HIGH-MASS STAR FORMATION IN THE NEAR AND FAR 3 kpc ARMS

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ABSTRACT

We report on the presence of 6.7 GHz methanol masers, known tracers of high-mass star formation, in the 3 kpc arms of the inner Galaxy. We present 49 detections from the Methanol Multibeam Survey, the largest Galactic plane survey for 6.7 GHz methanol masers, which coincide in longitude, latitude, and velocity with the recently discovered far-side 3 kpc arm and the well-known near-side 3 kpc arm. The presence of these masers is significant evidence for high-mass star formation actively occurring in both 3 kpc arms.

Key words: Galaxy: structure – masers – stars: formation

1. INTRODUCTION

The near 3 kpc arm (van Woerden et al. 1957), existing within 15° of the Galactic center, was long believed to be devoid of any significant star formation (Lockman 1980). The recent discovery of a far 3 kpc arm within the same range of longitudes (Dame & Thaddeus 2008) prompted further thought to this end, the authors speculating the narrow thickness of CO and H\(^\text{I}\) (and a Galactic bar).

Observational evidence already exists for a few regions of star formation within the near 3 kpc arm. Caswell & Haynes (1987) detected approximately five H\(^\text{II}\) regions associated with the near arm and Cersosimo (1990) inferred the presence of more diffuse H\(^\text{II}\) regions through H166α recombination line detections. Additionally, Busfield et al. (2006) kinematically located a group of infrared color selected massive young stellar objects from the Red MSX Source survey with the near arm. These few previous observations are restricted to only the near arm. To fully address the question of star formation in both 3 kpc arms, a reliable and readily observable tracer of high-mass star formation is required.

The methanol maser transition at 6.668 GHz has, since its discovery by Menten (1991), been demonstrated to be exclusively associated with high-mass star formation regions (Minier et al. 2003; Xu et al. 2008). Methanol masers of 6.7 GHz are typically observed toward the early hot core phases of the star formation process (e.g., Minier et al. 2005; Hill et al. 2005; Purcell et al. 2006), and have been found in association with other tracers of the early stages of high-mass star formation, such as infrared dark clouds (Ellingsen 2006) and Extended Green Objects (Cyganowski et al. 2008). They are also found in association with ultracompact regions of ionized hydrogen and are believed to be pumped by infrared radiation (Cragg et al. 2005). This species of maser is bright, widespread, and has already been shown to be present toward the Galactic center, possibly within the inner Galactic bar (Caswell 1996), demonstrating that the exotic environment of this region is not suppressing high-mass star formation.

Individual 6.7 GHz methanol maser sites tend to exhibit emission features over a range of velocities. The velocities of the peaks of the emission features are all typically within a few km s\(^{-1}\) (to at most ~10 km s\(^{-1}\)) of the velocity of the peak of CS (2–1) emission, a reliable tracer of dense gas (e.g., van der Walt et al. 2007). Methanol masers of 6.7 GHz therefore have a good velocity correlation with the molecular clouds in which they live and should trace the same regions in longitude–velocity space as the molecular emission attributed to the near and far 3 kpc arms in Dame & Thaddeus (2008).

2. THE EXISTENCE OF HIGH-MASS STAR FORMATION IN THE 3 kpc ARMS

The region delineated by the 3 kpc arms was observed for 6.7 GHz methanol masers with the 64 m Parkes radio telescope as part of the Methanol Multibeam (MMB) Survey, the full techniques of which are detailed in Green et al. (2009). The MMB has detected over 200 6.7 GHz methanol masers in the region \(-15° < l < 15°\) (J. L. Caswell et al. 2009, in preparation), of which 49 (23 new to the survey, 26 previously known) have the velocity of their peak flux density emission matching that of the near and far 3 kpc arms outlined by Dame & Thaddeus (2008). These 49 masers are shown, together with their velocity ranges of emission, in Figure 1. Three masers toward the Galactic center are most likely associated with Sagittarius B2, rather than the far 3 kpc arm (G000.650 – 0.050, G000.666 – 0.050, and G0.700 – 0.050). The CO emission of the near and far arms have full widths at half-maximums (FWHMs) of 1:1 and 0:52, respectively (Dame & Thaddeus 2008). Assuming full widths to zero of approximately 2:2 and 1:04 means we can exclude any sources with latitudes outside this range. Four sources, G011.500 – 1.484, G345.417 – 0.950, G345.500 + 1.467, and G348.200 + 0.767, are excluded by this criterion (the first coincides with the near-side Norma arm and the middle two the near-side Carina-Sagittarius arm). The remaining 42 masers have peak velocities coincident with the CO emission velocities of the 3 kpc arm features (Figure 1) and show a clear association with the longitude–latitude distribution...
Figure 1. Longitude–velocity diagram of 6.7 GHz methanol maser emission (symbols) and the CO 1–0 emission (contours) of Dame & Thaddeus (2008). The CO 1–0 emission is shown for a latitude of 0° with contours at 10 to 100% of the peak emission. Black diagonal lines delineate the near and far 3 kpc arms as defined by Dame & Thaddeus (2008). Symbols show the peak of the maser emission with the velocity extent of the line delineating the range of velocity over which emission is seen. The 21 blue squares show the masers located in the same longitude–velocity space as the near 3 kpc arm, the 21 red circles those located in the far 3 kpc arm. The green crosses show the 6.7 GHz methanol masers not associated with the arms, including the three masers associated with Sagittarius B2 and the four masers with comparable velocities to the 3 kpc arm sample and that of the complete sample of masers in the longitude range. The individual arm samples do however show a difference in distributions (Figure 3), with the near having a mean latitude of −0.091 with a standard deviation of 0.255 and the far having a mean latitude of 0.040 and a standard deviation of 0.137. A KS test shows a difference in the near and far arm distributions at a greater than 95% confidence level. With regard to the flux density, we see a difference in the medians, but not by the expected factor of 4, with the far side sources (excluding the Sagittarius B2 associations) having a lower median flux density of ∼2.3 Jy compared to the near side sources with a higher median flux density of ∼4.4 Jy. Unfortunately these comparisons are limited by small number statistics, preventing detailed analysis of the distributions. This is exacerbated by potential biasing of the far 3 kpc arm sample by a larger proportion of ambiguous (see the next section) sources, together with fewer detections of weak sources in the far arm.

2.1. Spiral Arm Cross-Over

The kinematics of small regions of the far 3 kpc arm between −15° < l < −10° and the near 3 kpc arm between +10° < l < +15° coincides with the spiral arm loci of the commonly adopted model of Galactic structure of Cordes & Lazio (2002, 2003), when it is applied to a typical rotation curve such as that of Brand & Blitz (1993). The majority of this crossover is with far-side spiral arms, but these are largely extrapolations of the logarithmic fits: for example, the Carina-Sagittarius arm is not significantly traced by either CO or HI at longitude greater than 315° (e.g., Dame et al. 2001; Hartmann & Burton 1997, respectively). However, it is apparent in the CO emission that more features exist in this region, and therefore some caution of the velocity integrated CO emission (Figure 2), providing strong evidence for the existence of high-mass star formation in these regions.

The near and far side 3 kpc arms have distances differing by approximately a factor of 2 (Dame & Thaddeus 2008), which causes the latitude distributions in CO emission to also differ by a factor of 2. We might therefore expect the masers associated with the arms to also show this difference. Likewise, we might expect the flux densities to differ on average by a factor of 4. Whilst we do not see these behaviors conclusively, we do see suggestions. The 3 kpc arm masers, 21 in the near arm, 21 in the far arm, have a mean latitude of −0:050 with a standard deviation of 0:216. This compares with the mean latitude of all the MMB sources in the region, which is −0:102 with a standard deviation of 0:367. A Kolmogorov–Smirnov (KS) test finds no statistically significant evidence for a difference between the latitude distribution in the 3 kpc arm sample and that of the complete sample of masers in the longitude range. The individual arm samples do however show a difference in distributions (Figure 3), with the near having a mean latitude of −0:091 with a standard deviation of 0:255 and the far having a mean latitude of 0:040 and a standard deviation of 0:137. A KS test shows a difference in the near and far arm distributions at a greater than 95% confidence level. With regard to the flux density, we see a difference in the medians, but not by the expected factor of 4, with the far side sources (excluding the Sagittarius B2 associations) having a lower median flux density of ∼2.3 Jy compared to the near side sources with a higher median flux density of ∼4.4 Jy. Unfortunately these comparisons are limited by small number statistics, preventing detailed analysis of the distributions. This is exacerbated by potential biasing of the far 3 kpc arm sample by a larger proportion of ambiguous (see the next section) sources, together with fewer detections of weak sources in the far arm.

Figure 2. Longitude–latitude distribution of the velocity integrated CO 1–0 emission of Dame & Thaddeus (2008) showing the boundary of the emission above 5 K km s⁻¹. The emission is integrated over velocities where the 3 kpc arms are believed to exist (see Dame & Thaddeus 2008 for details). Overlaid are the 6.7 GHz methanol masers associated with the 3 kpc arms (red circles) and the Sgr B2 sources (green crosses) from Figure 1. The masers lie within the CO emission boundaries with the exception of G011.500−1.484 in the near arm and G348.200+0.767 in the far arm; however, we suggest in the text that these should be excluded from the 3 kpc arm population.
should be applied. Hence only those masers outside these crossover regions are considered “unambiguous” (Figure 3).

3. SUMMARY

The 3 kpc arms have previously been believed to be devoid of significant star formation, but the current study shows not only star formation, but high-mass star formation is present in the newly discovered far 3 kpc arm and the well-known near 3 kpc arm. Although the Galactic center is a complex region in which there are a number of interpretations for the patterns and structures seen in longitude–velocity space, there is strong evidence that the 3 kpc arm features are real, and the 6.7 GHz methanol maser detections of the MMB survey have shown that it is very likely they exhibit high-mass star formation. As a consequence, these results imply high-mass star formation should be included in future models of the inner structure of our Galaxy.

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Figure 3. Latitude distribution of 6.7 GHz methanol masers for the inner 15° of Galactic longitude. Top: all the detections of the MMB. Middle: 22 sources associated with the near 3 kpc arm, with solid black showing the unambiguous associations (those that lie outside of the spiral arm crossover regions described in the text). Bottom: 24 sources associated with the far 3 kpc arm (excluding the 3 sources associated with Sgr B2), with solid black again showing the unambiguous associations. The four outlying sources (one in the middle plot and three in the bottom plot) are the four sources identified in the text as probably located nearer than the 3 kpc arms. The latitude spread of the far arm (bottom plot) is clearly smaller than for the near arm (middle plot), a difference mimicking that seen in CO.