We report the results of high-resolution (∼0.2 pc) CO(1–0) and CS(2–1) observations of the central regions of three star-forming molecular clouds in the far-outer Galaxy (∼16 kpc from the Galactic Center): WB89 85 (Sh 2-127), WB89 380, and WB89 437. We used the BIMA array in combination with IRAM 30-m and NRAO 12-m observations. The GMC's in which the regions are embedded were studied by means of KOSMA 3-m CO(2–1) observations (here we also observed WB89 399). We compare the BIMA maps with optical, radio, and near-infrared observations. Using a clumpfind routine, structures found in the CO and CS emission are subdivided in clumps, the properties of which are analyzed and compared with newly derived results of previously published single-dish measurements of local clouds (OrionB South and Rosette). We find that the slopes of the clump mass distributions (–1.28 and –1.49, for WB89 85 and WB89 380, respectively) are somewhat less steep than found for most local clouds, but similar to those of clouds which have been analyzed with the same clumpfind program. We investigate the clump stability by using the virial theorem, including all possible contributions (gravity, turbulence, magnetic fields, and pressure due to the interclump gas). It appears that under reasonable assumptions a combination of these forces would render most clumps stable. Comparing only gravity and turbulence, we find that in the far-outter Galaxy clouds, these forces are in equilibrium (virial parameter $\alpha \approx 1$) for clumps down to the lowest masses found (a few $M_\odot$). For clumps in the local clouds $\alpha \approx 1$ only for clumps with masses larger than a few tens of $M_\odot$. Thus it appears that in these outer Galaxy clumps gravity is the dominant force down to a much lower mass than in local clouds, implying that gravitational collapse and star formation may occur more readily even in the smallest clumps. Although there are some caveats, due to the inhomogeneity of the data used, this might explain the apparently steeper IMF found in the outer Galaxy. 

Introduction intro

Studies of molecular clouds have spanned size scales from many tens to tenths of parsecs. The large-scale properties of molecular clouds can be studied throughout the Galaxy as well as in external galaxies. For the smallest structures in molecular clouds, however, lack of resolving power has limited detailed studies to molecular clouds nearest to the Sun. Therefore, it has never been investigated whether the effects of a different physical environment influences the properties of those structures. The possibility of making high-resolution maps with mm-interferometers allows a study of clump properties in clouds at much larger distances from the Sun, and therefore in a potentially different physical and chemical environment. The outer part of the galactic disk is such a region, where molecular clouds are more sparsely distributed (Wouterloot et al. wbbk), the diffuse galactic interstellar radiation field is weaker (Cox & Mezger cox, Bloemen bloemen), the metallicity is lower (Shaver et al. shaver, Fich & Silkey fichsilk, Wilson & Matteucci wilson, Rudolph et al. rudolph97), and the cosmic-ray flux density is smaller (Bloemen et al. bloemenben), compared to the solar neighbourhood. Previously, we have studied molecular clouds at galactocentric distances $R > 15$ kpc (Brand & Wouterloot brandw1) and analyzed molecular cloud properties across the Galaxy (Brand & Wouterloot brandw2, hereafter BW95). It was found that cloud kinetic temperatures as well as CO luminosities are similar to GMCs of the same mass in the solar neighbourhood. These results were in contradiction with those of Mead & Kutner (mead1), who derived kinetic temperatures of 7 K for a sample of clouds at $R \sim 13$ kpc, significantly colder than GMCs in the solar neighbourhood, and Digel et al. (digel), who found that outer...
Galaxy molecular clouds appear to be underluminous in CO with respect to their virial mass, by a factor of four, compared to local clouds (suggesting that the CO-to-\text{H}_2 conversion factor, \(X\), should be four times higher). BW95 showed that the Digel et al. result is a consequence of the small number of clouds studied by them. BW95 also found that outer Galaxy clouds are generally less massive than inner Galaxy clouds, and that in the inner Galaxy there are relatively more large clouds (see also May et al. may); they furthermore noted that outer Galaxy clouds have larger radii than inner Galaxy clouds of the same mass, which in part could be explained by a lower pressure of the surrounding ISM at large \(R\), allowing the clouds to settle at larger equilibrium radii. Wouterloot et al. (wouterfieg), and Fich & Terebey (fichter), using far-infrared luminosities of IRAS point sources in the outer Galaxy determined by Wouterloot & Brand (wb89; hereafter WB89), measured a slope for the initial mass function in the outer Galaxy that is steeper than the IMF measured in the solar neighbourhood. A similar indication of steepening has been found by Garmany et al. (garmancy) from O-stars (\(M > 20 \, M_\odot\)) within 2.5 kpc from the Sun. These differences are generally attributed to the different conditions in the outer Galaxy. On the other hand Casassus et al. (casassus), from a study of IRAS sources with the colours of UCHii regions concluded that the exponent of the IMF does not seem to vary.

The aim of the present study is to investigate the properties of molecular clumps (sizes from 0.2 – 2 pc) in GMCs in the outer Galaxy, and to explain any differences with clump properties in local clouds in terms of effects due to a different physical environment. At the typical distances for these objects of 10 kpc, the resolution required for such a study is \(\sim 5\), which can only be obtained by using an interferometer. We employed the BIMA mm-interferometer (Welch et al. welch) to map CO(1–0) and CS(2–1) in three molecular clouds at \(R > 15\) kpc. To compensate for the lack of zero-spacing information, which is particularly important for structures that are extended over size-scales larger than 1, the data were complemented with observations from the Kitt Peak 12-m (CO) and the IRAM 30-m telescopes (CS). The combined maps allow us to compare clump properties in the far outer Galaxy with those obtained from single dish observations of nearby GMCs. Three clouds (2 of which were also observed with BIMA) were mapped with KOSMA, to allow derivation of their masses.

Sect. obs describes the sample of objects, the observations and the data reduction. In Sect. results we present the results for the individual sources, while in Sect. clumpana we describe the method used to identify clumps from the data. Sect. discuss is devoted to a discussion of the clump physical properties and a comparison with local clouds. In particular, in Sect. clumpstab we look at the implications of our observational results on the slope of the IMF as a function of \(R\). In Sect. summ we summarize the main results.

### Table

<table>
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<th>Source</th>
<th>Type</th>
<th>(\alpha) (1950)</th>
<th>(\delta) (1950)</th>
<th>Molecule</th>
<th>Array beam</th>
<th>pixel</th>
<th>rms (K/Jy)</th>
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<td>01045+6505</td>
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<td>CO</td>
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<td>0.26</td>
<td>3</td>
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<td>WB89 437</td>
<td>CO</td>
<td>02395+6244</td>
<td>02395+6244</td>
<td>CO</td>
<td>5×5</td>
<td>0.26</td>
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</table>

### Source Selection

The WB89-catalogue presents an extensive CO survey towards IRAS point sources located in the outer Galaxy (second and third quadrants), with infrared colours that discriminate in favour of sources frequently associated with \(\text{H}_2\text{O}\) masers and dense molecular cloud cores (Wouterloot & Walmsley wouterwalms), and hence with star forming regions. We selected the four sources at \(R > 15\) kpc with the highest far-IR luminosity, to wit WB89 85 (IRAS 21270+5423), WB89 380 (IRAS 01045+6505), WB89 399 (IRAS 01420+6401), and WB89 437 (IRAS 02395+6244). Unless specified otherwise, in the following we shall for convenience use the WB89-name to indicate the molecular clouds associated with these IRAS sources, rather than the IRAS source itself.

### Single-Dish Observations

**NRAO 12-m**

WB89 85, 380, and 437 were observed using position switching on a 9×9 grid with 30 spacing in CO J=1–0 with the Kitt Peak 12-m telescope on December 4-9, 1991. The emission was found to extend beyond this region in all three cases; subsequently the GMC near WB89 85 was completely mapped. The telescope beamwidth at 115 GHz is 56. The standard chopper wheel method (Ulrich & Haas ulich, Kutner & Ulrich kutnerul) was used for calibration. All intensities are on a a \(T^*_R\)-scale. System temperatures were typically 350 – 500 K. We used filterbanks of 128 channels of 100 kHz for each of the polarizations. The velocity coverage is therefore 33 kms\(^{-1}\) with 0.26 kms\(^{-1}\) resolution. After averaging, the rms noise level is

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We have also observed $^1$2CO(2–1), $^{13}$CO(1–0), CS(2–1), HCO$^+$ (1–0), and HCN(1–0) at various locations on and near the three main CO peaks surrounding IRAS21270+5423.

**IRAM 30-m**

WB89 85, WB89 380, and WB89 437 were observed in CS J=2–1, 3–2, and 5–4 with the IRAM 30-m telescope at Pico Veleta from July 24–26 1991. The maps are on a 11×11 grid with 15 spacing, covering all CS emission. The telescope beamwidth at these frequencies (98, 147, and 245 GHz) is respectively 26, 16, and 11. The standard chopper wheel method was employed for temperature calibration. All intensities are on a $T_\ast$-scale. System temperatures were typically 200 – 250 K. Using a 128 channel filterbank of 100 kHz per channel, the velocity coverage is 40 kms$^{-1}$ and the resolution 0.3 kms$^{-1}$. Observations were made by position switching; the typical rms noise level in the spectra is 0.08 K. Low-order polynomial baselines were subtracted. In addition, 15 more outer Galaxy clouds were observed in the same transitions, to search for potentially interesting objects. With a few exceptions, these were all single-pointed observations at the IRAS PSC position.

**KOSMA 3-m**

WB89 380, WB89 399, and WB89 437 were observed in $^1$2CO(2–1) in August 1998 and September 1999 with the refurbished KOSMA 3-m telescope (see Kramer et al. kramertel). The beamsize at 230 GHz is about 19 and the clouds were observed in position switching mode on a 1 raster in galactic coordinates, covering the region where Brand & Wouterloot (brandw1) detected $^1$2CO(1–0) at the lower resolution (and raster) of about 4. We used an acousto-optical spectrometer with a channel spacing of 167 kHz and effective resolution of 360 kHz (0.47 kms$^{-1}$). The sky transmission was estimated by measuring the radiation temperature of the blank sky at the elevation of the sources. Analogous to the standard chopper wheel calibration, the intensities were corrected to the $T_\ast$-scale. The rms noise level in the spectra is about 0.10 – 0.15 K. For the mass calculations (see Sect. results) we used $T_{mb}$ ($\eta_{mb} = 0.7$).

**Interferometer Observations**

WB89 85, 380, and 437 were observed with the three-element BIMA interferometer in 1991 October, May and June, respectively. CO(1–0) observations of WB89 85 and WB89 380 were made with the B- and C-array, and of WB89 437 with the C-array. CS(2–1) observations of WB89 380 were made with the B- and C-array, and of WB89 437 with the C-array. Flux- and phase calibrators were 3C84, BL Lac, and 3C454. The primary beam of the array is 100 at 115 GHz and 117 at 98 GHz. Table obspar lists the parameters of the observations. The instrumental phase and gain were determined with the standard BIMA data reduction package Miriad.

*figure !h2431f1.eps* NRAO 12-m map of CO peak $T_\ast_R$ (left) and $\int T_\ast_R dv$ (right) for $-100 < V_{lsr} < -88$ kms$^{-1}$ for WB89 85. Contour values are 1(1)9 K (left) and 4(4)32 K kms$^{-1}$ (right). The IRAS source position is indicated with the filled circle at (0,0), while the small crosses indicate the observed positions. fig1