DEEPLY EMBEDDED OBJECTS AND SHOCKED MOLECULAR HYDROGEN: THE ENVIRONMENT OF THE FU ORIONIS STARS RNO 1B/1C

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ABSTRACT

We present Spitzer IRAC and IRS observations of the dark cloud L1287. The mid-infrared (MIR) IRAC images show deeply embedded infrared sources in the vicinity of the FU Orionis objects RNO 1B and RNO 1C, suggesting their association with a small young stellar cluster. We resolve for the first time the MIR point source associated with IRAS 00338+6312, which is a deeply embedded intermediate-mass protostar driving a known molecular outflow. The IRAC colors of all the objects are consistent with those of young stars ranging from deeply embedded Class 0/I sources to Class II objects, some of which appear to be locally reddened. The two IRS spectra show strong absorption bands due to ices and dust particles, confirming that the circumstellar environment around RNO 1B/1C has a high optical depth. Additional hydrogen emission lines from pure rotational transitions are superposed on the spectra. Given the outflow direction, we attribute these emission lines to shocked gas in the molecular outflow powered by IRAS 00338+6312. The derived shock temperatures are in agreement with predictions for high-velocity C-type shocks.

Subject headings: circumstellar matter — ISM: jets and outflows — infrared: stars — stars: formation — stars: individual (RNO 1B, RNO 1C, IRAS 00338+6312) — stars: pre–main-sequence

1. INTRODUCTION

The dark cloud L1287 contains the Galactic nebulae GN 00.34.0 (associated with the young F-type star RNO 1) and GN 00.33.9, which harbors the point source IRAS 00338+6312 (d = 800 pc; Persi et al. 1988). Two young stars, RNO 1B and RNO 1C,1 lie slightly to the southwest of the catalog position of the point source. These objects exhibit properties of FU Orionis objects (FUors): (1) Staude & Neckel (1991) found that RNO 1B brightened by at least 3 mag over a period of 12 years and that it shows a variable and blueshifted P Cygni profile in Hβ; (2) Kenyon et al. (1993) obtained near-infrared spectroscopic data for both objects and found the FUoryrnotypical strong 2.3 μm CO absorption bands. As the error ellipse of the IRAS source includes both objects, it was debated whether there is yet another deeply embedded source close to the FUors or whether IRAS (the Infrared Astronomical Satellite) just measured the integrated flux from these two objects. From high-resolution, near-infrared polarimetric maps, Weintrub & Kastner (1993) concluded that an additional embedded object should be present close to the location of the IRAS source. This idea was supported by the discovery of a 3.6 cm continuum peak (Anglada et al. 1994) and an H2O maser (Fiebig 1995), both nearly coincident with the IRAS position. A bipolar outflow in the region was found by Snell et al. (1990) and later confirmed by Yang et al. (1991). As the positions of the IRAS source and the FUors line up along the outflow axis, it has long been uncertain which source is driving the outflow. From interferometric observations in CS, Yang et al. (1995) suggested that the IRAS source was the most likely candidate. Recently, Xu et al. (2006) mapped the outflow in CO and came to the same conclusion. However, McMuldrough et al. (1995) presented (sub-) millimeter observations favoring RNO 1C as the outflow’s driving source.

In this paper, we present mid-infrared (MIR) imaging and spectroscopic data taken with the Infrared Array Camera (IRAC) and Infrared Spectrograph (IRS) on board the Spitzer Space Telescope. For the first time, the MIR point source associated with the IRAS source is resolved, and we find additional, partly deeply embedded objects. The two IRS spectra probe the composition of the dense circumstellar environment in the vicinity of RNO 1B/1C and bear additional traces of shocked H2 gas.

2. OBSERVATIONS AND DATA REDUCTION

All data were part of Guaranteed Time Observation program 124 by R. Gehrz and are publicly available from the Spitzer archive. An overview of the observational setup and the data sets is provided in Table 1. The IRAC images were obtained in subarray mode, leading to an effective field of view of 40′′ centered on the position given in Table 1. The spectra taken with the IRS cover the wavelength range 5–37 μm. Overplotting the IRS spectral slits on the Two Micron All Sky Survey (2MASS) Ks-filter image reveals that RNO 1B and RNO 1C apparently were not centered within the slits (Fig. 1). The short-wavelength, low-resolution spectrum (5.2–14.5 μm, R = 64–128) and the short-wavelength, high-resolution spectrum (9.9–19.6 μm, R ~ 600) close to RNO 1B seem mainly to probe flux coming from between the two objects. The spectrum close to RNO 1C presumably also contains less flux than expected as a result of the slight mispointing. The long-wavelength, high-resolution part of each spectrum (18.7–37.2 μm, R ~ 600) includes flux from both components and additional flux from the IRAS source, as all three objects lie within the slit of the spectrograph.

The IRAC images were reduced with the MOPEX package provided by the Spitzer Science Center. Interpolation, outlier detection, and co-addition of the images were carried out for each

1 We use the same nomenclature as Staude & Neckel (1991).
filter individually. The astrometry was refined by comparing the positions of detected sources with known 2MASS objects. The photometry was carried out with the DAOPHOT package provided within the IRAF environment. As there were only a limited number of sources available within the small field covered by the camera, we measured the point-spread function (PSF) of RNO 1C and used it as a reference in order to perform PSF photometry for all the other sources. Following the IRAC Data Handbook (§5.1.1), we converted the pixel values from MJy sr$^{-1}$ to DN s$^{-1}$ and computed the corresponding magnitudes as $m = -2.5 \log x + \Delta ZP$, with $x$ denoting the flux measured in DN s$^{-1}$ and $\Delta ZP$ being the zero point for each filter. For the initial PSF fit we used a PSF size of 2 pixels and applied aperture corrections as described in the Data Handbook to obtain the final magnitudes.

Our final IRS spectra are based on the intermediate droopres (for the low-resolution data) and rasc (for the high-resolution data) products processed through the S13.2.0 version of the Spitzer data pipeline. Partially derived from the SMART software package (Higdon et al. 2004), these intermediate data products were further processed using spectral extraction tools developed by the “Formation and Evolution of Planetary Systems” (FEPS) Spitzer Legacy Science team (see Explanatory Supplement ver. 3.0 within the FEPS data deliveries).

For the short-wavelength, low-resolution observations, the spectra were extracted using a 6.0 pixel fixed-width aperture in the spatial dimension, resulting in a 39.96 arcsec$^2$ extraction aperture on the sky. The background was subtracted using associated pairs of imaged spectra from the two nodded positions along the slit. This process also subtracts stray-light contamination from the peak-up apertures and adjusts pixels with anomalous dark current relative to the reference dark frames. Pixels flagged by the Spitzer data pipeline as being “bad” were replaced with a value interpolated from an 8 pixel perimeter surrounding the errant pixel. The high-resolution spectra were extracted with the full aperture size (53.11 arcsec$^2$ for the Short-High and 247.53 arcsec$^2$ for the Long-High module). The sky contribution was estimated by fitting a continuum to the data. Both the low- and high-resolution spectra were calibrated using a spectral response function derived from IRS spectra appropriate for the two nod positions in the slit at which we extracted the spectra, and Cohen or MARCS stellar models for a suite of calibrators provided by the Spitzer Science Center. The multiple orders in our spectra match to within 10%. These small flux offsets are likely related to small pointing offsets. We computed correction factors for possible flux loss due to telescope mispointing based on the PSF of the IRS instrument. However, accurate results can only be obtained if the flux is dominated by one source. The offsets also result in low-level fringing at wavelengths longer than 20 $\mu$m in the low-resolution spectra and at all wavelengths in the high-resolution spectra. We removed these fringes using the IRSFRINGE package (developed by F. L.). The relative errors between spectral points within one order are dominated by the noise on each individual point and not by the calibration. Based on our experience with Spitzer IRS data, we estimate a relative flux calibration error across a spectral order of $\sim$5% and an absolute calibration error between orders or modules of $\sim$10%. These values, however, are based on point-source observations with accurate telescope pointing. The data presented here are more complicated, as at least part of the emission is moderately extended, multiple sources contribute to the observed fluxes, each contribution is wavelength dependent, and the telescope slits were not centered on the main objects. Thus, an accurate flux calibration between the different modules is difficult; apparent offsets are discussed further in §3.2.

### Table 1

| Instrument   | R.A.$^a$ (J2000) | Decl.$^a$ (J2000) | Date       | AOR Key | Filter or Module | Ramp Duration/ No. of Cycles | Frame Time/ Frames/ Dither Positions |
|--------------|------------------|-------------------|------------|---------|-----------------|------------------------------|--------------------------------------|
| Spitzer IRAC | 00 36 45.8       | +63 28 56         | 2003 Dec 20 | 5027072 | 3.6, 4.5, 5.8, 8.0 $\mu$m | ...                          | 0.4/1/4                               |
| Spitzer IRS  | 00 36 46.34b     | +63 28 53.76b     | 2004 Jan 7  | 6586624 | Low-resolution 6 $\times 3$ | ...                          |                                      |
|              | 00 36 46.89c     | +63 28 58.44c     | 2004 Jan 7  | 6586624 | Low-resolution 6 $\times 3$ | ...                          |                                      |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

$^a$ Average slit position of the low-resolution spectrograph.

$^b$ Close to RNO 1B.

$^c$ Close to RNO 1C.

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Fig. 1.—Slits of the different modules of the Spitzer IRS overplotted on the inverted 2MASS $K_s$-filter image. The two FUors RNO 1B and RNO 1C are not centered in the slits. (North is up, and east is to the left.)

2 See http://iraf.noao.edu.

3 Zero points taken from Hartmann et al. (2005): 19.66 (3.6 $\mu$m), 18.94 (4.5 $\mu$m), 16.88 (5.8 $\mu$m), and 17.39 (8 $\mu$m).

4 See http://ssc.spitzer.caltech.edu/legacy/fepshistory.html.
3. RESULTS

3.1. IRAC Photometry

Within the limited field of view of the IRAC subarray mode, we identified eight sources that were detected in at least three of the four IRAC bands. Figure 2 provides a comparison between the RNO 1B/1C region as seen in the 2MASS $K_s$ filter and the 5.8 $\mu$m IRAC filter. For the first time, the MIR point source related to IRAS 00338+6312 is detected in the IRAC band. Additional, fainter objects are also present, some of which are detected for the first time.

Figure 3 shows a color composite image of the RNO 1B/1C complex based on three IRAC filters. Table 2 lists all objects that were identified in at least three IRAC bands and summarizes the derived fluxes. The errors are based on the results from the PSF photometry.
Since we used the PSF of RNO 1C as reference, the corresponding errors are relatively small compared with the other objects. IRAS 00338 + 6312 and RNO 1G were not detected in the shortest IRAC band, at 3.6 μm. The 2MASS image in Figure 2 shows that at least the IRAS source is deeply embedded in a dense, dusty environment, explaining the nondetection at this wavelength. Figure 4 shows two color–color plots based on the four IRAC bands for all objects listed in Table 2. Following Hartmann et al. (2005), who analyzed a large sample of pre-main-sequence stars in the Taurus star-forming region, we use these plots to classify the different objects. The colors of the reddest objects (IRAS 00338 + 6312 and RNO 1G) are consistent with those of very young protostars. The colors of the newly discovered objects RNO1 IRAC 1 and RNO1 IRAC 3 are consistent with Class 0/I systems, although not highly reddened background sources. While the colors of the FUor RNO 1C fit in the region of Class II objects from Hartmann et al. (2005) in both plots (Fig. 4), RNO 1B fits into this regime only in one color–color diagram. In the right panel of Figure 4, RNO 1B is too red for a Class II source in the [4.5]–[5.8] color, but not red enough in the [3.6]–[4.5] color to be a Class 0/I object. Finally, RNO1 IRAC 2 and RNO 1F, which both show up in the 2MASS Ks-band image, can also be interpreted as Class II objects. However, the colors of RNO1 IRAC 2, and partly also those of RNO 1F, may have been altered by local extinction effects.

### 3.2. IRS Spectroscopy

In Figure 5, we show the Spitzer IRS spectra without any extinction correction. As pointed out above, the spectral slits of the short-wavelength modules were apparently not directly centered on the objects RNO 1B and RNO 1C, and thus the measured fluxes cannot be attributed to these objects with very high accuracy. Also, there seems to be an offset in the flux in the high-resolution regime compared with the low-resolution part of the spectrum. To see to what extent this effect is caused by different aperture sizes, we plot the spectra in intensities (i.e., flux density per solid angle) rather than in janskys per wavelength. This shows, however, that even after this correction significant offsets remain: around 13 μm, the difference between the low-resolution spectrum and the short-wavelength, high-resolution spectrum amounts to factors of ~1.25 and ~1.08 for RNO 1B and RNO 1C, respectively, with the high-resolution part showing higher intensities. At least for the RNO 1B spectrum, this offset is larger than normally expected from the calibration accuracy. We thus believe that part of this offset can be attributed to the different orientations of the

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**Table 2**

| No. | Object Name       | R.A. (J2000) | Decl. (J2000) | 3.6 μm (mag) | 4.5 μm (mag) | 5.8 μm (mag) | 8.0 μm (mag) |
|-----|-------------------|--------------|---------------|--------------|--------------|--------------|--------------|
| 1   | RNO 1B            | 00 36 46.05  | +63 28 53.29  | 7.16 ± 0.13  | 6.67 ± 0.06  | 5.76 ± 0.12  | 5.01 ± 0.09  |
| 2   | RNO 1C            | 00 36 46.65  | +63 28 57.90  | 6.56 ± 0.01  | 6.04 ± 0.01  | 5.58 ± 0.01  | 4.61 ± 0.02  |
| 3   | RNO 1F            | 00 36 45.74  | +63 29 04.09  | 10.28 ± 0.09 | 9.46 ± 0.08  | 8.58 ± 0.05  | 8.20 ± 0.03  |
| 4   | RNO 1G            | 00 36 47.14  | +63 28 49.95  | ...          | 10.33 ± 0.06 | 8.74 ± 0.04  | 8.05 ± 0.07  |
| 5   | IRAS 00338+6312   | 00 36 47.34  | +63 29 01.61  | ...          | 9.05 ± 0.07  | 7.19 ± 0.05  | 6.72 ± 0.03  |
| 6   | RNO1 IRAC 1       | 00 36 48.44  | +63 28 39.98  | 13.72 ± 0.15 | 11.82 ± 0.14 | 10.93 ± 0.20 | 9.65 ± 0.04  |
| 7   | RNO1 IRAC 2       | 00 36 47.90  | +63 28 36.30  | 12.00 ± 0.08 | 10.86 ± 0.10 | 10.86 ± 0.16 | 9.82 ± 0.14  |
| 8   | RNO1 IRAC 3       | 00 36 47.85  | +63 28 41.23  | 13.07 ± 0.10 | 11.78 ± 0.08 | 10.74 ± 0.10 | 9.74 ± 0.05  |

Note. — Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. The coordinates were measured in the 3.6 μm image. Only the positions of the IRAS source and RNO 1G were measured in the 4.5 μm exposure.

a Embedded YSO from Weintraub & Kastner (1993).

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5 The object we call RNO 1G appears to be identical to the embedded young stellar object (YSO) from Weintraub & Kastner (1993).

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Fig. 4.—IRAC color–color plots for the objects listed in Table 2. The dashed boxes indicate the regions corresponding to Class II objects from Hartmann et al. (2005). The dash-dotted region in the right panel defines the position of Class 0/I sources in Hartmann et al. (2005). In the left panel, the Class 0/I objects from Hartmann et al. have the same [5.8]–[8.0] colors as the Class II objects but redder [3.6]–[4.5] colors. Thus, they lie “above” the dashed box. The reddening vectors correspond to $A_V = 30$ mag and are based on a Vega-like spectrum and the reddening law given by Mathis (1990).
spectral slits on the sky probing different regions of the extended emission. The offset between the short- and long-wavelength ranges of the high-resolution data corresponds to factors of \[ \frac{1}{2.0} \] at 20 \( \mu \)m for RNO 1B and RNO 1C, respectively. The short high-resolution spectrum shows higher intensities. This can be explained by the approximately 80% smaller aperture in the Short-High module. Although this aperture is probing significantly smaller regions on the sky, these regions do presumably contribute in total to flux in the wavelength regime mentioned above. The large aperture of the Long-High module, on the other hand, is certainly also probing regions without any significant flux (see also Fig. 1).

### 3.2.1. Ices and Silicates

At 6 \( \mu \)m, both spectra show clear water ice absorption bands. At slightly longer wavelength (\(~6.85 \mu \)m), additional absorption, possibly arising from CH\(_3\)OH ice, is present (van Dishoeck 2004). The 10 \( \mu \)m silicate band is also seen in absorption in both spectra (stronger close to RNO 1C), although the shape of the feature differs from the absorption feature caused by typical silicate grains in the interstellar medium (ISM). To analyze the differences in more detail, we fitted a continuum to the 10 \( \mu \)m region of the spectra and computed the optical depth (Fig. 6). In both cases the peak...
of the absorption is slightly shifted toward shorter wavelengths, indicating a non–ISM-like dust composition. Additional absorption (RNO 1C) or possibly additional dust emission on top of the absorption feature (RNO 1B) is seen at longer wavelengths. At 15.2 μm, CO₂ ice creates a prominent absorption band, and at 18 μm additional silicate absorption seems to be present. All these features indicate the existence of a dense, dusty and icy environment in which the two FUors are embedded. A further analysis of these features and for a larger sample of FUors will be presented in a forthcoming paper (S. P. Quanz et al. 2007, in preparation).

3.2.2. Pure Rotational H₂ Emission

In addition to the ice and silicate features, H₂ emission lines from purely rotational quadrupole transitions are present in both spectra (Fig. 5). While in the spectrum close to RNO 1B all transitions from S(1) to S(7) can be identified, the spectrum close to RNO 1C shows only the lines from S(1) to S(5). This can be accounted for with the higher continuum flux close to the S(6) and S(7) lines in the latter spectrum and with apparently lower excitation temperatures (see below). The lowest transition, S(0), near 28.22 μm, is not detected in either spectrum. This is a consequence of the strongly rising continuum at longer wavelengths. Here the spectral slit contained flux from both RNO objects and also from the deeply embedded IRAS source, so that the continuum emission and the related flux errors completely dominate a possible weak emission line. A detailed analysis is provided in the Appendix.

Keeping in mind the existence of a molecular outflow that is powered by IRAS 00338+6312 and directly oriented in the direction of RNO 1C and RNO 1B (see, e.g., Xu et al. 2006), the detection of H₂ emission lines in both spectra hints at shock-induced emission related to the outflow. The spectra consequently bear information about the circumstellar material close to RNO 1B/1C and the outflow coming from the IRAS source. Since we observe H₂ lines even in the 10 μm silicate absorption bands, the outflow appears to lie in front of the dusty environment, as otherwise the high extinction (Aᵥ = 9.2 mag and Aᵥ ≈ 12.0 mag for RNO 1B and RNO 1C, respectively; Staude & Neckel 1991) would have prevented a detection. The measurement of the relative strengths of multiple H₂ lines allows an analysis of the physical conditions of the shocked material. For this we assume local thermal equilibrium (LTE) and optically thin line emission, which is supported by the low Einstein coefficients of the involved quadrupole transitions (Table 3). Following Parmar et al. (1991), the column density of an upper energy level Nₐ(J) is then given by

\[ Nₐ(J) = \frac{4\pi}{e^{-\tau} A_{ul} \Delta E_{ul} \text{ cm}^{-2}}, \]

where I(J) denotes the observed line intensity in ergs s⁻¹ cm⁻² sr⁻¹, \( \Delta E_{ul} \) is the energy difference between the two states involved in the transition, \( A_{ul} \) is the Einstein coefficient for the transition, and \( \tau \) is the optical depth at the observed wavelength. In Figure 7 we show Gaussian fits to the observed emission lines in the spectrum close to RNO 1B, and Figure 8 presents corresponding fits to the lines detected close RNO 1C. Before fitting the emission lines, we subtracted the underlying continuum, which was fitted with a second-degree polynomial. The integrated line fluxes and column densities that were finally derived are listed in Table 3. We corrected the line fluxes for extinction effects using the results of Mathis (1990) and assuming Aᵥ = 3.55 mag. This value represents the extinction found by Staude & Neckel (1991) toward the nearby star RNO 1 and should be a better estimate of the line-of-sight extinction than the extinction values mentioned above toward RNO 1B and RNO 1C. In any case, the influence of the extinction on the derived shock temperatures and column densities (see below) is negligible. The 1σ errors in the line flux, the line intensity, and the column density (Table 3) were derived by generating 500 spectra and adding Gaussian noise to each measured flux point based on the initial individual 1σ uncertainty. From these spectra we computed the mean values and related errors of the listed parameters. Especially at the short-wavelength end, this shows that not all lines were detected at the 3σ confidence level. However, since most lines were convincingly measured, we decided to keep the tentative detections in our analyses.

Since we assume LTE, the rotational energy levels will be populated following Boltzmann statistics with a unique temperature for several lines. The involved temperatures \( T_{rot} \) of the shocked material can be derived from a so-called rotational diagram. By using the results from equation (1), plotting the logarithm of \( Nₐ(J)/(g_0 g_J) \) against \( E_J/k \) (i.e., the formal temperature corresponding to the absolute upper energy level of the respective rotational
transition), and fitting a straight line to the data, one finds that the slope of the line is proportional to $-1/T_{\text{rot}}$. Here $g_J$ denotes the spin degeneracy of each energy level (1 for even $J$, 3 for odd $J$) and $g_J = 2J + 1$ is the rotational degeneracy. These numbers assume that the ortho-to-para ratio of the involved hydrogen is close to its LTE value of 3 at $T_{\text{rot}}$. A deviation from this LTE assumption (i.e., ortho-to-para < 3) would result in a downward displacement of the data points with an odd $J$-number (ortho-$\text{H}_2$) relative to the points with even $J$ (para-$\text{H}_2$) and thus create a “zigzag” pattern in the rotational plot (see, e.g., Neufeld et al. 2006; Wilgenbus et al. 2000).

In Figures 9, 10, and 11, we show rotational plots for the measured lines near RNO 1B and RNO 1C. In all the plots, the error bars for the data points denote the 1 $\sigma$ uncertainty in the measured column density.

The rotational diagram for RNO 1B in Figure 9 shows a clear curvature in the data points. This departure from a single straight line is indicative of several temperature components in the shocked material. We thus fitted the data with two superposed temperature regimes (hot and warm) that represent the minimum and maximum of the involved temperatures rather than any distinct intermediate value. The dash-dotted line fits the high-energy regime and represents the hot component, with a temperature of $2991 \pm 596$ K. The dotted line corresponds to a temperature of $1071 \pm 121$ K, designating the warm component. The uncertainties in the temperatures denote the 1 $\sigma$ confidence level of the

TABLE 3

| Transition | Wavelength (µm) | Energy $^a$ $E_j/k$ (K) | $A$-Coefficient$^b$ (s$^{-1}$) | Beam Size$^c$ (arcsec$^2$) | Line Flux$^d$ (W cm$^{-2}$) | Line Intensity$^d$ (ergs cm$^{-2}$ s$^{-1}$ sr$^{-1}$) | Column Density$^{de}$ (cm$^{-2}$) |
|------------|----------------|------------------------|-----------------------------|-----------------------------|-----------------------------|--------------------------------|--------------------------------|
| $^1S(1)$ $J = 3–1$ | 17.0348 | 1015.08 | 4.76(–10) | 53.11 | 7.91(–21) $\pm$ 3.8(–22) | 6.34(–5) $\pm$ 3.0(–6) | 1.44(19) $\pm$ 6.8(17) |
| $^1S(2)$ $J = 4–2$ | 12.2786 | 1681.63 | 2.75(–9) | 53.11 | 1.33(–20) $\pm$ 5.2(–22) | 1.06(–4) $\pm$ 4.1(–6) | 3.00(18) $\pm$ 1.2(17) |
| $^1S(3)$ $J = 5–3$ | 9.6649 | 2503.73 | 9.83(–9) | 39.96 | 6.75(–21) $\pm$ 1.2(–21) | 7.18(–5) $\pm$ 1.3(–5) | 2.03(18) $\pm$ 3.7(17) |
| $^1S(4)$ $J = 6–4$ | 8.0251 | 3474.48 | 2.64(–8) | 39.96 | 2.00(–20) $\pm$ 2.7(–21) | 2.13(–4) $\pm$ 2.9(–5) | 1.33(18) $\pm$ 1.8(17) |
| $^1S(5)$ $J = 7–5$ | 6.9095 | 4585.94 | 5.88(–8) | 39.96 | 9.12(–21) $\pm$ 1.9(–21) | 9.71(–5) $\pm$ 2.1(–5) | 1.87(17) $\pm$ 4.0(16) |
| $^1S(6)$ $J = 8–6$ | 6.1086 | 5829.66 | 1.14(–7) | 39.96 | 7.04(–21) $\pm$ 1.3(–21) | 7.50(–5) $\pm$ 1.4(–5) | 2.54(16) $\pm$ 4.8(15) |
| $^1S(7)$ $J = 9–7$ | 5.5112 | 7196.20 | 2.00(–7) | 39.96 | 1.32(–20) $\pm$ 6.1(–21) | 1.41(–4) $\pm$ 6.5(–5) | 2.46(16) $\pm$ 1.1(16) |

$^1S(1)$ $J = 3–1$ | 17.0348 | 1015.08 | 4.76(–10) | 53.11 | 3.26(–21) $\pm$ 2.7(–22) | 2.61(–5) $\pm$ 2.1(–6) | 5.92(18) $\pm$ 4.8(17) |
| $^1S(2)$ $J = 4–2$ | 12.2786 | 1681.63 | 2.75(–9) | 53.11 | 5.17(–21) $\pm$ 7.7(–22) | 4.14(–5) $\pm$ 6.2(–6) | 1.17(18) $\pm$ 1.7(17) |
| $^1S(3)$ $J = 5–3$ | 9.6649 | 2503.73 | 9.83(–9) | 39.96 | 7.52(–21) $\pm$ 2.0(–21) | 8.00(–5) $\pm$ 2.1(–5) | 4.98(17) $\pm$ 1.3(17) |
| $^1S(4)$ $J = 6–4$ | 8.0251 | 3474.48 | 2.64(–8) | 39.96 | 1.34(–20) $\pm$ 4.1(–21) | 1.43(–4) $\pm$ 4.4(–5) | 2.74(17) $\pm$ 8.5(16) |
| $^1S(5)$ $J = 7–5$ | 6.9095 | 4585.94 | 5.88(–8) | 39.96 | 1.10(–20) $\pm$ 3.3(–21) | 1.17(–4) $\pm$ 3.5(–5) | 8.69(16) $\pm$ 2.6(16) |

Notes.—The numbers in parentheses denote powers of 10. The 12.28 µm emission line close to RNO 1B was measured in the low- and high-resolution parts of the spectograph. See text for discussion about the apparent flux difference between the two measurements.

$^a$ Energy level of the upper state, following Jennings et al. (1987).
$^b$ Wolniewicz et al. 1998.
$^c$ Corresponds to the instrument aperture size in case of the Short-High module (53.1 arcsec$^2$; see the Spitzer Observer’s Manual). For all other transitions (i.e., Short-Low module), the number denotes the extracted beam size during the data reduction process (39.96 arcsec$^2$).
$^d$ Corrected for extinction using $A_V = 3.55$ mag.
$^e$ Upper energy state.
fits. As the derived temperature is extremely sensitive to the slope of the fitted straight line, the corresponding errors are rather large.

In addition to the temperatures, one can also derive the total H$_2$ column density of the observed shock within the given aperture. From the $y$-intersects of the fits, we estimate the hot component to have $N_{\text{hot}}(\text{H}_2) = 1.2 \times 10^{17}$ cm$^{-2}$, and for the warm component we find $N_{\text{warm}}(\text{H}_2) = 5.6 \times 10^{18}$ cm$^{-2}$.

For the column densities derived from the spectrum close to RNO 1C, we plotted the two rotational diagrams shown in Figures 10 and 11. First, we fitted the data with a single temperature component of 1754 K. However, the shocked material is apparently not in LTE, as the data points with odd and even $J$-numbers are difficult to fit simultaneously with a straight line or a curve. As mentioned above, this displacement is indicative of a departure from the LTE ortho-to-para ratio of 3. Figure 11 shows the same data, assuming an ortho-to-para ratio of 1. Now a two-component fit, similar to that in Figure 9, is possible. For the hot component we derive a temperature of 2339 K, while the warm component is significantly colder, with 466 K. The total H$_2$ column densities amount to $N_{\text{hot}}(\text{H}_2) = 5.5 \times 10^{17}$ cm$^{-2}$ and $N_{\text{warm}}(\text{H}_2) = 9.7 \times 10^{19}$ cm$^{-2}$, respectively. Table 4 summarizes the temperatures and total column densities of the different components for both spectra.

4. DISCUSSION

The IRAC images reveal for the first time the embedded MIR point source associated with IRAS 00338+6312. However, Weintraub & Kastner (1993) already concluded from polarimetric observations that an additional source should be present close to the position of the IRAS point source. Furthermore, many authors analyzing the bipolar outflow related to this region have concluded that a deeply embedded object was most likely the driving source (Weintraub & Kastner 1993; Yang et al. 1995; Xu et al. 2006) instead of one of the RNO objects (McMuldrough et al. 1995). Previous ground-based MIR observations (Polomski et al. 2005) may not have been sensitive enough to detect IRAS 00338+6312.

| Component | $T$ (K) | log MHz$^a$ |
|-----------|---------|-------------|
| RNO 1B    |         |             |
| Hot$^b$   | 2991 ± 596 | 17.09 ± 0.36 |
| Warm$^b$  | 1071 ± 121 | 18.75 ± 0.09 |
| RNO 1C    |         |             |
| Hot$^c$   | 2339 ± 468 | 17.74 ± 0.31 |
| Warm$^c$  | 466 ± 264  | 19.99 ± 1.17 |
| Single$^c$| 1754 ± 321 | 17.98 ± 0.31 |

NOTE.—For the data derived close to RNO 1C, the results from the two-component fit and the single-component fit with different ortho-to-para ratios are given.

$^a$ Column density in cm$^{-2}$.

$^b$ Ortho-to-para ratio of 3.

$^c$ Ortho-to-para ratio of 1.
The observed properties of IRAS 00338+6312 convincingly classify the object as a young protostar and support the idea that it is indeed driving the molecular outflow. From their CO measurements, Xu et al. (2006) derive a total mass for this bipolar outflow of 1.4 $M_\odot$, indicating that IRAS 00338+6312 is an intermediate-mass protostar. The detection of the IRAS source also solves the problem that, up to now, the spectral energy distributions of RNO 1B and RNO 1C were unusually steep, with IRAC 3 being, on average, 25 $\mu m$ for FUors (Weintraub & Kastner 1993). The images presented here have sufficient sensitivity and spatial resolution to show that the newly revealed source associated with IRAS 00338+6312 is most probably responsible for this flux excess.

In addition to the IRAS object, Weintraub & Kastner (1993) suspected another embedded source, which we identify with RNO 1G. Furthermore, the detection of RNO 1F (Weintraub et al. 1996), which was initially assumed to be a density enhancement rather than an independent, self-luminous source (Weintraub & Kastner 1993), is confirmed with our IRAC images. Only RNO 1D, which was thought to be located between RNO 1B and RNO 1C (Staude & Neckel 1991), does not show up in our images. This source was however also not detected by Weintraub & Kastner (1993) and only tentatively seen in the data of Weintraub et al. (1996).

It is not clear whether all the detected objects are physically confined to the RNO 1B/1C region. In particular, the membership of the newly discovered objects RNO1 IRAC 1, RNO1 IRAC 2, and RNO1 IRAC 3 needs to be confirmed. However, the IRAC observations suggest that RNO 1B and RNO 1C belong to a small cluster of (partly very) young objects. To our knowledge, although some FUors are known or suspected to be in binary or multiple systems (e.g., Reipurth & Aspin 2004), the existence of FUors in a cluster-like environment is so far, a unique finding. Only the FUor candidate V1184 Tau (CB 34) also belongs to a small cluster (Khanzadyan et al. 2002), but its classification as FUor is far less certain than for the RNO objects (Yun et al. 1997). In any case, the still deeply embedded protostars in the close vicinity of RNO 1B/1C place strong constraints on the age of the objects if one assumes coeval evolution.

The magnitudes we derive for the two FUor objects at 3.6 $\mu m$ can be compared with previous ground-based measurements at 3.8 $\mu m$ by Kenyon et al. (1993) and Polomski et al. (2005). However, one certainly has to keep in mind not only that the IRAC filter is different in terms of central wavelength but also that the spectral width differs from that of the ground-based instruments. While Kenyon et al. (1993) found $L_{3.6 \mu m} = 6.36$ mag and $L_{3.8 \mu m} = 6.5$ mag for RNO 1B and RNO 1C, respectively, Polomski et al. (2005) observed RNO 1C to be slightly brighter than RNO 1B ($L_{3.8 \mu m} = 6.27$ mag vs. $L_{3.8 \mu m} = 6.42$ mag). Also, in our measurements RNO 1C seems to be the brighter component. However, both objects appear to be fainter in our observations compared with those of Polomski et al. (2005). Apart from the differences in the filter properties, intrinsic variations in the luminosity of the FUors or changing local extinction effects can account for the apparent variability in these objects.

The detection of H$_2$ rotational line emission can in general be attributed to collisional excitation from C- or J-type shocks (e.g., Draine & McKee 1993; Moro-Martín et al. 2001). C-type shocks are magnetic and less violent toward molecules as compared with the mostly hydrodynamic J-type shocks, which can dissociate H$_2$ molecules even at lower shock velocities. From our rotational diagrams, we derived shock temperatures that are similar to those found in the outflow from Cepheus A by Froebrich et al. (2002). Those authors could fit a two-component C-shock model to their data and derived shock velocities between 25 and 30 km s$^{-1}$ for a cold and a hot component, respectively. By comparing our results directly with theoretical shock models, we find that the C-shock model 1 from Timmermann (1998) can explain both the hot and warm components in the spectrum close to RNO 1B. Considering our derived temperatures as an upper and a lower limit for the shocked material, shock velocities between 15 and 30 km s$^{-1}$ are required. However, model 1 of Timmermann (1998) predicts an ortho-to-para ratio of $\approx 2$ at the low-velocity/low-temperature limit, which is not directly evident from our observations. More recent models by Wilgenbus et al. (2000) predict lower shock temperatures in C-type shocks for the same shock velocities, in comparison with Timmermann (1998). Following their models, our hot component in Figure 9 requires velocities exceeding 40 km s$^{-1}$. Slightly slower velocities ($\approx 35$ km s$^{-1}$) are already needed to explain the hot component in the shock close to RNO 1C (Fig. 11). The warm component in this diagram represents shock velocities between 15 and 20 km s$^{-1}$. Although it is clear that some uncertainties between the observations and theory still remain, C-type shocks seem to provide a solid explanation for the observed shock temperatures.

The measurement of an ortho-to-para ratio smaller than 3 in Figure 11 implies that despite the high temperatures, the gas has not yet reached equilibrium between the ortho and para states. Thus, the observed ratio is the legacy of the temperature history of the gas (see, e.g., Neufeld et al. 1998, 2006), and transient heating by a recently passing shock wave has caused higher temperatures. As the corresponding region on the sky lies closer to the IRAS source than the region probed in Figure 9, the observations suggest that we are seeing the signatures of at least two shock waves: The first shock wave is probed close to RNO 1B (Fig. 9), where we observe several temperature components that have apparently reached their equilibrium state. A more recent shock wave is seen close to RNO 1C (Fig. 11), where the ratio of the line column densities also hints at high shock velocities and temperatures but the gas is not yet in thermal equilibrium.

5. CONCLUSIONS AND FUTURE PROSPECTS

Our conclusions can be summarized as follows:

1. We detected and resolve for the first time the MIR point source associated with IRAS 00338+6312, which appears to be an embedded intermediate-mass protostar driving the known molecular outflow in the RNO 1B/1C region.

2. The detection of additional (partly previously unknown) point sources suggests that the FU Orionis objects RNO 1B/1C belong to a young, small stellar cluster. To our knowledge, these are the only well-studied and confirmed FUors that apparently belong to a cluster-like environment.

3. All but two objects were detected in all four IRAC bands, and their colors are consistent with those of Class 0/I–II objects. The two objects that were not detected at 3.6 $\mu m$ (including IRAS 00338+6312) are still very deeply embedded protostars.

4. Having apparently extremely young objects in the direct vicinity of the FUors confirms the suspected young age for this type of objects, although their MIR colors are consistent with Class II objects.

5. The two MIR spectra of the region bear clear signs of a dense, icy and dusty circumstellar environment, as solid-state features are seen in absorption.

6. The spectra show also H$_2$ emission lines from purely rotational transitions. We presume that these lines arise from shocked material within the molecular outflow. The derived shock...
temperatures and velocities are in agreement with C-type shock models.

7. The observations of the H$_2$ lines suggest that the outflow lies in front of RNO 1B/1C, as otherwise the high optical depth toward these objects would have prevented the detection.

8. While in one spectrum the gas probed by the H$_2$ line emission seems to be in LTE, the other spectrum shows a deviation from the expected LTE ortho-to-para H$_2$ ratio. This indicates the presence of at least two shock waves, the most recent one being responsible for the non-LTE line ratios.

The results presented here advantageously combine space-based MIR imaging and spectroscopy. While the images give insight into the photometric properties of several young embedded objects and also FU Orionis type stars, the spectra provide information on the dusty and icy circumstellar environment of the young cluster, as well as on shocked gas within a molecular outflow. In this context the existence of FUors in a cluster-like environment needs to be pointed out. It is still a matter of debate whether all young low-mass stars undergo a FUor phase or whether these objects form a special subgroup of YSOs (e.g., Hartmann & Kenyon 1996). Our results suggest that the FUor phenomenon occurs also in young (small) stellar clusters, thus making it perhaps more common than so far expected. In addition, the coexistence of FUors and very young protostars in the same environment strengthens the idea that the FUor phase of YSOs is linked to the early stages of the star formation process.

Possible future investigations of the RNO 1B/1C region should address whether the observed objects do indeed belong to the same region and whether all of them are young stars. Furthermore, a detailed study of the shocked material, including high-resolution narrowband imaging and spectroscopic mapping (e.g., with the Spitzer IRS) will provide deeper insights into its extension, physical conditions, and relation to the molecular outflow. A complete analysis of the ice and dust features in the observed spectra is currently under way and will be presented in a forthcoming paper (S. P. Quanz et al. 2007, in preparation).

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Facilities: Spitzer

APPENDIX

NONDETECTION OF THE 28.22 MICRON EMISSION LINE

In the following, we analyze whether the nondetection of the 28.22 $\mu$m line in either spectrum is in agreement with the models. The two-component models in Figures 9 and 11 can be used to predict the column densities of the $S(0)$ emission line. One expects

$$\log \frac{N_{S(0)}}{g_f g_i} [\text{cm}^{-2}] \approx 18.3, \quad \log \frac{N_{S(0)}}{g_f g_i} [\text{cm}^{-2}] \approx 18.8$$

for the spectra close to RNO 1B and RNO 1C, respectively. With $g_i = 1$ and $g_f = 5$ and applying equation (1), the following line intensities are derived:

$$I(2)_{1B} \approx 1.64 \times 10^{-6} \text{ ergs} \text{s}^{-1} \text{cm}^{-2} \text{sr}^{-1}, \quad I(2)_{1C} \approx 5.20 \times 10^{-6} \text{ ergs} \text{s}^{-1} \text{cm}^{-2} \text{sr}^{-1}.$$  

The $A$-coefficient for the transition is $2.94 \times 10^{-11}$ s$^{-1}$ (Wolniewicz et al. 1998).

Taking into account the aperture size for the long-wavelength, high-resolution module of the spectrograph of 247.53 arcsec$^2$ ($\approx 5.82 \times 10^{-9}$ sr), the predicted integrated line fluxes amount to

$$F_{1B} \approx 9.57 \times 10^{-22} \text{ W cm}^{-2}, \quad F_{1C} \approx 3.02 \times 10^{-21} \text{ W cm}^{-2}.$$  

To estimate the peak of the 28.22 $\mu$m line in janskys, we assume that the spectral resolution in the high-resolution modules is constant and that the FWHM of the $S(0)$ line can be extrapolated from the FWHM of the $S(1)$ line at 17.03 $\mu$m. Since we fitted a Gaussian profile to the emission lines and we want to derive the peak flux of this Gaussian, we also have to take into account the relation between the FWHM we measure for the line and the $\sigma$ of the profile. This relation is $\text{FWHM} = (8 \ln 2)^{1/2} \sigma$. With the expected FWHMs of

$$\Delta \nu_{1B} \approx 2.84 \times 10^{10} \text{ Hz}, \quad \Delta \nu_{1C} \approx 2.12 \times 10^{10} \text{ Hz},$$

we thus find corresponding peak fluxes of

$$F_{1B}^{\text{peak}} \approx 0.034 \text{ Jy}, \quad F_{1C}^{\text{peak}} \approx 0.152 \text{ Jy}.$$  

These values have to be compared with the measured uncertainties in the spectra. The mean 1 $\sigma$ level in the spectral range between 28.0 and 28.4 $\mu$m is, however,

$$\bar{\sigma}_{1B} = 0.055, \quad \bar{\sigma}_{1C} = 0.082,$$

so that even in the more favorable case of RNO 1C, the emission line is not expected to be detected at a confidence level greater than $\approx 1.8 \sigma$.  

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