
HAYASHI: I agree with the above comment. In particular, the overlap (co-existence) between ^{12}CO (outflow) and ^{13}CO (bubble) implies that the shock will not be totally dissociative. Also I admit the name "snow-plough" may be misleading for this case, since the energetics and time scales in star forming regions are different from supernova explosions the phenomena for which this word was first used.