The Astrophysical Journal, 377:246–249, 1991 August 10

TWO MICRON SPECTROSCOPY OF INFRARED SOURCES IN NGC 2071

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Received 1991 January 7; accepted 1991 February 15

ABSTRACT

We present 2.10–2.35 μm spectra of seven compact infrared sources in the central region of the bipolar outflow NGC 2071. Line emission from CO at the wavelengths of the 2–0, 3–1, and 4–2 band heads has been detected in IRS 1 and IRS 7. In addition, Brγ line emission is present in IRS 1. We suggest that the NGC 2071 bipolar outflow is a composite of two or more outflows.

Subject headings: infrared: sources — infrared: spectra — nebulae: H II regions — stars: formation

1. INTRODUCTION

Four arcminutes north of the reflection nebula NGC 2071, located in the Lynds 1630 cloud, is a region of active star formation, which we designate NGC 2071IR. The region contains a bipolar outflow (Bally 1982; Snell et al. 1984; Moriarty-Schieven, Snell, & Hughes 1989) and associated line emission from shocked molecular hydrogen (Bally & Lane 1982; Burton, Geballe, & Brand 1989; Garden, Russell, & Burton 1990). The region has a total luminosity of 750 $L_\odot$ (Harvey et al. 1979). A cluster of four infrared sources, designated IRS 1–4, was found at 10 μm near the center of the outflow by Persson et al. (1981). Recent 2 μm imaging of the region (Walther, Robson, & Sandell 1991) has resulted in more accurate positions for these objects as well as detection of additional infrared sources. To date it is unknown which of these sources, if any, are responsible for the outflow.

In this paper we present spectroscopic observations of seven of the sources in and near the core of NGC 2071IR, in the wavelength band, 2.06–2.38 μm. None of these objects have known visible counterparts. The spectral region studied includes the Brγ (7–4) line of atomic hydrogen, the 2–0, 3–1, and 4–2 band heads of CO, and several lines of vibrationally excited H_2, and has proved useful in elucidating the natures of these sources and their possible relationships to the outflow.

2. OBSERVATIONS AND RESULTS

The *K*-band spectra were obtained at the 3.8 m United Kingdom Infrared Telescope on Mauna Kea, using a cold seven channel grating infrared spectrometer (Wade 1983) on 1990 September 4 and October 1 UT. A grating having 300 lines mm^{-1} was used in the first order and provided a resolution of 0.008 μm. All spectra were sampled every $\frac{1}{3}$ resolution element over the interval 2.10–2.35 μm, and less fully outside this interval.

The positions of the seven sources were determined from the *K*-band imaging of NGC 2071 by Walther et al. (1991). Figure 1 shows a portion of their *K* image of the region, with the positions of the seven sources, as well as several others, indicated. Much of the extended emission in the figure is from numerous H_2 lines, as demonstrated by the spectra of Burton et al. (1989) and by comparison of Figure 1 with the Garden et al. (1990) narrow-band image of the H_2 1–0 *S*(1) line. The spectroscopic measurements reported in this paper were made with a 5″ diameter beam, except for those of IRS 3 and IRS 5, which were observed in a 3″.8 aperture in order to reduce contamination from sources nearby. The chopper throw was 30″ east-west.

Flux calibration and correction for telluric absorption were obtained by dividing the spectrum of each source by that of BS 1543, a nearby bright star of *K*-magnitude 2.07 and spectral type F6, and by multiplying the resulting ratio by the blackbody spectral intensity corresponding to the inferred stellar temperature (6400 K). The spectrum of BS 1543 contains a strong Brγ absorption line, which was artificially removed, prior to the above arithmetic operations, by comparison with the spectrum of the K2 star BS 2037, which has no Brγ line. The resulting spectra are shown in Figure 2. They have been Hanning-smoothed and have a resolution of approximately 0.010 μm. Line fluxes are given in Table 1.

Of the seven embedded IR sources, IRS 1 and IRS 7 have CO band-head emission at 2.30, 2.33, and 2.36 μm. In contrast, the spectrum of IRS 6 shows CO absorption longward of 2.3 μm. IRS 1 was found to have a Brγ emission line. The association of this line with IRS 1 was verified by negative detections of the line at positions adjacent to IRS 1. In addition, the spectra of several sources show lines of H_2, the 1–0 *S*(1), 1–0 *S*(0), and 2–1 *S*(1) lines at 2.122, 2.224, and 2.248 μm, respectively. We believe these lines are extended emission from shocked gas along the line of sight (Burton et al. 1989; Garden et al. 1990) and not physically associated with the IR sources. The compact sources, IRS 2, IRS 3, IRS 4, and IRS 5, appear to have no detectable lines in the *K* window.

The continua of four of the seven sources rise steeply to longer wavelengths, indicating that these objects are deeply embedded. The most deeply embedded object is probably IRS 7. The continuum of IRS 4 turns over in the *K* window and that of IRS 6 flattens, indicating that the extinctions to these objects are considerably lower than the others and that they probably reside near the front edge of the molecular cloud.

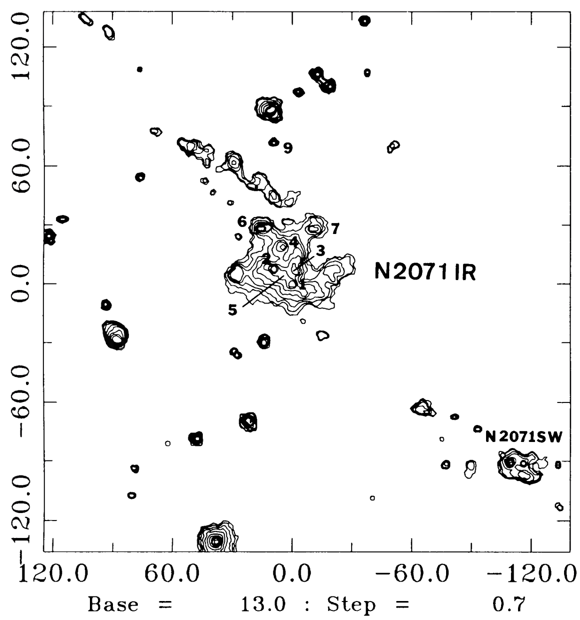

FIG. 1.—A 2.2 μm broad-band image of the NGC 2071IR region, obtained from a larger image (Walther, Robson, & Sandell 1991). R.A. and decl. scales are in arcseconds. (0, 0) is R.A. = $5^h44^m30^s.6$, decl. = $+00°20'42''.0$ (1950). The lowest contour line is 20.0 mag arcsec^{-2}, which represents a 3 σ detection, and the contours are spaced by 0.7 mag arcsec^{-2}. Numbers indicate infrared sources (1 = IRS 1).

3. DISCUSSION AND CONCLUSION

3.1. *Individual Sources*

3.1.1. *IRS 1 and IRS 7*

Emission from CO first-overtone band heads, which is seen in IRS 1 (along with Brγ) and IRS 7, is a frequent, though not universal, spectral feature in young stellar objects (Geballe & Persson 1987; Carr 1989). These spectral features imply that extended regions of hot gas exist near IRS 1 and IRS 7 and suggest that both objects are currently undergoing mass loss, although high-resolution spectroscopy is necessary to prove the latter. The fact that hot circumstellar regions are detectable at near-infrared wavelengths toward IRS 1 and IRS 7 indicates that these young stellar objects already have shed much of their natal material and are nearing the main sequence.

As discussed by Scoville et al (1979), the presence of band heads in emission implies gas kinetic temperatures of at least 3000 K and densities of at least 10^{10} cm^{-3}. Temperatures and densities such as these are possible in extended stellar atmospheres, in circumstellar shells or disks, or even in shock-heated regions which may be somewhat more distant from the star.

The intensity of the Brγ line in IRS 1 is roughly half the upper limit on Brα reported by Smith et al. (1987). Because the reddening between 2.17 and 4.05 μm is probably 1–2 mag, the Brγ line must be formed under conditions more similar to a dense protostellar wind or disk than those of a normal H II region (Simon et al. 1983). IRS 1 is coincident with a compact radio source which is surrounded by more extended radio emission (Snell & Bally 1986). No compact radio source was found by these authors at the location of IRS 7. Hence IRS 7 is probably considerably cooler than IRS 1.

3.1.2. *IRS 2 and IRS 3*

As in the case of IRS 1, the sources IRS 2 and IRS 3 are associated with compact radio sources (Snell & Bally 1986). No Brγ or other emission lines are seen in the 2 μm spectra of IRS 2 and IRS 3. Relative to IRS 1, the radio emission at IRS 2 is very low, but the limit on Brγ (Table 1) is not much less than the detected value at IRS 1. Therefore, it is difficult to draw conclusions about the evolutionary state of IRS 2 relative to IRS 1 and IRS 3. In the case of IRS 3 the limit on Brγ is considerably below the value at IRS 1, whereas the radio fluxes from the compact components are more comparable. This, together with the considerably redder *K* spectrum of IRS 3, suggests that IRS 3 is at an earlier phase of evolution than either IRS 1 or IRS 7.

3.1.3. *IRS 4 and IRS 6*

The continuum of IRS 4 turns over near the middle of the *K* band, suggesting that the extinction to it is low and that the contribution to its continuum by emission from warm circumstellar dust is small. A similar conclusion is drawn from the spectrum of IRS 6. We infer that at 2 μm the photospheres of both objects are being detected. The *K* spectrum of IRS 4 lacks both CO absorption and Brγ absorption, suggesting that its spectral type is late G. The spectrum of IRS 6 shows weak absorption at the CO band heads, suggesting that it is an early K dwarf.

The position of IRS 4 coincides approximately with that of the 10 μm source of the same name found by Persson et al. (1981). At 10 μm. IRS 4 is considerably fainter than IRS 1, IRS 2, and IRS 3, which is expected on the basis of its 2 μm spectrum and radio properties.

3.1.4. *IRS 5*

The spectrum of IRS 5, a perhaps slightly extended object that is situated between IRS 1 and IRS 2, is flat. IRS 5 is coincident with a region of diffuse radio continuum emission

TABLE 1
MEASURED LINE FLUXES[a] (10^{-21} W cm^{-2})

Source	Beam[b]	1–0 *S*(1)	Brγ	1–0 *S*(0)	2–1 *S*(1)	CO 2–0
IRS 1	5.0	13.5 (1.0)	2.7 (0.4)	4.5 (0.9)	1.2 (0.4)	4.1 (0.6)
IRS 2	5.0	20.2 (1.5)	<1.5	5.7 (0.9)	≤1.5	<1.5
IRS 3	3.8	1.9 (0.3)	<0.3	0.4 (0.2)	<0.3	≤0.3
IRS 4	5.0	9.0 (1.0)	<1.0	2.4 (0.5)	<1.0	<1.0
IRS 5	3.8	7.6 (0.6)	<0.5	2.3 (0.3)	0.6 (0.2)	<0.5
IRS 6	5.0	1.0 (0.5)	<0.8	<0.8	<0.8	Absorption
IRS 7	5.0	0.8 (0.2)	<0.3	<0.3	<0.3	1.5 (0.2)

[a] Uncertainties in parentheses.
[b] Aperture diameter in arcseconds.

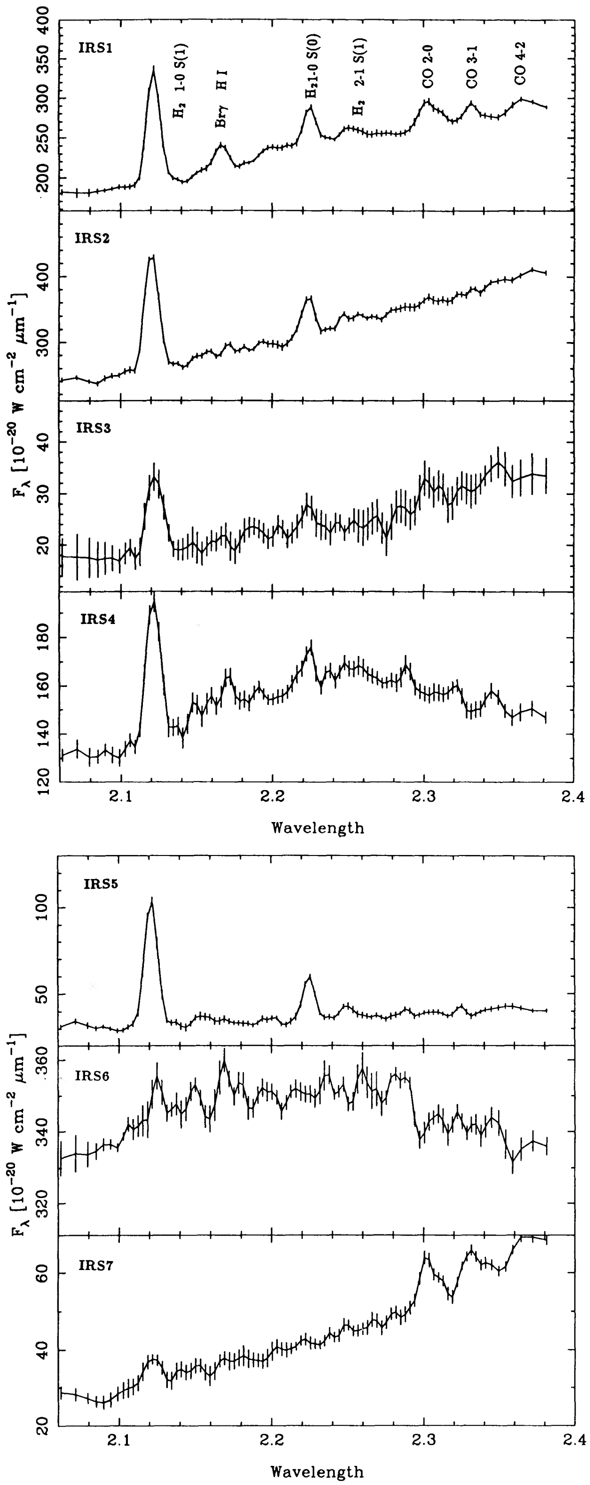

FIG. 2.—2.10–2.35 μm spectra of seven IR sources in the central region of the bipolar outflow, NGC 2071. The identifications of relevant spectral features are indicated in the top panel (IRS 1).

(Snell & Bally 1986); however, no Brγ line was detected at IRS 5. Given the weakness of the radio continuum emission, the present limit on Brγ probably is not interesting. The object is known to have considerably higher polarization at *K* than its neighbors (D. M. Walther, unpublished data) and is likely a reflection nebula.

3.2. *Morphology*

Evidence from infrared spectroscopy for mass loss from IRS 1 and IRS 7 has been presented in this paper. Therefore, it is of interest to examine the morphology of the NGC 2071 outflow to determine whether either of these objects could be driving all or part of the outflow. We do this below, with reference to the *K*-band image in Figure 1, showing the infrared sources as well as the shocked H_2, which delineates the outflow, rather than using millimeter CO maps, because of the considerably higher angular resolution of the former.

In Figure 1, IRS 1 is seen to be one of a cluster of stellar objects within the central area of H_2 line emission, which is the largest and brightest in NGC 2071. Its location is clearly consistent with it being the source of the outflow which shock-heats the surrounding cloud producing H_2 line emission directly in front and/or behind the central cluster. However, one cannot rule out contributions to the outflow from IRS 2 and IRS 3. There is no evidence from the *K* spectra that either of these sources is generating a substantial stellar wind. Nevertheless, each is associated with a compact H II region, and therefore could be producing such a wind. High-resolution spectroscopy of CO fundamental band lines could be an important means of investigating this possibility. For the present, one should note the parallel of the much higher luminosity OMC-1 outflow. IRc2, in OMC-1, is associated with a compact H II region but has no known intrinsic infrared spectral features, yet it is generally believed to be the source of the wind which drives the outflow. In contrast, the Becklin-Neugebauer star, which has both a strong Brγ line and CO band-head emission (Scoville et al. 1979), is considered to be at best a minor contributor.

In Figure 1 a linear set of clumps of molecular hydrogen line emission extend from IRS 7 to the northeast. These bear considerable similarity to the H_2 clumps in the Herbig-Haro objects HH 7–11 (Garden et al. 1990), which proceed from SSV 13, a young stellar object believed to have produced HH 7–11 and known to have CO band heads in emission (Carr 1989). We suggest that, analogous to SSV 13 and HH 7–11, IRS 7 is the source of an outflow that has produced the H_2 blobs extending to the northeast of it.

Thus, we conclude from this work that more than one outflow is present within NGC 2071IR. Indeed, from examination of Figure 1, we suspect that other objects close to the infrared cluster are undergoing significant mass loss and are responsible for some of the H_2 line emission in NGC 2071. The spatial relationship between IRS 9, situated 1′ north-northeast of IRS 7 (Figure 1), and a linear array of H_2 clumps to the northeast of it (Garden et al. 1990; see Fig. 7 [Pl. 6] of that paper), is strikingly similar to that of IRS 7 and its H_2 clumps. Southwest of the main cluster are a number of infrared and visible stars and several H_2 clumps whose relationship to the outflow from the main cluster (e.g., IRS 1) is unclear. Of particular interest is the recent detection of both blueshifted and redshifted CO 2–1 mm line emission in the latter region by Moriarty-Schieven et al. (1989). Infrared spectroscopy of IRS 9, the southwest point sources, and other pointlike objects within and near NGC 2071IR is warranted.

We would like to thank the staff of the United Kingdom Infrared Telescope for its support and Hans Zinnecker for useful discussions. Some of these data were obtained during UKIRT Service observing.

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