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ORIGINAL ARTICLE

Massive star formation in the southern Milky Way

From large scale surveys to high resolution observations

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Abstract During the past decade we have compiled a large molecular line data base of massive star forming regions in the southern Milky Way. These regions are confined into giant molecular clouds that trace the galactic spiral arms. Their radial distribution has a pronounced peak midway between the Sun and the galactic center, which in the IV quadrant corresponds to the location of the Norma Spiral arm. We study in some detail one of the foremost regions of massive star formation in the Norma arm, using millimeter continuum and line emission maps obtained with the SEST, APEX, and ASTE telescopes. It is a multiple system evolving along a complete GMC core, candidate for future ALMA observations.

Keywords Galaxy: structure · ISM: molecules · Stars: formation

1 Introduction

Massive stars ($M \geq 8M_o$) form in the dense cores of giant molecular clouds ($M \geq 5 * 10^5 M_o$). Their ultraviolet photons heat the surrounding dust, which reradiates the energy in the infrared, peaking at a wavelength of about 100 um. This emission is clearly seen in IRAS maps of the galactic disk, and has a large-scale correlation with the velocity integrated emission of CO, a tracer of molecular gas. After completion of the IRAS survey it became clear that identification of the individual IRAS galactic sources via molecular line emission would yield the distribution of massive star formation in the Galaxy. Because of the ubiquity of the CO molecule, however, it was rather difficult to use the velocity information yielded by the available CO surveys of the Galaxy to deconvolve the IRAS survey, determine the distances and luminosities of the sources, and produce a face-on map of massive star formation in the Milky Way. The CO(1-0) profiles, for example, are normally very complex toward the inner Galaxy, and it is very difficult to assign a single velocity component to a given infrared feature. A better tracer of high density gas would be needed for such purpose, and at an angular resolution comparable with that of the IRAS maps. However, to produce such a map of the Milky Way would take way too long; for a single pixel detector, for instance, observing one square degree of the sky at a resolution of 1 arcmin, at 6 minutes of time per position, would take 30 days. A way out of the dilemma is to carry on pointed observations of a large number of suitable representative sources. Even allowing a 100% overhead for changing the telescope position, it is possible to perform 1800 single-point observations in the same time it would take to map 1 square degree of the sky at a resolution of 1 arcmin.

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2 A CS(2-1) survey of UC H II regions

Ultraviolet photons from massive stars, as well as heating the nearby dust, ionize the surrounding gas forming ultra-compact (UC) H II regions. Most of these regions are detected as IRAS point-like sources. The SED (Spectral Energy Density) of these sources has a characteristic shape, that can be used to identify them from the vast number of point-like sources in the IRAS catalog. Using such criterion, Wood and Churchwell (1989) identified 1646 UC H

II region candidates which fall mostly in the galactic disk. To determine the distances of these sources, and hence their luminosities, it is necessary to carry on line observations of molecular species associated with the dense molecular gas cores surrounding the UC H II regions.

A very good tracer of high molecular gas density is the CS(2-1) transition line. It becomes excited at densities above 10^4–10^5 cm^{-3}, characteristic of star forming regions. The line is fairly insensitive to high column density resulting from large regions, along the line of sight, of low and intermediate gas volume density. In other words, it probes the small dense cores but not the large molecular cloud envelopes. A CS(2-1) survey of IRAS point-like sources with FIR colors characteristic of UC H II regions, along the whole galactic plane, was carried out with the SEST and the OSO telescopes in the early nineties (Bronfman et al. 1996), yielding 843 detections out of a total of 1427 sources observed. More recently the undetected sources have been re-observed using new detectors with better sensitivity; the latitude extent of the survey has been increased too, and a database of 1200 regions of massive star formation in the Galaxy has been compiled. This is the largest database in its kind so far.

3 Mean radial distribution of massive star formation in the Milky Way

A simple axisymmetric model fit to the sample of CS-IRAS sources from the survey yields the mean radial distribution of massive star formation in the galactic disk. The main feature in the mean radial distribution is a well defined annulus, peaking at $R = 0.55R_o$, with a FWHM of $0.28R_o$ (Bronfman et al. 2000). Such peak coincides with the so called molecular ring, which is somewhat broader ($0.51R_o$ FWHM). A lower limit for the total FIR luminosity originated by embedded massive stars in the galactic disk is of $1.5 * 10^8 L_o$, for a total H_2 mass of $2 * 10^9 M_o$ (Fig. 1). The face-on FIR luminosity at the peak of the massive star formation annulus is higher ($1.6L_o$ pc^{-2}) in the IV galactic quadrant (southern Galaxy) than in the I galactic quadrant ($1.2L_o$ pc^{-2}). Massive star formation extends, in the outer Milky Way, to galactocentric radii of about 17 kpc.

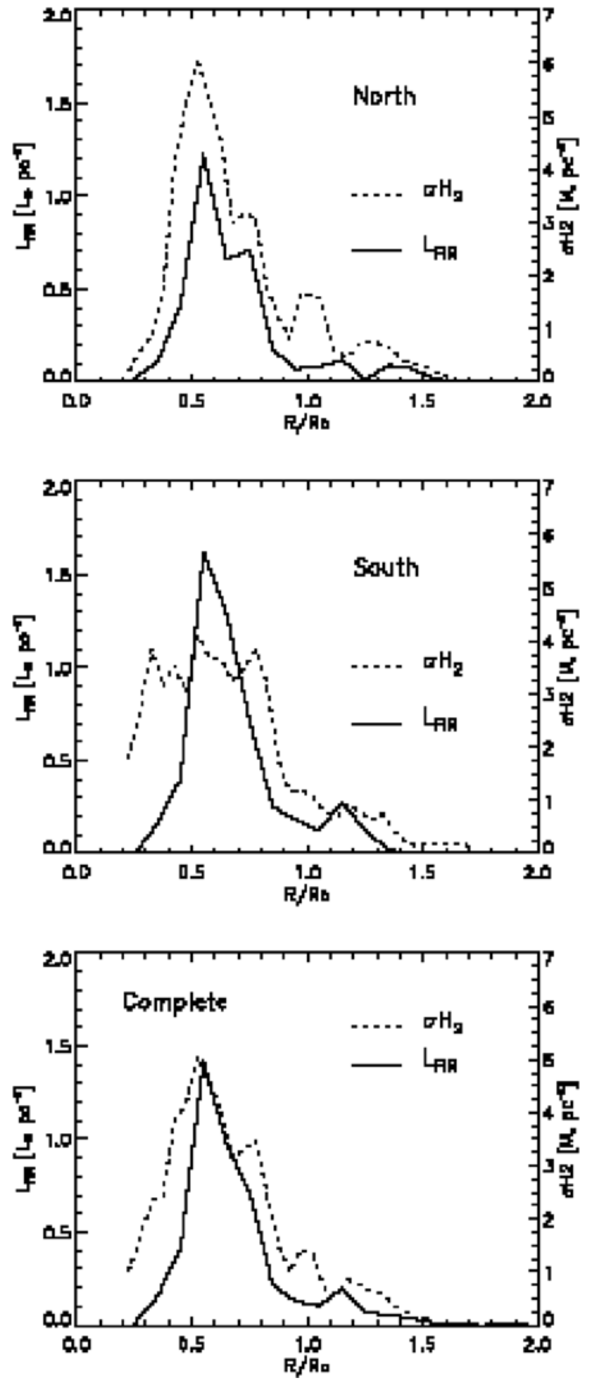
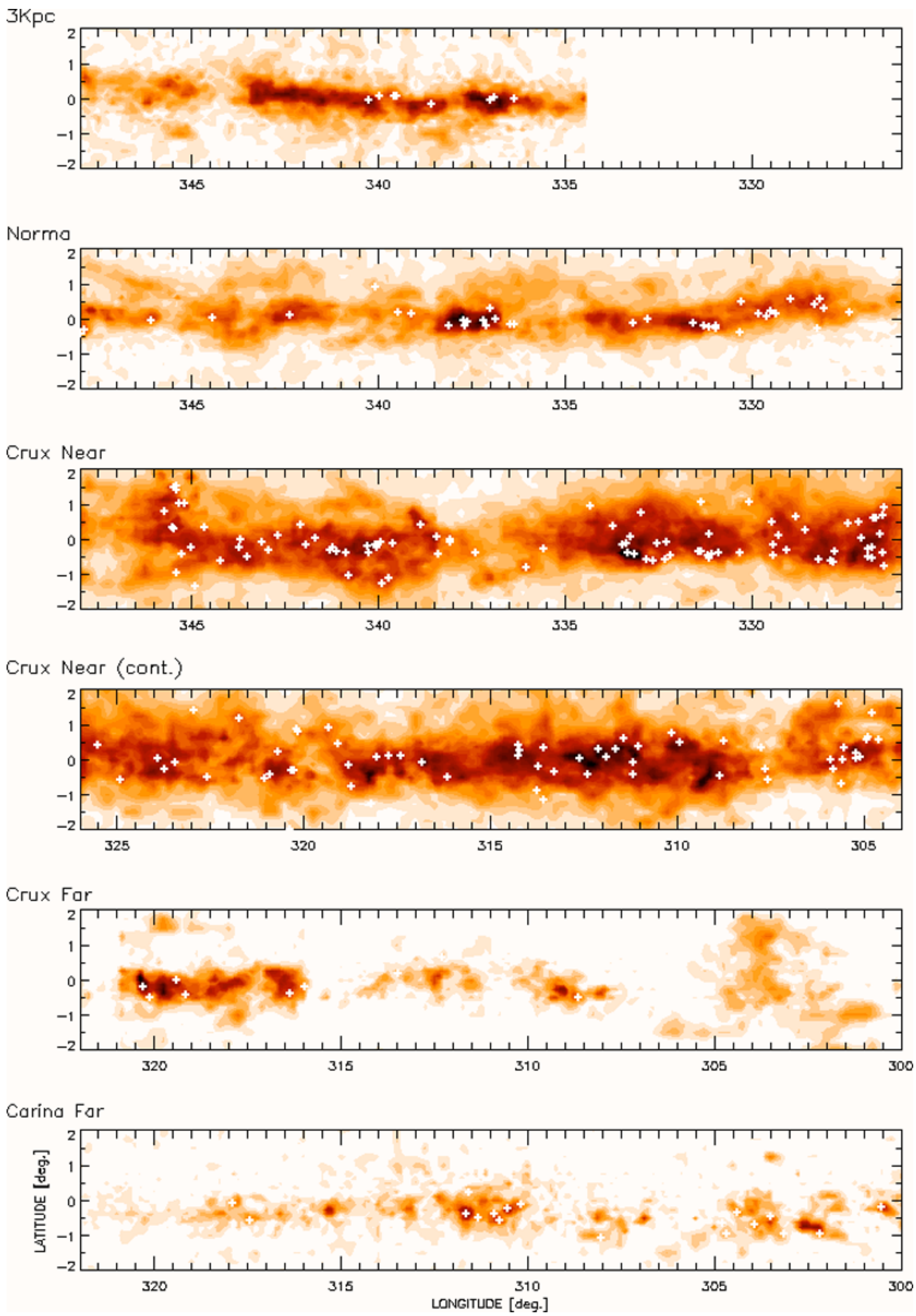


Fig. 1 The *solid line* shows the face-on FIR surface luminosity originated by dust heated by embedded young massive stars, as a function of galactocentric radius. The *dotted line* indicates the face-on surface density of molecular hydrogen (Bronfman et al. 2000, Fig. 10)

4 Molecular gas and massive star formation in the southern spiral arms

Spiral arms can be traced, in a longitude velocity diagram of the IV galactic quadrant, by identifying the largest molecular cloud complexes and estimating their distances using a rotation curve. A two-fold distance ambiguity must be resolved, using various methods, like latitude effect (high latitude clouds are most probably at the near distance), and line absorption against associated H II regions. The tangent regions of such spiral arms are found *a priori* from bumps in the rotation curve, originated from systematic de-

Fig. 2 Spatial maps of CO(1-0) emission integrated in velocity, within ranges associated with spiral arms. The *crosses* indicate the positions of IRAS point-like sources, detected in CS(2-1), within the same velocity ranges



viations from pure circular motion at the spiral arms (Luna et al. 2006). These tangent regions are, in the inner Galaxy, $l \sim 308$ deg for the Crux arm; $l \sim 328$ deg for the Norma arm; and $l \sim 336$ deg for the 3-kpc arm. Figure 2 shows a panel of spatial maps of CO(1-0) emission, integrated over velocity ranges associated with spiral arms from the longitude velocity diagram. The crosses indicate the position of IRAS point-like sources with FIR colors of UC H II regions, with their velocities obtained from the CS(2-1) profiles.

5 Statistical properties of dense cores harboring massive star formation

The CS(2-1) survey of IRAS point-like sources yields the distances an FIR luminosities of massive star forming regions in the Galaxy. To study the extension and morphology of the dense gas and dust cores, a set of 146 maps was obtained with the SIMBA bolometer at SEST at a wavelength of 1.2 mm (Faúndez et al. 2004). The sources selected, in the

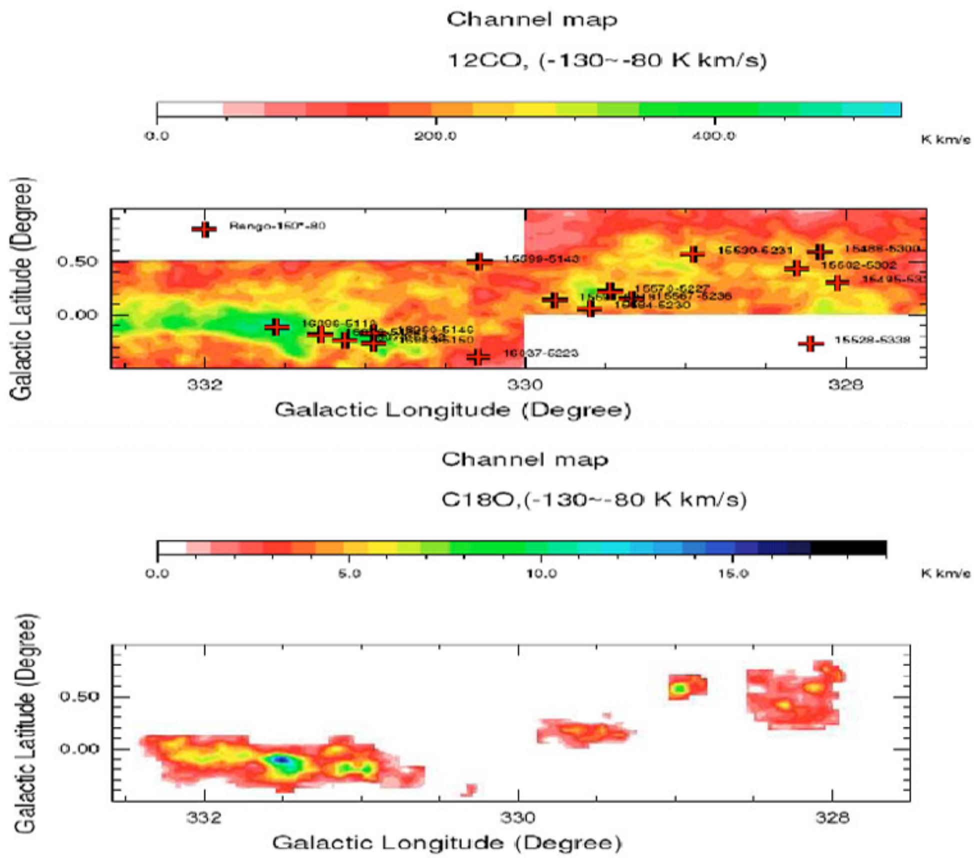


Fig. 3 Spatial maps obtained with the NANTEN Telescope, at a resolution of 2.5 arcmin, of CO(1-0) and $C^{18}O$(1-0) emission integrated in velocity, within the velocity range associated with the Norma Spiral Arm. The *crosses* indicate the positions of IRAS point-like sources, detected in CS(2-1), within the same velocity range

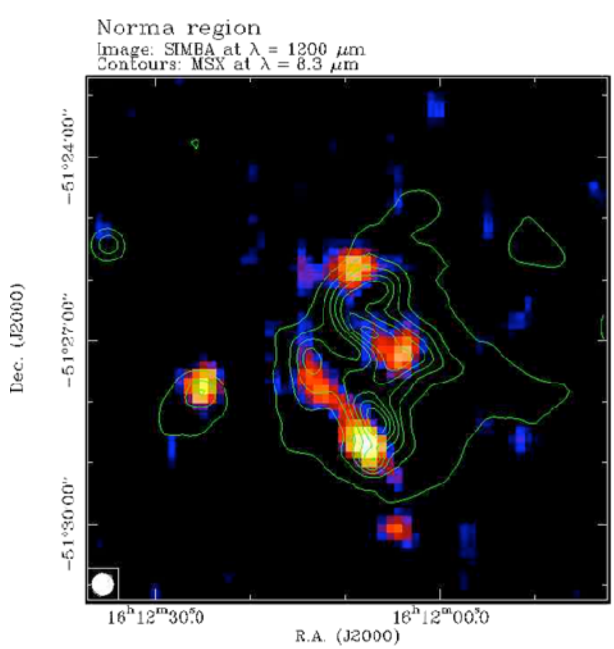


Fig. 4 The G331.5 massive star forming region in Norma. In color, 1.2 mm continuum emission observed with the SIMBA bolometer at the SEST Telescope. *Contours* show the mid infrared emission observed with MSX at 8.3 um

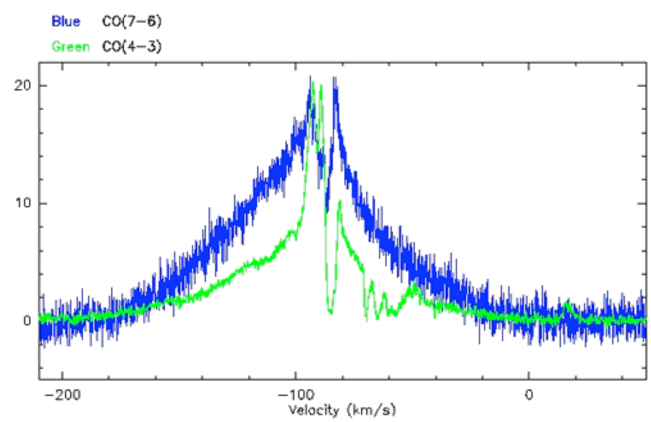


Fig. 5 Massive molecular outflow in G331.5, as observed with APEX telescope in CO(7-6) and CO(4-3) emission

I and IV galactic quadrants, had the most intense CS(2-1) emission in the Bronfman et al. (1996) catalog. The mean characteristics of these continuum sources were: a diameter of 0.4 pc; a mass of 5000 M_o; a luminosity of 230000 L_o; and a temperature of 32 K.

6 The G331.5 massive star forming region in the Norma Spiral Arm

The Norma Spiral arm contains the most massive giant molecular clouds and the most luminous regions of massive star formation in the Milky Way. A map of the tangent region of the arm, in CO(1-0), has been obtained with the NANTEN telescope from Nagoya University (Fig. 3). The high opacity of the CO line does not allow to discern the densest gas clumps; however, the $C^{18}O$ transition, more transparent, allows to detect an extended dense condensation at $l = 331.5$ deg. When observed with the SIMBA bolometer at SEST, at a wavelength of 1.2 mm, a region of multiple massive star formation can be readily seen (Fig. 4). The spatial extent of such region, at a non ambiguous distance of 7.4 kpc, is of 20 pc. The total gas mass, derived from the dust observations, is of 24000 M_o, while the mass of the brightest component is of 10000 M_o. It is suspected that the cluster components are at different evolutionary stages, a proposition that has to be tested via higher resolution observations of molecular transition lines. In any case, one of the 1.2 mm components is associated with a high mass molecular outflow (Fig. 5), with a very high velocity width (160 $\text{km}\,\text{s}^{-1}$). Analysis of these recent observations, obtained with the ASTE and APEX telescopes, is presently underway and will be published elsewhere.

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