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A Molecular Line Study of the Recently Discovered Class 0 Source Barnard 1-c

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Abstract. We present a BIMA molecular line study of the class 0 source Barnard 1-c in the Perseus molecular cloud. As followup to the detection of an atypical polarization pattern in this young stellar object by Matthews & Wilson (2002), we have obtained high resolution data in CO, $C^{18}O$, ^{13}CO, HCO^+, and N_2H^+ from BIMA, plus N_2H^+ data from FCRAO. N_2H^+ is destroyed in the core centre and along the jet axis due to the high abundance of CO. The N_2H^+ data demonstrate that this core is rotating with its rotation axis aligned with the observed molecular outflow. We have used high spectral resolution data of N_2H^+ to measure the velocity and linewidths across the core. We find that B1-c exhibits similar morphology and kinematics to IRAM 04191+1522, another very young class 0 source in Taurus.

1. Motivation

The Barnard 1 cloud is located at a distance of $\sim$ 330 pc in the Perseus molecular cloud complex. Barnard 1-c (B1-c) was identified as a star-forming core by Matthews & Wilson (2002) during the mapping of the center of the Barnard 1 cloud in polarized emission using the SCUBA camera on the James Clerk Maxwell Telescope (JCMT). It is the brightest core in dust emission in B1 at submillimeter wavelengths. The core is of particular interest because it exhibits an atypical polarization signature: the polarized intensity rises continuously to the intensity peak. Most cores exhibit a polarization hole, meaning that the fractional polarization declines as intensity rises (i.e., the polarized intensity is rather flat). The rising polarized intensity in B1-c indicates that dust grains are aligned in the densest parts of the core. We have undertaken a high resolution study of the core's interior in an attempt to determine whether this core has other unique properties which could explain the polarized emission signature.

2. Observations

We observed B1-c with the Berkeley-Illinois-Maryland Association (BIMA) array in 2002 and 2003 in the C and B array configurations. We observed several molecular species, including N_2H^+ 1-0, HCO^+ 1-0, CO 1-0 and $C^{18}O$ 1-0. In 2005, we obtained complementary single dish data in N_2H^+ 1-0 and HCO^+ 1-0 from the Five Colleges Radio Astronomy Observatory (FCRAO) 14 m.

3. Results

3.1. Morphology

The BIMA data reveal a double peaked morphology in the dense gas of the core and the destruction of N_2H^+ along the outflow axis and at the core center. This morphology is very similar to that of IRAM 04191+1522, a class 0 source in Taurus, with an age estimate of 3×10^4 yr (Lee, Ho & White 2005; André et al. 1999; Belloche et al. 2002, 2004).

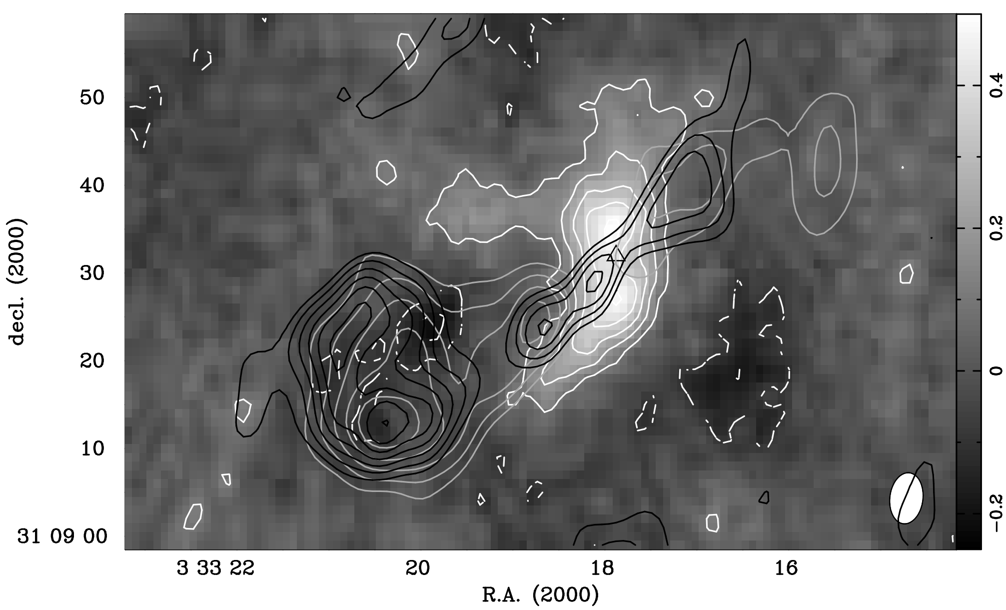

Figure 1. Morphology of the core/outflow interaction. The N_2H^+ data are shown in greyscale and in white contours from 2-10σ in steps of 2σ where $\sigma = 47$ mJy beam^{-1}. Black contours are CO 1-0 (2-8σ, 1$\sigma = 0.16$ Jy beam^{-1}) and grey contours are HCO^+ 1-0 (2-6σ, 1$\sigma = 35$ mJy beam^{-1}). The N_2H^+ beam is shown at the lower right, and the black triangle marks position of the central source as identified in 3 mm continuum.

As shown in Figure 1, the outflow emission is anticorrelated with the N_2H^+ core emission. The N_2H^+ is not centrally peaked and is absent along the outflow axis at the center of the core. To the eastern edge of the core, the N_2H^+ emission wraps the CO and HCO^+ emission, which are well correlated. A kinematic age estimate, based on the outflow and assuming an inclination of 45°, is a few $\times 10^4$ yr, very similar to the age of IRAM 04191+1522.

A moment zero map of the red and blue lobes of the CO 1-0 emission in the outflow is shown in Figure 2. The $C^{18}O$ 1-0 emission is seen to be centrally peaked, with extended $C^{18}O$ emission in the envelope. Interestingly, the $C^{18}O$ 1-0 emission is also anti-correlated with the outflow emission. The presence of red-shifted emission adjacent to blue-shifted emission suggests a change in outflow orientation or visibility of the back of a conical cavity in projection.

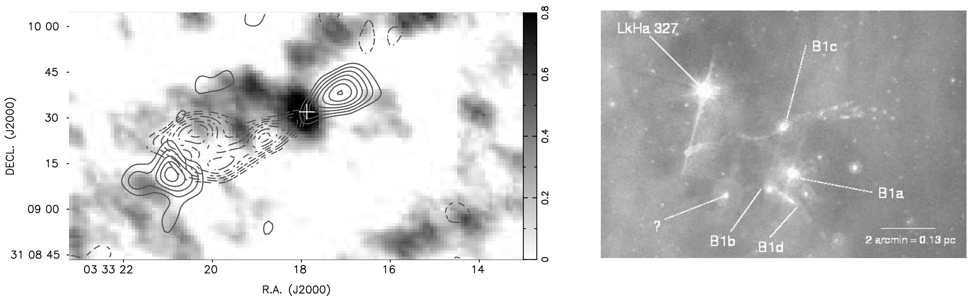

Figure 2. *Left:* Red- and blue-shifted emission from the outflow is illustrated by the solid and hashed contours, respectively (in intervals steps of 2-8 $\times$ 1.6 Jy beam^{-1} km s^{-1}). The greyscale emission is $C^{18}O$ 1-0. The cross marks the position of the continuum source. *Right:* Spitzer Space Telescope three color image of the Barnard 1 region. The jet emission centered on B1-c is clearly seen over several arcminutes. The emission is dominated by molecular hydrogen lines in the 4.5 μm band. This image is courtesy of the Spitzer "Cores to Disks" Legacy Survey.

Figure 2 also shows the outflow on much larger scales as detected by Spitzer. The jet extends for several arcminutes and is by far the most prominent in the region. As is typically observed, the jet is asymmetric at large distances from the powering source. The S-shaped morphology of the jet could indicate binarity (e.g. Hodapp et al. (2005)).

3.2. Rotation

Figure 3 shows the first and zeroth moments of N_2H^+ 1-0 emission from combined BIMA and FCRAO channel maps. N_2H^+ 1-0 has seven hyperfine components, of which only one is isolated and spectrally resolved from the others in our dataset. We have used only this component in generating the moment maps of Figure 3. The evidence of core rotation is clear from the first moment map. The axis of rotation is roughly aligned with the outflow direction.

The relative velocity of the two N_2H^+ peaks is 0.13 km/s, suggesting a rotation energy of $\sim 5 \times 10^{40}$ ergs. This is 6-7 orders of magnitude less than the gravitational, kinetic or magnetic energies Matthews & Wilson (2002). The predicted N_2H^+ thermal linewidth is 0.22 km s^{-1} in B1. The measured linewidth is 0.56 km s^{-1}, indicating strong turbulence.

4. Summary

Barnard 1-c ($\sim 2.7 M_\odot$) is a protostellar core driving a bipolar molecular outflow and jet, identified in BIMA array, FCRAO and Spitzer data. The core

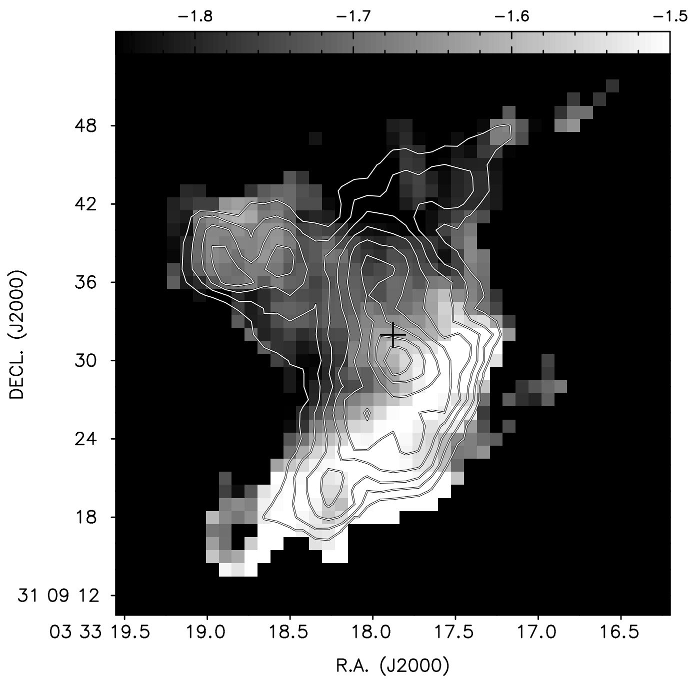

Figure 3. Greyscale shows the first moment of the N_2H^+ 1-0 emission from only the isolated hyperfine component. The contours show the zeroth moment taken over the same component, starting at 0.35 Jy beam^{-1} km s^{-1} in steps of 0.07 Jy beam^{-1} km s^{-1}. The cross marks the position of the continuum source.

shows evidence that N_2H^+ is destoyed along the outflow axis, leaving a double-peaked morphology. We see evidence of core rotation in the combined BIMA and FCRAO data. Further observations are scheduled on the Spitzer telescope, the Submillimeter Array and the JCMT for the fall of 2005.

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References

André, P., Motte, F., Bacmann, A. 1999, ApJ, 513, 57
Belloche, A., André, P., Despois, D., & Blinder, S. 2002, A&A, 393, 927
Belloche, A., & André, P. 2004, A&A, 419, 35
Hodapp, K.W., Bally, J., Eislöffel, J., & Davis, C.J. 2005, AJ, 129, 1580
Lee, C.-F., Ho, P.T.P., & White, S.M. 2005, 619, 948
Matthews, B.C., & Wilson, C.D. 2002, ApJ, 574, 822