High Resolution Millimeter Imaging of the R Corona Australis IRS 7 Region

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ABSTRACT

The R CrA IRS 7 region was observed in the $\lambda = 6.9$ mm continuum with a high angular resolution ($\sim 1''$). The map shows three compact objects located within 4'' (700 AU) of IRS 7A. Since the object in the middle of the complex has no known counterpart at centimeter wavelengths, its millimeter emission may mostly come from dust, suggesting that it may be a deeply embedded object. In contrast, IRS 7A is probably not as deeply embedded as the others since it was detected in near-IR and X-ray bands. It is not clear what causes the difference between IRS 7A and the others. If they belong to a coeval triple stellar system, either IRS 7A may have evolved faster and disrupted the parent cloud faster than the others, or IRS 7A may be in the process of being ejected. Alternatively, IRS 7A could be a relatively older object in the process of being captured by the other two objects that constitute a younger binary system. Yet another possibility is that IRS 7A may not be a young stellar object but may be a part of the outflow driven by the central object of the complex. The identity of the hard X-ray flare source previously found in this field needs to be clarified by further observations.

Subject headings: ISM: individual (R CrA IRS 7) — ISM: clouds — ISM: structure — radio continuum: ISM — stars: formation

1. INTRODUCTION

The Corona Australis dark cloud is one of the nearest star forming regions, at the distance of 170 pc from the Sun (Knude & Hog 1998). The most active site of star formation in this cloud is the R CrA region, where several embedded IR objects and Herbig-Haro objects were found (Vrba, Strom, & Strom 1976; Taylor & Storey 1984; Hartigan & Graham 1987). Among the 2.2 $\mu$m sources found by Taylor & Storey (1984), IRS 7 is the most deeply embedded and probably the youngest. The 2.2 $\mu$m image of IRS 7 by Chen & Graham (1993) revealed that the source is extended and shows multiple concentration with a loop-like structure. Molecular line observations show that IRS 7 is associated with a dense molecular core (Loren 1979; Anderson et al. 1997a; Anderson, Harju, & Haikala 1997b). The strong continuum emission at 1.3 mm suggests that the IRS 7 region hosts a class 0 source (Henning et al. 1994; Saraceno et al. 1996). The angular resolution of the single-dish millimeter observations, however, is not high enough to understand the precise relation between the dense core and IRS 7. High resolution images in centimeter continuum emission revealed several compact sources in the R CrA IRS 7 region (Brown & Zuckerman 1975; Brown 1987; Feigelson, Carkner, & Wilking 1998). The brightest among the centimeter sources is the IRS 7A/B pair. Deep IR imaging by Wilking et al. (1997) shows that IRS 7A is associated with IRS 7 while IRS 7B is a separate object of unknown nature. Wilking et al. (1997) suggested that the true position of the IRS 7 young stellar object is the 10 $\mu$m source position (3''1 away from the near-IR position).

Recent discovery of the X-ray emission from this region, especially the hard X-ray flare event, made the R CrA IRS 7 region even more interesting (Koyama et al. 1996). Though Koyama et al. identified IRS 7 as the X-ray flare source, the position uncertainty of their observations ($\sim 20''$) is too large to pinpoint its radio counterpart. Feigelson & Montmerle (1999) suggested that IRS 7 may be the only tentative class 0 source with X-ray detection. (See Tsuboi et al. 2001 for more recently found examples.) If such X-ray flares indeed occur in class 0 protostars, the implication for the protostellar evolution could be important.

In this paper, we present our high angular resolution observations of the R CrA IRS 7 region. In § 2, we report the results of the millimeter imaging. In § 3, we discuss the nature of the young stellar objects in this region and the relations among them.

2. OBSERVATIONS AND RESULTS

The R CrA IRS 7 region was observed using the Very Large Array of the National Radio Astronomy Observatory in the standard Q-band continuum mode ($\lambda = 6.9$ mm). Twenty-three antennas were used in the CnB-array configuration on 2002 September 23. The phase tracking center was $\alpha_{2000} = 19^h01^m55.33^s$ and $\delta_{2000} = -36^\circ57'21''66"$. The phase was determined by observing the nearby quasar 1924+292. The flux calibration was done by observing the quasar 1331+305 (3C 286). The measured flux density of the phase calibrator was 8.1$\pm$0.1 Jy.

The maximum $uv$ distance of the full array was 643 $\lambda$. However, the phase decorrelation of long baselines was severe owing to the low elevation of the source. The maximum elevation of R CrA IRS 7 was 19.1 degrees. As a result, data from longer baselines were less usable than those from shorter baselines. Two methods were tried for the phase calibration and imaging, and four maps with various weightings of the same data are presented to show how robust the detected source structure is. First, the phase calibration was done using the full array, and the imaging was done using Gaussian tapers in the $uv$ plane. The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.
Sources 2, 3, and 4 appear to be closely related to each other. They are aligned nearly in the north-south direction with a slight bend. To interpret the 6.9 mm map, it is important to understand the emission mechanism. Figure 3 shows the spectral energy distribution of the central complex and Table 1 lists spectral indices. Judging from the bright continuum emission at longer wavelengths, the 6.9 mm flux of source 4 (IRS 7A) may be mostly from either free-free or non-thermal emission, not from dust continuum emission. Since source 3 has no known counterpart at centimeter wavelengths and is located closest to the 10 μm source, its 6.9 mm emission may be from dust. Though Wilking et al. (1997) suggested that the 10 μm source is the young stellar object and that the 2 μm source is a scattering surface, the 6.9 mm map suggests that they could be separate young stellar objects. The nature of the 6.9 mm emission from source 2 is not clear because there is a ~1.5 difference in position between source 2 and its centimeter continuum counterpart (B9). Based on the emission mechanism discussed above, two possibilities are listed below for the nature of the three sources and the relation between them.

The first possibility is that each of them could be a young stellar object by itself. The evolutionary stage of source 3 is uncertain, but it is probably a class 0 source, considering the strong submillimeter emission and the lack of near-IR or X-ray detection. It is probably the most deeply embedded. Among the three sources, only source 4 was detected in the recent high-resolution X-ray observations (Garmire & Garmire 2002). Because source 4 is associated with the near-IR and X-ray sources, it may be less deeply embedded than the other two sources and is probably either a class I source or a T Tauri star. If the central complex is indeed a triple stellar system, why do they show very different amounts of extinction? There are several possible explanations: (1) They were born together in the same cloud core, but source 4 has evolved faster and disrupted the parent core faster than the others. (2) They were born together, but source 4 is in the process of being ejected from the system owing to the gravitational interaction among the three sources. (3) Source 4 was formed separately in an earlier star forming event, and it is in the process of being captured by sources 2/3. An important clue to this problem is the velocity structure of the system, but the angular resolution of currently available molecular line maps (for example, Anderson et al. 1997a, 1997b) is not high enough to provide the answer. In any case, the dynamical interaction in the triple system is an interesting subject to be investigated in the future. Recently, numerical simulations suggested that gravitational interaction between protostars may play an important role in the formation and evolution of multiple stellar systems and in the origin of brown dwarfs (Sterzik & Durisen 1998; Watkins et al. 1998; Reipurth & Clarke 2001; Bate, Bonnell, & Bromm 2003).

The second possibility is that the central complex could be a system of jet/outflow knots (sources 2/4) and the driving source (source 3) located between them. In this case, the near-IR and X-ray emission may indicate that source 4 may be a shocked region near the front surface of the cloud. Source 2 may be the counterpart of source 4. X-ray emission associated with outflows from other low-mass protostars was detected recently.
Table 1

<table>
<thead>
<tr>
<th>SOURCE</th>
<th>PEAK POSITION ( \alpha_{2000} )</th>
<th>PEAK POSITION ( \delta_{2000} )</th>
<th>PEAK FLUX ( \text{mJy beam}^{-1} )</th>
<th>TOTAL FLUX ( \text{mJy} )</th>
<th>( \alpha_{cm} )</th>
<th>ASSOCIATED OBJECTS (^c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>19 01 56.11</td>
<td>−36 57 11.9</td>
<td>1.3±0.3</td>
<td>3.5±1.1</td>
<td>&gt;2.6</td>
<td>B 9, FCW 6</td>
</tr>
<tr>
<td>2</td>
<td>19 01 55.35</td>
<td>−36 57 17.6</td>
<td>1.6±0.2</td>
<td>2.4±0.7</td>
<td>0.3±0.2</td>
<td>IRS 7 (10 ( \mu \text{m} )), vdA 3(?)</td>
</tr>
<tr>
<td>3</td>
<td>19 01 55.28</td>
<td>−36 57 19.4</td>
<td>2.1±0.2</td>
<td>2.1±0.6</td>
<td>&gt;2.3</td>
<td>IRS 7 (near-IR), IRS 7A (B 10W), FCW 7</td>
</tr>
<tr>
<td>4</td>
<td>19 01 55.34</td>
<td>−36 57 22.3</td>
<td>1.0±0.2</td>
<td>unresolved</td>
<td>−0.8±0.1</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>19 01 55.09</td>
<td>−36 57 27.3</td>
<td>1.2±0.2</td>
<td>2.0±0.5</td>
<td>&gt;2.3</td>
<td></td>
</tr>
</tbody>
</table>

Note:—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. Positions and flux densities are from the full-array map with 120 k\( \lambda \) Gaussian taper (Fig. 1).

\(^a\) Flux densities at \( \lambda = 6.9 \text{ mm} \), corrected for the primary beam response.

\(^b\) Spectral index between 6.9 mm and 3.5 cm. For sources 1, 3, and 5, lower limits were calculated assuming that the 3.5-cm flux density is lower than 48 \( \mu \text{Jy} \) which is 3 times the rms noise level of the observations by Feigelson et al. (1998).

emission with a high angular resolution is needed to clarify the identity of the flare source. Therefore, whether or not class 0 objects exhibit X-ray flare events remains an open question.

The density of young stellar objects in this region is very high, and their evolutionary stage spans from the youngest (class 0 objects) to pre-main sequence stars (R and T CrA). To better understand the structure and the star formation history of this region, more sensitive observations with high angular resolution are needed.

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