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Giant Molecular Outflows in the L1448 Class 0 Cluster

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Abstract. We present evidence of highly-collimated, parsec-scale *molecular* outflows driven by the cluster of protostars in the L1448 dark cloud. This discovery was made possible using the On-The-Fly (OTF) mapping capability of the NRAO 12-m telescope, with which we acquired large-scale ($47' \times 7'$ - corresponding to 4 pc $\times$ 0.6 pc at the source), sensitive ($T_R^* \sim 0.1$K), CO (J=1$\rightarrow$0) maps at 55″ resolution. Comparison of the spatial and velocity distribution of the high-velocity CO with previously published optical images and spectra (Bally et al. 1997) and near-infrared images (Eislöffel 2000) has led to the positive identification of four distinct molecular outflows in our CO maps, driven by the Class 0 protostars, L1448C, L1448N(A), L1448N(B), and L1448 IRS2. The famous, well-collimated, high-velocity CO outflow from L1448C can now be traced to distances over an order of magnitude greater than previously (Bachiller et al. 1990). We show that L1448C is the most likely exciting source of HH267, 2.3 pc away. These data also confirm the speculation that L1448N(B) is the driving source of HH196D and HH196 (Barsony et al. 1998), at distances of 0.3 and 0.7 pc from the driving source, respectively. We confirm the CO outflow driven by L1448 IRS2, which encompasses the HH195 complex, as reported by O'Linger et al. (1999). In addition, we report evidence for a second CO outflow driven by L1448 IRS2 from these observations. This second outflow could account for the excitation of HH193, 1 pc downstream from its driving source.

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1. Introduction

The 100 $M_\odot$ L1448 dark cloud is remarkable in harboring no less than five extremely young ($\sim$ a few $\times$ 10^4 yr old) protostars in their early collapse phase

(Class 0 protostars). These protostars are forming in two dense NH_3 cores, which contain 50 $M_\odot$ of gas and dust distributed over a 1 pc × 0.5 pc area at a distance of 300 pc (Bachiller & Cernicharo 1986; Anglada et al. 1989). The NH_3 core at $V_{LSR} = 4.2$ km s^{-1} contains the Class 0 protostar, L1448 IRS2 (O'Linger et al. 1999), whereas the NH_3 core at $V_{LSR} = 4.7$ km s^{-1} harbors four Class 0 protostars: L1448C, L1448N(A), L1448N(B), and L1448NW (Barsony et al. 1998; Eislöffel 2000).

A highly collimated, high-velocity ($\pm$ 70 km s^{-1}), bipolar molecular outflow, exhibiting symmetrically placed CO "bullets" was discovered to emanate from L1448C via CO J=2→1 and CO J=1→0 mapping of a $\sim 2' \times 6'$ area (corresponding to 0.17 pc × 0.51 pc area at the source) a decade ago (Bachiller et al. 1990). This flow is deduced to have an inclination angle, $i \sim 70°$,implying actual jet velocities in excess of 200 km s^{-1} (Bachiller et al. 1995). Subsequent wide-angle ($\sim 70'$ field-of-view), narrowband optical imaging of the entire extent of the L1448 cloud has revealed several systems of Herbig-Haro objects, some of which are displaced several parsecs from any exciting source (Bally et al. 1997). In order to explore the connection between the L1448 Class 0 sources, the recently discovered HH objects, and the dynamics of the molecular gas in this cloud, we acquired a large-scale ($47' \times 7'$), OTF (On-The-Fly) map of the CO J=1→0 emission of L1448. Further details of the observations and data reduction can be found in Wolf-Chase, Barsony, & O'Linger (2000).

2. Results

Figure 1 shows the extent of high-velocity CO J=1→0 emission within our mapped boundary which is outlined by the zigzag lines. Map center is at the position of L1448 IRS2. Blue-shifted, high-velocity CO ($-12.1 \leq V_{LSR} \leq -1$ km s^{-1}) is found mostly in the northwestern hemisphere centered on L1448 IRS2, whereas red-shifted, high-velocity CO ($+8.1 \leq V_{LSR} \leq +17.8$ km s^{-1}) is found chiefly in the southeastern hemisphere. The locations of the Class 0 protostars, L1448 IRS2, L1448C, L1448N(A)+(B), and L1448NW are indicated by the solid stars. The location of the Class I source, L1448 IRS1, is indicated by the solid square, and the locations of the Herbig-Haro objects are indicated by plusses, and labelled following the nomenclature of Bally et al. (1997).

Figure 2 shows the same high-velocity CO wing emission as in Figure 1, but with the various protostellar outflow axes indicated. Solid lines denote flow position angles and extents previously mapped at arcsecond-scale spatial resolution, via millimeter interferometry, near-infrared imaging of H_2 line emission, and/or optical imaging of shocked [SII] emission. The dashed lines indicate likely extensions of these flows that are consistent with our larger-scale, but lower spatial resolution data (55″ beam–indicated in the lower right-hand corners of Figs. 1 & 2).

2.1. The L1448C CO Outflow

The major result of our CO mapping of the L1448C outflow is the discovery that the true extent of its high-velocity *molecular* gas is on the scale of several parsecs: increasing its known extent by an order of magnitude. In particular, the blue-shifted lobe of the L1448C CO flow (to the NW) is consistent with

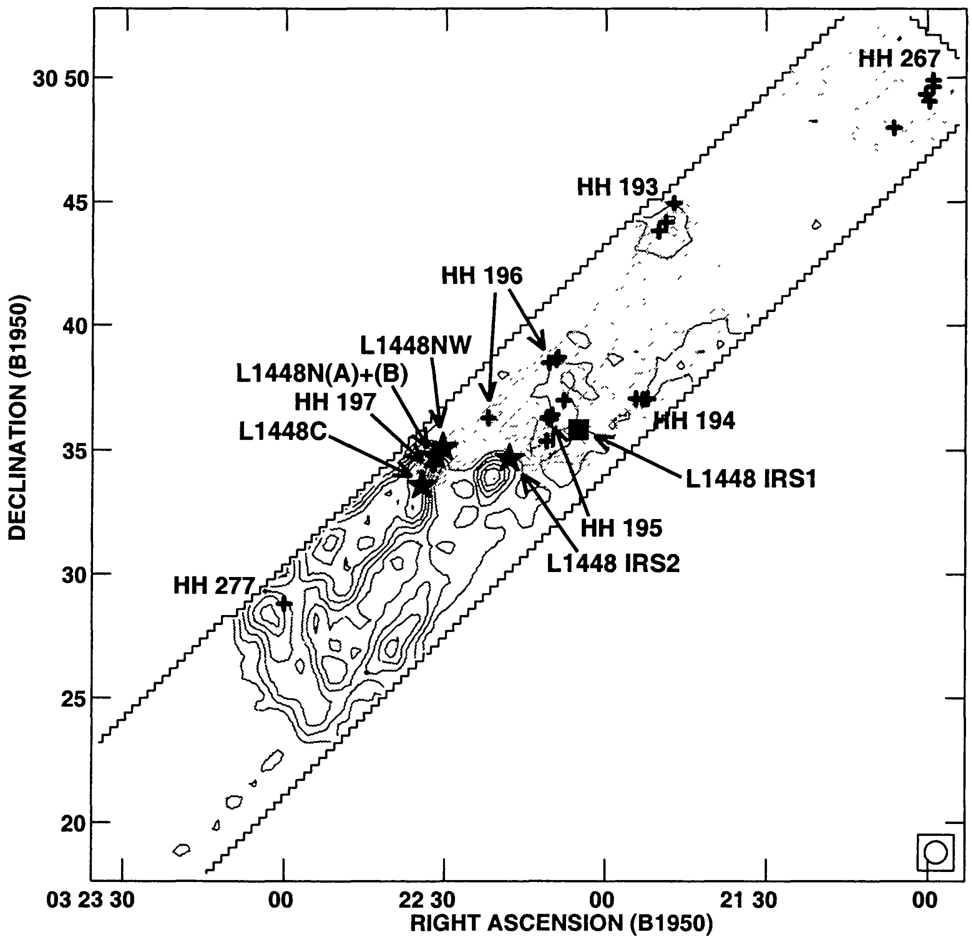

Figure 1. L1448 High-Velocity CO Wing Emission Showing Locations of Protostars and Herbig-Haro Objects

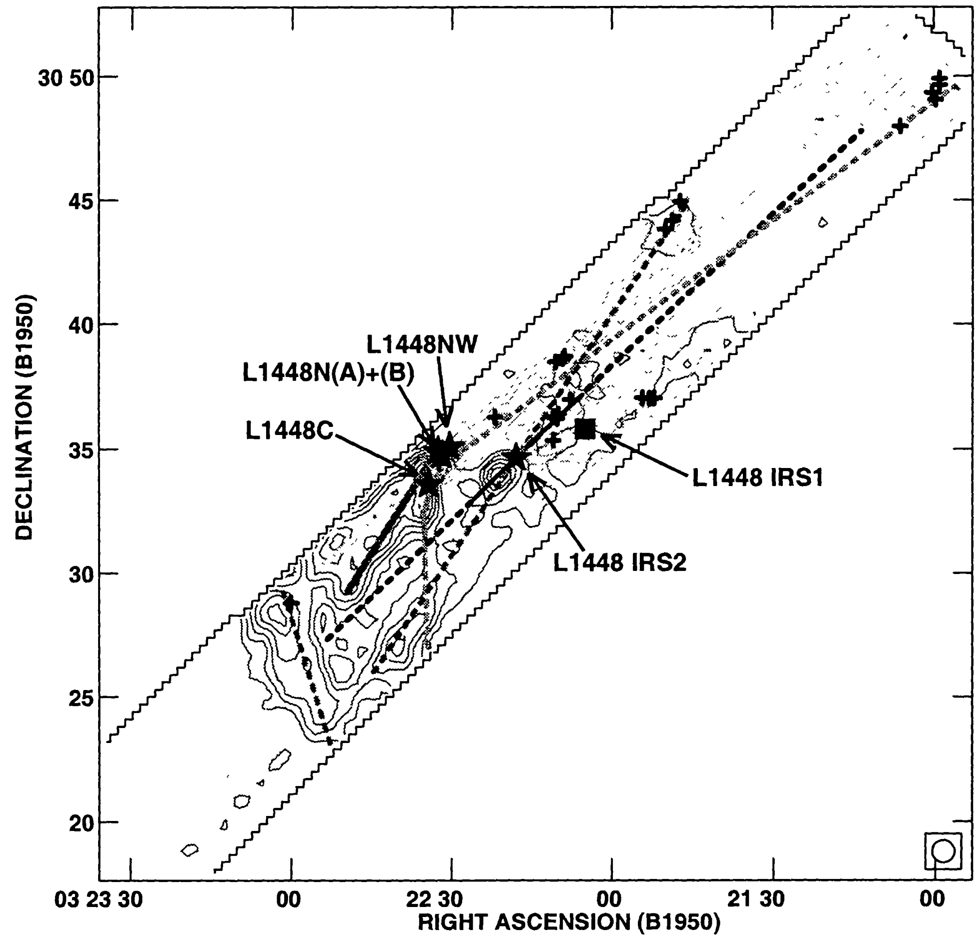

Figure 2. L1448 High-Velocity CO Wing Emission with Outflow Axes Superposed

a length of 2.3 pc (the distance from L1448C to the high-velocity, blue-shifted CO associated with the HH 267 complex). Note that the entire L1448C outflow remains unresolved in our 55″ resolution OTF map: after an initial conical outflow opening angle of $\phi/2$=22.5″, the L1448C outflow cavity walls become parallel $\sim$ 1′ (= 0.08 pc) downstream from the driving source, with a width of just $\sim$20″. From interferometric observations, it is known that the blue-shifted CO flow from L1448C starts out at P.A. = +159°. It is then deflected through a total angle of 32°, as observed in NIR H_2 maps. Assuming no further deflection of the blue-shifted flow, it would then intersect the system of HH 267 knots 2.3 pc downstream, where some high-velocity, blue-shifted gas is detected in our CO map (see Figure 2). We note that the combination of relatively low sensitivity (1 $\sigma \sim$ 0.1K) coupled with severe beam dilution conspires to preclude the detection of the highest-velocity (and presumably) on-axis CO.

The redshifted lobe of the L1448C outflow similarly starts out at a P.A. $\sim$ 160°, only to be deflected by 20° from its original direction near the position of the CO "bullet" known as R3. A string of H_2 emission knots along this P.A. = 180° extends nearly 2′ further to the SE, as indicated by the solid line in Figure 2 (Eislöffel 2000). The red-shifted CO lobe of the L1448C outflow can be traced for $\sim$ 0.5 pc in our map, as indicated by the dashed lines to the SE of L1448C.

2.2. The L1448N(A) and L1448N(B) CO Outflows

L1448N(A) and L1448N(B) form a close (7″ separation) protobinary, which is unresolved in our OTF map. Although redshifted CO J=2→1 outflow gas (obtained at 12″ resolution) had been previously identified as originating from L1448N (Bachiller et al. 1990), comparison with subsequent arcsecond scale H_2 imaging (Davis & Smith 1995) was required to determine that each component of the protobinary was driving its own outflow (Barsony et al. 1998). As was the case for the L1448C outflow, neither the L1448N(A) nor the L1448N(B) CO outflows are spatially resolved in our maps. However, high-velocity CO emission along each of their individual outflow axes is detected in our data.

For L1448N(A), no blue-shifted CO is detected along its outflow axis at P.A. = 150°, as determined from the symmetry axis of the U-shaped near-infrared reflection nebulosity to its NW (Bally, Lada, & Lane 1993). Most likely the this is because the flow in this direction has broken out of the molecular cloud. Red-shifted CO along this P.A. is detected to the Southeast of L1448N(A), however, both in interferometric CO maps (see the V_{LSR} = + 8 km s^{-1} channel map of Bachiller et al. (1995)) and in our OTF map to a distance of 0.8 pc (see Figure 2).

The L1448N(B) flow is oriented along P.A. $\sim$ 129°. A finger of high-velocity blue-shifted CO emission towards the NW along this P.A. connects L1448N(B) to HH196D, 0.3 pc downstream, and to HH 196ABC, 0.38 pc further downstream in our CO map. Thus, the blue-shifted molecular flow driven by L1448N(B) is at least 0.7 pc long. If the blue-shifted L1448N(B) flow extends unimpeded past HH196 along this P.A. to reach the high-velocity blue-shifted CO structure seen at the NW extremity of our map (see Fig. 2), then the extent of just the blue-shifted gas driven by this protostar could reach 2 pc (see dashed lines along this

P.A. in Fig. 2). The red-shifted flow from L1448N(B) can be traced for ~ 0.6 pc in our CO map, as indicated by the solid line to the SE of L1448N(B) in Fig. 2.

2.3. High-Velocity CO Associated with L1448 IRS2

The solid line passing through L1448 IRS2 along P.A. 133° indicates the extent of the unconfused high-velocity CO flow from this source as previously reported (O'Linger et al. 1999). The blue-shifted flow to the NW from L1448 IRS2 along this direction intersects the HH195 complex (excepting HH195 E). The true extent of this flow, indicated by the dashed lines along this same P.A. along which there is evidence of high-velocity CO in our map, may be as long as 2.6 pc in total.

A long finger of high-velocity, blue-shifted CO along P.A. = 152°, connecting L1448 IRS2 with HH193, 1 pc downstream, suggests that L1448 IRS2 may be driving a second outflow. This second flow is indicated by the dashed line passing through the position of L1448 IRS2 in Figure 2. Enhanced red-shifted high-velocity CO emission is also seen ~ 1pc from L1448 IRS2 along this same position angle. We refer the reader to Wolf-Chase et al. (2000) for an in-depth discussion of the pros and cons of the previously proposed constant opening-angle, single outflow model of the high-velocity CO driven by L1448 IRS2 (O'Linger et al. 1999), vs. the currently presented model in which two outflows are driven by an as yet unresolved ($\leq 7''$ separation) protobinary.

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