Massive Star Birth: A Crossroads of Astrophysics
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High mass star formation in the giant molecular cloud NGC 6334: an infrared view

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Abstract. Sub-arcsec images in the JHK_s, H_2 and Br_γ of three areas (I(N), F and NGC 6334 IV (MM3)) of the giant molecular cloud NGC 6334 are presented. The preliminary results indicate the presence of a deeply embedded young stellar cluster in the northermost part of the cloud (I(N)). We have identified the exciting source of the cometary UCHII NGC 6334 F. This source has an infrared luminosity $L_{IR} = 3\ 10^3\ L_\odot$ and a very steep infrared spectral index. Finally, a new center of massive star formation associated with the millimeter peak MM3 has been found east of the bipolar HII region NGC 6334 A.

Keywords. ISM: Infrared, Stars: formation, ISM: HII regions, ISM: clouds

1. Introduction

NGC 6334 is a giant molecular cloud extending more than 45′ parallel to the Galactic plane (l = 351°.0 b = 0°.7) (Dickel 1977) located at a distance of 1.74 Kpc (Neckel 1978). The far-IR map of McBreen *et al.* (1979) shows five centers of active star formation (NGC 6334 I-V). Six radio continuum sources (NGC 6334 A-F) ranging in angular size from very compact (∼0″.3) to extended (⩾40″) were detected at 6 cm using the VLA (Rodríguez, Cantó, & Moran 1982). A wide variety of activity generally associated with high mass star formation, such as OH, H_2O, CH_3OH, and NH_3(3,3) maser emission (Moran, & Rodríguez 1980; Gaume, & Mutel 1987; Forster, & Caswell 1989; Menten, & Bartla 1989; Norris *et al.* 1993; Kraemer, & Jackson 1995) have been found in the region.

Millimeter and sub(millimeter) continuum observations were addressed toward the northern (NGC 6334 I), and the central (NGC 6334 IV) part of the molecular cloud complex (Sandell 1999; Sandell 2000). In particular bipolar molecular outflows and shocked H_2 emission were found in NGC 6334 I close to the UCHII region NGC 6334 F (Bachiller, & Cernicharo 1990; Persi *et al.* 1996) and associated with the millimeter peak NGC 6334 I(N) found by Cheung *et al.* (1978) and proposed as a high-mass Class 0 object. ((Megeath & Tieftrunk 1999; McCutcheon *et al.* 2000).

Infrared studies of NGC 6334 have been carried out by different authors. Persi, & Ferrari-Toniolo(1982) and Harvey, & Gatley(1983) identified a few young stellar objects from the different centers of activity, while a near-IR survey of the whole region at the limit of K = 14 mag was obtained by Straw, Hyland, & McGregor (1989). Near-IR images

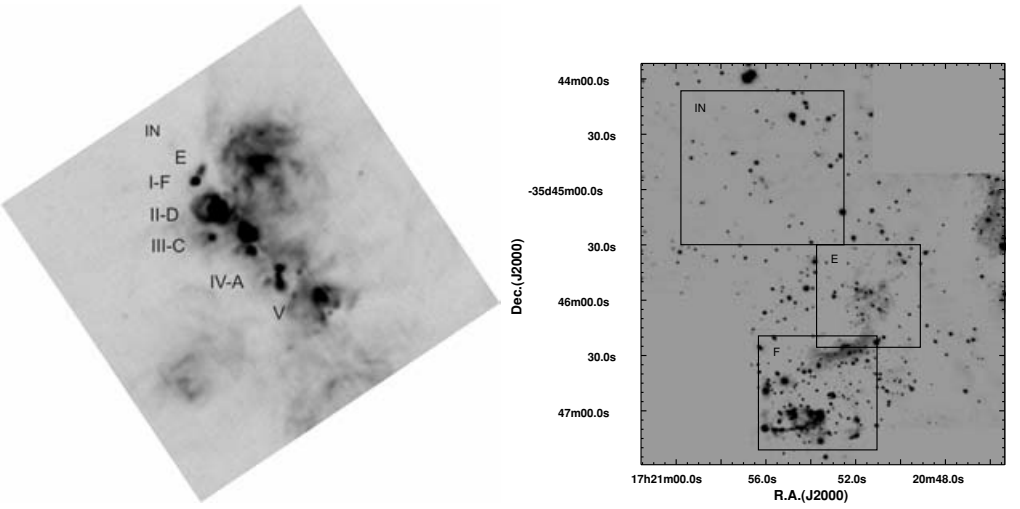

Figure 1. *Left panel:* 21 μm MSX image of NGC 6334. North is at top, east to the left. *Right panel:* K_s image of NGC 6334 I. The boxes (IN, E, and F) indicate the three distinct centers of star formation in the northern part of the cloud.

at resolution of $\sim$1″ and sensitivity of K $\simeq$ 16 mag were obtained by Tapia, Persi, & Roth (1996) who identified an embedded young stellar cluster in NGC 6334 I, while no evidence of a developed stellar cluster was found in NGC 6334 IV although a small number of luminous (O-B2) young stellar objects were detected (Persi, Tapia, & Roth 2000). Mid-IR imaging were obtained around the UCHII region NGC 6334 F in the northern part of the cloud and in NGC 6334 IV and NGC 6334 V (Persi *et al.* 1998; Kraemer *et al.* 1999; De Buizer *et al.* 2002). Warm dust and ionized gas are well mixed in the UCHII region, while toward NGC 6334 IV, warm dust is associated with the inner portion of the massive molecular torus that surrounds the region (Kraemer *et al.* 1997). Finally, images in the narrow band filters centered on the PAH feature at 3.3 μm and Brα line obtained by Burton *et al.* (2000) reveal a complex structure of the photodissociation regions (PDRs) in NGC 6334 and bubbles and loops of PAH emission.

The different centers of activities in NGC 6334 are reported over the 21 μm image of the MSX satellite (Figure 1, left panel).

We discuss in this paper the preliminary results of new broad band JHK_s and narrow band (H_2 and Brγ) near-IR images of NGC 6334 I and of an adjacent area of NGC 6334 IV associated with the millimeter source MM3. These images were obtained with the near-IR camera PANIC attached at the Magellan-Clay 6.5m telescope at Las Campanas Observatory (Chile), using a scale of 0.125″/pix and with a sensitivity in $K_s \sim 19.5$ mag (3σ). In addition, new mid-IR images collected with the mid-IR camera TIMM2 at the 3.6m ESO telescope (Chile) with a scale of 0.2″/pix, are also discussed.

2. Results and Discussion

2.1. *NGC 6334 I*

Our K_s image of NGC 6334 I (196 × 218 sq arcsec) is illustrated in Figure 1 (right panel). This represents the deepest and highest resolution near-infrared image available of the region. We have studied the stellar population within three distinct areas (I(N), E, and F). Preliminary results relative to the shell-like HII region NGC 6334 E have

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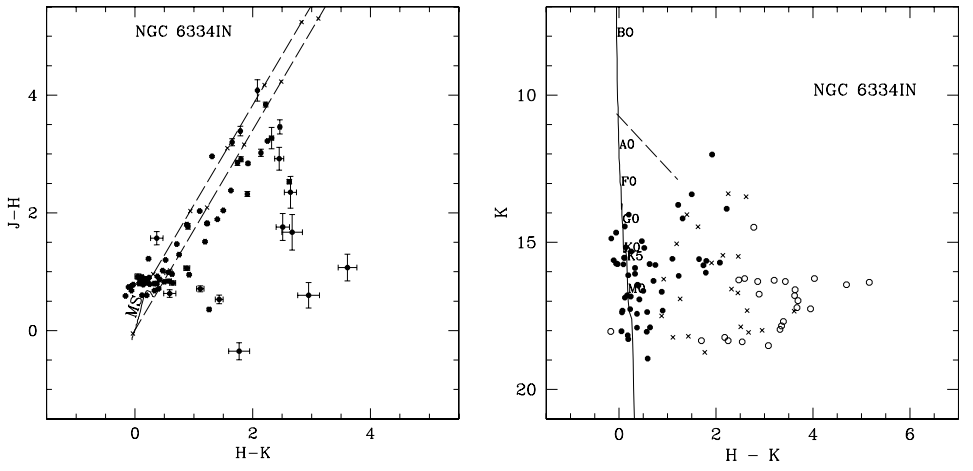

Figure 2. *Left panel:* $J-H$ vs $H-K_s$ diagram of the sources detected in the three colors towards I(N).The continuous line marks the locus of the MS stars taken from Koornneef (1983) *Right panel:* K_s vs $H-K_s$ diagram .The reddening vector corresponding to $A_V = 20$ is indicated with a dashed line, while the continuous line is the locus of MS stars at d = 1.7 Kpc.

been reported by Persi *et al.* (2005), while here we discuss the northermost part of the molecular cloud I(N) and the UCHII F .

2.1.1. *NGC 6334 I(N)*

I(N) is the brightest millimeter and sub(millimeter) source of the cloud complex. Megeath , & Tieftrunk(1999) proposed this region to be a rare example of a molecular core in an early stage of cluster formation. Tapia, Persi, & Roth (1996) report that the number of near-IR sources in this area is very small. The new JHK_s images here discussed show the presence of 110 sources detected in K_s in 94 × 94 sq.arcsec. From their near-IR photometry we have derived the $J-H$ vs. $H-K_s$ and the K_s vs $H-K_s$ diagrams (Figure 2).

More than a dozen sources show clear infrared excesses in the color-color plot, and ∼25 not detected in J have a $H-K_s \geqslant 2.5$. This result suggests that about ∼34% of the sources observed in I(N) are young stellar objects and form an embedded cluster.

From the comparison between the H_2 and the continuum images we have found six H_2 knots in this area. Figure 3 show these knots and the positions of the sources with IR excess. Two very faint and compact radio continuum sources were detected by Carral *et al.* (2002). One of them lies within 0.3" of the position of a Class II methanol maser (see Fig.3, left panel) suggesting that the radio source is associated with a young embedded massive star.

In addition this source may also be associated with the I(N) sub(millimeter) source. Neither of the two radio sources are coincident with near-IR sources. Particularly interesting is the jet-like structure of the two H_2 knots here designed with C and B at the center of the region. (Figure 3, right panel).

A source with near-IR excess at the apex of the knot C is probably the driving source of the H_2 jet.

2.1.2. *NGC 6334 F*

NGC 6334 F is a cometary UCHII region found by Rodríguez, Cantó, & Moran (1982). The 11.2 μm image of Persi *et al.* (1998) shows a cometary shape similar to that observed

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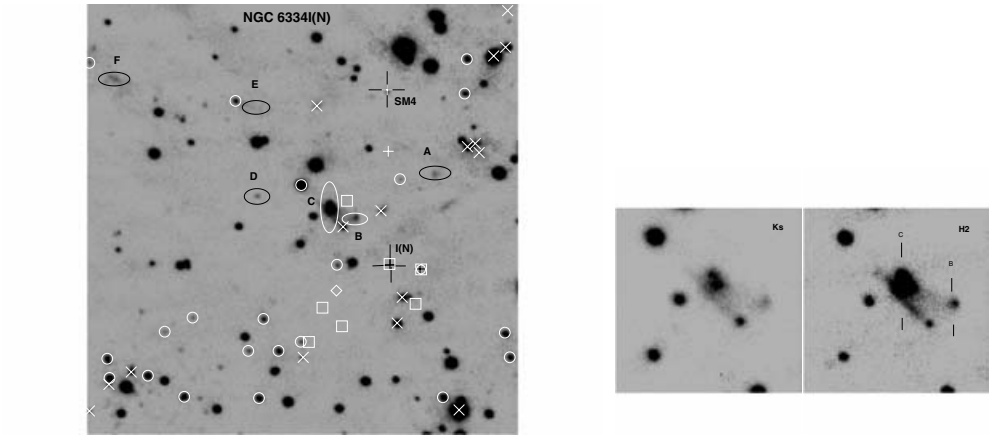

Figure 3. *Left panel:* Narrow band H_2 image of I(N). The ellipses indicate the positions of the observed H_2 knots. The symbols (X) represents sources with IR excess, while the open circles show the sources with $H - K_s \geqslant 2.5$. Open squares are methanol maser sources and the small cross indicate the positions of two very faint radio continuum sources. *Right panel:* K_s and H_2 images of the hydrogen molecular knots B, and C.

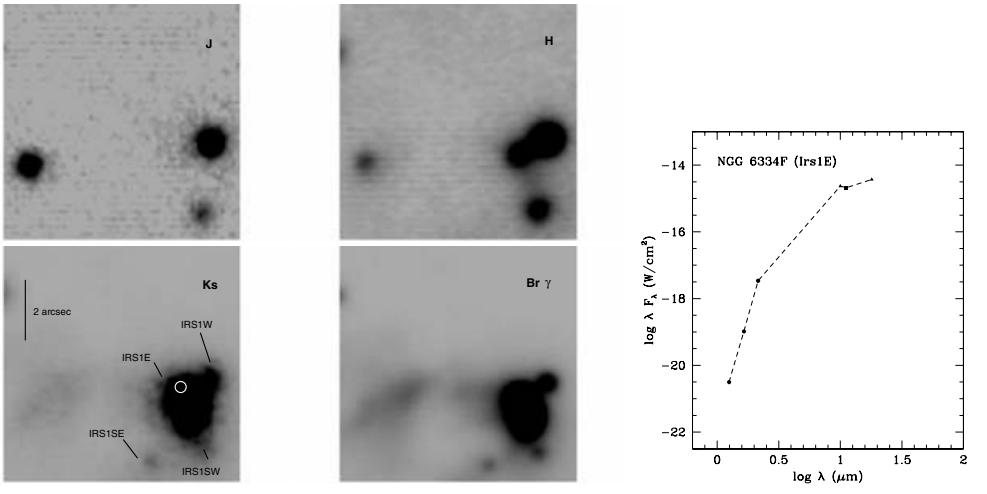

Figure 4. *Left panel: JHK_s* and Brγ images of NGC 6334 F. The open circle in the K_s image shows the position of the Mid-IR source. *Right panel:* Infrared spectral energy distribution of the source IRS1E in NGC 6334 F.

in the radio continuum. Four very faint and red near-IR sources were found by Persi *et al.* (1996) within 3″ of the radio peak. Figure 4 (left panel) shows the new *JHKs* and Brγ images around the UCHII. These sources are resolved in our images. IRS1E is coincident with the mid-IR source observed by Persi *et al.* (1998), Kraemer *et al.* (1999) and De Buizer *et al.* (2002).

Combining the near-IR and the mid-IR photometry, we have obtained the spectral energy distribution (SED) of this source (Figure 4, right panel). Integrating the SED we have determined an infrared luminosity $L_{IR} = 3\ 10^3\ L_\odot$ and an infrared spectral index $\alpha(IR) = 3.8$ computed between 2.2 and 12 μm. These values indicate that IRS1E is a high mass young star deeply embedded in the cloud that is responsible of the excitation

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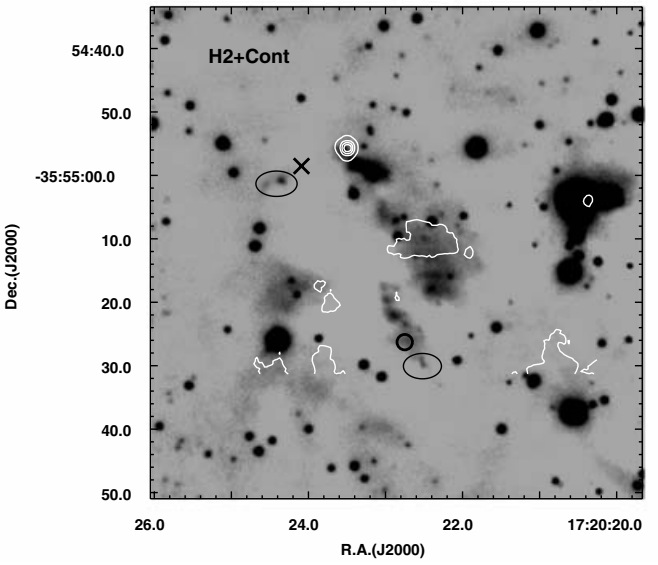

Figure 5. H_2 image of NGC 6334 IV (MM3). The contours represent the 11.9 μm emission, while the ellipses show the positions of the H_2 knots. The MM3 peak and the radio continuum source G351.25+0.65 are represented by a cross and open circle respectively.

of the UCHII region. This source and IRS1SE have also been detected in X-ray by the Chandra satellite.

2.2. *NGC 6334 IV MM3*

The sub(millimeter) maps of Sandell (1999) around the bipolar HII region NGC 6334 IV show the presence of four millimeter sources in this area. Within a few arcsec of one of this sources (MM3), Persi, Tapia, & Roth (2000) found a very red nebulous emission seen only in K-band. The H_2 image reported in Figure 5 indicates two hydrogen emission knots. One in proximity of the MM3 peak and the other very close to the radio continuum source G351.25 + 0.65 detected by Moran, *et al.* (1990).

The 11.9 μm image (contours in Fig. 5) shows a very red object (IRMM3) in the vicinity of MM3. This source, observed also in the K_s-band, is a massive young star responsible for the observed H_2 jet. This result confirms that MM3 is another active center of massive star formation in NGC 6334 IV.

3. Conclusions

From the analysis of our sub-arcsec resolution and very deep infrared images of some regions of the complex giant molecular cloud NGC 6334 we can derive the following conclusions:

1) There is evidence of the presence of a young stellar cluster also in the northermost part of the cloud (I(N)) in which we have detected six H_2 knots. We have identified candidates for the driving sources for two of these jets.

2) The exciting source of the UCHII region NGC 6334 F has been identified. This source named IRS1E here identified with a Chandra X-ray source, has an infrared luminosity of 3 10^3 $L_\odot$ and a very steep spectral index (α(IR) = 3.8).

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3) A new center of massive star formation has been identified in the eastern part of the bipolar HII region NGC 6334 A associated with the millimeter peak MM3. An arc shaped H_2 jet is probably excited by the IR source (IRMM3) detected in K_s and at 11.9 μm. Another H_2 knot has been detected in proximity of the radio continuum source G351.25 + 0.65.

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