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IRAS 11590−6452 IN BHR 71: A BINARY PROTOSTELLAR SYSTEM?

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ABSTRACT

New Anglo-Australian Telescope near-infrared and Swedish-ESO Submillimetre Telescope ^{12}CO $J = 2 \rightarrow 1$ observations are combined with existing *Infrared Space Observatory* mid-infrared and Australia Telescope Compact Array centimeter radio continuum observations to examine the protostellar content of the Bok globule BHR 71. Together with observations of Herbig-Haro objects, these data show the following: (1) Two protostellar sources, IRS 1 and IRS 2, with a separation of ∼17″ (3400 AU) are located within BHR 71. (2) Each protostar is driving its own molecular outflow. The outflow from IRS 1 is much larger in extent, is more massive, and dominates the CO emission. (3) Both protostars are associated with Herbig-Haro objects and shock-excited 2.122 μm H_2 $v = 1–0$ $S(1)$ emission, which coincide spatially with their CO outflows. (4) IRS 1 is associated with centimeter continuum emission, with a flat or rising spectrum, which is consistent with free-free emission, a signpost of protostellar origin.

Subject headings: binaries: general — ISM: globules — ISM: individual (BHR 71) — ISM: jets and outflows — stars: formation — stars: pre–main-sequence

On-line material: color figures

1. INTRODUCTION

BHR 71 (Bourke, Hyland, & Robinson 1995a; Bourke et al. 1995b) is a well-isolated Bok globule located at ∼200 pc, which harbors a highly collimated bipolar outflow (Bourke et al. 1997, hereafter B97). The outflow is driven by a very young class 0 protostar with a luminosity of ∼9 $L_\odot$.

This Letter brings together new observations with existing observations to show that BHR 71 contains two embedded protostars with a separation of ∼3400 AU. Each protostar is driving a molecular outflow seen in CO, but only one appears to be associated with a substantial amount of circumstellar material. The observations suggest that BHR 71 may contain an embedded binary protostellar system.

2. OBSERVATIONS

Near-infrared (NIR) observations were undertaken with the 128 × 128 HgCdTe array camera IRIS on the Anglo-Australian Telescope. Mounted at the f/36 Cassegrain focus, IRIS provided a field of view of approximately 100″ with a resolution of 0″.79 pixel^{-1}. A 4 × 4 mosaic at K' (2.11 μm) with 90″ offsets between frames was obtained on 1992 February 15, with an integration time of 200 s per frame. A 3 × 3 mosaic in the H_2 $v = 1–0$ $S(1)$ transition at 2.12 μm (1% bandpass) with 80″ offsets was obtained on 1993 January 11, with an integration time of 60 s per frame. Standard data reduction was performed with the Starlink FIGARO data reduction package.

Observations of the ^{12}CO $J = 2 \rightarrow 1$ transition at 230537.99 MHz were obtained with the 15 m Swedish-ESO Submillimetre Telescope during 2000 May. The back end used was an acousto-optical spectrometer providing a channel separation of 43 kHz (0.055 km s^{-1}) over 2000 channels. The observations were performed in dual beam-switching mode with a beam separation of 11′47″ in azimuth. System temperatures of 220 K were recorded during the observations. A small 13-point map with 30″ offsets about the position of the embedded source BHR 71 mm (B97) was made, with an integration time of 60 s per point. The beam size at this frequency is ∼23″.

BHR 71 was observed by the *Infrared Space Observatory* (*ISO*) on 1996 August 19 as part of program DMARDONE. Observations in the LW2 (5.0–8.5 μm) and LW3 (12.0–18.0 μm) bands were obtained with a field of view of ∼90″. Full details of the observations can be found in M. E. van den Ancker, D. Mardones, & P. C. Myers (2001, in preparation; see also Myers & Mardones 1998).

The Australia Telescope Compact Array (ATCA)[1] was used to obtain images of BHR 71 at 3 and 6 cm (8.64 and 4.80 GHz, respectively) as part of program C368 (D. J. Wilner, B. Lindsey, S. Curiel, & L. F. Rodríguez 2001, in preparation). Observations were made on 1994 November 12 with the 6D configuration, observing both frequencies simultaneously with 128 MHz bandpasses. The data were reduced with MIRIAD and imaged using natural weighting, resulting in beam sizes of ∼2″ at 3 cm and ∼4″ at 6 cm. Full details can be found in D. J. Wilner, B. Lindsey, S. Curiel, & L. F. Rodríguez 2001, in preparation.

3. RESULTS

The NIR images are shown in Figure 1. The K' image is shown in Figure 1*a*, and the narrowband 2.12 μm image in Figure 1*b*. No continuum subtraction has been performed on the narrowband image. It is immediately evident by comparison of the two images that most of the nonstellar emission is due to the emission in the H_2 $v = 1–0$ $S(1)$ line. This is most likely due to shocks in the outflowing gas (Eislöffel 1997). In BHR 71, the large-scale CO outflow lies at a position angle of ∼165° (B97) and so is well aligned with the NIR emission.

Mid-infrared emission in the *ISO* LW2 band is overlaid on the K' image in Figure 1*a*, labeled as "*ISO* 7 μm." Two of the 7 μm sources appear to be located at the apexes of NIR emission, strongly suggesting that they are associated with the emission. Source 1 (hereafter IRS 1) lies at the apex of the reflection nebulosity seen also in the *I*-band image presented by B97, which is associated with the large blueshifted CO outflow lobe. IRS 1 is also coincident with the position of the millimeter source BHR 71 mm, also known as IRAS 11590−6452 (B97). No such counterpart exists for source 2 (hereafter IRS 2), which is the weaker

[1] The ATCA is part of the Australia Telescope, which is funded by the Commonwealth of Australia for operation as a National Facility managed by CSIRO.

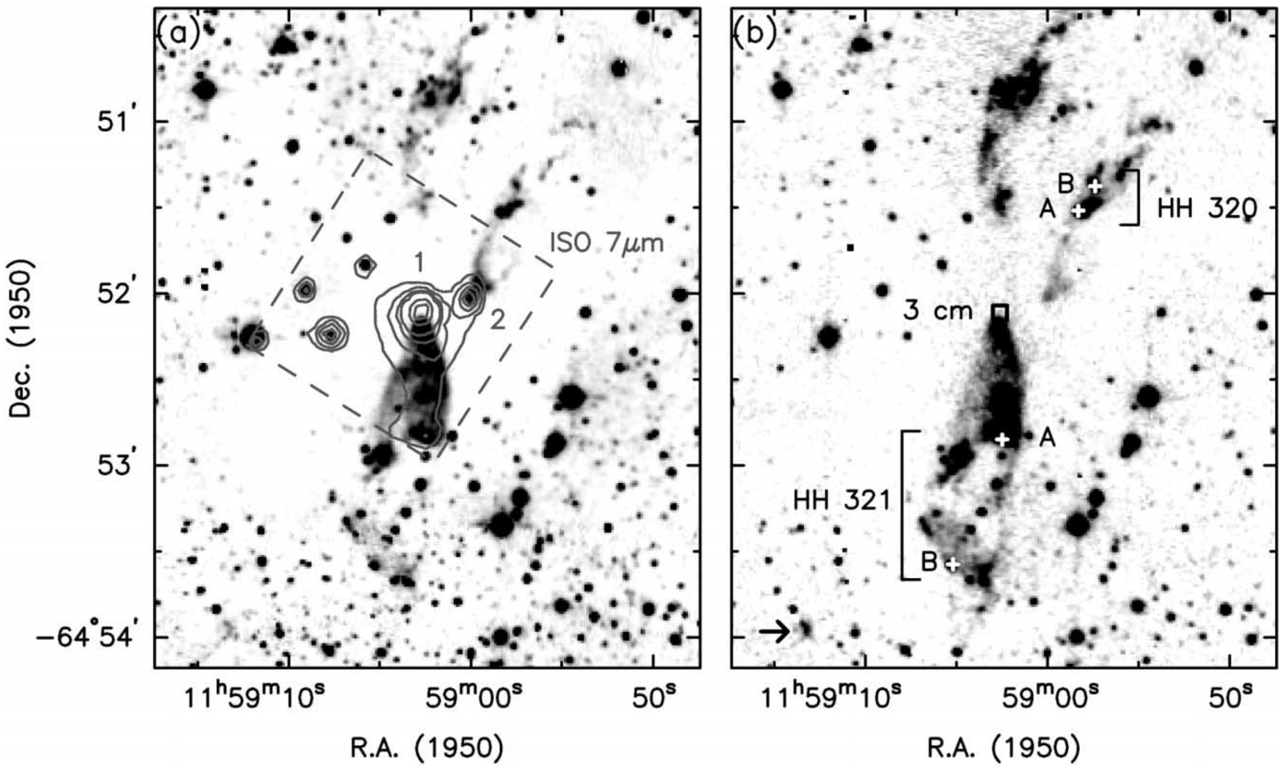

FIG. 1.—(*a*) K' image of BHR 71 (*gray scale*) overlaid with *ISO* LW2 contours (5.0–8.5 μm). The approximate region observed by *ISO* is indicated by the dashed box, and the embedded protostars IRS 1 ("1") and IRS 2 ("2") are labeled. (*b*) Narrowband 2.12 μm + continuum image (*gray scale*). The positions of HH 320 and HH 321 (Corporon & Reipurth 1997) are marked with plus signs, and the position of the 3 cm continuum source is marked with an open square. [*See the electronic edition of the Journal for a color version of this figure*.]

of the two sources at 7 μm. The fluxes for IRS 1 and IRS 2 in the *ISO* LW2 (7 μm) and LW3 (15 μm) bands are listed in Table 1. IRS 2 is not seen directly at 2 μm. The NIR feature coincident with IRS 2 in Figure 1*a* is nonstellar, by comparison of its point-spread function with stars in the same image.

One centimeter continuum source was detected toward BHR 71, at both 3 and 6 cm (D. J. Wilner, B. Lindsey, S. Curiel, & L. F. Rodríguez 2001, in preparation). The position of the source at 3 cm is indicated in Figure 1*b* and is listed in the notes to Table 1. It coincides with the position of IRS 1 and has a spectral index at centimeter wavelengths that is consistent with a flat or rising spectrum due to free-free emission, a signpost of protostellar origin (Rodríguez 1994).

TABLE 1
POSITIONS AND FLUXES

NAME	POSITION (B1950) R.A.	POSITION (B1950) Decl.	7 μm (mJy)	15 μm (mJy)
ISO Sources				
IRS 1[a]	11 59 02.7	−64 52 06	346	230
IRS 2	11 59 00.1	−64 52 02	39	<18
Herbig-Haro Objects[b]				
HH 320A	11 58 58.3	−64 51 31	…	…
HH 320B	11 58 57.4	−64 51 23	…	…
HH 321A	11 59 02.5	−64 52 51	…	…
HH 321B	11 59 05.2	−64 53 35	…	…

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.
[a] The 3 cm position of IRS 1 is R.A. (B1950) = $11^{h}59^{m}02^{s}.61$, decl. (B1950) = $-64°52'06''.7$.
[b] Positions are different from those given in Corporon & Reipurth 1997; see text.

Corporon & Reipurth (1997) discovered two Herbig-Haro associations in BHR 71—HH 320 and HH 321. Their locations are shown in Figure 1*b*. The positions of the HH objects as listed in Corporon & Reipurth (1997) are incorrect (P. Corporon 1997, private communication). As discussed below, the plate solutions for their S II image have been redetermined and the positions of HH 320 and HH 321 remeasured. The correct positions, accurate to less than 1″, are given in Table 1. From Figure 1*b* it can be seen that HH 320 is coincident with the NIR emission associated with IRS 2, while HH 321 is coincident with the NIR emission associated with IRS 1.

In Figure 2*a* is shown an enlarged view of the central part of the 2.12 μm image presented in Figure 1*b*. Indicated on this figure are the locations of the *ISO* sources IRS 1 and IRS 2 (*open squares*). Overlaid on the figure are contours of integrated ^{12}CO $J = 2 \rightarrow 1$ emission, with solid contours representing emission that is blueshifted (-20 km s$^{-1} < V_{lsr} < -6$ km s^{-1}) with respect to the cloud systemic velocity ($V_{lsr} \sim -4.5$ km s^{-1}; B97) and dotted contours representing redshifted emission (-3 km s$^{-1} < V_{lsr} < 30$ km s^{-1}). The large-scale CO outflow mapped by B97 is evident as open blue- and redshifted contours, oriented approximately north-south with IRS 1 lying between them. On scales larger than is mapped in the present CO $J = 2 \rightarrow 1$ observations, this outflow has a position angle of ∼165°. Closed contours of blueshifted emission peak at the position of HH 320.

In Figure 2*b* is shown the CO $J = 2 \rightarrow 1$ spectrum at the ($-30''$, $30''$) offset position (HH 320). The high-velocity out-

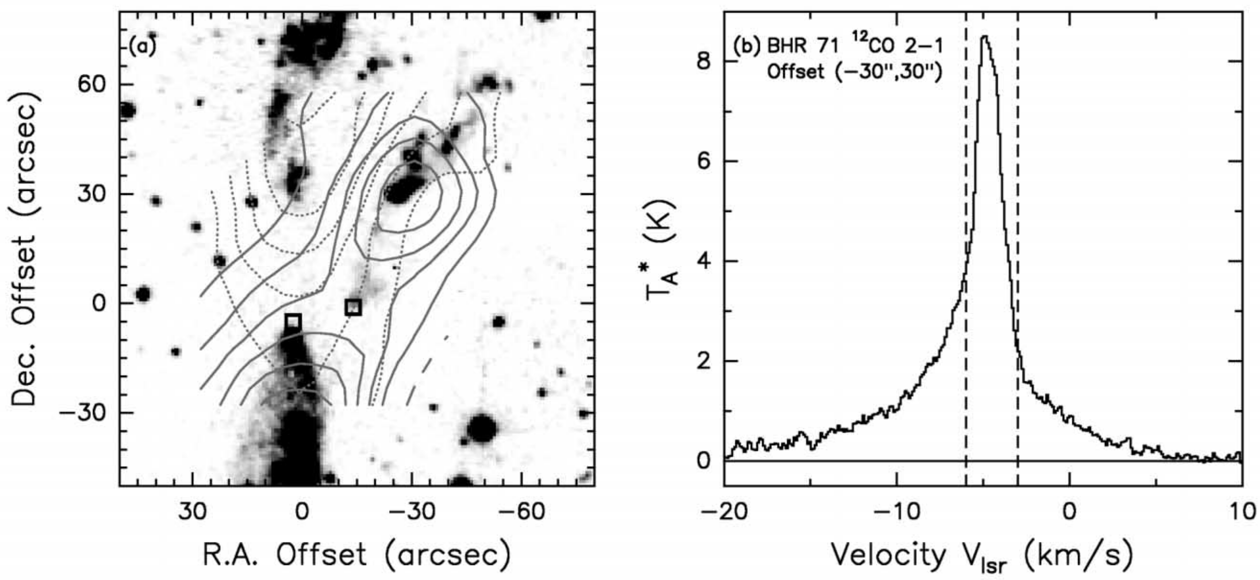

FIG. 2.—(*a*) Narrowband 2.12 μm + continuum image (*gray scale*) overlaid with contours of CO $J = 2 \rightarrow 1$ emission. The solid (dotted) contours represent emission integrated over the velocity range -20 km s$^{-1} < V_{\rm lsr} < -6$ km s^{-1} (-3 km s$^{-1} < V_{\rm lsr} < 30$ km s^{-1}), which is blueshifted (redshifted) with respect to the cloud systemic velocity. The positions of IRS 1 and IRS 2 are marked with open squares. Offsets are relative to R.A. (B1950) = 11$^{\rm h}$59$^{\rm m}$02$^{\rm s}$.3, decl. (B1950) = $-64°52'01''$. (*b*) CO $J = 2 \rightarrow 1$ spectrum at the ($-30''$, $30''$) offset position. The dashed lines represent the limits of the ambient cloud emission (-6 km s$^{-1} < V_{\rm lsr} < -3$ km s^{-1}). High-velocity blueshifted (redshifted) line wings are present at velocities $V_{\rm lsr} < -6$ km s^{-1} ($V_{\rm lsr} > -3$ km s^{-1}). [*See the electronic edition of the Journal for a color version of this figure*.]

flow wing emission at this position due to IRS 1 (redshifted) and IRS 2 (blueshifted) is clearly seen.

In order to determine accurately the *ISO* positions and the relative positions of the centimeter source and HH objects, it was necessary to register the images to the same spatial system. First, a plate solution for a 40′ field of view Digital Sky Survey (DSS) image centered on BHR 71 was determined by comparison with 25 stars from the *Hubble Space Telescope* Guide Star Catalog (GSC). Using both the corrected DSS image and the GSC, plate solutions for the *I*-band image and the S II image (Corporon & Reipurth 1997, kindly provided in digital form by P. Corporon) were determined, using 14 stars common to all three bands. The uncertainty in positions measured from these frames is believed to be less than 1″, by comparison with the GSC and with each other.

The plate solution for the NIR images was determined using stars common with the *I*-band image, 20 for the K' image, and 10 for the narrowband 2.12 μm image, respectively. Finally, the *ISO* 7 μm plate solution was determined using the three *ISO* sources visible in Figure 1*a* and not associated with NIR nebulosity. The positions of the HH objects were measured directly from the corrected S II image, using the peak positions due to their nonsymmetric shape. All positions quoted here are believed to be accurate to $\lesssim 1''$.

4. DISCUSSION

4.1. *Two Protostars: Two Outflows*

The data presented here clearly indicate that two protostellar sources are present in BHR 71, each driving its own molecular outflow. IRS 1 and its large-scale outflow has been discussed in detail by B97. The spectacular shock chemistry in the outflow has been studied by Garay et al. (1998). B97 discovered extended 1.3 mm emission associated with IRS 1 and suggested that this is due to a massive circumstellar disk.

IRS 2 has been noted previously (Myers & Mardones 1998). The data presented here show that it is driving a compact CO outflow and is associated with NIR molecular hydrogen emission (Fig. 2*a*), which is coincident with HH 320 and most likely shock excited (Eislöffel 1997). Earlier evidence for the blue lobe can be seen in the channel maps of the IRS 1 outflow presented in B97. Their Figure 6 shows the emission from the CO $J = 1 \rightarrow 0$ transition, and the outflow associated with IRS 2 can be seen in the velocity range -10.8 km s$^{-1} < V_{\rm lsr} < -8.4$ km s^{-1}.

Comparison of the *I*-band image and the IRS 1 outflow suggests that its blue lobe has broken through the near side of the globule (B97). The presence of HH objects in the blue lobe of the IRS 2 outflow suggests that this outflow is also penetrating the near side of the globule. The relative mass of the blue and red outflow lobes of IRS 1 suggests that the red lobe of the IRS 1 outflow has not penetrated the far side of the globule (B97). It is likely that IRS 1 and IRS 2 are located at a similar depth within the globule from the near side and that their angular separation of ∼17″ is a good indication of their physical separation, which is therefore 3400 AU for the assumed distance of 200 pc.

The limited CO observations do not reveal a redshifted lobe to the IRS 2 outflow. Due to the large inclination of the IRS 1 outflow to the line of sight, both blue- and redshifted outflow emission is seen in the southeast part of the IRS 1 outflow (B97), which probably masks any emission from the redshifted lobe of the IRS 2 outflow. However, the NIR image shows a knot of H_2 line emission, shown by the arrow in Figure 1*b*, which is a possible counterflow to the IRS 2 blueshifted outflow lobe. A line drawn from this knot through and extending past IRS 2 bisects the limb-brightened conical reflection nebulosity (connecting IRS 2 and HH 320) at the base of the blue outflow lobe of IRS 2. Taking this to define the outflow axis, the IRS 2 outflow has a position angle of ∼−36°.

Combining the IRS 2 CO $J = 2 \rightarrow 1$ data with the CO $J = 1 \rightarrow 0$ data of B97 for IRS 2 allows for an estimation of the CO excitation temperature $T_{\rm ex}$, although the signal-to-noise ratio of the latter data set is poorer and the sampling grids are different. As no isotopic data are available, optically thin conditions are assumed, which implies $T_{ex} \sim 10$ K. The mass of the blueshifted emission in the IRS 2 outflow is ∼0.004 $M_\odot$, significantly less than the ∼0.06 $M_\odot$ in the blueshifted gas of the southeast lobe of the IRS 1 outflow (B97—using CO $J = 1 \rightarrow 0$ data and assuming optically thin conditions). The IRS 1 outflow is moderately optically thick ($\tau \sim 2$; B97), so the optical depth of the IRS 2 outflow would have to be significantly greater to modify this comparison. Although significantly less massive than the IRS 1 outflow, the IRS 2 outflow is still able to produce shock-excited H_2 emission and HH objects.

Previous observations by B97 show that IRS 1 is a class 0 protostar. Compared to IRS 1, IRS 2 is much weaker at 7 μm and drives a much less massive outflow and is not detected at 1.3 mm (§ 4.2). This suggests that IRS 2 is more evolved than IRS 1 and is most likely a class I protostar.

4.2. *A Binary Protostellar System?*

The presence of two sources in BHR 71 with a separation of 3400 AU, neither detected at wavelengths less than 7 μm, and both driving molecular outflows, suggests that a binary protostellar system has formed within the globule. Observations by B97 show that strong 1.3 mm continuum emission is associated with the protostellar pair, but the emission is highly peaked on IRS 1, and no obvious extension including IRS 2 is seen (their Figs. 9 and 13). The lack of millimeter emission and the weakness of the 7 μm emission compared to IRS 1 suggests that IRS 2 is not surrounded by a significant amount of circumstellar dust. This situation is similar to that observed in Bok globule CB 230 (Launhardt 2001). High angular resolution observations (∼2″) of CB 230 show compact millimeter emission associated with only one component of an NIR protostellar pair separated by ∼10″, suggesting that like BHR 71 only this component has a substantial circumstellar disk, although both protostars in CB 230 drive CO outflows. Another wide binary protostellar pair, SVS 13 (Bachiller et al. 1998; separation 4300 AU), shows millimeter emission from both protostars.

Kinematic information indicating a common center of gravity is required to show that a stellar pair is a binary. Launhardt (2001) has also observed N_2H^+ $1 \rightarrow 0$ emission (93.7 GHz) from CB 230 with a resolution of less than 10″ and found two cores with a separation of 10″ (4500 AU), each spatially coincident with an NIR source and which rotate about the axis perpendicular to the axis joining the cores. This implies that CB 230 contains a true binary protostellar system. Molecular line observations to date of BHR 71 (B97) do not have sufficient angular resolution to determine if IRS 1 and IRS 2 are each associated with their own molecular core. Although there are similarities between BHR 71 and CB 230—both contain two protostellar sources in a Bok globule, each driving a CO outflow, and large-scale millimeter emission is centered on only one of the sources—BHR 71 can only be considered as a candidate binary protostellar system until high angular resolution molecular line observations become available.

5. CONCLUSIONS

New NIR and ^{12}CO $J = 2 \rightarrow 1$ observations have been combined with existing *ISO* mid-infrared and ATCA centimeter radio continuum observations to examine the protostellar content of the Bok globule BHR 71. Together with observations of Herbig-Haro objects, these data show the following:

1. Two protostellar sources, IRS 1 and IRS 2, with a separation of ∼17″ (3400 AU) are located within BHR 71, as revealed by *ISO* mid-infrared observations. IRS 1 is the brighter of the two by about a factor 10.
2. Each protostar is driving its own molecular outflow, as revealed by the ^{12}CO $J = 2 \rightarrow 1$ observations. The outflow from IRS 1 is much larger in extent, is more massive, and dominates the CO emission.
3. Both protostars are associated with Herbig-Haro objects and shock-excited 2.122 μm H_2 $v = 1$–0 $S(1)$ emission, which coincide spatially with their CO outflows.
4. IRS 1 is associated with centimeter continuum emission, with a flat or rising spectrum, which is consistent with free-free emission, a signpost of protostellar origin.

The observations suggest that a binary protostellar system has formed within BHR 71. IRS 1 is a class 0 protostar, while IRS 2, associated with much less circumstellar dust and driving a much weaker CO outflow, is probably a more evolved class I protostar. High angular resolution millimeter molecular line observations are required to determine if IRS 1 and IRS 2 are a physically bound binary.

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