Herbig-Haro Objects in the ρ Ophiuchi Cloud

Bruce A. Wilking

Department of Physics and Astronomy, University of Missouri-St. Louis

8001 Natural Bridge Road, St. Louis, MO 63121

brucew@newton.umsl.edu

Richard D. Schwartz

Department of Physics and Astronomy, University of Missouri-St. Louis

8001 Natural Bridge Road, St. Louis, MO 63121

schwartz@newton.umsl.edu

Tina M. Fanetti

Department of Physics and Astronomy, University of Missouri-St. Louis

8001 Natural Bridge Road, St. Louis, MO 63121

fanetti@newton.umsl.edu

and

Eileen D. Friel [1]

National Science Foundation [2], Division of Astronomical Sciences

4201 Wilson Blvd., Arlington, VA 22230

friel@hyades.bu.edu

---

[1]Visiting Astronomer, Cerro Tololo Inter-American Observatory. CTIO is operated by Association of Universities for Research in Astronomy, Inc., under contract to the National Science Foundation.

[2]The views expressed in this paper are those of the authors and do not reflect the views of the National Science Foundation.

Received ______________________; accepted ______________________

ABSTRACT

Using deep, narrow-band images of the main ρ Oph dark cloud centered on the wavelengths of Hα and [S II], we present evidence for three new Herbig-Haro objects. This increases the total number in the cloud to five. In addition, positions for 5 candidate Herbig-Haro objects are given. Relatively high [S II]/Hα ratios indicate low excitation conditions for all of these nebulae. We list potential exciting stars for each Herbig-Haro object and candidate by identifying nearby young stellar objects with strong infrared excesses and/or millimeter continuum emission. The location of most of these nebulae near the cloud edges underscores the important role that extinction by dust plays in the ρ Oph cloud in masking the presence of Herbig-Haro objects. Among the newly identified Herbig-Haro objects is a jet-like string of emission nebulae emanating from the classical T Tauri star SR 4. [S II] emission is also found coincident with a knot of strong molecular hydrogen emission associated with the highly-collimated VLA 1623 molecular outflow. Indeed, the low excitation nature of all of the objects in our study, coupled with the high extinction of the cloud, suggests that a deep survey for shocked molecular hydrogen at λ=2.122 μm would be the best way to search for evidence of strong winds from the large population of young stellar objects in the cloud.

Subject headings: ISM: jets and outflows – nebulae: individual (ρ Ophiuchi) – infrared: stars

1. Introduction

The ρ Ophiuchi dark cloud is one of the closest, active sites of low-mass star formation. At a distance of only 160 pc, it has been the focus of numerous infrared and Hα emission-line surveys. These surveys have revealed over 100 young stellar objects (YSOs) in the main cloud alone (L1688; Wilking, Schwartz, & Blackwell 1987; Greene & Young 1992; Comerón *et al.* 1993; K. Strom *et al.* 1995). A recent infrared spectroscopic study has found that YSOs in the core have ages of $<10^6$ years suggesting that stars have formed in a relatively efficient burst (Greene & Meyer 1995). Despite the large number of YSOs, there has been only two reported cases of shock-excited optical nebulae, also known as Herbig-Haro or HH objects: HH 79 (Reipurth & Graham 1988) and HH 224 (Reipurth 1994). At first glance, this would seem unusual given that it appears all YSOs in this age range undergo a phase of energetic mass loss that will give rise to HH objects (e.g., Lada 1985). Yet the unusually high visual extinctions in the cloud core, estimated to range from 25 – 100 mag from $C^{18}O$ observations (Wilking & Lada 1983), will mask the presence of optical emission-line nebulae except for YSOs at the surface of the cloud. Indeed, observations less sensitive to extinction by dust have revealed other signs of mass loss activity. Water maser emission at 22 GHz has been reported for 4 YSOs in the main cloud: YLW 16A, YLW 16B, GSS 30, and VLA 1623 (Terebey *et al.* 1992; Wilking *et al.* 1994; Claussen *et al.* 1996). High velocity CO and shock-excited molecular hydrogen emission at 2.12μm have also been found associated with the protostellar object VLA 1623 (André *et al.* 1990; Davis & Eislöffel 1995; Dent, Matthews, & Walther 1995).

We report the acquisition and analysis of deep Hα and [S II] images, as well as broad-band R and I images, of over a square degree centered on the main ρ Oph cloud. We confirm the presence of the two previously reported HHs and report the discovery of three new HH objects. The latter group includes a string of [S II] knots which form a jet-like feature associated with the YSO SR 4. In addition, five sources of weak [S II] emission are identified as HH candidates. The possible sources responsible for the excitation of the HH nebulae and HH candidates are discussed.

2. Observations and Analysis

Images of the ρ Oph cloud were obtained with the 0.9 m Curtis Schmidt Telescope at Cerro Tololo Interamerican Observatory. The observations were performed by REU students Marc Kassis and Maritza Tavarez using the 2048^2 CCD during its commissioning run in March 1995. The pixel scale was $2.03''$ pixel^{-1} resulting in a field of view of $69.3'$ squared. Images were obtained in narrow-band Hα (λ=659.3 nm, 6.4 nm FWHM) and [S II] (λ=674.2 nm, 4.5 nm FWHM) filters and in standard broad-band R and I filters. Five minute exposures were made in R and I, and nine dithered 5 minute exposures were obtained in each of the narrow-band filters.

Zero bias and readout bias corrections and flat-fielding were performed using the CCDPROC task in the Image Reduction and Analysis Facility (IRAF) and flats of the twilight sky. To produce the final narrow-band images representing 45 minutes of integration, the individual frames were shifted and median-combined. In this manner, most bad columns, hot pixels, and cosmic rays were removed from the final image. The final median-filtered images cover an area from $16^h21^m32.2^s$ to $16^h26^m40.5^s$ in R.A. (1950) and -23°48′08″ to -24°57′34″ in Dec. (1950).

To determine accurate positions for the new HHs and HH candidates, we used the ASTROM program distributed by the Starlink Project and a set of secondary astrometric standards. The secondary position references were 27 Hα emission-line stars with accurate positions determined relative to SAO stars in a 5° squared region on the Red Palomar

Sky Survey plate (Wilking, Schwartz & Blackwell 1987). The resulting positions have rms uncertainties of $<0.5''$ relative to the astrometric standards and absolute uncertainties $<2''$.

3. Results

In order to establish the presence of an HH object, we required (1) the detection of extended [S II] emission and either Hα or shocked molecular hydrogen emission and (2) the absence of emission in the broad-band I image. The [S II] and Hα emission-lines lie outside the I filter bandpass. Our results are summarized in Table 1 and Fig. 1. The first six objects in Table 1 were detected in both the [S II] and Hα images except for HH 313 which is a [S II] knot coincident with strong molecular hydrogen emission in the VLA 1623 outflow. These are identified as bona-fide Herbig-Haro objects. The six objects listed at the bottom of Table 1 display weak [S II] emission and usually have no corresponding Hα emission. These objects are in need of confirmation before being classified as HH objects. The locations of the HH objects and candidate HH objects are shown in Fig. 1 on the grayscale [S II] image. The positions given in cols. (2) and (3) of Table 1 are for the brightest pixels in the source except for C 3 where the quoted position is for an associated star. The morphology is described in col (4); the compact sources look star-like but have a FWHM of $\sim 6''$ compared to the stellar FWHM of $4''$. None of the objects listed in Table 1 are coincident with stars as determined from comparison with our R and I band images which were about 1 mag more sensitive to point sources ($<$18.5 mag) than the narrow-band images. Moreover, objects HH 312, HH 313, HH 314, HH 79, C 1, and C 3 are within the boundaries of sensitive infrared surveys performed by Greene & Young (K$<$13 mag, 1992) and Strom *et al.* (K$<$14.2 mag, 1995) and are not coincident with any near-infrared source.

Except for HH 312 and HH 313, the sources of excitation for the HHs are very uncertain. Due to extinction by dust, the HH nebulae must be near the surface of the cloud.

This could arise as the wind from a deeply embedded source breaks out to the surface of the cloud (e.g., VLA 1623 and HH 313) or as the wind from a YSO near the cloud surface burrows into the cloud. In the former case, the YSO would be expected to be close to the HH while in the latter case the separation could be much larger. The nearest potential exciting stars to the HH or HH candidate are listed in col (7) of Table 1 along with their projected distance from the HH in arcseconds. The locations of these exciting stars are shown relative to the HHs and candidate HHs in Fig. 1. Because of the requirement of a strong stellar wind, we list only YSOs in an embedded or T Tauri phase of evolution (also referred to as Class I or Class II sources) that have significant circumstellar disks as indicated by a strong infrared excess and/or millimeter continuum emission (e.g., Cabrit & André 1991; Reipurth *et al.* 1993). For example, we associate HH 314 with DoAr 25 (250″ away) which has an infrared energy distribution of an embedded source viewed through its outflow cavity and strong λ=1.3mm emission, rather than WSB 37 (50″ away) which has little or no circumstellar dust (André & Montmerle 1994). Likewise, we associate HH 79 with either GSS 39 (170″) or SR 21/VSSG 23 (330″) even though GSS 37 sits a projected distance of only 50″ to the west. GSS 39 and SR 21 possess more massive circumstellar disks (λ=1.3mm fluxes of 300 mJy and 150 mJy, respectively) compared to GSS 37 (λ=1.3mm flux of 15 mJy). Only for C 3 and C 4 are the associated YSOs chosen by proximity as the strengths of their infrared excesses and λ=1.3mm flux densities are unknown.

As a group, the objects in Table 1 have ratios of [S II]/Hα emission greater than one (col (5)). This is characteristic of low-excitation HH objects whose line ratios are consistent with low shock velocities (<50 km s^{-1}). It is common for such objects to display molecular hydrogen emission which might otherwise be dissociated in a higher velocity shock (Schwartz, Cohen, & Williams 1987; Wilking *et al.* 1990). Thus far, sensitive searches for H_2 emission in the main ρ Oph cloud have only been performed for the VLA 1623 region.

3.1. Notes on Individual Sources

3.1.1. The SR 4 Jet: HH 312

The YSO SR 4 is a classical T Tauri star near the surface of the dark cloud. It was first reported as an emission-line star by Struve and Rudkjobing (1949). It has a K5-K7 spectral type, a visual extinction of $A_v \sim 2$ mag, and a bolometric luminosity of 5.5 $L_\odot$. (Cohen & Kuhi 1979; Bouvier & Appenzeller 1992; Wilking, Lada, & Young 1989). It is also a weak x-ray source (ROX 6, Montmerle *et al.* 1983; Casanova *et al.* 1994) and a millimeter-continuum source with a flux density of 70 mJy at λ=1.3mm (André & Montmerle 1994). The unresolved IRAS 12μm and 25μm flux densities from the source are about 10 times that measured in a 6$''$ aperture with a ground-based telescope. This implies extended mid-infrared emission around the star on a scale of 6-45$''$ due to unresolved sources or a halo of very small dust grains.

The [S II] image of the SR 4 region is shown in Fig. 2. A jet-like series of knots that comprise HH 312 extends 89$''$ (0.07 pc) southeast from SR 4 with the brightest knot at the terminus of the "jet". The star below HH 312 is a weak x-ray source, Chini 8 (Casanova *et al.* 1994).

3.1.2. HH 313

Narrow-band images centered on $\lambda = 2.12\mu$m of ρ Oph core A have revealed numerous knots of shocked molecular hydrogen (Davis & Eislöffel 1995; Dent *et al.* 1995). The brightest knots are associated with a blue-shifted clump of high velocity CO gas in the northwest lobe of the VLA 1623 molecular outflow (André *et al.* 1990; Dent *et al.* 1995). Previous studies have mistakenly identified the bright knots as young stars; objects 2317.6-1622 and 2316.0-1626 in the study of Comerońet *al.* (1993) are associated with H_2

knots A and B in the study of Davis & Eislöffel and knots H 5 and H 4 in the study of Dent *et al.* Additional H_2 knots are associated with the southeast lobe of the VLA 1623 outflow as shown in the images of Dent *et al.* (1995).

Slightly extended [S II] emission is observed toward the brightest H_2 knot, labeled A by Davis & Eislöffel and H 5 by Dent *et al.* Based on these two emission features, we designate this object as HH 313. The optical visibility of H 5/HH 313 implies relatively low extinction which is consistent with the blue-shifted velocities of the associated CO. The failure to detect any corresponding Hα emission underscores the low-excitation nature of this object. There is no detectable [S II] or Hα emission found with any of the other H_2 knots.

3.1.3. HH 224 & C 3

A possible knot of Hα emission was observed on the southwestern edge of the dark cloud in an objective prism plate of the region (Wilking *et al.* 1987). Deep, narrow-band imaging of this area resulted in the discovery of HH 224 by Reipurth (1994) The southern component of the YSO binary SR 24 was proposed as the exciting star. Our [S II] image of this region (Fig. 3) reveals two distinct HH nebulae: HH 224N lies between WSB 47 and WSB 49, and HH 224S is an arc-like feature west of WSB 49. Additionally, as shown in Fig. 3, there are several patches of [S II] emission north of HH 224. The most prominent of these, labeled C 3, is an extended, linear feature associated with the star GY193 (Greene & Young 1992). No direct connection with SR 24 is evident.

The YSO (or YSOs) responsible for the HH 224 system is unclear at this time. Unfortunately, it is too far south to have been included in sensitive near-infrared surveys. The nearest YSOs are the Hα star WSB 49 and the double emission-line system ROX 20 (WSB 45/46) which is 200$''$ to the southwest (Montmerle *et al.* 1983; Bouvier & Appenzeller

1992). But neither of these sources would be expected to have strong stellar winds since they have no evidence for significant circumstellar disks as indicated by the absence of detectable λ=1.3mm emission (André & Montmerle 1994). Therefore, the double T Tauri star and λ=1.3mm source SR 24 remains the most viable candidate despite being nearly $6'$ to the west. Another possibility is that the entire system of HHs and [S II] features are associated with GY 193. Yet little is known about this source except that it is a visible star not associated with Hα emission and not detected by IRAS. GY 193 is $24''$ south of the ROSAT source ROXR1-36 but its association is unclear as it is well outside the 90% maximum likelihood error radius for the source of $6''$ (Casanova *et al.* 1994).

4. Conclusions

We present evidence for three new Herbig-Haro objects in the ρ Oph main cloud (L1688). This raises the total number of HHs in the cloud to five. In addition, positions are given for 5 HH candidates which are in need of confirmation. Potential sources of excitation are identified for all HHs and HH candidates. In general these objects lie at the cloud edges, emphasizing the role of extinction in masking the visible signs of energetic winds from young stars in the cloud. The ratio of [S II] to Hα in these HHs suggest they are low excitation objects. This fact, coupled with the high extinction in the cloud, should make deep surveys for shocked molecular hydrogen emission at $\lambda = 2.122\mu$m the most fruitful way to search for evidence of winds from YSOs within the cloud.

We would like to thank Marc Kassis and Maritza Tavarez for obtaining the images reported in this paper. We also thank Bo Reipurth for his helpful comments that significantly improved the paper and for the HH designations. B. W. gratefully acknowledges RUI grant NSF AST-9417210 to the University of Missouri-St. Louis and E. F. acknowledges NSF sponsorship of the NOAO/CTIO REU program which supported these observations.

REFERENCES

André, P., Martin-Pintado, J., Depois, D., & Montmerle, T. 1990, A&A, 236, 180

André, P. & Montmerle, T. 1994, ApJ, 420, 837

Bouvier, J., & Appenzeller, I. 1992, A&AS, 92, 481

Cabrit, S. & André, P. 1991, ApJ, 379, L25.

Casanova, S., Montmerle, T., Feigelson, E. D., & André, P. 1995, ApJ, 439, 752

Claussen, M. J., Wilking, B. A., Benson, P. J., Wootten, A., Myers, P. C., & Terebey, S. 1996, ApJS, in press

Cohen, M. & Kuhi, L. V. 1979, ApJS, 41, 743

Comerón, F., Rieke, G. H., Burrows, A., Rieke, M. J. 1993, ApJ, 416, 185

Davis, C. J. & Eislöffel, J. 1995, A&A, 300, 851

Dent, W. R. F., Matthews, H. E., & Walther, D. M. 1995, MNRAS, 277, 193

Grasdalen, G. L. Strom, K. M., & Strom, S. E. 1973, ApJ, 184, L53.

Greene, T. P. & Meyer, M. R. 1995, ApJ, 450, 233.

Greene, T. P. & Young, E. T., 1992, ApJ, 395, 516

Lada, C. J., 1985, ARA&A, 23, 267

Montmerle, T., Koch-Miramonde, L. Falgarone, E., & Grindlay, J. E. 1983, ApJ, 269, 182

Reipurth, B. 1994, *A General Catalogue of Herbig-Haro Objects*, electronically published via anon. ftp to ftp.hq.eso.org, directory /pub/Catalogs/Herbig-Haro

Reipurth, B., Chini, R., Krugel, E., Kreysa, E., & Sievers, A., A&A, 273, 221

Reipurth, B. & Graham, J. 1988, A&A, 202, 219

Schwartz, R. D., Cohen, M., Williams, P. M. 1987, ApJ, 322, 403

Strom, K. M., Kepner, J., & Strom, S. E. 1995, ApJ, 438, 813

Struve, O. & Rudkjobing, M. 1949, ApJ, 109, 92

Terebey, S., Vogel, S. N., & Myers, P. C. 1992, ApJ, 390, 181

Vrba, F. J., Strom, S. E., Strom, K. M., & Grasdalen, G. L. 1975, ApJ, 197, 77

Wilking, B. A., Claussen, M. J., Benson, P. J., Myers, P. C., Terebey, S, & Wootten, A. 1994, ApJ, 431, L119

Wilking, B. A. & Lada, C. J. 1983, ApJ, 274, 698

Wilking, B. A., Lada, C. J., & Young, E. T. 1989, ApJ, 340, 823

Wilking, B. A., Schwartz, R. D., & Blackwell, J. H. 1987, AJ, 94, 106

Wilking, B. A., Schwartz, R. D., Mundy, L. G., & Schultz, A. S. B. 1990, AJ, 99, 344

This manuscript was prepared with the AAS LaTeX macros v4.0.

Figure Captions

Fig. 1.— A [S II] grayscale image of a $58' \times 43'$ area centered on the main Ophiuchus dark cloud. Labeled in the image are bright stars, HH objects, candidate HH objects, and the possible HH exciting stars (see Table 1). The positions of embedded sources are indicated by a '+'. The scale for the figure is displayed in the lower right-hand corner and corresponds to $10'$ or 0.5 pc. The only molecular outflow and molecular hydrogen emission identified in this region of the cloud complex are associated with the deeply embedded object VLA 1623.

Fig. 2.— A [S II] grayscale image of the jet associated with the YSO SR 4. A string of [S II] knots is seen east of the star with the brightest knot at the terminus of the jet. The star just below the jet is Chini 8 and the bright star at the bottom of the frame is the nonthermal radio star DoAr 21/GSS 23.

Fig. 3.— A [S II] grayscale image of the HH 224 region. HH 224N lies between WSB 47 and 49 and HH 224S west of WSB 49. On the western edge is the double T Tauri system SR 24 (unresolved). Above the HH 224 system, a wisp of [S II] emission labeled C 3 is seen coincident with the source GY 193.