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## Letter to the Editor

# High signal/noise $^{13}\text{CO}$ observations of the bipolar outflow in L 1551

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**Summary.** We report new high signal/noise  $^{13}\text{CO}$  observations of the bipolar outflow in the molecular cloud L1551. Contrary to earlier observations of CO J=1-0 and 2-1, we find no strong spatial dependence for the velocity profile of our spectra. The implications of our observations are such, that the model of an empty shell for this source is less likely, and we suggest a model consisting of a shell which contains significant amounts of outflowing molecular gas inside the swept-up cavity walls

**Key words:** Interstellar medium: clouds: L1551 – molecules – Herbig-Haro objects – Radio lines: molecular

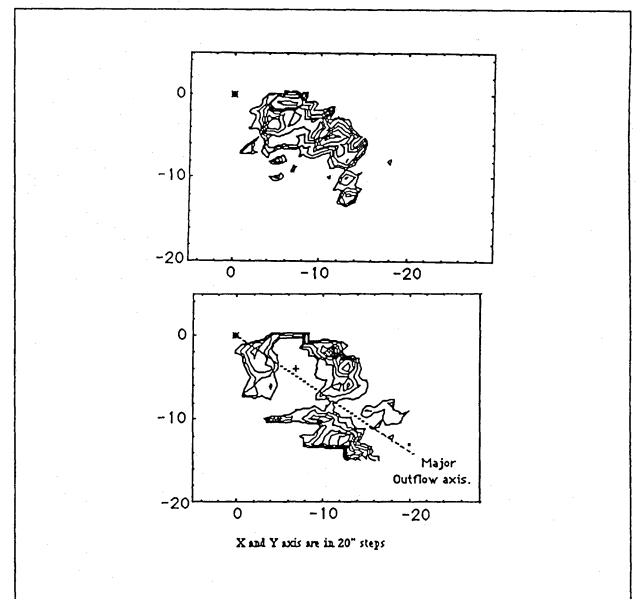
### 1. Introduction

The bipolar outflow in the molecular cloud L1551 is among the best studied, at least as what concerns low mass star forming regions. The generating source, L1551 IRS5 (Strom et al., 1976) has been suggested to be a low mass star in an early stage of formation (Fridlund et al., 1980). Two spatially well separated lobes of red- and blue-shifted molecular (CO) gas centered on IRS5 were discovered by Snell et al. (1980). Several authors (e.g. Moriarty-Schieven et al., 1987; Moriarty-Schieven and Snell, 1988; Fridlund, 1987; Fridlund et al., 1989; Rainey et al., 1987) have suggested that the outflow takes the form of an empty shell, consisting of a dense surface of swept-up molecular gas. This model has its origin in integrated temperature-velocity maps such as Fig.1. In the low velocity regime one clearly sees a "hole" in the center of the outflow, which assuming that the outflow gas is moving out with a rather small velocity dispersion, can be interpreted such that no molecular gas is present within the outflow.

The general shape of the outflow in velocity space is the same, regardless of if one uses the CO J=1-0 transition (Moriarty-Schieven and Snell, 1988; Fridlund et al 1989) or higher transitions of the same molecular species (Rainey et al, 1987). However, Fridlund et al. (1989) noted that in one of the few positions where they had  $^{13}\text{CO}$  observations, there were indications of a possible self reversal of the CO J=1-0

line at low velocities. Since that position was coincident with the position of the Herbig-Haro object HH29, they suggested that it could be a local density enhancement connected with the HH object.

In order to clarify this issue, we have undertaken a set of very high signal/noise observations of  $^{13}\text{CO}$  J=1-0. Integration times have to be long, since the wing emission in  $^{13}\text{CO}$  is very weak, typically in the range 0.1-0.8 K. The results indicate clearly that the velocity structure of  $^{13}\text{CO}$  depends much less on the position.



**Fig. 1.** Integrated  $T_R^*$ -velocity maps of the blue shifted outflow lobe in L1551. The top panel has been integrated between  $-9 \text{ km s}^{-1}$  and  $1.5 \text{ km s}^{-1}$  and the lower panel between  $1.5$  and  $5.5 \text{ km s}^{-1}$  respectively. The star symbol shows the position of IRS5 while the cross marks the position of the spectrum in Fig.3a. Position offsets are given in steps of  $20''$  both in Ra and Dec, with the  $(0'', 0'')$  at the position of IRS5.

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At the position of the "hole" in Fig.1, we find  $^{13}\text{CO}$  present at all low velocities, even though the  $^{13}\text{CO}$  emission has a much lower temperature at these velocities, than along the edges. We argue that this indicates that the outflow consists of a filled lobe (at least as what concerns the blue-shifted lobe), and that the absence of emission in CO J=1-0 and 2-1 is due to optically thick gas at the low velocities in the center of the outflow. This has severe implications for the models of the structure and origin of bipolar molecular outflows.

## 2. Observations

The  $^{13}\text{CO}$  observations were carried out in 1988-1989 with the Onsala 20m telescope<sup>1</sup>, equipped with a cooled Schottky diode mixer and a multichannel backend with 250 kHz resolution, resulting in a velocity resolution of  $0.68 \text{ km s}^{-1}$  for  $^{13}\text{CO}$ . SSB system temperature were typically 450 K. The observation set consists of 58 positions, all integrated not less than one hour, and in some cases more. The rms noise in these spectra vary between 0.02K and 0.2K and a close check was kept on the spectra during observation, so that the wing features at least reach above 3 times the rms noise level.

Calibration was performed by observing S140 before and after every observing shift, and an "internal" calibration was also performed every few minutes by observing the position of IRS5, which is assumed to have a  $T_R^* = 7.0\text{K}$  (Fridlund et al., 1989). All the observations reported in this paper have been calibrated to a scale of  $T_R^*$ , and conforming to the standards layed down by Kutner and Ulich (1981), and all positions are offset relative to IRS5 which is assumed to have 1950.0 coordinates  $\alpha = 4^{\text{h}}28^{\text{m}}40^{\text{s}}.0$ ,  $\delta = 18^{\circ}01'45''$ .

The  $^{12}\text{CO}$  J=1-0 observations are mostly taken from Fridlund et al. (1989), although a few positions in the most interesting spots were improved upon using the OSO 20m and the frontend/backend combination given above. In producing integrated temperature-velocity maps, the cloud component has been subtracted by using the empirical cloud profile of Fridlund et al. (1989).

The  $^{12}\text{CO}$  J=2-1 observations are taken from Rainey et al. (1987) and were originally obtained using the 12m dish at Kitt Peak (NRAO). Given the size of the two telescopes involved, the beam sizes are similar enough (about  $33''$ ) to allow a direct comparison between the different lines.

## 3. Results

In Fig.2, we have displayed spectra obtained along the NW part of the southern section of the outflow, and thus on the edge of the hypothesized shell. The profiles of the 3 lines follow each other very well. The further out from IRS5 we get, the less the velocity extent on the "blue" side of the line. This can be understood in terms of gas along the edge of the outflow interacting more severely with the ambient medium, leading to deceleration.

In a shell-model the projected center of the outflow is devoid of low-velocity gas. In  $^{12}\text{CO}$  J=1-0 and J=2-1 this is

<sup>1</sup> The Onsala 20m telescope is operated by The Chalmers University of Technology with support from the Swedish Science Foundation, NFR.

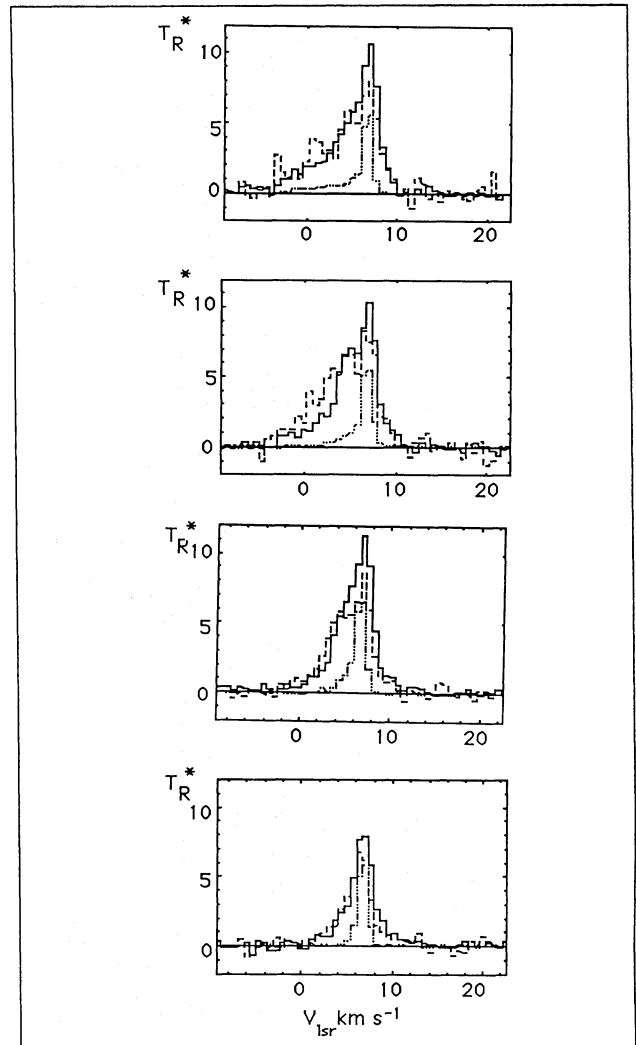
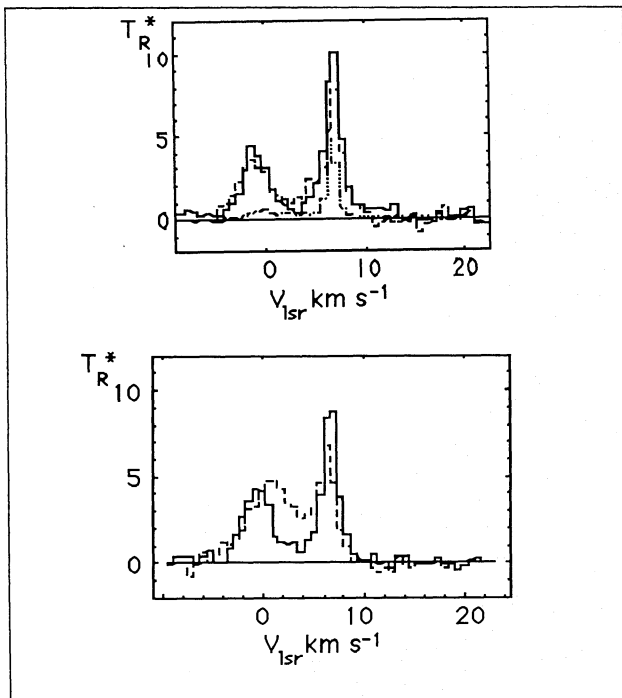


Fig. 2. CO J=1-0 (full line), J=2-1 (dashed) and  $^{13}\text{CO}$  J=1-0 (dotted) obtained along the NW edge of the blue-shifted outflow in L1551. Offsets from IRS5 are, from the top:  $(-180'', -20'')$ ,  $(-200'', -20'')$ ,  $(-240'', -20'')$  and  $(-300'', -20'')$ .

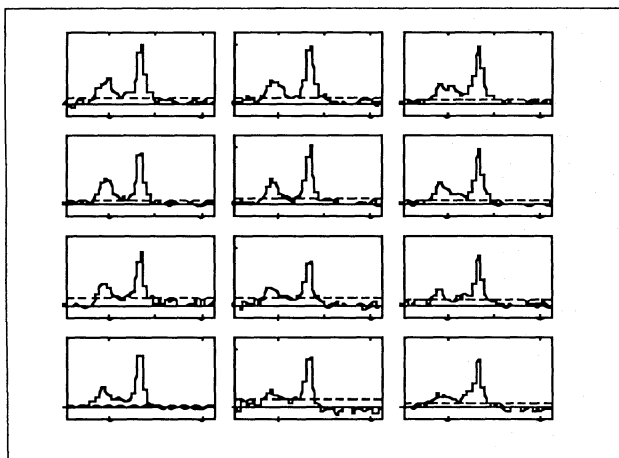
what one observes as can be seen from Fig.3a which shows a spectrum obtained within the cavity (at a position offset  $-140'', -80''$  from IRS5). However, one would also expect to see  $^{13}\text{CO}$  with the same velocity structure as CO. This is not the case in the center of the "hole" in L1551. Fig. 3a shows well aligned  $^{12}\text{CO}$  J=1-0 and 2-1 profiles, but  $^{13}\text{CO}$  does not show the minimum expected at low velocities. Instead one sees a more or less constant velocity distribution going out to the highest relative velocities of the gas.

The improved  $^{12}\text{CO}$  spectra (Fig.4) also shows that only in one of the positions within the cavity, does the CO intensity really fall below 3 times the rms noise level.

If we assume that the emission in both transitions is optically thick and that they share a common excitation temperature, the radiation temperature is given by:



**Fig. 3.** Figure 3a (top) displays the three lines obtained at the position marked with a cross in Fig.1. (Offset  $-140''$ ,  $-80''$  from IRS5). Figure 3b (bottom) shows a position  $20''$  to the east of the first position, where we unfortunately do not have any  $^{13}\text{CO}$  data. Otherwise as in Fig.2.



**Fig. 4.**  $^{12}\text{CO}$  spectra obtained within the cavity in the low velocity panel in Fig.1. The horizontal dashed line shows the 3 sigma rms noise level.

$$T_R^*/\eta_c = J(T_{ex}) - J(T_{bg}) \quad (1)$$

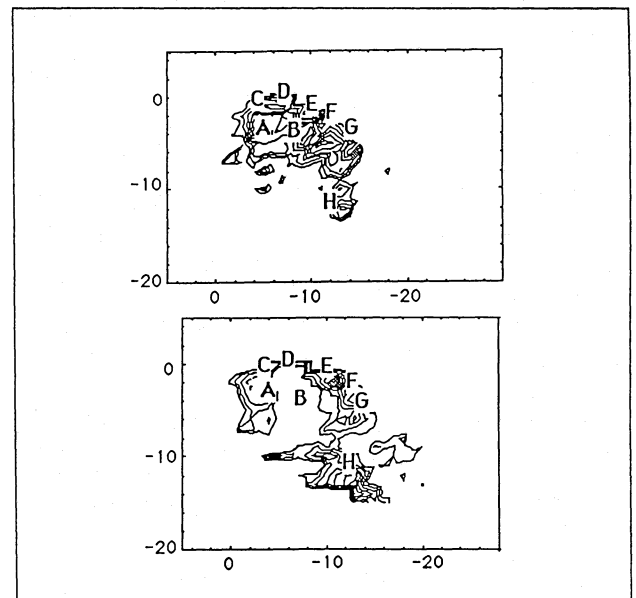
where  $T_{bg}$  is the background radiation,  $\eta_c$  is the source coupling efficiency (assumed to be unity) and

$$J(T) = (h\nu/k)/(e^{h\nu/kT} - 1) \quad (2)$$

For optically thick lines the ratio between the two transitions  $T_R^*$  should approach 1 for values of  $T_{ex}$  above 10 K, and given the uncertainties, the ratio between the values of  $T_R^*(2-1)$  and  $T_R^*(1-0)$  is equal to 1 over the total velocity extent of the blue wing in the spectrum in Fig.3a. The  $J=1-0$  line of CO is most certainly optically thick, from the  $^{13}\text{CO}$  data, and the constant line ratio of the 2-1 and 1-0 transitions, is indicative that also the 2-1 transition is optically thick.

This however, is not the case in all positions. Only  $30''$  towards the east, we obtain the spectrum in Fig.3b. Here the minimum in the 2-1 wing is much less pronounced than in the 1-0 transition. This further attests to the rapid temperature/density changes – the “clumpiness” of this outflow.

Assuming that  $^{12}\text{CO}$  and  $^{13}\text{CO}$  shares a common excitation temperature, we can also calculate the optical depth and column density in  $^{13}\text{CO}$ , following Bally and Lada (1983) and Dickman (1978). At most positions, and velocities, we find  $^{13}\text{CO}$  to be optically thin. It is only in the center of the low velocity cavity, that the  $^{13}\text{CO}$  optical depth approaches 1, at the same velocities where CO  $J=1-0$  and 2-1 show a distinct minimum.



**Fig. 5.** Positions of maximum column density, overlaid onto the integrated temperature-velocity maps of Fig.1

Fig. 5 is a plot of the integrated temperature-velocity with the  $^{13}\text{CO}$  column density peaks overlaid. We clearly see the density enhancement along the NW edge, but also two clear peaks along the main outflow axis. From inspection of the individual spectra, it is clear that one of these (A) is associated with the high velocity gas and one (B) with the low velocity

regime. The peak associated with the high velocity gas is also at roughly the position of HH29. The  $^{13}\text{CO}$  column density at positions A-H is found to be on the average  $4.5 \times 10^{15} \text{ cm}^{-2}$ , while the average for the other 51 positions that we have observed in  $^{13}\text{CO}$  is  $1.5 \times 10^{15} \text{ cm}^{-2}$ . The linear size of the clumps is about 0.01 - 0.02 pc.

#### 4. Discussion

The interpretation of the structure of this outflow in previous work rests on the assumption that an outflow from the vicinity of IRS5 has swept up the ambient medium into two expanding shell-like lobes (e.g. Moriarty-Schieven and Snell, 1988; Fridlund et al., 1989). Observing an empty shell along the major outflow axis, one would see two velocity components, one from the backside and one from the frontside, with a clear minimum in between. Along the edges one would on the other hand see a smooth velocity distribution. In L1551 one observes only one high velocity component in the center of the outflow, but this can be explained such that most of the gas on the backside of the shell is moving in the plane of the sky (e.g. Fridlund et al., 1989). However, our results now indicate that we have the highest optical depths, not only along the edges of the shell, but also in the center of the outflow, and at very low velocities. Furthermore, when looking at the optically thin transition of  $^{13}\text{CO}$  we do not see the spatial dependence on velocity encountered in the CO transitions. This indicates that the outflow is filled with molecular gas, and that earlier determinations of the mass and energetics of the outflow are to low. The strength of the  $^{13}\text{CO}$  line at low velocities and in the center of the outflow lobe is not very different from that which we find in the high velocity regime, which means that a significant amount of molecular gas must be found within the cavity. Since the cavity within the outflow in the low velocity regime is a sizable fraction of the blue-shifted lobe, the outflow could be considerably more massive than previously thought (Fridlund et al., 1989). The "missing mass", however, consists predominantly of low velocity gas and the change in the lower limit to the energetics ought therefore not to be substantial. A better estimate of the mass and energetics of the outflow awaits a better sampled grid of  $^{13}\text{CO}$  positions, and radiative transfer calculations.

Observations of  $\text{HCO}^+$ ,  $^{13}\text{CO}$  and CO in the close vicinity of IRS5 (Liljeström, 1989; Knee and Fridlund 1989) show clearly that high velocity gas is present close to the source of the outflow, possibly emanating from a large molecular disk (Kaifu et al., 1984; Fridlund, 1987; Fridlund et al., 1989; Liljeström, 1989), and that the outflow is contemporary. It is therefore not implausible that the true structure of the outflow in L1551 consists of a cone like shell of ambient gas that has been swept up by outflowing gas during the life time of the outflow (roughly few  $\times 10^4$  years), but that the outflow is still being generated close to IRS5, and that this gas now fills all or part of the shell. The column density along the line of sight through the middle of the outflow then becomes so great, at lower velocities, that the CO transitions suffer self reversals.

The fact that we observe clear evidence of self reversals also gives us another view of the alleged acceleration along the main outflow axis (Fridlund et al., 1984). This velocity gradient has been explained as a consequence of the magneto-hydrodynamics of the model of Uchida and Shibata (1984), or as just

a geometrical effect of the outflow expanding as it progresses out from IRS5 (Fridlund, 1987; Fridlund et al., 1989). Our new data, though not incompatible with these models, also shows that the apparent acceleration could be a function of the self reversal becoming increasingly more important, at low velocities, further out.

Summarizing the results we find:

1. We find that the  $^{13}\text{CO}$  spectra show a velocity structure that depends on position, much less, than CO,  $J=1-0$  and  $J=2-1$ . We find that  $^{13}\text{CO}$  is optically thin everywhere except in the center of the outflow, and can trace the velocity structure of the molecular outflow much better than the standard probe, CO.
2.  $^{13}\text{CO}$  gas is present at both low and medium velocities within the low velocity cavity seen in CO.
3. The implications of 1) and 2), are that the outflow is filled with molecular gas. Taken together with earlier results, and with the data of Knee and Fridlund (1989), we can conclude that molecular gas is still streaming out from IRS5, filling the outflow lobe.

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