Multiple Outflows and Protstars Near IC348 and the Flying Ghost Nebula

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ABSTRACT

Using optical (H\textalpha{}, [S ii], & i'), near-IR (H\textsc{2}, J, H, & K\textsc{s}), mid-IR (Spitzer IRAC 4.6\textmu{}m), and submillimeter (850 \textmu{}m & 450 \textmu{}m) data, we have examined the region surrounding the IC 348 cluster and the neighboring “Flying Ghost Nebula” and found a multitude of shocks from protostellar outflows including HH 211 which had previously not been detected in visible wavelength images. We have identified 13 protostars in the region which drive protostellar outflows. The region surrounding the FGN is rich in ongoing star formation with a number of outflows similar to those found in other sites of moderate star formation in Perseus (e.g. L1448, L1455, & Barnard 1). We have also found a candidate bent jet in this region. The axis defined by the bending angle suggests that this source may have been ejected from a multiple star system near the IC 348 IR source.


1. Introduction

Star formation is usually accompanied by bipolar outflows which can be traced by optical emission lines as Herbig-Haro (HH) objects (for a review see Reipurth & Bally 2001). New large
format, wide field CCDs are enabling the study of how outflows shape molecular clouds and influence the process of star formation. Shocks from outflows heat, dissociate, and ionize the gas. They also inject kinetic energy and momentum into the cloud which may drive turbulence and affect the rate of gravitational collapse of cores within these clouds (e.g., Leorat et al. 1990). Chains of HH objects and/or H$_2$ shocks often trace internal working surfaces in parsec scale outflows (Reipurth & Bally 2001). Their locations and orientations, together with their morphology, indicate the presence of embedded protostars. Outflows may play a fundamental role in the evolution of star forming molecular clouds, turbulence generation, and cloud destruction.

The IC 348 cluster, located at the eastern end of the Perseus molecular cloud is the most populous cluster of young stars in this star forming region. The distance to the cluster is somewhat uncertain, but is roughly 300 to 350 pc (Herbig & Jones 1983; Herbig 1998). For the calculations in this paper, we will assume a distance of 320 pc.

The stellar population in IC 348 has been well studied (e.g., Strom et al. 1974; Herbig 1998; Preibisch & Zinnecker 2001; Muench et al. 2003; Luhman et al. 2003; Cohen et al. 2004; Preibisch & Zinnecker 2004; Luhman et al. 2005a,b). Luhman et al. (2003) concluded that the IC 348 cluster contains 288 members, 23 of which are spectral type M6 or later and are likely brown dwarf candidates. In addition, the IC 348 cluster contains a handful of early type B and A stars, with the most massive being the $m_V = 8.68$ magnitude B5V star BD +31 643. The giant ø Per (B1III, $m_V = 3.855$), located North of IC 348 is a member of the somewhat older Perseus OB2 association which is centered to the East of IC 348. Muench et al. (2003) found 66 sources with near-IR excesses indicating the likely presence of a circumstellar disk. In addition, their near-IR photometry is consistent with earlier conclusions that star formation in IC 348 has been taking place between roughly 0.5 and 3.5 Myr ago (Palla & Stahler 2000). This is in slight contrast to Herbig (1998) who found an additional population of stars with ages up to 12 Myr, however Muench et al. (2003) suggest that the older generation of stars in the Per OB2 association may have contaminated the Herbig (1998) results causing an excess of older stars. The IC 348 cluster is located close to the molecular cloud surface as evidenced both by reflection nebosity associated with the brighter members and by the extinction maps of Muench et al. (2003).

Active star formation continues in the immediate vicinity of IC 348. The Barnard 5 cloud core, located about 60′ to the northwest (e.g., Yu et al. 1999; Walawender et al. 2005b), contains several protostars and a giant bipolar outflow powered by the infrared source B5 IRS1.

The dense cloud core located 10′ southwest of IC 348 is one of the brightest in integrated $^{13}$CO emission in the entire Perseus molecular cloud complex (e.g., Walawender et al. 2005b). This cloud core is associated with an optical and near-IR reflection nebula which Boulard et al. (1995) have named the “Flying Ghost Nebula” (FGN). Strom et al. (1974) found a near-IR source (IC 348 IR) with colors consistent with a deeply embedded B star which is probably illuminating the nebula. Based on the the comparison between models and the appearance of a disk shadow in the reflection nebula, Boulard et al. (1995) concluded that the appearance of the FGN and photometry of its
central star could be produced by a B7.5 star behind 28-36 magnitudes of visual extinction with a disk of radius 2400 AU (scaled to the 320 pc distance we are using) and mass of 0.03 $M_\odot$. However, Avila et al. (2001) used the VLA at 3.5 cm and 7 mm to study this same source and concluded that the disk must be much smaller ($r_{\text{disk}} \lesssim 10$AU) with a mass of 0.05 $M_\odot$.

The region also appears as a dense core in an extinction map of Perseus, determined using stellar reddening data from 2MASS (Kirk et al. 2006). Kirk et al. (2006) found the Perseus molecular cloud is made up of distinct regions of high extinction (“cores”), and also associated with larger regions (“super cores”). The FGN corresponds to Kirk et al. (2006) core #5, with a total peak visual extinction of $\sim 10$ magnitudes and a mass of $\sim 200$ $M_\odot$ based on Gaussian modeling. The larger region in which the FGN is embedded (Kirk et al. 2006 super core #2) spans a region of $\sim 30'$ and contains $\sim 2000$ $M_\odot$ of material.

Approximately $1'$ south of IC 348 IR, McCaughrean et al. (1994) discovered a highly collimated outflow (HH 211) by means of its shock excited molecular hydrogen emission. Eislöffel et al. (2003) using 1.2 mm continuum emission, discovered HH 211-mm, the driving source for the HH 211 outflow. HH 211-mm is not visible in near-IR wavelengths, thus it is likely a class-0 protostar.

McCaughrean et al. (1994) also found a chain of H$_2$ knots north of HH 211. Eislöffel et al. (2003) found the southern extension of this North-South flow and identified a candidate driving source (IC 348 MMS) which is bright in the submillimeter, but not visible in the near-IR indicating that it is also a likely class-0 source.

2. Data Acquisition and Reduction

Visible wavelength images were obtained as part of an NOAO Survey Program using the Mosaic CCD camera on the 4 meter Mayall telescope at Kitt Peak and were described in Walawender et al. (2005b). Single exposures, each with a duration of 400 seconds, were obtained through the H$\alpha$ and [S$\text{ii}$] filters, and exposures with a duration of 60 seconds were obtained through the broad-band SDSS i' filter (see Fig. 1).

The Perseus cloud was imaged on a regular grid of pointings chosen to follow the contours of CO emission from the cloud. As a result, the HH 211 region southwest of IC 348 fell into the northeast corner of one of the pointings, IC 348 itself fell onto another, and the region immediately to the South fell onto a third. The images presented here were obtained by combining portions of these three different fields. The data were reduced with the MSCRED package in IRAF. Because these are single exposures in each filter, the gaps between individual CCD chips are still visible in the images (a loss of about 3% of the area coverage).

Near-IR images to the East and North of the FGN were obtained on the nights of Dec. 22, 2005 and Jan. 13, 2006 using the NIC-FPS camera at the Apache Point Observatory 3.5-meter telescope, which is owned and operated by the Astrophysical Research Consortium. Fields were
imaged in narrowband (0.007µm passband) H$_2$ 2.12 µm and broadband (0.32µm passband) K$_S$ filters. Narrowband exposures were a total of 20 minutes (4 minute individual exposures) and broadband exposures were a total of 100 seconds (20 second individual exposures). The field containing SMM 17 and HH 799 was repeated to bring the total exposure time to 60 minutes in H$_2$ and 5 minutes in K$_S$; however on both nights sensitivity was impacted by thin cirrus clouds, thus the final sensitivity is less than the exposure time would indicate.

A more complete set of near-IR observations of just the field containing the FGN and SMM 17 were obtained on Jan. 28 using NIC-FPS on the ARC 3.5 meter. A complete set of J, H, K$_S$ broadband observations were obtained in addition to 1 hour of integration in the 2.12µm H$_2$ filter and the corresponding narrowband continuum filter just redward of H$_2$.

Additional near-IR images of HH 211 and the FGN were obtained on Nov. 25, 2002 with the University of Hawaii 88 inch telescope on Mauna Kea, Hawaii. The instrument used was QUIRC (Hodapp et al. 1996) at a pixel scale of 0.189″ pixel$^{-1}$ and using narrowband H$_2$ (2.12 µm) and [Fe II] (1.64 µm) filters. We obtained eighteen 180 second exposures in H$_2$ and nine 180 second exposures in [Fe II]. The conditions during the observing period resulted in a stellar FWHM of ≈1″.

The submillimeter data from SCUBA was taken from the JCMT$^1$ archives, run by the CADC$^2$. The 850 and 450 µm data were first flat-fielded and extinction corrected using the standard SCUBA software (Holland et al. 1999). We then applied the matrix inversion technique (Johnstone et al. 2000a) to convert the two data sets into images with pixel sizes of 3 arcsec. The 850 µm map has an intrinsic beamsize of 14 arcsec, however, it was convolved with a $\sigma = 1.5$ pixel (4.5 arcsec) Gaussian to aid in the reduction of pixel noise, producing an effective 17.6 arcsec beam. Similarly, the 450 µm map has an intrinsic beamsize of 8.5 arcsec, and was convolved with a $\sigma = 1$ pixel (3 arcsec) Gaussian, yielding an effective beamsize of 10.6 arcsec.

Structure in the submillimeter map on scales several times larger than the chop throw (>120 arcsec) may be an artifact of the image reconstruction (this is independent of reconstruction technique; Johnstone et al. 2000a), and so we also removed these from the map. This was done through the subtraction of a map convolved with a sigma of 90 arcsec. To minimize negative “bowling” around bright sources, all points with values outside of ±5 times the mean noise per pixel were set to those values before convolution. The noise in the 850 µm map is $\sim 7$ mJy bm$^{-1}$ and $\sim 69$ mJy bm$^{-1}$ in the 450 µm map.

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3. Results

3.1. Submillimeter Clumps

The SCUBA map of the IC 348 region shows that the IC 348 cluster is mostly devoid of dust, while the FGN region to the southwest contains two bright filaments (Fig. 2). One filament is oriented predominantly East-West containing SMM 2\(^{(3)}\) (SMMJ 034395+32031, which is IC 348 MMS in the nomenclature of Eislöffel et al. 2003) as its brightest condensation. The other filament runs northeast-southwest and contains SMM 1 (SMMJ 034395+32008 or IC 348 IR) as its brightest condensation. Approximately 10\('\) East of the FGN lie several fainter filaments with the SMM 7 (SMMJ 034473+32015) clump being the only bright clump in that region.

We identify 17 submillimeter clumps in the 850 µm map using the 2D version of Clumpfind (Williams et al. 1994). Hatchell et al. (2005) also studied the clumps in IC 348 and their clump properties are similar to ours. The locations and names of the clumps along with the Hatchell et al. (2005) designations are provided in Table 1. The observed and physical properties of these clumps are presented in Table 2. In addition, Kirk et al. (2006) used these data in an analysis of the entire Perseus cloud.

A useful parameter for classifying the clumps is the degree to which they are centrally condensed. This parameter can be found using the values obtained by Clumpfind. Following Johnstone et al. (2000b), F is the total flux (in Jy), S is the peak flux density (in Jy arcsec\(^{-2}\)), and R\(_{\text{eff}}\) is the effective radius (in arcsec) combine to measure the concentration of a clump; \(C = 1 - \frac{F}{\pi R_{\text{eff}}^2 S}\). This parameter can be physically interpreted in the context of the Bonnor-Ebert sphere model (Bonnor 1956; Ebert 1955; Hartmann 1998) where thermal support within the clump balances self-gravity and external bounding pressure. Stable Bonnor-Ebert spheres can only exist for concentrations below 0.72 (Johnstone et al. 2000b); objects possessing higher concentrations require additional support (e.g. from turbulence or magnetic fields) or else they will collapse. At the other end of the concentration spectrum, a uniform density sphere has a concentration of 0.33. Clumps with concentrations below this value are likely poorly defined or not in equilibrium. Since the concentration gives a measure of the importance of self-gravity within an object, one would expect that objects with a higher concentration, especially near or above 0.72, would generally be more evolved than their lower concentration counterparts (Johnstone et al. 2000b).

We can estimate the internal dust temperature clump by modeling each clump as a Bonnor-Ebert sphere. Following the procedure outlined by Johnstone et al. (2006), we assume that each clump is in equilibrium, supported against gravitational collapse by an equal amount of thermal and non-thermal turbulent pressure. Conversion between the observed total flux and mass requires

\(^{3}\)For clarity we will refer to the submillimeter clumps in the text as SMM 1 through SMM 17 (see Table 1). More formal designations are based on the J2000 coordinates: SMMJ hhmm.mmddmm.m (e.g. SMMJ 033336+31075). We will note this designation at the first mention in the text of any particular clump. In addition, Table 1 contains both designations.
knowledge of both the dust opacity at 850 µm, which we take to be $\kappa = 0.02$ cm$^2$g$^{-1}$, and the distance to IC 348 which we take to be $d = 320$ pc. The resulting temperatures range from 15 to 21 K. An alternate estimate for the clump temperatures can be derived from the ratio of flux found at 850 and 450 µm. To prevent misleading results from the differing beam sizes at these two wavelengths, we first convolve the image at each wavelength with the estimated beam of the other wavelength (see Reid & Wilson 2005 for the procedure and Johnstone et al. 2006 for the beam parameters). Assuming that the dust opacity follows a power-law with index $\beta = 2$, we estimate temperatures ranging from 8 to 23 K. Significant uncertainty remains for each of these temperature measures and thus we adopt a ‘typical’ dust temperature of 15 K in order to measure the mass associated with each clump. Thus, the conversion from 850 µm total flux in Janskys to clump mass, in Solar masses, is 0.8. Table 2 lists the mass of each clump.

3.2. Protostars and Outflows in The IC 348 Region

Our visible wavelength images (Fig. 1) have revealed 10 Herbig-Haro objects in the IC 348 region (Walawender et al. 2005b). Most are clustered around the FGN to the southwest of the IC 348 cluster. Infrared counter-parts to some of these shocks can be seen in the K-band images presented by Muench et al. (2003) and the H$_2$ images presented by Eisloffel et al. (2003). Using the morphology of the shocks in the visible wavelength images and their proximity to clumps in the submillimeter map or sources in the IRAS point source catalog, we have linked several shocks into coherent flows and tentatively identified their driving protostar.

Our near-IR images reveal 18 new H$_2$ shocks in the region (Table. 3). New H$_2$ shocks are found primarily in the region East of the FGN, however 4 of the new knots are embedded in the FGN. We have also inspected the IRAC 4.6µm images obtained by the Cores to Disks Legacy Program on the Spitzer Space Telescope. Several of the near-IR shocks (MH 5, 7, 10, 11, HH 211, and Eisloffel et al. 2003 regions 1, 3, & 4) show counterparts in the Spitzer 4.6µm images (see Table 3).

SMM 3: SMM 3 (SMMJ 034385+32034) lies near HH 795 (Fig. 3), a faint wisp of [S II] emission oriented roughly East-West and about 10′′ long. Several H$_2$ shocks seen by Eisloffel et al. (2003) (and designated region 2 in their discussion) also lie nearby. The H$_2$ shocks appear to trace two flow axis. The first contains two knots labeled by Eisloffel et al. (2003), however our H$_2$ images reveal only one knot. The broadband K images, however reveal a faint reflection nebula coincident with SMM 3 which also shows up brightly in the Spitzer images (Fig. 4). In the Spitzer images the reflection nebula is elongated roughly along PA~ 155°. The H$_2$ knot lies at the base of the reflection nebula.

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4We have only assigned MH numbers to H$_2$ shocks which were not cataloged by Eisloeffel et al. (2003), are clearly not part of an shock complex cataloged by Eisloeffel et al. (2003), and which do not have HH catalog counterparts.
The other flow axis lies about 10″ South of SMM 3 and is oriented roughly East-West terminating in HH 795 on the West. The flow appears to have an S-shaped bend in the H$_2$ images (Fig. 4) and originates at a star visible in the near-IR and Spitzer images. Thus the region immediately surrounding SMM 3 appears to contain two protostars, one coincident with the submillimeter peak which also illuminates a near-IR reflection nebula and another less extincted source, just south of the SMM 3 peak.

**SMM 1 / HH 211-mm:** This clump drives the well known HH 211 outflow first detected by McCaughrean et al. (1994) by means of its shock-excited H$_2$ emission. Our visible wavelength images (Figs. 3 & 5 and in Walawender et al. 2005b) represent the first visible wavelength detection of this outflow. The eastern and western ends of the flow are brighter in [S ii] than in H$_\alpha$ and closely resemble the H$_2$ and [Fe ii] images (Fig. 5).

**SMM 2 / IC 348 MMS:** This bright clump appears to drive the large (10′ long) North-South outflow (Fig. 6) of McCaughrean et al. (1994) and Eislöffel et al. (2003). The flow axis passes through the bright SMM 2 source indicating that it is the likely source. We detect two new H$_2$ shocks (MH 1 & 2) where the axis of the flow passes near the FGN. Our near-IR images reveal no new H$_2$ shocks in a field approximately 4.5′ square located just North of the northernmost shock cataloged by Eislöffel et al. (2003).

We detect two HH objects (HH 797A & HH 797B; Fig. 3) which coincide with H$_2$ shocks which define the flow axis of the north-south outflow. HH 797A consists of a pair of faint [S ii] knots, separated by 6″ and is located about 5′ North of HH 211 W. HH 797B consists of a faint [S ii] and H$_\alpha$ knot, possibly a bow shock facing toward PA $\approx$ 330° – consistent with the PA of the North-South H$_2$ flow.

In addition, we detect HH 840 approximately 6.7′ to the South. HH 840 is a faint [S ii] bow which faces southeast. A faint knot of [S ii] emission is located 15″ downstream. HH 840 is also coincident with several H$_2$ knots seen by Eislöffel et al. (2003) and designated region 5. Eislöffel et al. (2003) also find a group of H$_2$ knots (designated region 4) between the SMM 2 clump and HH 840, we detect no visible wavelength counterpart to these H$_2$ shocks.

**IC 348 IR / The FGN:** The southeastern rim of the FGN is sharp in our visible wavelength images but fades gradually toward the northwest (Fig. 3). A shadow bisects the nebula. The shadow appears to be due to a nearly edge-on disk (Boulard et al. 1995), which is embedded in the eastern rim of the nebula and is seen in silhouette against reflected light. The disk-axis is oriented toward PA $\approx$ 20°. IC 348 IR is visible as a faint star, centered in the disk shadow in the i′ image. This star is brighter in H$_\alpha$ than in [S ii]. There are no SMM clumps coincident with IC 348 IR indicating that there is less than $\sim$ 0.05 M$_\odot$ of dust in the disk.

A knot of H$_\alpha$ and [S ii] emission (HH 798; Fig. 3) is located 14″ North of the star and a line drawn between the star and the knot is oriented about 10° West of the disk axis. This feature is brighter than the brightest parts of HH 211 in H$_\alpha$ and comparable to HH 211 in [S ii]. The knot is elongated North-South by several arc-seconds and is brightest at its northern tip. HH 798 was
also detected by Eislöffel et al. (2003) in the near-IR and shows up brightly in our H$_2$ images.

We see two H$_2$ shocks (MH 3 & 4) South of IC 348 IR which are candidate counterflow shocks. The MH 4 shock is roughly equally spaced on the opposite side of the FGN as HH 798 is on the North. It is possible that one of MH 3 & 4 are elements of the SMM 2 flow as that flow axis passes near this region, however, they lie somewhat North of the SMM 2 flow axis when it is extrapolated through this region, so the association of these shocks with the IC 348 IR source seems more likely.

**SMM 5:** SMM 5 (SMMJ 034402+32019) is the brightest clump in a filament also containing SMM 6 (SMMJ 034405+32024). SMM 5 is about 20″ east of the IC 348 IR source which Strom et al. (1974) conclude is illuminating the FGN. About 10-15″ northeast of SMM 5 is a complex of H$_2$ knots designated region 3 by Eislöffel et al. (2003). Region 3 contains five knots detected by Eislöffel et al. (2003), however, in our images, it appears that two of those knots are primarily continuum flux and appear to be embedded stars in the Spitzer IRAC 4.6μm image and only three are comprised of strong H$_2$ emission (Fig. 6). We suggest that these shocks are driven by SMM 5. However, the association is not as solid as the others described here, other sources may potentially be associated with these shocks including SMM 6, IC 348 IR, and two embedded stars visible in the Spitzer images.

**J034405.7+320028:** This star is invisible in our broadband J exposure (an approximate upper limit to the J magnitude is about 18.6), but is bright in the K$_S$ image. The H and K$_S$ magnitudes were determined to be 17.7 ± 0.2 and 13.9 ± 0.2 respectively$^5$ indicating that the star is heavily reddened. The star drives an outflow containing MH 5 1.16′ to the West and MH 10 & 11 (0.94′ and 1.45′ to the East respectively). MH 5 is a bright compact knot with H$_2$ filaments stretching 30″ back toward J034405.7+320028. The counterflow components are visible as two H$_2$ shocks (MH 10 & 11) on the East side of the source. MH 11 is bright with the morphology of a small bow shock. MH 10 is a faint, elongated shock which may trace the wall of the outflow cavity.

**J034406.9+320155:** This star (J = 15.8 ± 0.2, H = 16.1 ± 0.2, K$_S$ = 15.9 ± 0.2), cataloged by Preibisch et al. (2003), shows indications of a K$_S$ reflection nebula stretching a 8″ to the South. The reflection nebula has a fan shaped morphology to the South. Though the northern extent of the reflection nebula is fainter, the overall morphology appears to be that of a roughly edge on disk shadow.

The morphology of HH 799 and its H$_2$ counterpart (Fig. 3 & 7) indicates that J034406.9+320155 is the most likely source. HH 799 is a bright North-facing bow shock at the tip of a column of Hα bright gas that can be traced for over an arc-minute to the South. The Hα column points back toward this star. In addition, a remarkable outflow cavity outlined by H$_2$ emission (Fig. 7) can be traced South from the tip of HH 799 to within 20″ of the star which is centered between the two

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$^5$Rough magnitude estimates for J034405.7+320028 and J034406.9+320155 were measured from our J, H, and K$_S$ images. The photometric zero point was determined by the average of 3 unsaturated 2MASS point source catalog stars in the same field and is the primary source of error.
walls of the cavity. There is also a faint filament of H\textsubscript{2} emission (MH 6) which can be traced for about 5″ South of the star, possibly indicating a counterflow. No shocks are seen further South of the source indicating that the southern lobe is likely redshifted and burrowing into the cloud and thus heavily extincted.

**LRL 276:** Initially cataloged as a candidate young star by Luhman et al. (1998), this star lies near HH 799, but does not lie upon the apparent flow axis. Preibisch & Zinnecker (2001, 2002) detected this star in x-rays and estimate its visual extinction based on 2MASS colors to be 8.72 magnitudes. Luhman et al. (2003) determined its spectral type to be M0 and noted emission lines in its spectrum. Although it shows no submillimeter emission, a small optical and near-IR reflection nebula is visible in our broadband (J, H, & K\textsubscript{S}) images. In addition, faint H\textsubscript{2} shocks (MH 7 & 8) are visible emanating from the object (Fig. 7), roughly equally spaced about 10″ from the source along PA -30°.

Continuum subtracted H\textsubscript{2} images reveal that the faint H\textsubscript{2} emission surrounding this source appears to have C-shaped symmetry. Such symmetries in outflows indicate that the source and the surrounding medium are in relative motion (Bally & Reipurth 2001; Masciadri & Raga 2001). C-shaped flows seen in Orion (e.g. Bally et al. 2006) are likely due to large scale nebular motions as gas is expelled away from the cluster center due to heating by UV radiation. Since there is no nearby H\textsc{ii} region along the axis defined by this bent jet, we conclude that the bending, in this case, is due to motion of the source. Similar bent jets have been seen elsewhere in Perseus, in NGC1333 (Bally & Reipurth 2001) and in Barnard 5 (Bally et al. 1996). In the absence of large scale nebular motions such as those which exist in Orion, the likely scenario is that the source star has been ejected from a dense cluster and thus is moving rapidly relative to the ambient cloud.

It is possible that the C-shaped symmetry of this source is not due to motion. The K\textsubscript{S} reflection nebula surrounding the star is also curved along the same axis and while our continuum subtracted images show that the H\textsubscript{2} emission clearly has a bent morphology, this may be due to the structure of the envelope surrounding the source.

Assuming that the C-shaped symmetry of the flow is due to motion of the source, we can estimate the orientation of the velocity vector from the morphology of the jet. This indicates that the source is moving along a PA≈70°. Tracing that vector back to the southwest, it passes through the FGN and very near to IC 348 IR and other nearby sources.

**SMM 17:** This source is roughly coincident with IRAS 03410+3152. In addition, the visible wavelength images show a star at this location (Fig. 3) which is noticeably elongated along PA∼45°. The near-IR images of this region reveal a small reflection nebula surrounding the star.

Several H\textsubscript{2} shocks (Fig. 7) lie on either side of this star. To the northeast lie two shocks. About 2.9′ north of SMM 17 lies MH 13, a compact shock with a faint filament stretching about 40″ to the southwest. About 25″ from SMM 17 lies MH 12, a faint, compact knot. To the southwest are three shocks (MH 7, 10, & 11). We find the MH 7 shock to be the likely counterflow to the MH 12 & 13 shocks. It lies about 2.5′ southwest of SMM 17. The other two shocks (MH10 & 11)
we associate with a crossing flow (see discussion of the J034405.7+320028 source above).

**SMM 14:** This source is roughly coincident with a moderately bright star in the near-IR and Spitzer IRAC images (the star is invisible in the visible wavelength images). A bright, compact knot is found \( \sim 10'' \) North of the star. Our \( \text{H}_2 \) images do not extend South of the star, so it was not possible to search for a counterflow.

**SMM 7:** This clump lies \( \sim 9' \) East of the FGN and is coincident with a cone shaped reflection nebula opening toward the southwest (Fig. 8). No star is visible in the optical images, however both the near-IR and Spitzer images show a bright star coincident with the apex of the reflection nebula. The reflection nebula is about 15'' in extent and contains HH 841, a small \( [\text{S}\ II] \) and H\( \alpha \) knot which is also visible as a bright \( \text{H}_2 \) knot. There is a second \( \text{H}_2 \) knot (MH 15; see Fig. 8) between HH 841 and the source star.

This clump also appears to drive a flow to the North (Fig. 8). Faint \( \text{H}_2 \) emission (MH 16-18) appears to trace a filament stretching northward from the source. The filament is visible for about 1' and then is lost at the edge of our \( \text{H}_2 \) image. No pointing North of SMM 7 was completed, so the northern extent of this flow is uncertain. Optical images, however, do show that HH 842 lies about 9 North on roughly the same position angle as the filament. It is possible that HH 842 is also part of this flow, however, no intermediate optical shocks are found in between SMM 7 and HH 842, so deeper follow up observations in the optical and near-IR are needed to confirm this association.

### 3.3. Unassociated Shocks and Other Objects

There are several shocks in this region which we were unable to confidently associate with a particular protostar or outflow.

**HH 796.** This faint knot of H\( \alpha \) and \( [\text{S}\ II] \) emission (Fig. 3) is located 1' northwest of the FGN and 10'' southeast of a star at PA \( \approx 250^\circ \) with respect to the star. Diffuse H\( \alpha \) emission and a faint reflection nebula extend toward the northwest. This shock also shows up faintly in the near-IR \( \text{H}_2 \) and \( [\text{Fe}\ II] \) images. Due to the proximity of many nearby submillimeter clumps, we cannot positively associate this shock with a source protostar.

**HH 842.** This is a bright northeast facing bow shock visible only in \( [\text{S}\ II] \) (see Walawender et al. 2005b, Fig. 34). We postulate in §3.2 that this may be driven by a flow emerging from SMM 7, however the connection in tenuous at best. If not driven by SMM 7, the source may be lost in the glare of the IC 348 cluster in the optical images.

**HH 843.** This nearly 2' long chain of H\( \alpha \) knots (see Walawender et al. 2005b, Fig. 37) is located about 10' southwest of IC 348. The brightest knot is located at the western end of the chain and is faintly visible in \( [\text{S}\ II] \). A star at J(2000) = 3:45:20.4, 32:06:35 is located several arcminutes East of this chain and has a faint East-facing reflection nebula. It may be that HH 843 is a jet emerging from this star. However, another star located at J(2000) = 3:45:16.3, 32:06:10 coincides
with the eastern end of the chain. A filament of Hα emission can be seen protruding from the southeast side of this star. If this second star is the source of the flow, then HH 843 is either deflected toward the South or has suffered a major orientation change.

4. Discussion & Conclusions

Other than the 10′ (0.93 pc at an assumed distance of 320 pc) long North-South outflow emerging from SMM 2, none of the shocks in and around the FGN appears to be more than 5.4′ (0.50 pc at an assumed distance of 320 pc) from its source. Assuming a jet velocity of 100 km s\(^{-1}\), the SMM 2 flow has a dynamic age of \(\sim 5 \times 10^3\) years while the other flows in the region have smaller dynamic ages. We suggest that the FGN region is a region of recent star formation triggered by the influence of the nearby IC 348 cluster, possibly due to heating and compression of the gas by soft-UV radiation induced photo-ablation flows (e.g. Gorti & Hollenbach 2002). This is supported by the observation by Muench et al. (2003) that the sources in IC 348 with a near-IR excess (indicating the likely presence of a disk, a tracer of youth) tend to lie outside of the core of the IC 348 cluster and that the surface density of those sources appears to increase toward the south. Thus, the stars in the southern portion of IC 348 are younger than those in the core. Possibly indicating that star formation has propagated outward from the IC 348 core along the molecular ridge to the south and west. The orientation of dust filaments in Fig. 2 is consistent with the triggered star formation scenario. In addition, YSOs tend to be located on the sides of filaments facing IC 348.

Of the 17 SCUBA clumps identified by CLUMPFIND, we have tentatively identified 7 as containing at least one protostar. Other protostars (IC 348 IR, LRL 276, J034406.9+320155, & J034405.7+320028) have no submillimeter counterparts. Of our candidate protostars, 9 (counting two within SMM 3) lie within about 3′ of the FGN. This is a number density of protostars of about 100 stars pc\(^{-3}\) in a region 0.56 pc across centered on the FGN.

All 4 of the 17 clumps which have a concentration value larger than 0.6 contain protostars. Of the remaining 13 clumps with concentrations less than 0.6, two contain a protostar and a third (SMM 5) is a strong candidate. The concentration we measure for submillimeter clumps is approximate since SCUBA’s beam size is a significant fraction of the clump size, however, there appears to be a good correlation between the concentration of a submillimeter clump and whether it contains a protostar. Our results are consistent with the results of Walawender et al. (2005a) in Barnard 1 that the concentration is a measure of stability – i.e. clumps with high concentrations are likely to be unstable to collapse.

The MH 8 & 9 bent jet is remarkable in that if it is due to source ejection, then this is one of only a handful of bent jets known to be due to source motion rather than nebular motions (as in Orion). In addition, comes from a relatively sparse stellar cluster with of order a dozen currently active protostars. In contrast, three of the other such sources are in NGC 1333 which is a much more populous cluster where dynamical encounters are much more likely due to the higher stellar
densities. Because it comes from such a sparse cluster, this may be an example of a disintegrating multiple star system (Reipurth 2000) rather than a chance dynamical encounter.

This work is based in part on observations obtained with the Apache Point Observatory 3.5-meter telescope, which is owned and operated by the Astrophysical Research Consortium. This work is also based in part on observations made with the Spitzer Space Telescope, which is operated by the Jet Propulsion Laboratory, California Institute of Technology under a contract with NASA.

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REFERENCES
Avila, R., Rodríguez, L. F., & Curiel, S. 2001, Revista Mexicana de Astronomia y Astrofisica, 37, 201
Ebert, R. 1955, Zeitschrift fur Astrophysics, 37, 217


Reipurth, B. 2000, AJ, 120, 3177


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Table 1. Positions of SCUBA Clumps in the IC348 Region.

<table>
<thead>
<tr>
<th>Name</th>
<th>Designation</th>
<th>$\alpha$</th>
<th>$\delta$</th>
<th>Hatchell Name</th>
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<td>(J2000.0)</td>
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<td></td>
</tr>
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Table 2. Properties of SCUBA Clumps in the IC348 Region.

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<th>Name</th>
<th>Peak Fluxa</th>
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<th>Peak Fluxb</th>
<th>Total Flux</th>
<th>Radius</th>
<th>Massc</th>
<th>Concc</th>
<th>Protostar?</th>
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<tr>
<td>SMM</td>
<td>850 µm (Jy)</td>
<td>850 µm (Jy/bm)</td>
<td>450 µm (Jy)</td>
<td>450 µm (Jy/bm)</td>
<td>(&quot;)</td>
<td>(M⊙)</td>
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<td>1.41</td>
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<td>0.81</td>
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<td>4.57</td>
<td>2.6</td>
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<td>3.23</td>
<td>0.65</td>
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<td>33.</td>
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<td>0.52</td>
<td>?</td>
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<td>6</td>
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<td>7</td>
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<td>3.1</td>
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<td>1.99</td>
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<tr>
<td>11</td>
<td>0.21</td>
<td>1.05</td>
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<td>29.</td>
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<tr>
<td>12</td>
<td>0.17</td>
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<td>7.</td>
<td>0.07</td>
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<td>Y</td>
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</tbody>
</table>

- **a** Peak flux within a beam of 17.6″
- **b** Peak flux within a beam of 10.6″
- **c** Mass derived from the total flux at 850 µm assuming $T_d = 15$ K and $\kappa_{850} = 0.02$ cm$^2$g$^{-1}$.
- **d** Concentration measure (see text)
Table 3. New $\text{H}_2$ knots with no optical counterparts.

<table>
<thead>
<tr>
<th>Number</th>
<th>$\alpha$(J2000)</th>
<th>$\delta$(J2000)</th>
<th>4.6µm Counterpart?</th>
<th>Associated Source</th>
<th>Comments</th>
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<td>MH 1</td>
<td>3:43:58.6</td>
<td>32:02:02</td>
<td></td>
<td>SMM 2</td>
<td></td>
</tr>
<tr>
<td>MH 2</td>
<td>3:43:58.6</td>
<td>32:01:50</td>
<td></td>
<td>SMM 2</td>
<td></td>
</tr>
<tr>
<td>MH 3</td>
<td>3:43:59.4</td>
<td>32:01:36</td>
<td></td>
<td>IC 348 IR</td>
<td></td>
</tr>
<tr>
<td>MH 4</td>
<td>3:43:59.5</td>
<td>32:01:44</td>
<td></td>
<td>IC 348 IR</td>
<td></td>
</tr>
<tr>
<td>MH 5</td>
<td>3:44:00.9</td>
<td>32:01:02</td>
<td>Y</td>
<td>J034405.7+320028</td>
<td>bright knot with filament stretching to the southeast</td>
</tr>
<tr>
<td>MH 6</td>
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<td>32:01:52</td>
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<td>J034406.9+320155</td>
<td></td>
</tr>
<tr>
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<td>3:44:08.7</td>
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<td>SMM 17</td>
<td></td>
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<td>LRL276</td>
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<tr>
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<td>Y</td>
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<td>SMM 17</td>
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</tr>
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<tr>
<td>MH 14</td>
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<td>SMM 7</td>
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<td>3:44:43.4</td>
<td>32:02:31</td>
<td></td>
<td>SMM 7</td>
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</table>
Fig. 1.— An Hα + [S ii] image of the IC 348 and FGN regions. HH objects are marked with circles and labeled. The region covered by Fig. 2 is boxed and labeled.
Fig. 2.— Grayscale image of the 850 µm SCUBA map of the FGN region. Boxes and triangles represent HH objects and H$_2$ shocks respectively. Asterisks represent IRAS sources. Submillimeter clumps are marked by numbered circles according to their SMM designation. Dashed line represents likely outflow orientations including the north-south flow of McCaughrean et al. (1994). The boxed region shows the coverage of Fig. 3.
Fig. 3.— An Hα + [S ii] image of the FGN region. HH objects are marked with boxes and labeled. Submillimeter clumps are marked with circles and labeled. Likely outflow orientations, including the North-South flow of McCaughrean et al. (1994), are marked with dashed lines.
Fig. 4.— $\text{H}_2$, $K_s$, IRAC 4.6 $\mu$m, & H$\alpha$+[S II] images of the SMM3 region respectively.
Fig. 5.— Hα, [S ii], H$_2$, & [Fe ii] images of HH 211 respectively.
Fig. 6.— $H_2$ and IRAC Channel 2 (4.6 µm) images of the McCaughrean et al. (1994) North-South flow. The MH 1-4 shocks are circled and Eisloeffel et al. (2003) regions 3 & 4 are marked. The bright source slightly left and below center in the IRAC image is IC 348 IR.
Fig. 7.— An H$_2$ image of the region containing SMM 17, LRL276, and HH 799
Fig. 8.— $\text{H}_2$, $K_S$, H$\alpha$+[S II], & IRAC 4.6$\mu$m images of of HH 841 and its associated reflection nebula.