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A bipolar-outflow object in the field of M 36

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Abstract. We have discovered an object in the field of the Galactic open cluster M 36 which exhibits a nebulous tail-like structure and a high velocity outflow. We first observed the jet morphology in optical images taken at the Michigan-Dartmouth-MIT (MDM) Observatory at Kitt Peak. This source, located at $05^{h}\,36^{m}\,05\overset{s}{.}9$, $34^{\circ}\,06'\,12\overset{''}{.}1$ (J2000), is found to be coincident with IRAS 05327+3404. CO (1 – 0) observations (Wouterloot & Brand 1989) showed this object to be a strong emission-line source. We performed CO (2 – 1) observations at the James-Clerk-Maxwell Telescope at Mauna Kea which suggest that the outflow is bipolar in nature. Optical spectroscopy obtained at the La Palma Isaac-Newton 2.5m Telescope shows strong emission lines, reminiscent of Herbig-Haro emission and confirming the outflow. The object is probably not associated with M 36, and may be a far-flung member of the nearby region of star formation, S235. The optical spectra are quite unusual. We conclude that the spectra represent two views of the same jet structure from different viewing angles, one the result of a reflection off the nebulous tail. The IRAS fluxes, optical morphology, and aspects of the optical spectra are similar to the FU Orionis system L 1551 IRS 5, and may indicate that this object is also an FU Orionis star.

Key words: radio lines: ISM – stars: formation – pre-main sequence – open clusters: M 36 – ISM: jets and outflows

1. Introduction

Several classes of Galactic astrophysical objects which exhibit bipolar outflow are now known. Pre-main sequence stars (i.e., Young Stellar Objects or YSOs) are known to exhibit molecular bipolar outflows with flow velocities of $\sim$5 – 60 km sec^{-1}extending for $\sim$0.05 – 5 pc (see e.g., Cabrit 1993) and ionized flows with velocities of typically 200 km sec^{-1}(see e.g., Panagia 1993). Cometary and bipolar nebulae are also commonly associated with young stellar objects (see Staude & Elsässer, 1993, for a review of this topic) Asymptotic Giant Branch (AGB) stars of various types (i.e., Miras and OH/IR stars) show high mass-loss rates (10^{-7} – $>10^{-4}$ M$_{\odot}$year^{-1} – see e.g., Van der Veen & Habing 1988) and can exhibit bipolar jets, as reviewed by Habing et al., (1989). Planetary nebulae, particularly when still young or developing, also show bipolar outflows, usually seen in optical emission lines (see, e.g., Solf 1992). We report the discovery of a bipolar-outflow object in the field of the Galactic open cluster M 36. The optical spectra and IRAS fluxes strongly suggest that this object is a young stellar object, with many similarities to the FU Orionis star L 1551 IRS 5.

2. Observations

2.1. Optical images

Our object, which we give the name *Holoea*[1], was discovered in our recent CCD observations of the Galactic open cluster M 36 in Auriga. These observations were performed at the Michigan-Dartmouth-MIT (MDM) Observatory 1.3m McGraw-Hill telescope at Kitt Peak on the nights of October 2 and 3, 1993. The observations were made using the 2048^2 Tektronics CCD known as "Wilbur" (Metzger et al., 1993). The CCD was read out with a 2 × 2 pixel binning factor. At the f/7.5 focus of the 1.3m telescope, the effective pixel scale was $0\overset{''}{.}63$, and the CCD therefore covered $\sim 10\overset{'}{.}8 \times 10\overset{'}{.}8$. We obtained follow-up images to confirm the existence of the object on Feb 3, 1994 at the 1.0m Jacobus Kapteyn Telescope at La Palma (kindly provided as part of the service time allocations) as well as Feb 4, 1994 again at the MDM 1.3m McGraw-Hill telescope using "Wilbur" (kindly provided by Sam Conner).

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[1] Hawaiian for "flowing gas"

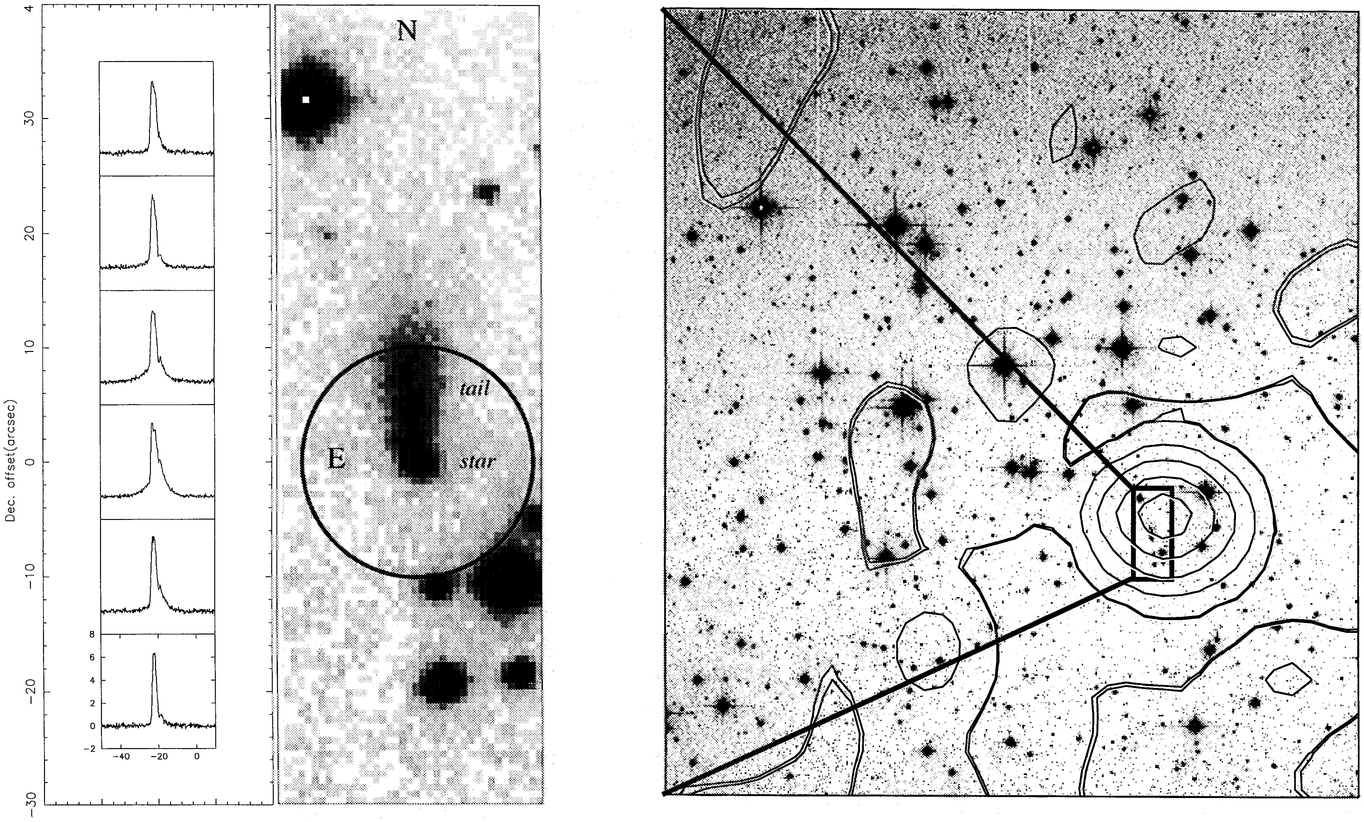

Fig. 1. This figure shows the CO (2 – 1) spectra (left), optical (*I*) images (center and right panels) and the IRAS 100 μm flux contours (right panel). The 6 CO (2 – 1) spectra are located vertically at positions which correspond to the location of the beam center along the *tail* in the center panel. The *star* has coordinates of $05^h\ 36^m\ 05^s\!.9$, $34°\ 06'\ 12''\!.1$ (J2000), and the coordinates along the outer box of the spectra also corresponds to the *I* image in the center panel. The large circle shows the FWHM of the JCMT beam. The coordinates on the bottom spectrum give velocity in km sec^{-1} (abcissa) and antenna temperature in K (ordinate). The right panel shows the location of *Holoea* in the field of M36. This panel is $10'\!.8$ tall. It is clear from this picture that *Holoea* is within the bounds of the open cluster. The IRAS 100 μm contours are shown at flux densities of: 1.00, 1.01, 3.33, 10.00, 33.33, 100.00 MJy sr^{-1}. The bipolar-ouflow nature is evident in the CO spectra: Note the strong, broad line that appears at the position of the star, and the blue-shifted emission that is present north of the star, but not at the southern position

Holoea was discovered in the images of M36 because of its striking optical morphology (see Fig. 1). We will call the two major optical components the *star* and the *tail*, as labeled in the figure. *Holoea* can be seen in several *BVRI* images, though the *tail* is only barely detectable in the longest B images (100 second exposures), while the *star* is not detected in B at all. Measurements of the flux of the *star* are difficult to perform accurately because the flux from the *tail* component contaminates that of the stellar component. There is a 4σ difference between the average I magnitudes measured on Oct 2 and on Oct 3, but this is probably due to systematic errors in the flux rather than variability on these timescales. There is some evidence that the *star* has varied substantially in the past 41 years – on red Palomar Observatory Sky Survey (POSS) plates taken in 1952, the *tail* is visible, but the *star* is not detected. In comparison with a nearby, somewhat fainter star of essentially the same color, the *star* must have been $\gtrsim$1 magnitude (R) fainter in 1952 than today. Table 1 gives the observed optical magnitudes of the two components. The errors for the *star* are typically 0.1 mag, dominated by the uncertainty in the contamination from the *tail*. Errors for the *tail* + *star* are much smaller, roughly 0.03 mag. The $V-R$, $V-I$ colors of the *star* suggest the presence of optical extinction. However, because we have only *VRI* colors, and because of the systematic errors due to the contamination, the extent of the extinction is not well determined. We obtained a further set of R and I images on Dec 16, 1994 at the Nordic Optical Telescope at La Palma using the Instituto de Astrofísica de Canarias CCD camera. These images have substantially better spatial resolution, with a FWHM of $\sim 0''\!.5$. There is no evidence of variability between the Oct 3, 1993 and Dec 16, 1994 R or I images – the flux of the *star* is found to remain constant within 2%.

2.2. IRAS and CO line emission

An IRAS point source is coincident with *Holoea*. IRAS 05327+3404 is found to be within 15″ of the optical position of the *star*, as seen in Fig. 1. We have used the IRAS-GIPSY system developed at the Laboratory for Space Research Groningen (Wesselius et al., 1992) to investigate the IRAS source associated with *Holoea*. Image restoration techniques were applied to the 60 and 100 μm IRAS survey data to improve the spatial

Table 1. Observed optical magnitudes of *Holoea*

	B	V	R	I
star	> 19.00	18.62	17.43	16.08
tail + star	16.77	15.48	14.62	13.71

resolution (see Bontekoe et al., 1994 for a detailed description). These techniques allow a spatial resolution of about 1′ and 1′.7 at 60 and 100 μm respectively. We show the 100 μm flux contours in Fig. 1. The IRAS 12, 25, 60, and 100 μm fluxes are: 0.87, 2.61, 10.68, 15.95 Jy, respectively (IRAS Point Source Catalog, 1985). This IRAS source has very cool colors and the integrated spectrum falls off in a non-Planckian way (see Fig. 2), suggesting the emission is due to regions with a range of temperatures. This is consistent with the picture of a star shrouded by dust, and lends credence to the optical extinction mentioned above. The luminosity in the IRAS bands is $\sim 41 L_\odot$. If we assume the break to the Wien tail of the spectrum occurs near 100μm, the total luminosity should be roughly double this number, or about $82 L_\odot$.

Wouterloot & Brand (1989) observed 1302 IRAS sources, including IRAS 05327+3404, in the CO (1-0) line. These objects were selected on the basis of their IRAS colors as possible H II regions beyond the solar circle. Our source was found to be a strong source of molecular emission. A reference was given in this paper to the proximity of the source to the open cluster M36, but no further discussion was made.

Observations of the $J = 2-1$ transition of CO were thus carried out with the 15-m James Clerk Maxwell Telescope (JCMT) on April 10, 1994. In total 6 positions with 10″ spacing along the north-south direction were observed, starting 20″ south of the *star* and ending 30″ north (see Fig. 1). Background subtraction was performed using pointings offset by 3′ in azimuth at 1 Hz. The beam size (HPBW) is 20″ and is shown in Fig. 1.

The CO spectra appear to consist of two components. A strong, rather narrow ($\sim$3 km sec^{-1}) component at $V_{LSR} \sim -22$ km sec^{-1} is roughly constant (both in brightness and LSR velocity) in the six pointings, and is probably from an extended molecular cloud along the line of sight. There is also a weaker but much broader component with a peak at roughly -18.7 km sec^{-1}. The red and blue wings of this component have very different appearances at points north and south of the object. The red wing is strongest in the pointing centered on the star, and it drops in intensity symmetrically in the pointings north and south of the star. The blue wing is equally strong in the pointing centered on the star and the pointing 10″ north of the star, suggesting that the maximum of this wing is a few arcseconds north of the star. A close examination of the spectral profile in the pointing centered on the star suggests that the blue wing may be due to a second peak slightly displaced from the peak at -18.7 km sec^{-1}, but buried in the narrow line. Interferometric observations can test this suggestion by spatially removing the background cloud. Thus, the CO $(2-1)$ line suggests the existence of a bipolar outflow from the central star. The peak of the broad CO emission associated with *Holoea* is roughly between that of the background cloud (at -22 km sec^{-1}) and that of M36, at -13 km sec^{-1}. However, relative velocity difference is too small for us to completely rule out the possibility that *Holoea* is associated with M36.

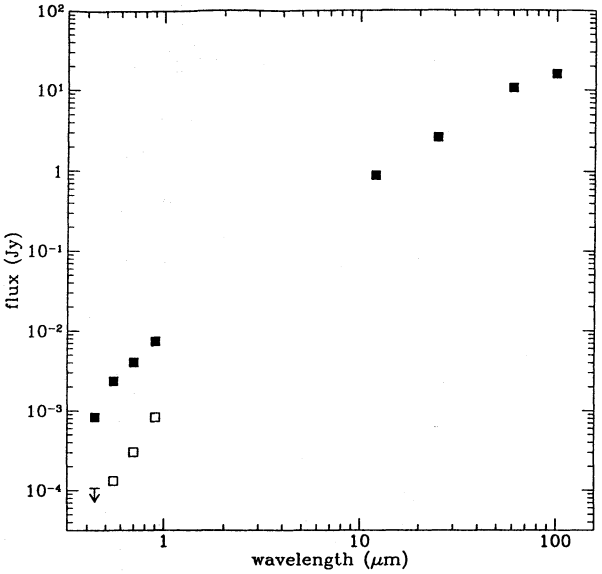

Fig. 2. Broadband spectrum of *Holoea*. Errors are much smaller than the individual points. Filled squares are *star + tail*, open squares are *star* only

The star-forming region S235 is the nearest region of substantial star formation activity, as well as the closest large molecular cloud to M36, with an angular seperation of roughly 2°. For a distance of 1.2 kpc (M36, Hron 1987) to 1.6 kpc (S235, Blitz et al., 1982), this angular separation corresponds to 42 – 56 pc. CO observations of the star-forming region have given a V_{LSR} of -18.8 to -20.0 km sec^{-1} (Blitz et al., 1982; Snell et al., 1990). The velocity of the narrow component in the CO spectra suggests that this feature is associated with S235, and the velocity of *Holoea* is also consistent with this range of velocities. In a wide-angle Hα picture of this area (Parker et al., 1979), M36 lies on the outskirts of a large H II complex containing S235. The distribution of emission seen by IRAS shows that star formation is taking place over a large area north of *Holoea.* In Fig. 3, we present an overlay of the IRAS 60μm map on the POSS plate. In this figure, M 36 is circled, near the bottom of the picture. Based on this picture, it is reasonable to suggest that *Holoea* is an outlying member of this star forming region.

2.3. *Optical spectroscopy*

We obtained optical spectra of the *star* and *tail* of Holoea using the 2.5m Isaac Newton Telescope at La Palma on Feb 6, 1995 (kindly provided as part of the service time program). Two spectra were taken, one along the *tail* (position angle 0°) and one perpendicular to the *tail* (position angle 90°). The spectral resolution is FWHM $\sim$ 70 km sec^{-1}. In Fig. 4, we present

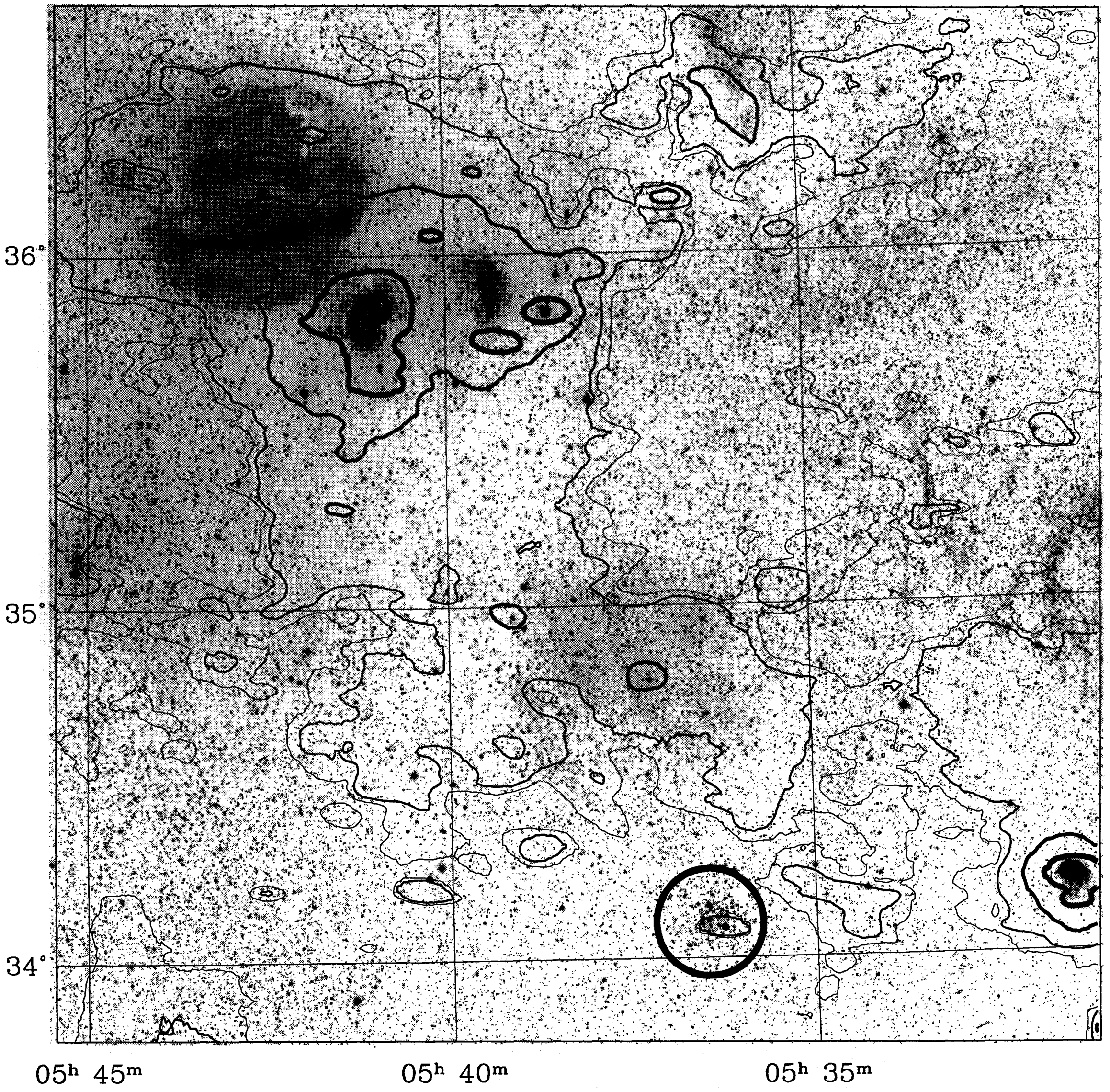

Fig. 3. Star formation in the field of M 36. This picture shows the 60μm IRAS contours overlaid on the POSS plate image. The location of M36 is marked by a large circle, which also contains *Holoea*. The star formation region S235, located near the top of the picture, is clearly seen by the extensive IRAS emission and the optical nebulosity. Diffuse IRAS emission in the large region north of M36 implies the presence of star formation thoughout this area

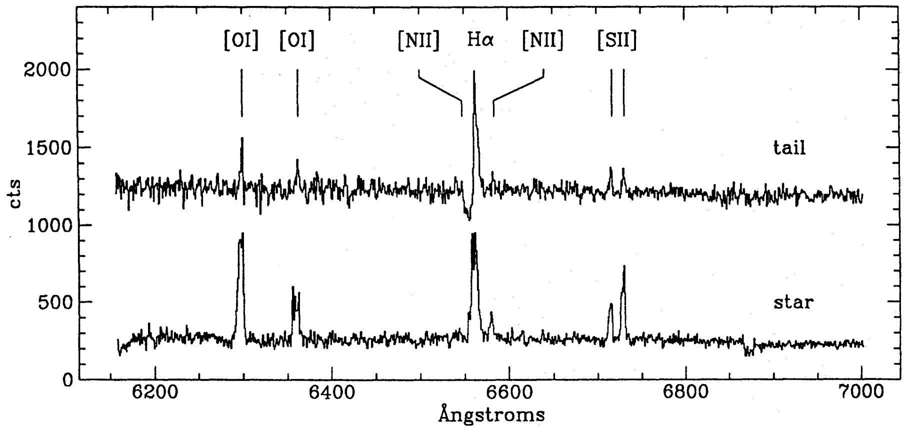

Fig. 4. Optical spectra of *Holoea*. The upper spectrum is from just the *tail*, while the lower one is from just the star. The *tail* spectrum has been displaced by 1000 counts. The forbidden emission lines and Hα are marked

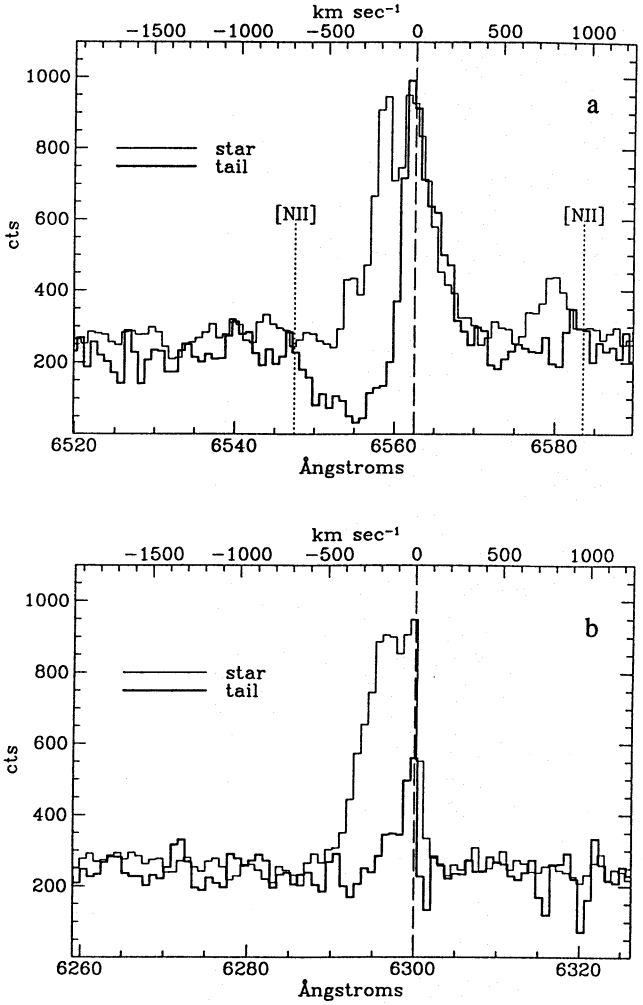

Fig. 5. **a** Hα profiles from the *star* and *tail*. The P Cygni profile seen in the *tail* spectrum is probably due to light from the star reflected off dust grains in the cometary tail (see text). **b** [O I] λ 6300Å profiles seen in the *star* and *tail*. Note the sharp cut-off of the flux redwards of zero velocity. In both panels, the rest velocity of the system, determined from both the stellar absorption lines and the CO emission, is shown as a vertical line. The vertical scale is in counts and is not renormalized. Thus, the similarity of the fluxes in the continuum and the peak of the Hα line is coincidental

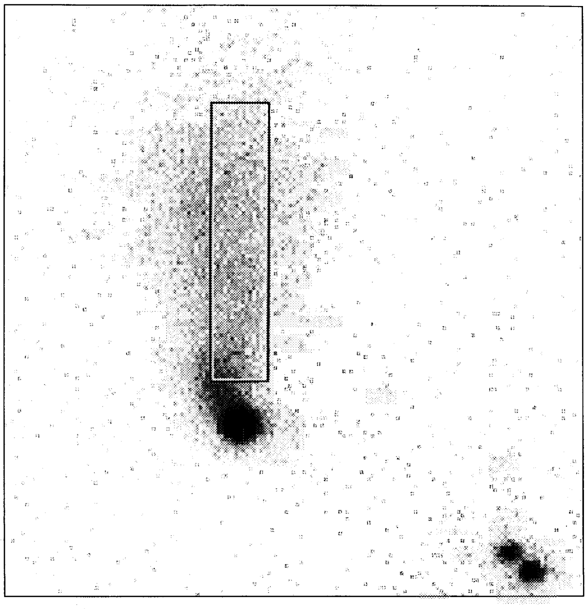

Fig. 6. *I* band image of Holoea taken at the NOT. The rectangle marks the region where the *tail* spectrum, shown in Figs. 4 and 5, was taken. Seeing in this image is $0\farcs5$. Note the absence of obvious Herbig Haro concentrations in the tail region. The small enhancment of the tail to the northeast of the *star* may contain unresolved Herbig Haro objects, but higher resolution images would be needed to determine the validity of this possibility

the spectrum of just the star and the spectrum of just the *tail*, in which the flux of the star was excluded when the spectrum was extracted. Although the signal-to-noise in the continuum is low ($\sim$20), weak stellar absorption lines (e.g., Fe I, Ca I) can be seen in the spectra, and a comparison with a K0III star shows that the lines are typical of a late-type star with a rough spectral class of K0 – K5. The location of the absorption lines is consistent with the $\sim$−20 km sec^{-1} radial velocity determined from the JCMT CO observations. Emission lines are also clearly evident in both spectra, and we have marked the significant detections. The emission lines in the *tail* are increasingly weak further from the star. The Hα emission line in the *tail* exhibits a P Cygni profile, and we show a close-up of this portion of the spectra in Fig. 5a. In this figure, we have marked the rest frequency of Hα in the system, taking the system radial velocity to be $V_{LSR} \sim -20$ km sec^{-1}, based on the CO observations. The absorption in the P Cygni profile can be seen out to a velocity of ~ -650 km sec^{-1}, while the red side of the emission line in both the star and *tail* spectrum can be seen out to $\sim$250 km sec^{-1}. The spectrum of the star also shows a second peak which is blueshifted by ~ -220 km sec^{-1}. The forbidden lines in the spectrum of the star also show broad or double-peaked profiles with similar ranges of velocities, and we present the [O I] λ6300Å line profile in Fig. 5b. A very striking feature of this line profile is the sharp cutoff of flux redwards of zero velocity. This strongly suggests an absorbing medium which hides the redward flowing gas. Fig. 6 demonstrates the positioning of the slit, and the region from which the spectra were extracted, on the image taken at the NOT (see above).

3. Interpretation

We conclude from the spectral class of the star, the presence of the cometary *tail*, and the strength of the forbidden-line emission that this source is a young stellar object of some variety. Gas outflows are often associated with YSOs in molecular clouds. Optical and infrared jets have been seen toward several T Tauri stars and Herbig-Haro objects (e.g., Dopita et al., 1982; Mundt et al., 1984; Reipurth 1985). In fact, the recently discovered jet-like structure at 2.2 μm toward Bok globule L810 (Yun et al., 1993; see also Xie & Goldsmith 1990) shows a very similar morphology to the *tail* of our source. CO outflows are usually associated with the earliest stages of star formation, usually when the star itself is still embedded in the molecular cloud. Indeed, it is rare for the central star to be visible in systems which exhibit molecular outflows (Bally & Lane 1993). Moreover, the [25 μm - 60 μm] color of *Holoea* is much redder than the IRAS colors typical of most T Tauri stars (Gregorio-Hetem et al., 1992). In the spectral classification scheme of Lada & Wilking (1984), T Tauri stars are found to be Class II objects, which show a falling or flat spectral energy distribution longwards of 2μm. *Holoea* is more similar to the Class I objects which show rising spectra in the IRAS bands. The IRAS colors are consistent with those of FU Orionis stars, and we discuss this possibilty in more detail below.

It would be very surprising for a YSO to be a member of M36, since M36 is 20 - 50 Myr old (Harris 1976) and clusters older than 5 Myrs are rarely, if ever, associated with molecular clouds or contain on-going star formation (Lada & Lada 1991). Alternatively, *Holoea* may be an evolved AGB star, like Miras or OH/IR stars, which are occasionally seen with bipolar outflows (Habing et al. 1989). However, the progenitor mass (implied by the most massive unevolved star in M36 – B2V) would be surprisingly high compared to known systems of this type. Furthermore, the IRAS colors imply a very high mass-loss rate: Van der Veen and Habing (1988) have discussed the IRAS two-color diagram (employing 12 μm, 25 μm, and 60 μm fluxes) as a test of the evolutionary state of late-type stars. Stars lie in this two-color plot in an "evolutionary sequence" in order of increasing mass-loss rates. *Holoea* lies beyond the end of their sequence, but roughly on the projected line. If the sequence applies to the IRAS colors of *Holoea*, the implied mass-loss rate is $\gg 10^{-4}$ $M_\odot$ year^{-1}. Furthermore, the 100 μm flux and outflow velocity are fairly atypical of AGB stars. Finally, the total luminosity of the star, at the assumed distance of 1.2kpc, is much less that the expected luminosity of post-AGB stars. Thus, we argue that the AGB star scenario is quite unlikely.

The morphology of the optical spectra is somewhat unusual, and requires a careful explanation. A close examination of the Hα line profile reveals three particular puzzles. The first peculiarity is that the P Cygni profile is seen in the spectrum of the *tail*, while a double peak is seen in the spectrum of the star. The second pecularity is that the P Cygni profile lacks much of the redshifted flux one might expect: typically, the maximum redshift of the emission is comperable to the maximum blue-shift of the absorption. Here, the absorption extends to -650 km sec^{-1}, which the redshift only goes to $\sim$250 km sec^{-1}. The third puzzle is that the double peak is relatively blue-shifted so that the red-most peak is found at zero velocity and the blue-most peak is found at ~ -250 km sec^{-1}. At first glance, this profile looks like either a bipolar outflow or a rotating disk, but normally in such scenarios, zero velocity would be coincident with the minimum between the two peaks. Some explanation for these phenomena is in order.

First, we claim that the spectrum from the *tail* is primarily the result of a reflection. In this scenario, the continuum flux is due to the continuum flux of the star, and the P Cygni profile is due to the *tail*, acting as a reflector, "looking" through outflowing gas at the photosphere of the star. The reflection model gains support in the fact that the stellar absorption features seen in the spectrum of the star increase in strength when the spectrum of the *tail* is added to it. Furthermore, the optical colors of the *tail* are rather bluer than the star, as expected for scattered light. The absorption portion of the P Cygni profile shows that the outflow has a maximum velocity of $\sim$650 km sec^{-1}. A very similar situation occurs in the FU Orionis star L 1551 IRS 5, in which a P Cygni profile is evident in the spectrum of a reflection nebula associated with the source. There are other similarities between *Holoea* and IRS 5 which we discuss in more detail below.

Next, we conclude that the spectrum of the star reveals the blue-shifted outflow in emission because our viewing angle avoids projecting this outflow on the photosphere of the star. This shows that the outflow is collimated in a jet. Furthermore, the difference between the maximum velocity in the P Cygni profile and the maximum velocity from the star (~ -400 km sec^{-1}) shows the jet is tilted by $\sim$45° to our line of sight, assuming the spectrum of the *tail* represents the full doppler shift of the jet.

In the Hα profile of both the *tail* and the *star*, the redshifted emission only extends to $\sim$250 km sec^{-1}, substantially less than the blue-shifted portion. There are three possible explanations for this effect, illustrated in Fig. 7: 1) The redshifted gas is not moving in a tightly collimated jet, instead spraying out in a wide range of directions. This can have the effect of both reducing the maximum velocity, because the acceleration is not as efficient, and reducing the total amount of gas moving away from our line of sight. This description is similar to the model of Kwan & Tademaru (1988) to describe the profiles of forbidden-line emission seen in T Tauri winds. This scenario helps to explain the details of the CO profiles, since the diffused gas will not be displaced to the south by as much as the more collimated jet, and also why the optical nebula is only visible in the north, since the poorly collimated jet in the south may be less likely to leave behind a compact cloud of dust. 2) There is a south-pointing jet of similar strength and velocity as the north-pointing jet, but the emission is shadowed from both us and the nebula by a circumstellar disk. As a result, both the reflection and the direct light only show emission from south side after it has moved far from the star and has lost much of its velocity. Circumstellar disks are frequently invoked to describe the asymmetric profiles of T Tauri line emission (see Staude & Elsässer 1993 for a rewiew). Such a circumstellar disk would also explain the sharp cut-off of the red portions of the forbidden lines (see Fig. 5b), and provide a natural source for the strong IRAS emission. 3) The south-pointing jet is similar in flux and velocity to the north, blue-shifted jet, but they are mis-aligned so that the redshifted jet is moving more nearly perpendicular to the line of sight. We consider this last description to be the least likely scenario as we have no physical understanding of why the two jets would be inclined with respect to one another. In fact, it is reasonable to assume a combination of (1) and (2) are responsible for the observational phenomena.

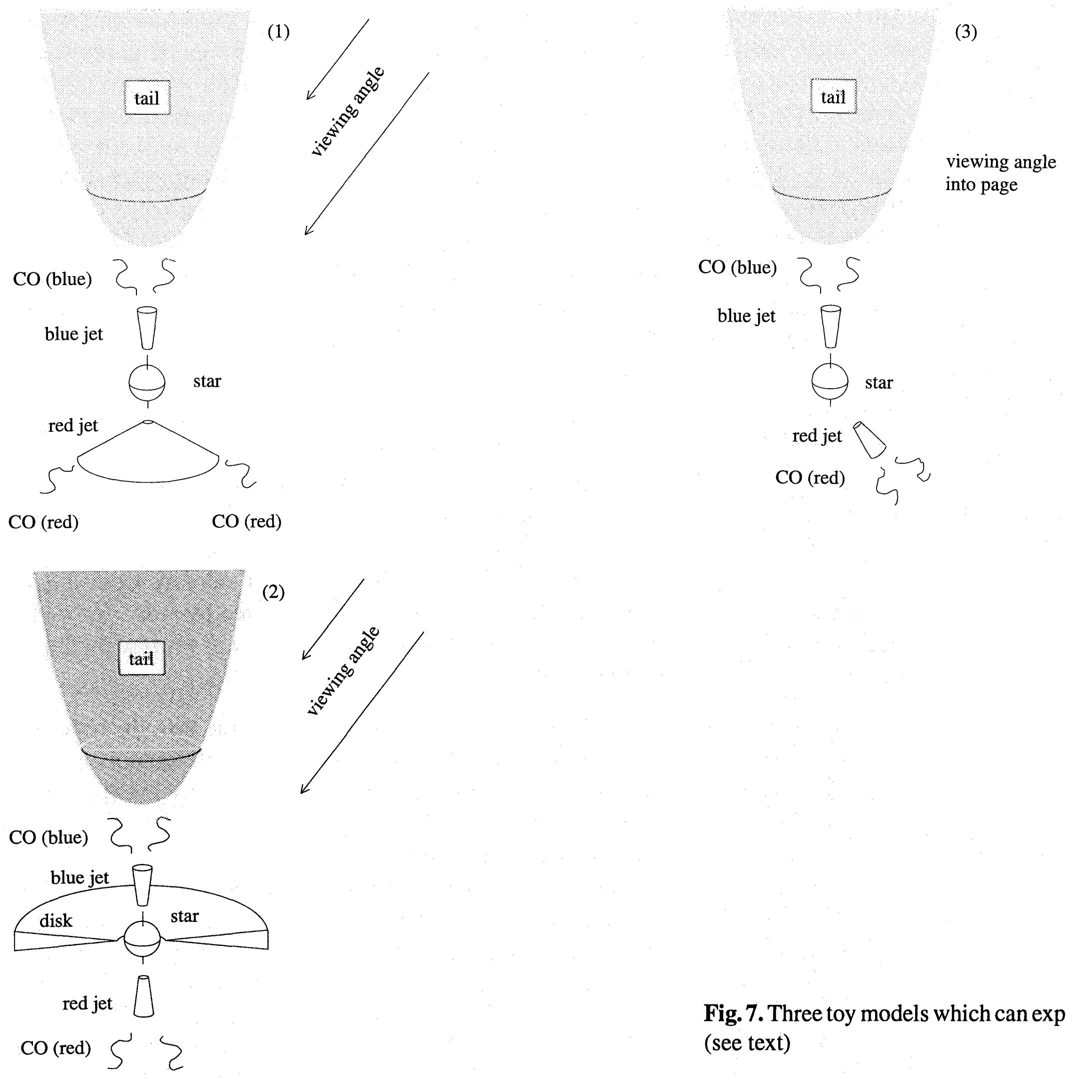

Fig. 7. Three toy models which can explain the peculiar Hα line profiles (see text)

3.1. Similarity to L 1551 IRS 5

L 1551 IRS 5 is a well-studied object with CO and ionized gas outflows which is thought to be an FU Orionis object (see Staude & Elsässer, 1993 for a review). In many ways, *Holoea* is quite similar to this source, and may be a related type of object. Both sources show bipolar CO and ionized outflows. Both sources have reflection nebulae which show a P Cygni profiles in Hα. Both stars have a similar spectral class (G – K for IRS 5; early K for *Holoea*). Both objects have similar spectral shapes in the IRAS bands, though L 1551 IRS 5 is somewhat redder, and similar luminosities ($32 L_\odot$ vs $\sim 82 L_\odot$). Both have high outflow velocities considering their low-mass and low-luminosity (see, e.g., Panagia 1993). Thus, it is possible that *Holoea* is an object similar to L 1551 IRS 5. However, there are several specific ways in which *Holoea* is rather different from IRS 5: 1) The cometary *tail*, which is presumably connected to the outflow gasses, is much more tighly collimated than the reflection nebula surrounding L 1551 IRS 5, and no Herbig Haro objects are evident in the *tail* of *Holoea* (see Fig. 6). 2) The maximum outflow velocity evident in the P Cygni profile is rather larger than that of L1551 IRS 5 (650 km sec^{-1} vs 500 km sec^{-1}). 3) The central star of *Holoea* is visible in the optical, while IRS 5 is blocked from sight by an extremely thick layer of dust. It is thought that L 1551 IRS 5 has a disk which blocks our line-of-sight, while the light illuminating the associated nebula escapes through the polar axis where the column density is low (Staude & Elsässer, 1993). In this respect, the viewing angle to *Holoea* appears to be more favorable, perhaps indicating that the associated disc is thinner than that of L1551 IRS 5. The fact that the central star of *Holoea* has brightened by $\gtrsim 1$ mag in R since 1952 (by comparison with the POSS plates), along with higher outflow velocity, suggests that it is clearing out the dust in the immediate vicinity of the central star. Note that this is rather different than the normal FU Orionis outbursts, which are believed to be due to elevated levels of accretion.

4. Conclusions

We have found an object which appears to exhibit a bipolar outflow, which is seen in both CO and optical spectra. Based on the IRAS fluxes, the optical spectra, and the optical morphology, we conclude that this object is a young stellar object. The IRAS colors are similar to those of FU Orionis stars, but this classification is not yet certain because the star has not exhibited a large increase in brightness nor do we know of strong 2.3μm CO absorption bands. The optical spectra show some unusual characteristics: a P Cygni profile from the optical nebula, similar to that in L 1551 IRS 5, and a double-peaked emission line profile from the star. We conclude that these spectra represent two views of the same outflows from two distinct viewing angles. This provides an exciting system in which we can study a single system jet from two points of view.

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