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# Multifrequency behaviour of high mass star forming regions: The case of NGC 6334

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**Abstract.** We present a coordinated study of the complex star forming region NGC 6334 including a wide range of observations from radio to X-ray.

**Key words.** ISM: giant molecular cloud –ISM: HII regions– Stars:formation – Infrared: stars – Infrared: general

## 1. Introduction

Multifrequency observations represent a crucial point in understanding the physical processes in Astronomy. Thanks to the recent satellites that operates at different wavelengths (i.e Chandra and Integral for X and gamma-ray, Spitzer and Herschel for infrared astronomy) and the use of large ground-based telescopes, it is now possible to explore the whole electromagnetic spectrum at high sensitivity and spatial resolution.

In the present paper we will present a coordinated study including radio, millimeter, infrared optical and X-ray observations of one of the most interesting high mass star forming region of our Galaxy; the giant molecular cloud complex NGC 6334. Most of the results here discussed, have been reported in a recent review paper by Persi & Tapia (2008).

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## 2. Large scale structure of NGC 6334

NGC 6334 also known as the *Cats Paw Nebula*, is one of the most complex natural star formation laboratories known in the Galaxy. It extends $32' \times 40'$ near the galactic plane ($l = 351^o$, $b = 0.7^o$). The visible nebula associated with the complex was discovered in 1837 from the Cape of Good Hope by William Herschel, who catalogued it as H3678. The visible nebula (see Fig.1 left panel) classified as an optical HII region, is ionized by a small number of lightly reddened O-B0 stars which seem, in projection, to be scattered around the whole complex. From accurate photometry and spectroscopy of these stars obtained by Neckel (1978) and Walborn (1982), a visual extinction $< A_V >= 4.12 \pm 0.20$ and a distance $< d >= 1.61 \pm 0.08$ Kpc was derived for the nebula.

The whole region was mapped in the radio continuum at $\lambda = 6$ cm (5000 MHz) with the Parkes 210 foot antenna by Goss, & Shaver (1970) with a $4'$ beam (Fig.1 right panel). The radio continuum maps align almost perfectly

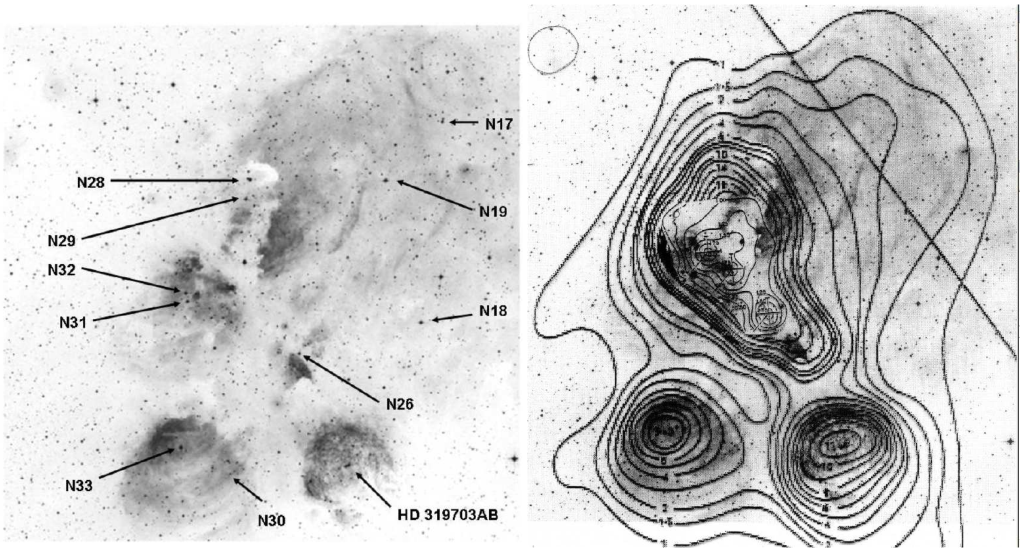


**Fig. 1.** *Left panel:*The red Digital Sky Survey image of the region centred at (J2000) $\alpha = 17^{\mathrm{h}}\ 20^{\mathrm{m}}\ 19.9^{\mathrm{s}}$, $\delta = -35^{o}\ 51'\ 24''$ containing NGC 6334 with the optically visible O-B2 stars marked. *Left panel:* Radio continuum contour plot at 6 cm overposed to the gray-scale image from the red Digital Sky Survey. The field of view is $38' \times 45'$. The diagonal thick straight line goes parallel to the galactic equator with $b = 0.9^{o}$

with the area covered by the H$\alpha$ emission, implying that the ionized gas away from the dense molecular ridge is very lightly reddened.

Subsequent higher spatial resolution radio observations made with VLA by Rodríguez, Cantó, & Moran (1982) show the presence of six compact and ultracompact HII regions (labeled A to F) displaying a wide range of sizes, from very compact (e.g. A and F) and presumably very young, to extended ($> 40''$) and well developed (e.g. E) (see Fig2 left panel).

Maps in the far-infrared of the region were obtained at the beginning with a balloon-borne telescope in five wavebands ($\lambda_{\mathrm{eff}}$ = 21, 42, 69, 71 and 134 $\mu$m) (McBreen et al. (1979), Loughran et al. (1986)). These maps indicate the presence of at least six far-IR sources (designated I, IN to V) approximately equally spaced along the molecular ridge with a large and diffuse emission in the northeastern region (see Fig.2 right panel). The total luminosity of the sources was determined to be $1.7 \times 10^{6} L_{\odot}$ and a total mass of $1.4 \times 10^{5} M_{\odot}$. Finally, Loughran et al. (1986) proposed that a Rayleigh-Jeans instability created by acceleration toward the Galactic Plane may explain the regular separation of the centres of activity in the cloud.

Molecolar gas emission from NGC 6334 was found by Dickel, Dickel, & Wilson (1977) observing the $^{12}$CO, $^{13}$CO lines ($J = 1 - 0$). Higher resolution maps in several transitions of $^{12}$CO, $^{13}$CO, CS and $NH_3$ by Jackson, & Kraemer (1999) show that the molecular gas has a complex filamentary structure along the dense molecular ridge as illustrated in Fig.3. These observations indicate the presence of a giant molecular cloud in NGC 6334.

The first ground-based near-IR obsertvations around the six far-IR peaks and compact HII regions obtained by Persi & Ferrari-Toniolo (1982) have shown the presence of very young stellar objects surrounding these peaks at a different evolutionary stages. In order to study the young stellar population in NGC 6334, Straw, Hyland, & McGregor (1989) using a single detector, mapped a large area of the region in $JHK$ bands. These authors reported that the $K$-band luminosity functions are

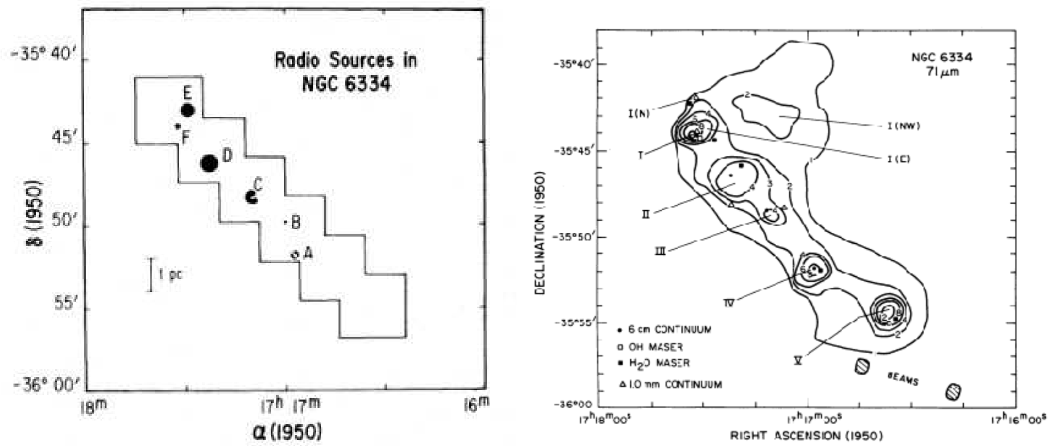


**Fig. 2.** *Left panel:* Compact and ultracompact HII region in NGC 6334. *Right panel*:71 $\mu$m map from Loughran et al. (1986).

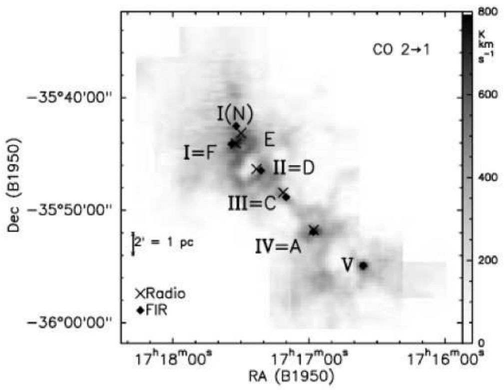


**Fig. 3.** $^{12}$CO($J$ = 2 − 1) integrated intensity from NGC 6334. Positions of the FIR ( filled diamonds) and radio (crosses) continuum sources are labeled with the corresponding roman numeral (FIR) or alphabetical (radio) designations.(from Kraemer, & Jackson (1999))

similar in all NGC 6334 activity centres and not very different to other large star formation complexes.

The most complete coverage in the near-IR of the region was obtained by the 2MASS survey. One important conclusion from a panoramic view of the wide-field 2MASS image (Fig.4) is the very high obscuration not just along the activity ridge, but extending to the NE of far-infrared source IV (where regions I and I(N) are located) and to the S and SW of FIR sources IV and V, just as seen in the $^{12}$CO intensity map (cf. Fig.3).

The entire NGC 6334 region was covered within the GLIMPSE survey conducted by the *Spitzer* telescope. Deep images in the four IRAC bands centred at 3.6, 4.5, 5.8 and 8 $\mu$m are now publicly available (see Fig5). Most of the mid-IR emission is concentrared in the oscured part of the complex region in coincidence with the far-IR peaks. A large-scale study of all active regions based on narrow-band images, at 3.3 $\mu$m and Br$\alpha$ (4.05 $\mu$m ) was performed by Burton et al. (2000) with SPIREX from the South Pole. They found around several of the active star formation centers, a number of bright filaments and shells of photodissociated gas emitting in the 3.3 $\mu$m line, in many cases in coincidence with strong [CII] 158 $\mu$m emission.

Very recently, using the array bolometric instrument SCUBA at the JCMT telescope, Mattwes et al. (2008) obtained sub-millimeter images at 450 and 850 $\mu$m (see Fig.6). The authors found that the cold dust mapped at these wavelengths, is distributed very similarly to the molecular gas. In addition the observations reveal an ensemble of dust clumps (mostly hav-

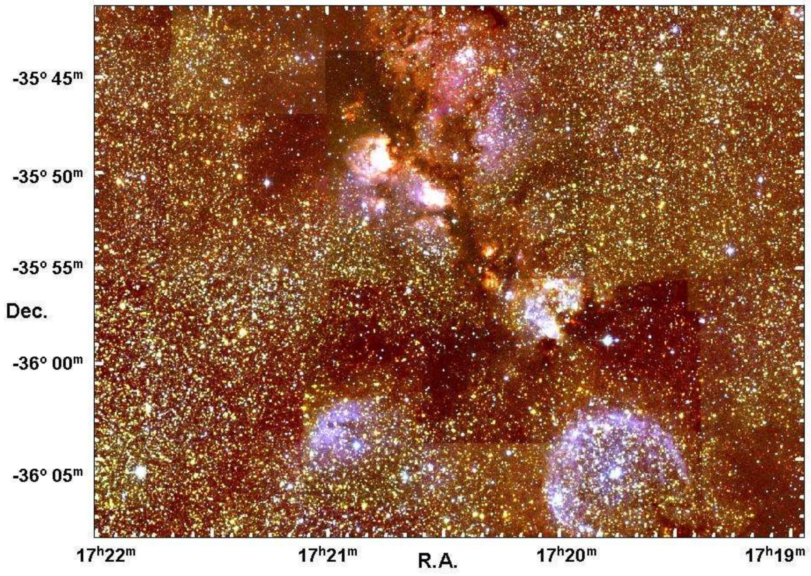


**Fig. 4.** 2MASS *JHK* colour-composite image of NGC 6334.

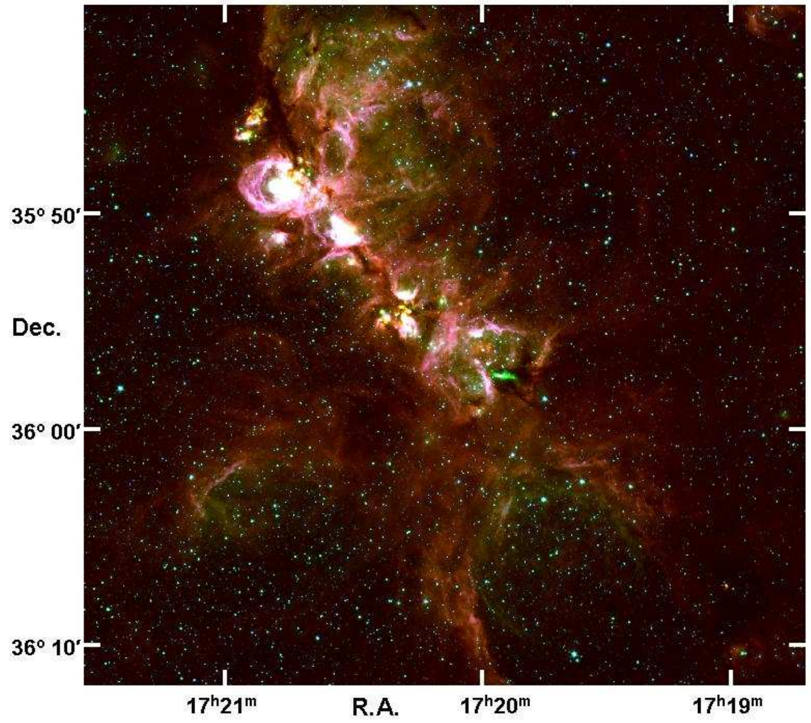


**Fig. 5.** *Spitzer*/IRAC colour-composite image of NGC 6334 from the GLIMPSE survey. IRAC channel 1 (3.6 $\mu$m) image is in blue, channel 2 (4.5 $\mu$m) in green and channel 4 (8 $\mu$m) is in red. The coordinates are J2000.

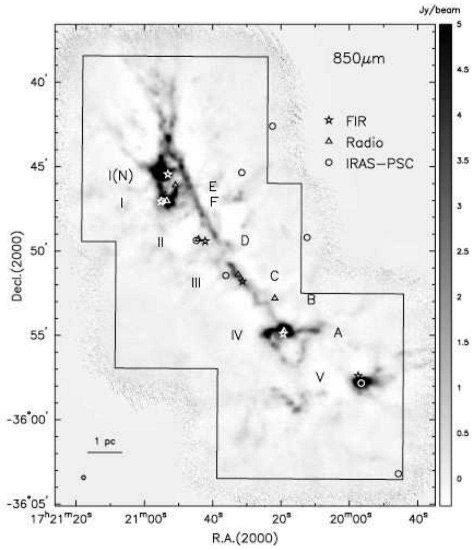


**Fig. 6.** The 850 $\mu$m image of NGC6334

ing masses much greater than 10 $M_\odot$, assuming a temperature of 25 K).

Feigelson et al. (2009) analysing a mosaic of two *Chandra X-ray Observatory* images of the region using sensitive data analysis methods, giving a list of 1607 faint X-ray sources with arcsecond positions and approximate line-of-sight absorption. About 95% of these are expected to be cluster members, most lower mass pre-main sequence stars. The cross-identification between the X-ray and infrared sources is in progress.

Ezoe et al. (2006) after removing the X-ray point sources, found extended X-ray emission over a $5 \times 9$ pc$^2$ region to have a 0.5-8 Kev luminosity of 2 $10^{33}$ erg s$^{-1}$ (Fig.7). The emission becomes brighter in the vicinity of the massive star forming cores, suggesting a stellar-wind shock scheme as the main mechanism to produce the extended X-ray emission. Diffuse X-ray emission were found with *Chandra* in other massive star forming regions (Townsley et al. 2003). Finally a hard X-ray emission source with a non-thermal spectrum (up to 100 keV) was found by Bykov et al. (2006) on images taken with the JEM-X and IBIS/ISGRI telescopes aboard the Gamma-Ray Astrophysics Laboratory *INTEGRAL*. This source result to be a background extra-galactic radio source (Bassani et al. 2005)

In the next sections we will present the main results relative to the northern part of NGC 6334 and the region NGC 6334 IV-A.

## 3. NGC 6334 North

The northern part of the cloud extends across approximately $3' \times 4'$ and contains three distinct active centres: the far-infrared source NGC 6334 I corresponding to the ultra compact HII region labeled F ; the shell-like HII region E (Carral et al. 2002), and the 1 mm peak I(N) found by Cheung et al. (1978).

1.3 mm maps with a resolution of about $2''$ obtained by Hunter et al. (2006) show the presence of two extremely young, massive, prototrapezium-type systems, each of 4 to 7 embedded components with typical separations of around 8000 AU. These multiple dust-emission sources, are located in NGC6334 I and NGC6334 I(N) and are probably in the earliest detectable phase of their (proto)stellar life. In addition high velocity molecular outflows (McCutcheon et al. 2000) , and H2 knots (Persi et al. (1996), Davis, & Eisloffel (1995)) are present.

On the contrary, the shell-like morphology of the HII region E, suggests a state of evolution considerably later than its neighbours, regions I and I(N). Nearly at the centre of the HII region E, Persi et al. (2005a) found a source with an infrared spectral index $\alpha_{\rm IR}$ = 2.1 and an infrared luminosity $L_{\rm IR}$ = 8.4 $L_\odot$. These values suggest the presence of a Class I low mass young stellar object at the centre of NGC 6334 E.

The ultracompact HII region F (Rodríguez, Cantó, & Moran 1982), has a cometary shape in the radio, millimeter, near-infrared, and mid-infrared with its head pointing to the northwest and the tail running to the southeast (see Fig.8). Two near-IR sources, IRS1E and IRS1SE have been identified by Persi & Marenzi (2006) with two Chandra X-ray sources. IRS1E shows a very steep spectral energy distribution with a spectral index $\alpha_{\rm IR}$ = 3.8 and an infrared luminosity $L_{\rm IR} = 3 \times 10^3$ $L_\odot$. This very interesting young

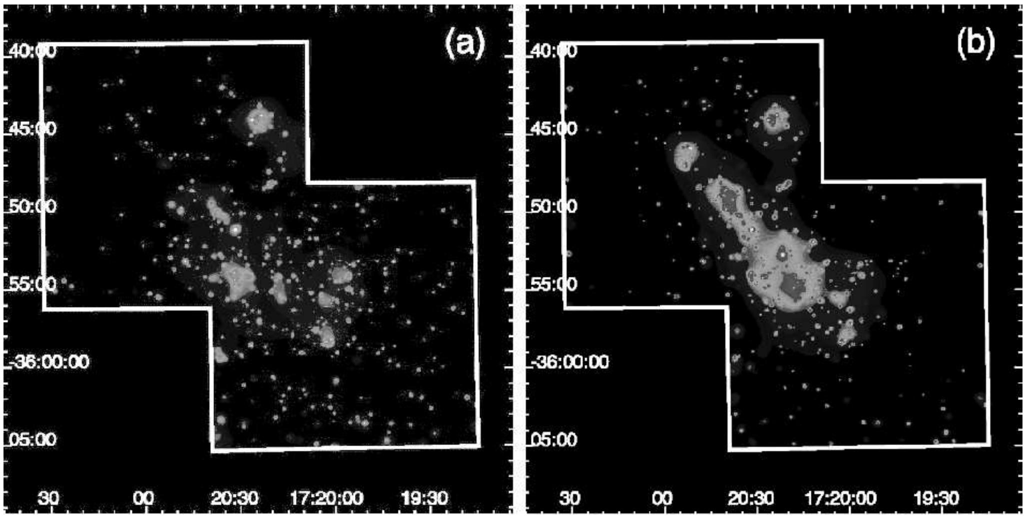

**Fig. 7.** Smoothed X-ray images of NGC 6334 in the 0.5 - 2 keV (a) and in the 2 - 8 keV (b) bands from Ezoe et al. (2006)

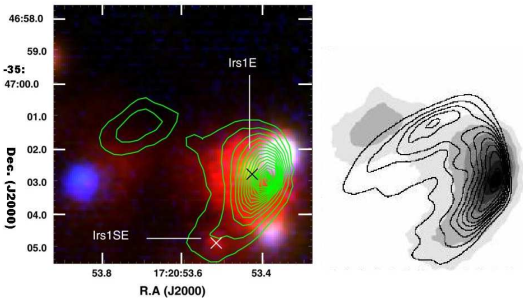

**Fig. 8.** *Left panel*: The 18 $\mu$m contour map from De Buizer et al. (2002) superimposed on the colour composite $JHK_s$-band image of NGC 6334 F. The crosses mark the position of the two *Chandra* X-ray sources in the field as reported by Persi & Marenzi (2006). *Right panel*: The 3.5 cm radio-continuum map of Carral et al. (2002) (contours) with the 18 $\mu$m grey-scale image. The scale in both panels is the same

stellar object is responsible for the inization of the HII region F.

Using sub-arcsec resolutions and high sensitivity $JHKs$ images (Fig.9), Persi et al. (2005b), obtained a census of the young stellar population in NGC 6334 North. 405 sources were detected in $K_s$ and 60% of them in the three colours. From the analysis of the near-IR color-color plot, the authors concluded that about 30% of the sources have $K_s$-band excesses or $H - K_s \geq 2.5$ and, thus, are considered young stellar objects members of the complex. A simple statistical analysis of the results show that most of the young stellar cluster members have $K_s \leq 16$, though a significant number of the sources with near-infrared excess have $K_s \geq 18$. At the distance of the region, this result implies the presence of a population of low-mass young stellar objects in NGC 6334 North cohabiting with high and intermediate-mass young stars in different evolutionary stages.

## 4. NGC 6334 IV (A)

In the radio continuum, NGC 6334 IV (radio source A) has a small ($\sim 20''$) shell-like structure, with two large radio bipolar plumes that extend some $2'$ ( Rodríguez et al. 1988) to the north and south of NGC 6334 A. The same bipolar structure is observed from the near-IR (Persi et al. 2000) (see Fig.10) to the far-infrared frequencies ( Kraemer et al. 1999). Two luminous (O-B2) young stellar objects (IRS19 and IRS20 ) are embedded in the densest part of the molecular cloud that is at the centre of the giant bipolar structure seen in

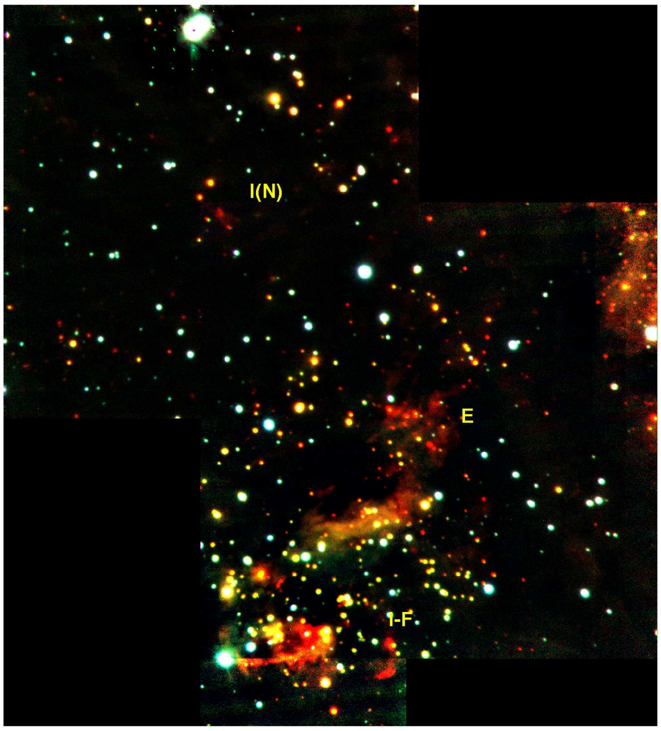


**Fig. 9.** 196″ × 218″ RGB-coded image of NGC 6334 North made from $J$ (blue), $H$ (green), and $K_s$ (red) mosaics. North is to the top, east to the left (from Persi et al. (2005b).

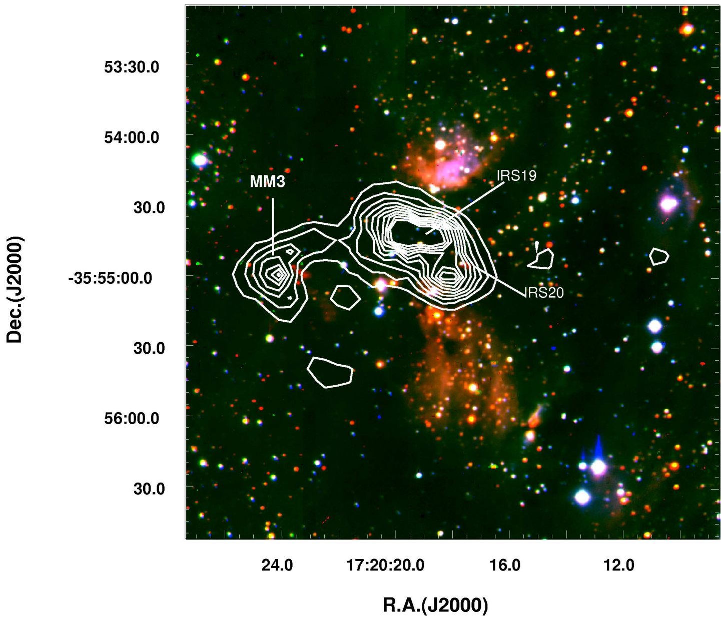


**Fig. 10.** Composite image of NGC 6334 IV made from $J$ (blue), $H$ (green) and $K_s$ (red) individual images from Persi et al. (2000). The contours are the 1.1 mm emission of Sandell (2000).

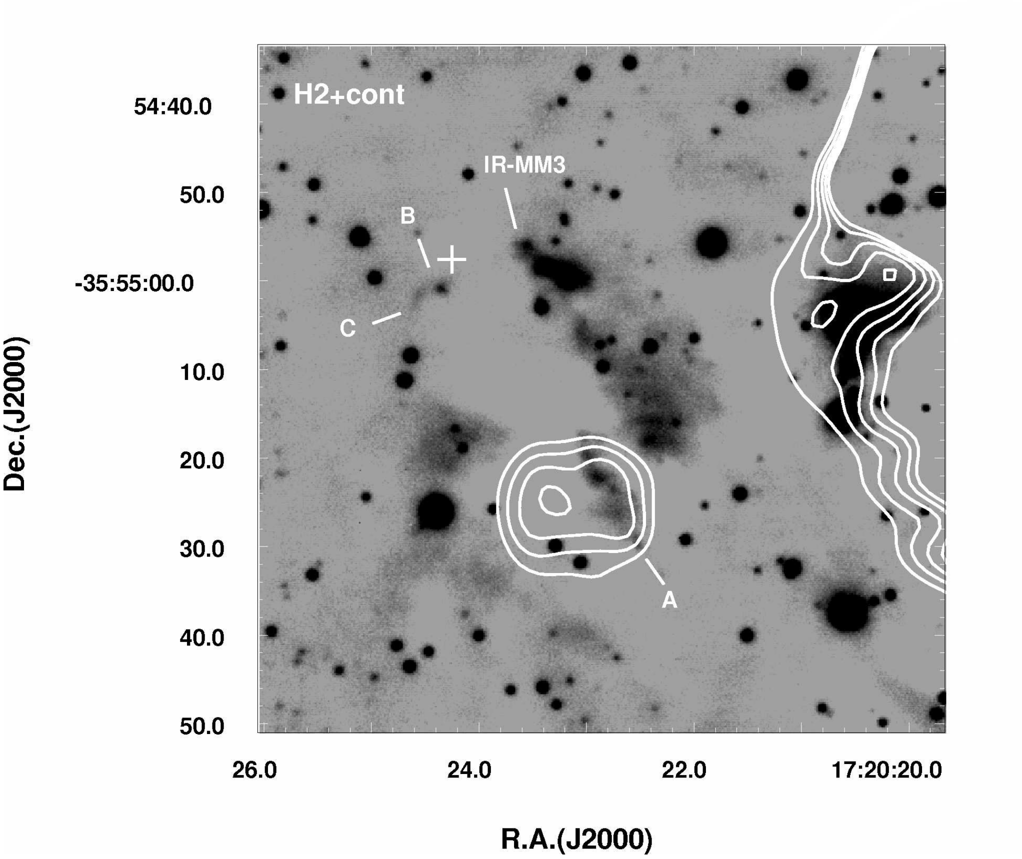


**Fig. 11.** $H_2$ + continuum image of NGC 6334 IV (MM3) region. The contours represent the 3.6 cm radio continuum. The $H_2$ knots A,B, and C are indicated. The symbol (+) marks the position of the sub-mm peak (Persi et al. 2009)

the radio and the infrared. This morphology is the result of the effect of massive stellar winds originating from a source at the centre of a dense molecular toroid which, in turn, collimates the outflow material giving rise to two lobes of thermal gas and dust emission. High resolution mid and near-infrared images by Kraemer et al. (1999) and Persi et al. (2000) showed that IRS19 and IRS20 are extended and multiple. In particular, IRS 20 has been found to be a system composed of at least two ZAMS B2-B3 stars.

A new centre of active star formation was found by Persi et al. (2009) to the east of the central region, in corrispondence with the sub-millimeter peak named MM3 by Sandell (2000). Sub-arcsec infrared observations that include narrow-band $H_2$ and Br$\gamma$, and mid-infrared images (Persi et al. 2009) show the presence of a number of $H_2$ emission knots (the brightest three, A, B and C indicated in Fig. 11) suggesting the presence of collimated outflows. Knot A is very close to the radio continuum source G351.25+0.65, while knots B and C are in the vicinity of the sub-millimeter peak and may be excited by the nearby bright mid-infrared source IR-MM3 at the apex of the extended polarized infrared reflection nebula IRN IV-3 (Haschimoto et al. 2008). The source coincides with the OH maser found by Brooks, & Whiteoak (2001) and is within the positional error of the continuum millimeter source MM3. An infrared spectral index $\alpha_{\rm IR}$ = 3.5, and a bolometric luminosity $L_{\rm bol}$ = 985$L_\odot$ was derived for this sources. These values confirm that IR-MM3 is a Class I object with a luminosity lower than that of a B3 ZAMS.

## 5. Conclusions

The multifrequency observations of the bright nebula NGC 6334 have shown that this region contains some of the most active sites of massive star formation in our Galaxy.

Discovered by their bright far-infrared emission associated with radio continuum peaks, these nuclei of activity are aligned along a dense molecular ridge that runs parallel to the Galactic Plane and stretches some 10 pc. It has a total mass of a few $10^5$ $M_\odot$ The physical characteristics of the active spots range widely, from well developed expanding HII regions to deeply embedded, still contracting, young objects detected only as millimeter sources, thus at their earliest observable stage of their evolution. The oldest optically visible round HII regions with central O-type stars are found in the southern parts. There is no clear spatial evolutionary correletion across the region.

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