

A PRECESSING JET EXCAVATING A PROTOSTELLAR ENVELOPE. Jason Ybarra, *Department of Physics & Astronomy, San Francisco State University*, Mary Barsony, *Department of Physics & Astronomy, San Francisco State University and Space Science Institute*, Karl E. Haisch, Jr., *Utah Valley State College*, Thomas H. Jarrett, *Infrared Processing and Analysis Center*, Raghvendra Sahai, *Jet Propulsion Laboratory*, Alycia J. Weinberger, *Department of Terrestrial Magnetism, Carnegie Institute of Washington*.

Powerful, bipolar supersonic outflows are a hallmark of the earliest protostellar stages. Since protostars are deeply embedded in molecular clouds, the outflow phenomenon was first discovered in the cold gas emission lines of the CO molecule, at millimeter wavelengths [1,2]. Narrow, highly-collimated, low-surface brightness optical jets powered by protostars were discovered with the advent of narrowband CCD imaging [3]. It took over a decade to convince researchers that the high-velocity, narrow-angle optical jets power the lower-velocity, generally wider-angle, molecular outflows. The concomitant problem of how jets produce the wide-angle outflow cavities in protostellar envelopes has remained unsolved [4,5].

In order to explore the relationship between driving sources and their outflows, we have embarked on a large-scale survey using sensitive, narrowband molecular hydrogen imaging [6]. The technique involves imaging the protostellar environs at near-infrared wavelengths through two narrowband filters: one containing a shocked H₂ emission line of interest, the other excluding any H₂ lines. After appropriate scaling and subtraction, the resulting images show the morphology of the pure H₂ emission from the jet. We report first results from this survey here: the discovery of a precessing jet carving out a protostellar envelope's cavity.

Infrared imaging data of a late-stage protostar were obtained on the night of 11 July 2004 with the Wide-Field Infrared Camera (WIRC) on the Hale 5-meter telescope at Palomar Observatory, and, subsequently, on the night of 16 June 2005 with Persson's Auxiliary Nasmyth Infrared Camera (PANIC) on the Baade 6.5-meter telescope at Las Campanas Observatory. K-band seeing was 1'' at 0.25''/pixel for WIRC and 0.3'' at 0.125''/pixel with PANIC. Total on-source integration times were 28 minutes per filter at Palomar and 70 minutes per filter at Las Campanas.

Figure 1 shows the morphology of the Class I protostar observed with WIRC. N is up, and E is to the left in this, and all subsequent figures. This image was acquired with a filter centered at 2.120 μm ($\Delta\lambda/\lambda = 1.5\%$), that included both the shocked H₂ emission line at 2.122 μm , as well as

some continuum emission. Note the bipolar appearance of the infrared reflection nebulosity, typical of scattered light images of late-stage protostellar envelopes with large opening angle cavities [7,8].

A corresponding WIRC continuum image (not shown) was obtained through a filter centered at 2.270 μm ($\Delta\lambda/\lambda = 1.7\%$). The resulting continuum-subtracted H₂ line image is displayed in Figure 2. Artifacts within a 5'' radius of the central protostar are due to saturated pixels. Pure H₂ emission regions are labelled. The observed and inferred scattered light cavity walls are traced by the solid and dotted lines, respectively.

Several striking facts stand out in the image presented in Figure 2: The sinuous nature of the H₂ emission, the S-shaped point symmetry of the jets about the position of the central protostar, and the brightest H₂ knot impinging on the SE cavity wall.

Figures 3 and 4 represent corresponding PANIC images. The image of Figure 3 was acquired with a filter centered at 2.125 μm ($\Delta\lambda/\lambda = 1.1\%$), again including both continuum emission and the 2.122 μm H₂ line. An image through the Br γ filter centered at 2.165 μm ($\Delta\lambda/\lambda = 1.0\%$) (not shown) was used as a continuum filter. Figure 4 shows the resulting continuum-subtracted, pure H₂ line-emission image (again, excepting for artifacts at the protostellar position caused by saturation).

This object is known to be single, so the jet precession is likely to be caused by disk warping due to the outflow [9]. Numerical hydrodynamical models of continuous and pulsed fast-precessing jets and slow-precessing jets have recently been published, and comparison with model images suggests we are observing a continuous, slow-precessing jet [10]. Previous 3-D, smoothed particle hydrodynamic modelling of jet-driven molecular flows showed that the only way to account for the wide-angle molecular flows (and, in this case, the wide-angle outflow cavity traced by the reflection nebulosity) is by a "wandering" jet, *i.e.*, one that changes its direction. After a decade, observational evidence in support of this conjecture is now in hand.

Funding from NSF grant AST-0206146 is gratefully acknowledged.

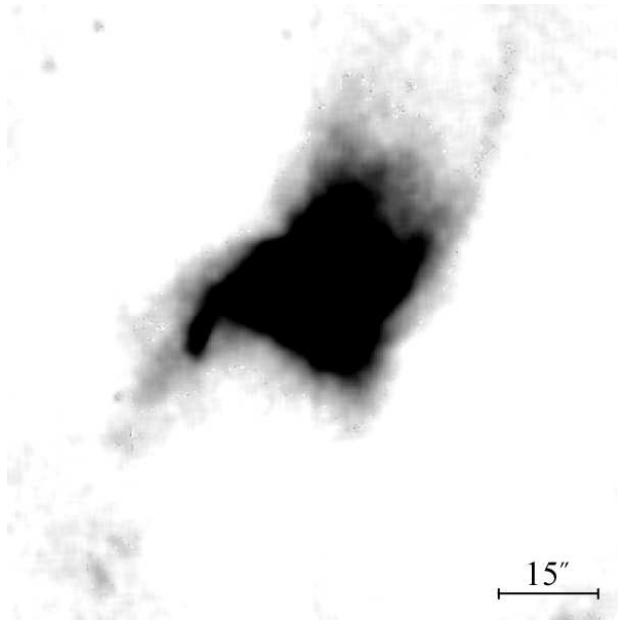


Fig. 1. WIRC image of a Class I protostar. Although observed through a narrowband H_2 filter, the origin of the bright bipolar nebulosity is continuum emission from scattered light.

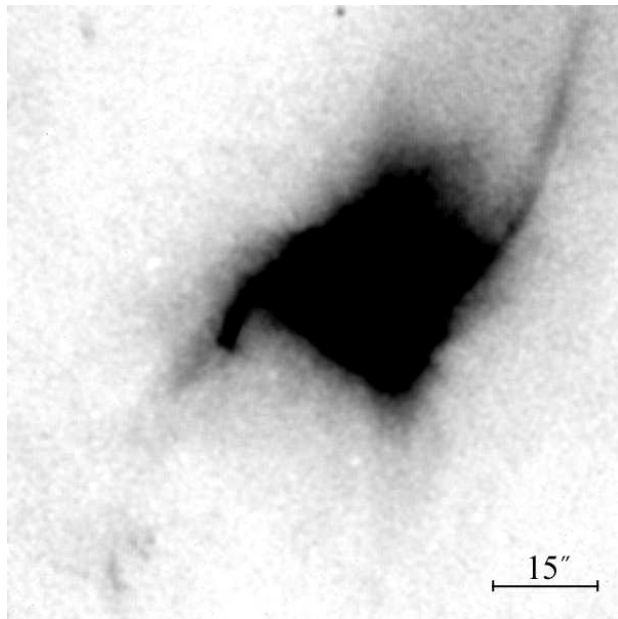


Fig. 3. PANIC image of the same Class I protostar viewed through a narrowband H_2 filter.

References: [1] Zuckerman, B., Kuiper, T.B.H., Rodriguez-Kuiper, E.N. (1976), *ApJ*, 209, L137. [2] Snell, R. L., Loren, R. B., & Plambeck, R.L. (1980), *ApJ*, 239, L17. [3] Mundt, R. & Fried, J.W. (1983), *ApJ*, 274, 83. [4] Velusamy, T. & Langer, W.D. (1998), *Nature*, 392, 685. [5] Arce, H.G. & Sargent, A.I. (2005), *ApJ*, 624, 232.

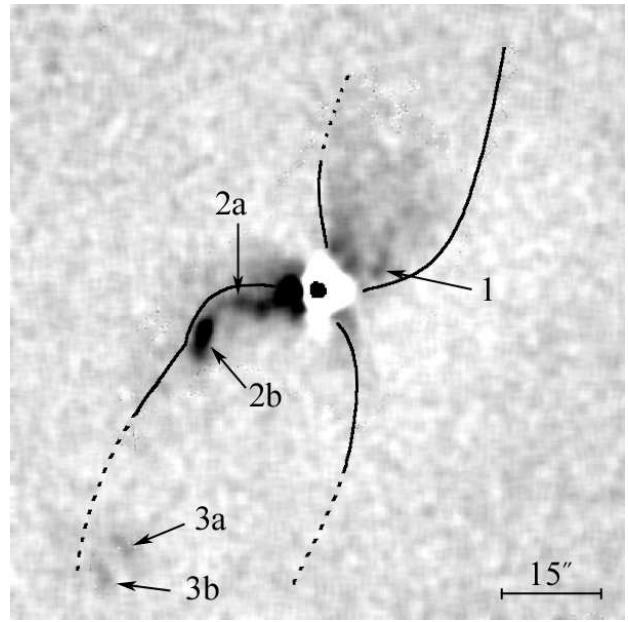


Fig. 2. Continuum-subtracted WIRC image of the protostar, revealing pure H_2 line emission from the sinuous jet. The protostellar envelope's cavity is traced by the solid and dotted curves.

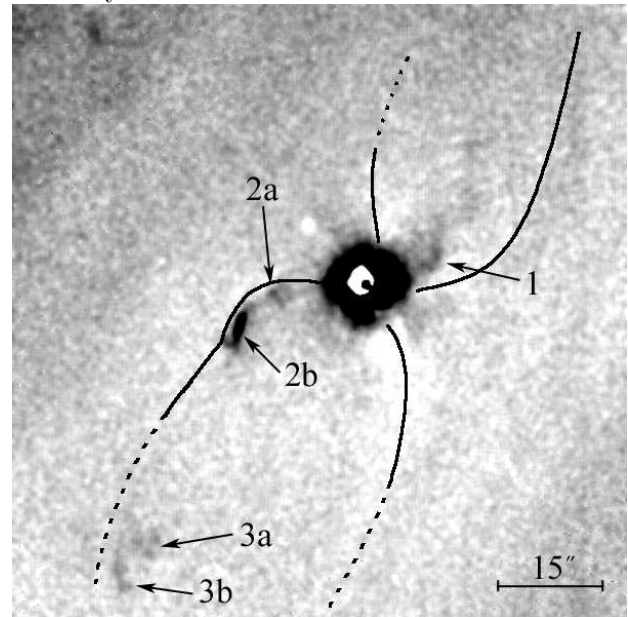


Fig. 4. Continuum-subtracted PANIC image, revealing the same faint H_2 features first identified in the WIRC data.

[6] Barsony, M., et al. (2005), in prep. [7] Padgett, D.L. et al. (1999), *AJ*, 117, 1490. [8] Whitney, B.A. et al. (2003), *ApJ*, 598, 1079. [9] Lai, D. (2003), *ApJL*, 591, L119. [10] Smith, M.D. & Rosen, A. (2005), *MNRAS*, 357, 579. [11] Chernin, L. et al. (1994), *ApJ*, 426, 204.