MOLECULAR CLOUDS AND STAR FORMATION AT LARGE R[†]

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1. INTRODUCTION

In the outer Galaxy (defined here as those parts of our system with galactocentric radii $R>R_0$) the HI gas density (Wouterloot *et al.*, 1990), the cosmic ray flux (Bloemen *et al*, 1984) and the metallicity (Shaver *et al.*, 1983) are lower than in the inner parts. Also, the effect of a spiral density wave is much reduced in the outer parts of the Galaxy due to corotation. This changing environment might be expected to have its influence on the formation of molecular clouds and on star formation within them. In fact, some differences with respect to the inner Galaxy have been found: the ratio of HI to H_2 surface density is increasing from about 5 near the Sun to about 100 at $R\approx 20$kpc (Wouterloot *et al.*, 1990). Because of the "flaring" of the gaseous disk, the scale height of both the atomic and the molecular gas increases by about a factor of 3 between R_0 and $2R_0$ (Wouterloot *et al.*, 1990), so the mean volume density of both constituents decreases even more rapidly than their surface densities. The size of HII regions decreases significantly with increasing galactocentric distance (Fich and Blitz, 1984), probably due to the fact that outer Galaxy clouds are less massive (see section 3.3), and therefore form fewer O-type stars than their inner Galaxy counter parts. There are indications that the cloud kinetic temperature is lower by a few degrees (Mead and Kutner, 1988), although it is not clear to what extent this is caused by beam dilution.
A study of the properties of molecular clouds at large R could be used to put constraints on their formation mechanisms, such as reviewed e.g. by Elmegreen (1990).

[†] Partly based on observations collected at the European Southern Observatory, Chile

H. Bloemen (ed.), The Interstellar Disk-Halo Connection in Galaxies, 121–130.

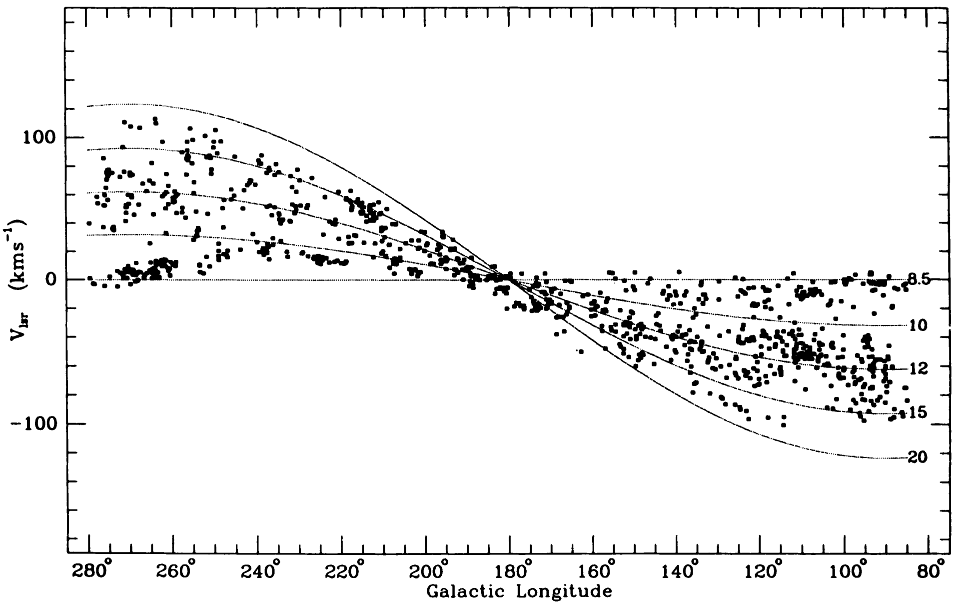

Figure 1. Longitude-velocity diagram of the CO emission components which were judged to be physically associated with the IRAS point sources. The lines indicate constant galactocentric radii (based on the rotation curve given in the text).

2. STAR FORMATION AT LARGE R

From optical studies of the outer Galaxy (Fich and Blitz, 1984; Brand,1986) it has become clear that the Galaxy contains HII region/molecular cloud complexes at distances R from the galactic centre of up to 20kpc. Because of interstellar extinction, these surveys found only a few very distant regions, most of them seen in certain directions of low extinction. In order to get a more representative view of star-forming molecular clouds in the outer Galaxy, we have looked for CO emission towards a large number (1302) of IRAS sources in the second and third galactic quadrant. These were selected from the Point Source Catalogue, using colour criteria that discriminate in favour of those sources that are frequently associated with H_2O masers and NH_3 cores (Wouterloot and Walmsley, 1986; Wouterloot *et al.*, 1988b). As all star formation takes place in molecular clouds, these IRAS sources were used as flags for their location. In the direction of 1077 (83%) of the IRAS sources CO emission was detected, with the ESO 15-m SEST and the IRAM 30-m telescope (Wouterloot and Brand, 1989). The longitude-velocity diagram for this sample is shown in figure 1. Comparison with data from regular-grid surveys of the outer Galaxy (e.g. May *et al.*, 1988) shows that these have missed almost all the emission with velocities in excess of 50-70 kms^{-1}, due to a combination

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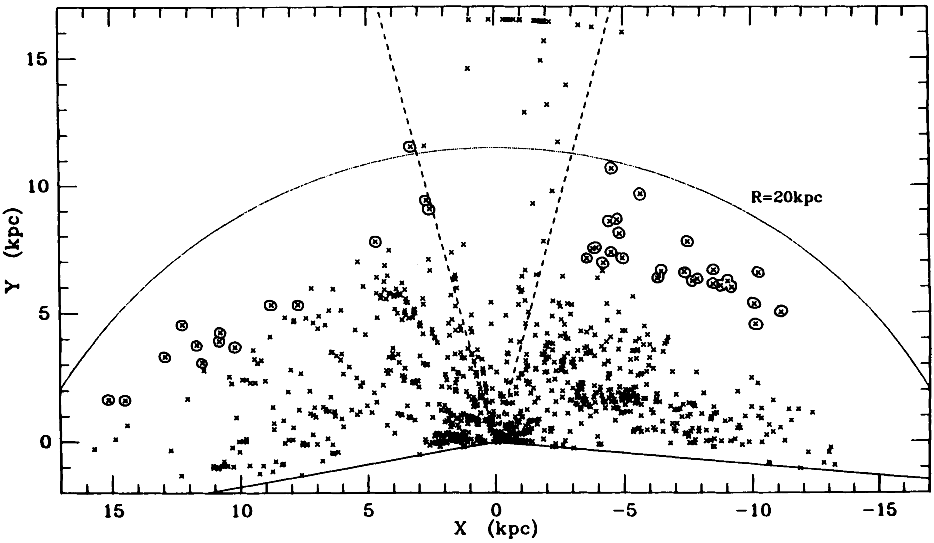

Figure 2. Distribution projected onto the galactic plane of all CO emission components shown in figure 1. The Sun is at (0,0), the galactic centre at (0,−8.5). The full-drawn lines show the longitude limit of the point source sample. The dashed lines mark the region within ±15°of the galactic anticentre where kinematic distances are particularly uncertain. The circle segment represents the galactocentric distance R=20kpc. The clouds that are discussed in the present paper (section 3.1) are identified by an open circle.

of coarser sampling, lower sensitivity, and insufficient coverage in galactic latitude. Kinematic distances to the clouds in our survey were derived using a rotation curve $\Theta=220(R/8.5)^{0.0382}$ (Brand, 1986; Wouterloot *et al.*, 1990). The distribution of these clouds, projected onto the galactic plane, is shown in figure 2.

Molecular clouds with embedded IRAS sources are found up to about 20kpc from the galactic centre (i.e. $R\approx2.5R_0$), and in contrast to the optical surveys, distant objects are distributed more or less evenly over galactic longitude. Because of the selection criteria used, this implies that star formation is taking place in the outer Galaxy up to R=20kpc, the radius defining the edge of the molecular disk of the Galaxy. Towards alsmost 600 of the IRAS sources in figure 2 we have searched for H_2O emission, finding an overall detection rate of 17%; for clouds with $R=R_0$-$1.5R_0$ 16.5% is detected; for those with $R> 1.5R_0$, 18.5%. This is another indication that star formation is active in this part of the Galaxy. Most of the IRAS sources in figure 2 have luminosities between 10^3 and 5 10^4 $L_\odot$, corresponding to (ZAMS) stars of spectral types B3 to O8.5 (Panagia, 1973). From VLA data (Wouterloot *et al.*, 1988a; Mead *et al.*, 1990) and optical studies (Georgelin, 1975; Moffat *et al.*, 1979; Brand, 1986) there is no indication that the average spectral type of the stars that ionize distant HII regions differs from that in comparable (i.e. of the same size) regions closer to the Sun. Therefore the most massive stars formed in the outer Galaxy are not as massive as those near the Sun, explaining the smaller size of the largest HII regions in the outer parts. The cause of this may be in the properties of the molecular clouds.

3. MOLECULAR CLOUDS AT LARGE R

3.1 Observations

We have used the results of Wouterloot and Brand (1989) to select those clouds at the largest distances from the galactic centre (that are located at the edge of the molecular disk of the Galaxy) to obtain their properties (e.g. sizes and masses). A sample of 56 clouds with 16kpc<R<20kpc has been studied using the 3-m KOSMA telescope at Gornergrat for the northern hemisphere clouds and the 15-m SEST for the southern hemisphere clouds. The distance from the Sun of these clouds is about 10kpc, which translates to linear beamsizes of the two telescopes at 115GHz of about 12pc (KOSMA) and 2.5pc (SEST). This means that if these IRAS sources would be embedded in giant molecular clouds such as found in the inner Galaxy, these clouds would be resolved with the 3-m telescope.

At Gornergrat we have observed 32 clouds in ^{12}CO(J=1-0) and 5 clouds in ^{13}CO(J=1-0) at the IRAS position. The sensitivity was 0.05-0.10K for ^{12}CO(J=1-0) and 0.01-0.03K for ^{13}CO(J=1-0), respectively. Observations were made with a resolution of 0.4kms^{-1} and in frequency-switching mode. Subsequently we have mapped 13 of these clouds in ^{12}CO(J=1-0) on a 4' grid, tracing the clouds until the signal disappeared.

With the SEST we have mapped 14 clouds in ^{12}CO(J=1-0) on a 40" or 80" grid. We used a resolution of 0.11kms^{-1} and frequency-switching, and obtained spectra with an rms of about 0.5K. Some positions have been observed in ^{13}CO(J=1-0) (rms$\approx$0.1K). In addition to these maps, ^{12}CO and ^{13}CO were observed at the IRAS position in 11 clouds.

At the IRAS position the ratio $T_A^*(^{12}CO)/T_A^*(^{13}CO)$ is 7.1$\pm$1.0 for the Gornergrat clouds, and 8.9$\pm$7.6 for the SEST clouds (the latter number is greatly influenced by two sources with ratios of 21 and 33, respectively). For the inner galaxy, Solomon and Sanders (1980) found values between 3 and 20 with an average value of 5.5 and possibly an increase for larger R. Before any conclusions can be drawn from this, we need to obtain ^{13}CO data at positions in the clouds, away from the IRAS sources.

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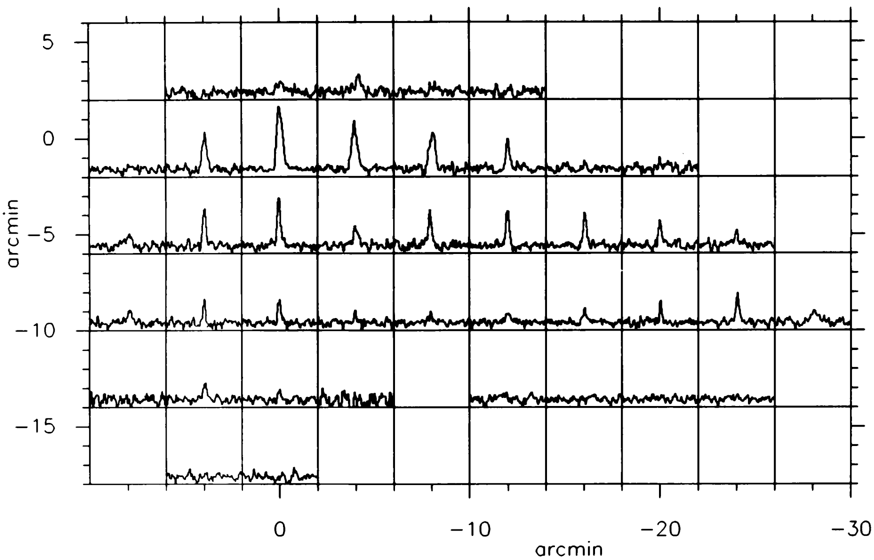

Figure 3. KOSMA-spectra of the cloud associated with IRAS01037+6504 (L=2.8 $10^3 L_\odot$) and IRAS01045+6505 (L=1.1 $10^5 L_\odot$). The sources are at (−5.4,−0.6) and (0,0), respectively. Offsets are in galactic coordinates. For each spectrum the x-range is −110 to −65kms^{-1} and the y-range is −0.2 to 1.8K.

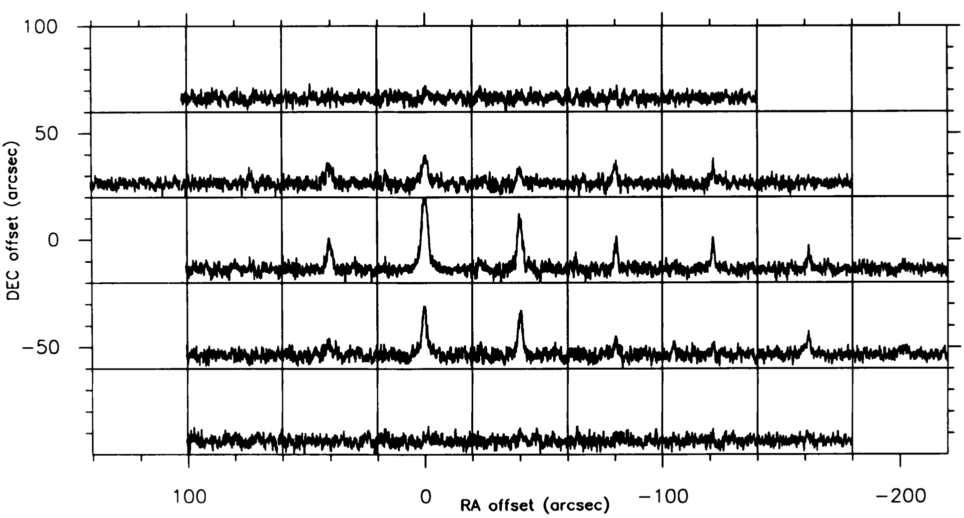

Figure 4. SEST-spectra of the cloud associated with IRAS06145+1455 (L=1.9 $10^4 L_\odot$), which is at (0,0). For each spectrum the x-range is 10 to 55kms^{-1} and the y-range −1.5 to 8K.

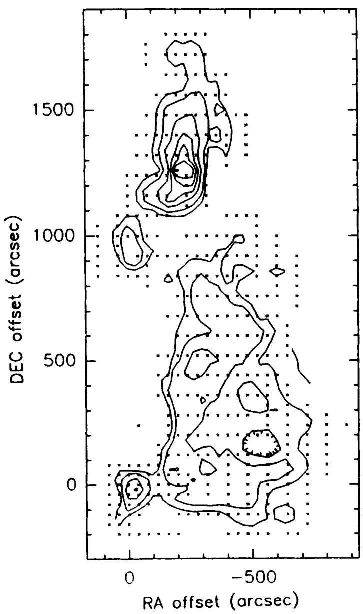

Figure 5. Contour map for the cloud complex associated with IRAS07257−2033 (L=8.7 $10^3 L_\odot$) of $\int T_A^* dv$ between 77 and 84kms^{-1} (SEST data). The IRAS source is at (0,0). Offsets are in arcseconds. Contour levels are 2.5, 5,10,15,20,25Kkms^{-1}.

3.2 Sizes

With the 3-m telescope we detected 30 of the 32 clouds. The size of the clouds that were not, or only marginally, detected is expected to be less than 10pc. The T_A^* at the IRAS position is 0.2 to 2.5K and typically 1K, which is about one order of magnitude lower than when observed with the 30-m IRAM telescope. The reason is that the IRAS source usually is associated with a relatively warm, small molecular cloud (or clump) as is shown by some maps made by Wouterloot *et al.* (1989) and by our SEST maps. Also the beam filling factor for the 3-m telescope of the extended lower temperature emission of the cloud surrounding this clump will generally be less than one.

The 13 molecular clouds mapped at Gornergrat were detected at between 2 and 22 positions. The largest clouds are elongated, reaching lengths of 80-100pc. All clouds have a maximum in T_A^* (or $\int T_A^* dv$) at, or close to, the IRAS position. Examples of the spectra for two clouds are given in figures 3 (Gornergrat) and 4 (SEST), respectively.

Contour maps of two cloud complexes mapped with the SEST are shown in figures 5 and 6. In figure 5, the source IRAS07257−2033 at (0,0) may be displaced from the integrated CO peak by 1pc (less than half a beam). The complex in figure 5 consists of several clouds that are separated by a few parsec, similar to the situation in Orion or Mon OB1. The northern cloud contains an IRAS source that

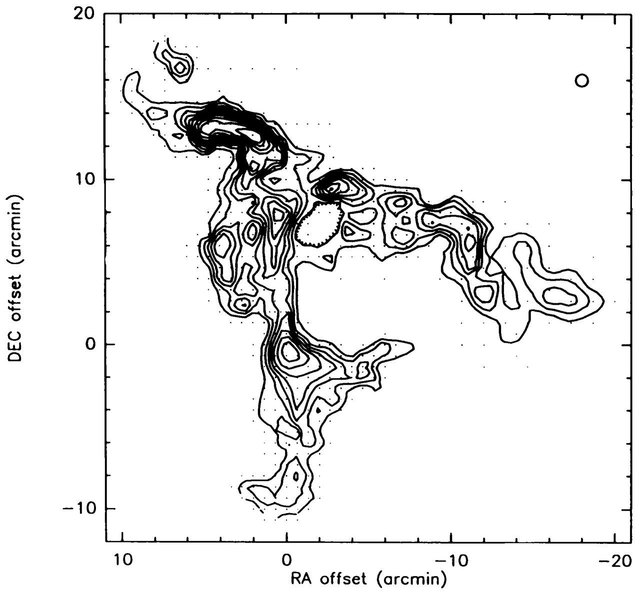

Figure 6. Distribution of $T_A^*(^{12}CO)$ for the cloud associated with IRAS06158+1506 (L=3.9 $10^3 L_\odot$; at (0,0)) and IRAS06158+1517 (L=6.4 $10^4 L_\odot$; at (0.75,11.72)); SEST data. Contour levels are 1 to 10K in steps of 1K. The circle in the upper right-hand-side corner indicates the HPBW.

is equally strong at 60μm as the one at (0,0), but it was not included in our survey because its flux density has an upper limit at 100μm.

Figure 6 shows the distribution of $T_A^*(^{12}CO)$ for the cloud associated with IRAS06158+1506 and IRAS06158+1517. With a maximum length of 80pc, this is one of the largest clouds in our sample. However, as this object is at a galactic longitude of 195°, its kinematic distance is uncertain, and it may well be closer by than the derived 9.6kpc, and consequently its size may be smaller.

Observing two small areas of sky, Terebey *et al.* (1986) found several clouds at an average R of 12.9kpc (when using the same rotation curve as here), and derived that the size spectrum there is the same as that near the Sun, and in the inner Galaxy.

A rough estimate of the diameter of a cloud is determined from the square root of the surface area where emission is detected, rather than from the area above some value of T_R^*, as is usually done. For the clouds observed with the 3-m telescope, it ranges from 14 to 55pc with a median value of about 25pc. The diameter of the clouds mapped with the SEST ranges between 3 and 50pc. These values are smaller than what is found for inner Galaxy clouds, but similar to the outer Galaxy clouds at around R=13kpc studied by Mead and Kutner (1988). In figure 7 we show the distribution of cloud radii.

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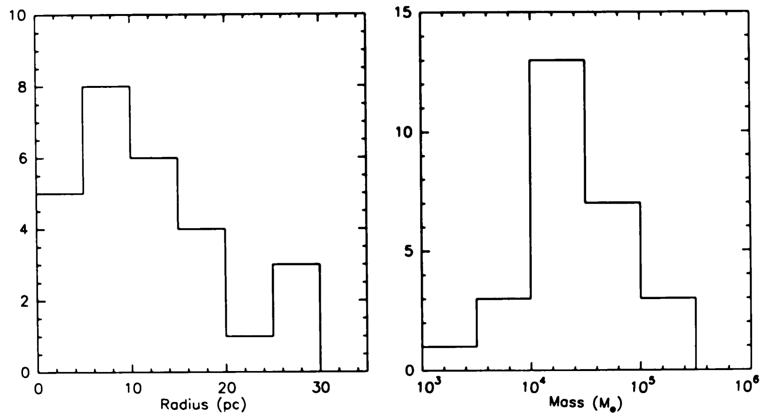

Figure 7. (left panel) Distribution of radii of the 27 clouds discussed here.

Figure 8. (right panel) Distribution of masses of the 27 clouds.

3.3 Masses

We derive virial masses assuming spherical clouds, with density falling off with cloud radius as r^{-1}: $M_{vir}=363r(\Delta v)^2$. Here Δv is the line width, for which we take the value at the IRAS position. Masses then range from 1.3 $10^4 M_\odot$ to 1.5 $10^5 M_\odot$ for the clouds observed at Gornergrat, and from 2.8 $10^3 M_\odot$ to 1.6 $10^5 M_\odot$ for those observed with the SEST.

Figure 8 shows the distribution over cloud masses; it is essentially identical to that for the sample of Mead and Kutner (1988). Almost all clouds in the latter sample are at R=13kpc (and in the first galactic quadrant), while our clouds are at R>16kpc. We find almost no clouds with a mass higher than $10^5 M_\odot$, which are often found in the inner Galaxy. It is not yet clear whether the lack of very high mass clouds ($M>10^6 M_\odot$) is real, or due to the relatively small number of objects investigated, or perhaps a consequence of the definition of cloud sizes and the calculation of masses.

The sum of the masses of the clouds is 7.2 $10^5 M_\odot$ (Gornergrat) and 5.2 $10^5 M_\odot$ (SEST) for about equal intervals (about 60°) in galactocentric azimuth investigated. The results of Wouterloot *et al.* (1990) give a total molecular mass within these sectors of about 1.2 $10^7 M_\odot$, which would mean that the mapped clouds contain only 10% of this mass. Because we mapped only clouds associated with 27 of the 50 IRAS sources in the interval 16-20kpc, we estimate that 10-20% of the extrapolated H_2 mass is associated with IRAS sources. It is possible that because clouds are smaller (i.e. less massive) at large R, Wouterloot *et al.* (1990) have overestimated the molecular surface density in the outer Galaxy when extrapolating the value near the Sun, scaling it with the surface density of IRAS sources; but only unbiased surveys can show whether in the outer Galaxy there are many clouds which have no embedded IRAS sources with luminosities above 10^3-$10^4 L_\odot$. This may be the case if there exists an external triggering mechanism of star formation that is unrelated to cloud formation. The surveys of Mead *et al.* and others however do not suggest that there is a large population of such clouds. It seems then, that in spite of the differences between the inner- and outer parts of the Galaxy, star formation occurs at large R, but cloud formation is much more inefficient than at smaller R.

Elmegreen and Elmegreen (1987) conclude from a study of HI superclouds in the inner Galaxy, that the total hydrogen mass (being about $10^7 M_\odot$) of these objects does not vary with R, but that their molecular fraction is decreasing with R, probably because of a systematic variation with R of the pressure, metallicity, and radiation field within the galactic disk. HI measurements of the most massive molecular clouds in our sample will show whether these objects are enveloped by $10^7 M_\odot$ HI clouds.

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