

Variations in the Galactic star formation rate and density thresholds for star formation

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ABSTRACT

The conversion of gas into stars is a fundamental process in astrophysics and cosmology. Stars are known to form from the gravitational collapse of dense clumps in interstellar molecular clouds, and it has been proposed that the resulting star formation rate is proportional to either the amount of mass above a threshold gas surface density, or the gas volume density. These star formation prescriptions appear to hold in nearby molecular clouds in our Milky Way Galaxy's disc as well as in distant galaxies where the star formation rates are often much larger. The inner 500 pc of our Galaxy, the Central Molecular Zone (CMZ), contains the largest concentration of dense, high-surface density molecular gas in the Milky Way, providing an environment where the validity of star formation prescriptions can be tested. Here, we show that by several measures, the current star formation rate in the CMZ is an order-of-magnitude lower than the rates predicted by the currently accepted prescriptions. In particular, the region $1^\circ < l < 3.5^\circ$, $|b| < 0.5^\circ$ contains $\sim 10^7 M_\odot$ of dense ($> \text{several } 10^3 \text{ cm}^{-3}$) molecular gas – enough to form 1000 Orion-like clusters – but the present-day star formation rate within this gas is only equivalent to that in Orion. In addition to density, another property of molecular clouds must be included in the star formation prescription to predict the star formation rate in a given mass of molecular gas. We discuss which physical mechanisms might be responsible for suppressing star formation in the CMZ.

Key words: masers – stars: formation – stars: massive – ISM: clouds – ISM: evolution – Galaxy: centre.

1 INTRODUCTION

Stars play a pivotal role in shaping the cosmos. High-mass stars contributed to the ionization of the Universe after the Cosmic Dark Ages. They drive energy cycles and chemical enrichment on galactic scales, hence sculpting galactic structure. Thus, the conversion of gas into stars is fundamental to astrophysics and cosmology.

The rate at which gas is converted into stars has been measured extensively and several different prescriptions for the relation between them have been proposed (see e.g. Schmidt 1959; Kennicutt 1998; Wong & Blitz 2002; Bigiel et al. 2008; Leroy et al. 2008; Narayanan et al. 2008; Kennicutt & Evans 2012; Shetty, Kelly & Bigiel 2012b; Krumholz, Dekel & McKee 2012; Lada et al. 2012). When averaged over hundreds of parsec in nearby galaxies, a strong correlation is observed between the star formation rate (SFR) surface density and the gas surface density (Kennicutt 1998; Bigiel et al. 2008; Kennicutt & Evans 2012). The SFR density is also observed to be linearly proportional to the total gas mass divided by

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the free-fall time multiplied by an efficiency factor estimated to be about 1 per cent (Schmidt 1959; Kennicutt 1998; Krumholz et al. 2012). Observations of nearby star-forming regions show the SFR varies linearly with gas above a local extinction threshold, $A_K \sim 0.8$ mag at a near-infrared wavelength of $2.2 \mu\text{m}$, corresponding to a gas column density of $\sim 7.4 \times 10^{21}$ hydrogen molecules per cm^{-2} or a gas surface density Σ_{gas} , of $\sim 116 M_{\odot} \text{pc}^{-2}$ (Lada et al. 2012). For a typical 0.1 pc radius cloud core, this corresponds to a volume density 3×10^4 hydrogen molecules cm^{-3} .

These relations potentially unify our understanding of SFRs from the nearest star-forming regions to ultra-luminous infrared galaxies (ULIRGs) and even star-forming regions at intermediate to high redshifts (Swinbank et al. 2010; Danielson et al. 2011). In this paper we aim to test the predictions of star formation (SF) scaling relations across large volumes of the Milky Way (MW). In Section 2 we start by looking at the limitations of available observational diagnostics of dense gas and SF activity in the Galaxy, and in Section 3 we present the survey data used in this work. In Sections 4 to 6 we undertake a two-step approach to testing the SF relations using these data.

First we use observational tracers that pinpoint the location of dense gas and SF activity across the whole Galactic plane, with the aim of identifying regions with large deviations in the ratio of dense gas to SF activity. Under the assumption that the proposed SF relations are universal, this ratio should be relatively constant when averaged over large volumes of the Galaxy. However, in Section 4 we show the inner 500 pc of our Galaxy – the central molecular zone (CMZ) – appears deficient in SF activity tracers by at least an order of magnitude given the large reservoir of dense gas available. In Section 5 we investigate if any observational or systematic biases may be causing the observed deficiency in SF activity tracers.

We find no evidence that the results are strongly affected by observational or systematic biases. This motivates our second, follow-up approach in Section 6, where we perform a quantitative analysis of the SFR and gas mass in the CMZ and directly compare this to predictions of proposed column density threshold and volumetric SF relations. In Section 8 we summarize the results and discuss the implications for the universality of SF relations in general.

2 OBSERVATIONAL DIAGNOSTICS OF DENSE GAS AND STAR FORMATION ACTIVITY IN THE MILKY WAY

We aim to test SF scaling relations for representative samples of SF regions across large volumes of the MW. Such systematic studies are now possible thanks to the (near) completion of many blind, multi-wavelength, continuum and spectral line Galactic plane surveys. However, care must be taken in the choice of SF activity diagnostics. All surveys aiming to observe a large fraction of the dense gas in the Galaxy must look directly through the Galactic disc plane. Extinction therefore makes traditional UV, optical and even near-IR diagnostics of SF activity unusable for all but the closest regions. $24 \mu\text{m}$ emission, commonly used to trace SF in extragalactic studies, suffers from extinction only in extreme environments (like the GC) but contamination from evolved stars can be significant, requiring other wavelength data to determine the source nature. Sensitivity and completeness limits mean counting young stellar objects still heavily embedded in their natal molecular clouds can only be done reliably for the closest SF regions.

Diagnostics are required at wavelengths longer than a few hundred micrometre, for which the Galaxy is effectively optically thin. Sub-mm dust continuum emission is a robust gas mass tracer, but

from this alone it is difficult to impose a volume density cutoff on the sample selection. Molecular line emission has the advantage that it can be used to probe gas within a certain density range. The actual density of gas probed by observations of a given transition is related to the critical density of that transition (the density at which the collisional de-excitation rate equals the Einstein A coefficient), but also depends non-trivially on the sensitivity of the observations, the line opacity and gas kinetic temperature. A useful concept, taking into account these affects, is the effective critical density (Evans 1999). For a given transition, this is the density of gas probed by observations of a particular brightness temperature sensitivity for gas at a given kinetic temperature. Assuming detected emission comes from gas at a similar kinetic temperature (a reasonable assumption for dense gas clumps in molecular clouds) and that beam dilution is not an issue, a uniform sensitivity molecular line transition survey offers a natural way to probe the amount of gas at, and above, the effective critical density.

Masers are well-known indicators of SF activity and with strong transitions in the cm/mm wavelength regime they can be detected at large distances. However, it is not currently possible to derive an absolute SFR from first principles using masers. Free-free emission from ionized gas in H II regions created by young high-mass stars is readily traced by cm-continuum and radio recombination line (RRL) emission, both of which are readily observable over large wavelength/frequency ranges (Peters, Longmore & Dullemond 2012). The number count of H II regions can give a handle on the relative numbers of SF sites across the Galaxy. The absolute SFR can be estimated from the luminosity of the cm-continuum emission by calculating the rate of ionizing photons from high-mass stars (Murray & Rahman 2010), although contamination from non-thermal emission (which can lead to an overestimate of the SF activity) must be taken into account, especially towards the GC. It should be noted that each of these SF diagnostics traces the SF activity over different time-scales. Masers are only observed towards regions that are still actively forming stars, so signpost SF activity on time-scales of a few 10^5 yr . Free-free emission from H II regions is observed over the lifetimes of the high-mass stars providing the ionizing photons, i.e. time-scales of a few Myr (Murray & Rahman 2010). When we refer to the SFR throughout this work, we are implicitly talking about SF activity over these time-scales, which is significantly shorter than other diagnostics (e.g. UV emission).

Of the recent and planned surveys,¹ the H₂O Galactic Plane Survey (HOPS: Walsh et al. 2008, 2011; Purcell et al. 2012) is the only blind molecular line survey covering a large fraction (100 deg^2) of the Galactic plane simultaneously in multiple thermal molecular lines (including the important NH₃ molecule), masers and RRLs. Below we describe HOPS and several newly available Galactic plane surveys (see Table 1) which we use to investigate how the SFR relations and proposed density thresholds hold for more representative SF regions across the MW.

3 OBSERVATIONAL DATA

Determining the rate of SF per unit mass of gas requires measuring (i) the total gas mass and (ii) how much SF is taking place within this gas. We make use of recently available NH₃(1, 1) data from HOPS and 70 to $500 \mu\text{m}$ data from the Herschel Infrared Galactic Plane

¹ Although other large Galactic, molecular line mapping projects are also being conducted on the Mopra telescope (e.g. Barnes et al. 2011; Foster et al. 2011; Jones et al. 2012).

Table 1. Properties of the Galactic plane surveys used in this work.

Survey	Angular resolution	Transition or continuum	Frequency or wavelength	l_{\min}	l_{\max}	b_{\min}	b_{\max}	Notes
GBT HRDS	82 arcsec	H86 α –H93 α	9 GHz	–17°	67°	–1°	1°	Targeted H II region survey
HOPS	2 arcmin	NH ₃ (1, 1)	23.4 GHz	–70°	30°	–0°:5	0°:5	$n_{\text{crit}} \sim 10^3 \rightarrow 4 \text{ cm}^{-3}$
HOPS	2 arcmin	Water maser	22 GHz	–70°	30°	–0°:5	0°:5	Traces SF activity
HOPS	2 arcmin	H68 α	22 GHz	–70°	30°	–0°:5	0°:5	Traces H II regions
MMB	~1 arcsec	Methanol maser	6.7 GHz	–180°	20°	–2°	2°	Traces SF activity
Hi-GAL	35 arcsec	Continuum	70, 160, 250, 350, 500 μm	–60°	60°	–1°	1°	Optically thin dust emission ($S_{\nu} \propto M_{\text{gas}}^{\text{dense}}$)

Survey (HiGAL; Molinari et al. 2010) to trace the mass of dense gas across the Galaxy. Ammonia (NH₃) is well known as an excellent tracer of dense molecular gas at all evolutionary phases of the SF process (Ho & Townes 1983; Longmore et al. 2007; Beuther, Walsh & Longmore 2009; Hill et al. 2010; Longmore et al. 2011), including the earliest phases where low temperatures mean molecules like CO freeze out on to dust grains and no longer reliably trace the gas. Given the HOPS sensitivity of 0.2 K we expect to detect gas with an effective critical density of a few 10^3 , probing gas close to, and above, the proposed volume density threshold (Evans 1999). The 500 μm HiGAL data trace optically thin dust emission, providing a measurement of the gas column density along a given line of sight. To directly compare the 500 μm and NH₃(1, 1) emission, we first re-binned the 35 arcsec 500 μm map to the HOPS pixel scale using Montage (<http://montage.ipac.caltech.edu/>), then applied the HOPS NH₃(1, 1) emission mask to the re-binned HiGAL map. This provided the 500 μm emission from all HOPS NH₃ emission regions.

We use data from HOPS and the methanol multi-beam (MMB; Caswell et al. 2010, 2011b; Green et al. 2010, 2012) surveys to detect the 22 GHz water maser emission and 6.7 GHz Class II methanol maser emission, respectively, across the Galactic plane. Both water and methanol masers are well-known indicators of SF activity within molecular clouds. In particular, the 6.7 GHz Class II methanol maser transition is known to exclusively trace regions of high mass ($>8 M_{\odot}$) (Minier et al. 2003).² Water masers are detected towards evolved stars, but these are found outside the disc plane and the emission is typically two orders of magnitude weaker (Caswell et al. 2010). So sensitivity-limited, water maser Galactic plane surveys should predominantly trace SF regions. Removing evolved star contaminants is typically straightforward using other readily available multi-wavelength data (Lumsden et al. 2002).

We use the RRL data from HOPS and the Green Bank Telescope (GBT) H II Region Discovery Survey (HRDS; Anderson et al. 2011) to compare the Galactic H II region number distribution to the dense gas and maser distributions. The HRDS completeness limit is sufficient to detect all H II regions ionized by single O-stars to a distance of 12 kpc. Both HOPS and HRDS use RRLs to detect emission from H II regions and the kinematic dimension helps to mitigate line-of-sight confusion that can affect continuum surveys. HRDS is much more sensitive than HOPS but is a targeted survey based on previous large-area cm-continuum and IR surveys. The HOPS RRL emission is less sensitive but allows for direct comparison with the maser, NH₃ and 500 μm data over the full 100 deg² of the HOPS survey region.

The H II region number counts provide a measure of the relative distribution of SF sites across the Galaxy but we make use of recent analysis of *Wilkinson Microwave Anisotropy Probe* (WMAP) data (Murray & Rahman 2010) to derive the absolute SFR in the GC.

4 COMPARING DENSE GAS EMISSION AND SF ACTIVITY TRACERS ACROSS THE GALAXY

As the Galaxy is optically thin to the NH₃(1, 1), 500 μm , water maser, methanol maser and RRL emission, the emission surface density ratios between these tracers in the plane of the sky is equivalent to that in a face-on view of the Galaxy. Comparing the emission ratios as a function of longitude and making the reasonable assumptions that (i) the integrated intensity of the far-IR and NH₃(1, 1) emission is proportional to the mass of dense gas, and (ii) the number of water masers, methanol masers, H II regions and RRL integrated intensity³ is proportional to the amount of SF, we now investigate the relationship between the dense gas and SFR in the Galaxy.

Fig. 1 shows the dense gas emission and current SF activity tracers as a function of Galactic longitude (l) and latitude (b). The dense gas distribution is dominated by the very bright and spatially extended emission within a few degrees of the Galactic Centre – the CMZ (Morris & Serabyn 1996; Ferrière, Gillard & Jean 2007). This is easily distinguished from the rest of the Galactic plane by the very high intensity of dense gas emission and large gas velocity dispersion as indicated by wide spectral lines. While the dense gas emission is highly concentrated in the CMZ, the distribution of SF activity tracers is relatively uniform across the Galaxy. Quantitatively, the CMZ accounts for ~80 per cent of the integrated NH₃(1, 1) intensity but only contains 4 per cent of the survey area. Yet, the CMZ does not stand out in either water or methanol maser emission, or in the number of H II regions, which all trace recent high-mass SF. A qualitatively similar trend is reported by Beuther et al. (2012) who compare the sub-mm dust continuum emission and Galactic Legacy Infrared Mid-Plane Survey Extraordinaire (GLIMPSE) point sources as a function of Galactic longitude.

Fig. 2 shows Galactic longitude distributions of dense gas and SF activity indicators summed over the observed latitude range ($-0°:5 \leq b \leq 0°:5$) for each longitude pixel. To make a direct comparison of dense gas and SF tracers as a function of longitude, we first sampled in 2° longitude bins to ensure the volume of the Galaxy covered in

² Although the origin of the masers in discs or outflows is debated (e.g. Norris et al. 1998; Minier, Booth & Conway 2000; De Buizer et al. 2009; De Buizer, Bartkiewicz & Szymczak 2012).

³ Deriving absolute SFRs from RRL integrated intensities requires knowing the physical properties (temperature, density, etc.) of the ionized gas, which is known to vary across the Galaxy. For this reason, in this paper we restrict our interpretation of the RRL emission to that of a qualitative tracer of SF activity.

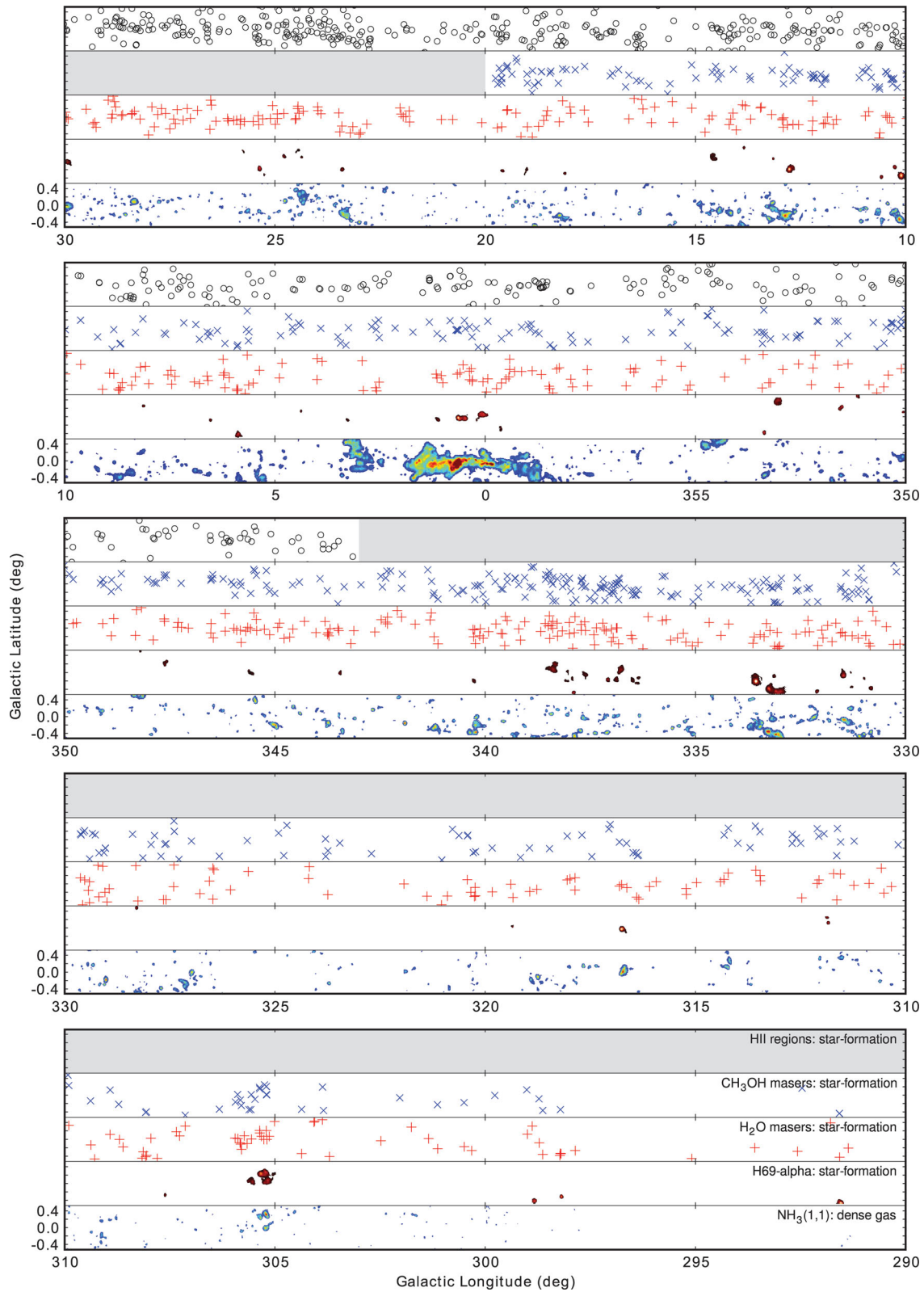


Figure 1. Distribution of dense gas and SF activity tracers as a function of Galactic latitude and longitude. Black circles mark the positions of H II regions, blue crosses show methanol masers and red plus symbols mark water masers. Regions of sky not covered in these surveys are shaded in grey. $\text{NH}_3(1, 1)$ (bottom) and $\text{H}69\alpha$ (second-bottom) integrated intensity emission is displayed using a square-root image stretch. The tracers and their function as either a dense gas or SF activity tracer are labelled at the right-hand edge of the bottom row. The CMZ can be seen as bright, extended $\text{NH}_3(1, 1)$ emission from longitudes of roughly 358° to 4° .

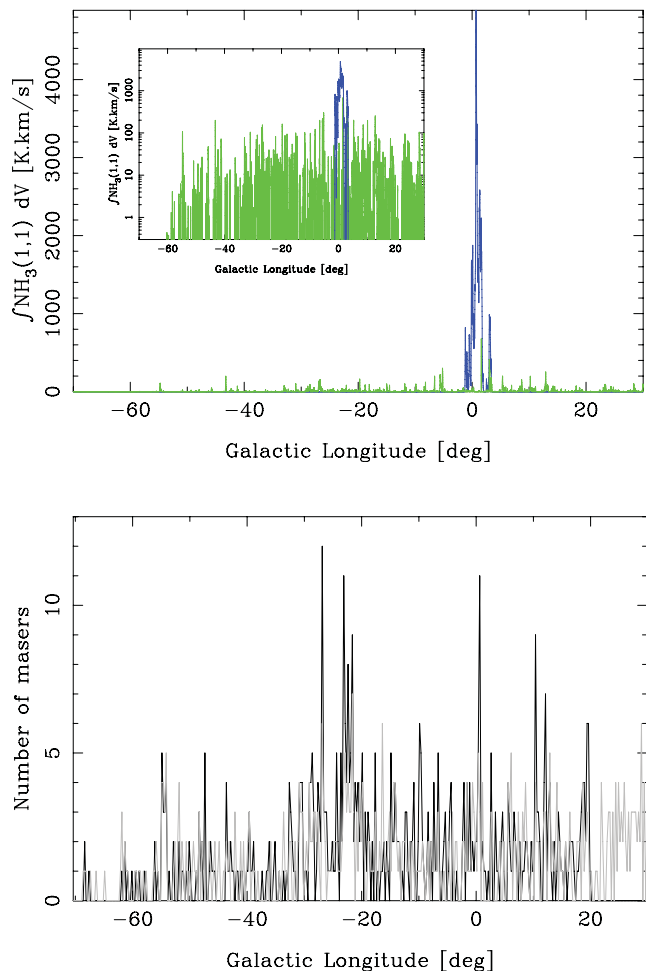


Figure 2. Top: dense gas distribution, traced by the $\text{NH}_3(1, 1)$ integrated intensity, as a function of Galactic longitude (2 arcmin bins). The emission was split into two regions: a Galactic Centre region encompassing the CMZ (blue) and the rest of the Galaxy (green). The Galactic Centre region clearly dominates, accounting for ~ 80 per cent of the $\text{NH}_3(1, 1)$ integrated intensity emission, despite only accounting for ~ 4 per cent of the total survey area. The inset shows the same plot but with a logarithmic scale on the y-axis. Bottom: SF activity, traced by the number of water masers (grey) and methanol masers (black: data for $l > 20^\circ$ unavailable), as a function of Galactic longitude (0:25 bins). In comparison to the $\text{NH}_3(1, 1)$ emission, the distribution of both maser species is relatively flat with Galactic longitude.

each bin contains a large number of SF regions and so is appropriate for testing SF relations (Onodera et al. 2010). The emission or number count in each 2° longitude bin was then normalized by the total emission or number in the full survey area.

The top panel of Fig. 3 shows that there is a strong correlation between independent dense gas tracers. To separate the CMZ emission from that in the rest of the MW, from here on we refer to the region $|l| < 5^\circ$ with $\text{NH}_3(1, 1)$ line widths $\Delta V > 15 \text{ km s}^{-1}$ as ‘GC-only’, to distinguish it from the rest of the Galaxy, which we refer to as the ‘non-GC’ region. No offset is seen in the correlation between the GC-only and non-GC regions. The middle panel of Fig. 3 shows a correlation between the dense gas and SF tracers for the non-GC regions. However, the GC-only regions are clearly distinct, with at least an order of magnitude brighter dense gas emission for the number of SF activity tracers.

The bottom panel of Fig. 3 shows the resulting dense gas versus SF tracer surface density ratio in Galacto-centric radius, R_{GC} , annuli

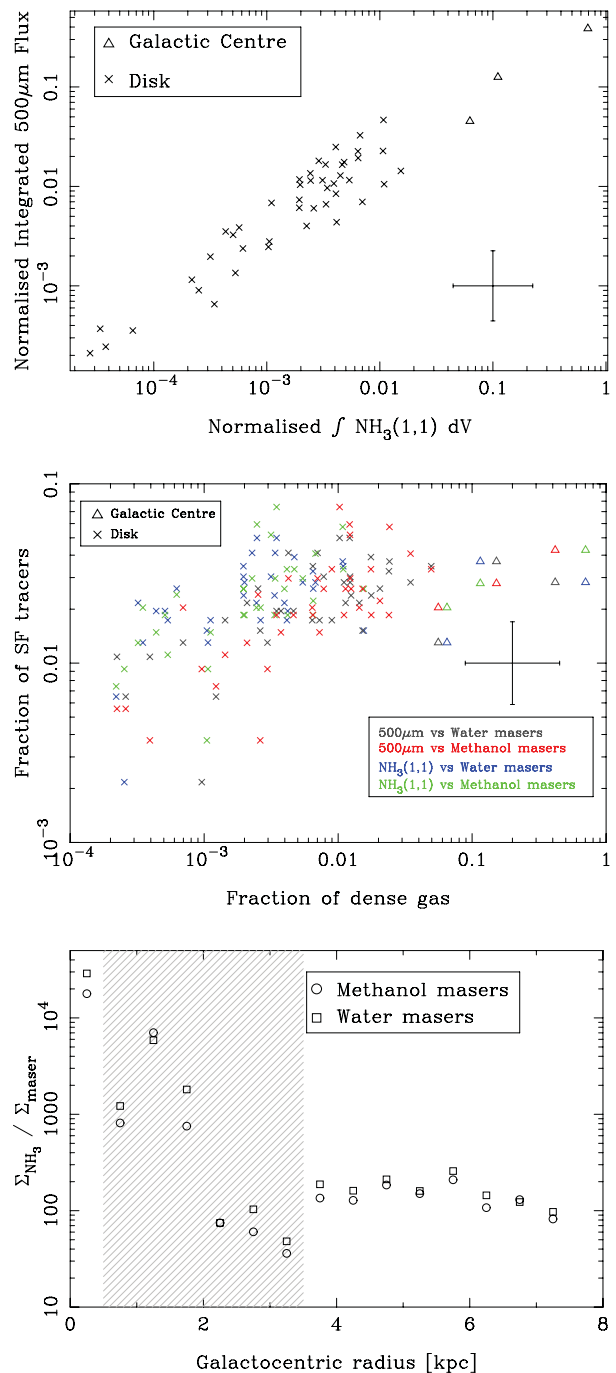


Figure 3. Top: comparison of two independent dense gas tracers, $\text{NH}_3(1, 1)$ integrated intensity versus the integrated $500 \mu\text{m}$ flux, for each 2° longitude bin (normalized to the total flux in that tracer). Middle: the fraction of dense gas tracers [$\text{NH}_3(1, 1)$ integrated intensity and $500 \mu\text{m}$ flux] versus fraction of SF tracers (water and methanol masers) for each 2° longitude bin between $-70^\circ < l < 20^\circ$ (the mutually overlapping coverage of MMB and HOPS). Different colours show different combinations of dense gas and SF tracers. In both top and middle plots, the Galactic Centre (GC-only) and disc (non-GC) regions are shown as triangles and crosses, respectively. Representative uncertainties of a factor of 5 in dense gas mass and 3 in maser counts are shown as error bars. Bottom: ratio of dense gas surface density [$\text{NH}_3(1, 1)$ integrated intensity] to SF surface density (methanol and water masers) as a function of Galacto-centric radius, R_{GC} . The hatched region shows the radial range over which the rotation curve used to derive R_{GC} is unreliable. The surface density ratios over this region should be ignored.

of 0.5 kpc. R_{GC} was calculated using the Galactic rotation curve of Brand & Blitz (1993) and assuming a distance to the Galactic Centre of 8.5 kpc and a solar velocity of 220 km s^{-1} . The gas between the CMZ and $R_{GC} \sim 3 \text{ kpc}$ shows emission at anomalous velocities so the rotation curve does not place reliable constraints on R_{GC} over this range. The surface density ratios over this region, highlighted by the hatched rectangle, should be ignored. The ratio is approximately constant at $R_{GC} > 3 \text{ kpc}$. This suggests the linear relationship observed between the quantity of gas above the proposed extinction threshold and the SFR (Gao & Solomon 2004; Wu et al. 2005; Lada et al. 2012) extends to a larger number of more representative SF regions across the Galaxy. By comparison, the dense gas surface density towards the GC ($R_{GC} < 0.5 \text{ kpc}$) is orders of magnitude too large compared to the SF activity surface density.

5 VARIATION IN SFR PER UNIT MASS OF DENSE GAS BETWEEN THE DISC AND GALACTIC CENTRE?

We now investigate the striking difference between the longitude and surface density distribution of dense gas and SF tracers between the GC-only and non-GC regions (Fig. 3). If the number of masers and H II regions were directly proportional to the integrated intensity of the dense gas emission, as would be expected if assumptions (i) and (ii) outlined in Section 4 hold, and the SFR was set by the amount of dense gas, how many would be expected towards the GC-only region? With $\sim 1/25$ of the HOPS survey area and four times the total $\text{NH}_3(1, 1)$ integrated intensity outside the GC, the GC-only region has ~ 100 times the dense gas integrated intensity per unit survey area compared to the non-GC region. Therefore, the expected number of masers and H II regions towards the GC should also be 100 times larger per unit area. The SF activity per unit area as traced by methanol masers is a factor of 3 to 6 higher in the inner 250 pc of the Galaxy compared to the spiral arms (Caswell et al. 2010). However, our results show that this increase in maser surface density is dwarfed by the increase in the dense gas surface density. Given the amount of dense gas, the GC-only region appears deficient in SF tracers by two orders of magnitude. Taken at face value this suggests large differences in SFR per unit mass of dense gas between the disc and Galactic Centre. Below we investigate if such a large deficit could be caused by observational or systematic biases affecting the emission from one or more of the tracers used in this study.

5.1 Potential observational biases

These data are from blind large-area surveys with approximately uniform sensitivity. Therefore, the results should not be affected by target selection criteria or variable sensitivity. But what about the sensitivity limits themselves? For example, could HOPS be missing a large fraction of the dense molecular gas outside the GC-only region as this $\text{NH}_3(1, 1)$ emission falls beneath the sensitivity threshold? Purcell et al. (2012) show HOPS should detect $400 M_{\odot}$ clumps to 5.1 kpc and $5000 M_{\odot}$ clumps to the Galactic Centre distance. These limits suggest completeness is not a problem.

Alternatively, as the GC-only clouds are more distant on average than the non-GC regions, could there be a large number of weak water masers towards the GC-only region which fall below the HOPS detection limit? Ott et al. (in preparation) have mapped the entire CMZ from 20 to 28 GHz with Mopra in a similar setup to the HOPS observations but with approximately eight times better sensitivity and using the correlator in broad-band rather than

zoom mode (resulting in velocity resolution of 3.5 km s^{-1} rather than 0.4 km s^{-1} as for HOPS). They find approximately twice the number of masers – not enough to account for the apparent deficit.

Sites of maser emission observed with a single dish may be resolved into multiple sites when observed at higher angular resolution with an interferometer. This will not affect the methanol maser counts as they all have interferometric follow-up, but may affect the HOPS water maser distribution. To investigate this, we compared the HOPS detections to approximately four times deeper, interferometric water maser observations towards a 0.5 deg^2 region surrounding the GC (Caswell, Breen & Ellingsen 2011a). In the same region ($|l|, |b| < 0.4$), 27 masers were found compared to the eight found by HOPS, and three of the eight HOPS detections were resolved into two maser sites. If this is representative of the whole GC-only region HOPS may have underestimated the number of water masers by a factor of 3. Preliminary results from a deeper, interferometric EVLA water maser survey covering $|l| < 1.5$, $|b| < 1^\circ$ also recover a similar factor of 3 increase in the number of detections compared to HOPS over the same region (J. Ott, F. Yusef-Zadeh, private communication). This is not sufficient to explain the large disparity between the maser and dense gas distributions in the GC-only and non-GC regions. Just as importantly, there is also no reason to expect a systematic difference between the number of maser sites each HOPS detection will be resolved into between the GC and non-GC regions. This is confirmed by preliminary results from the interferometric follow-up observations of the HOPS masers (Walsh et al., in preparation). As a further check, repeating the analysis using the integrated intensity of the masers (which will not be affected by how many maser sites each HOPS detection is resolved into at higher resolution), rather than number of masers, as a function of longitude produces the same results in Figs 2 and 3. We adopt a conservative factor of 3 uncertainty in the maser counts, which we illustrate by the error bar in the middle panel of Fig. 3. The similarity of both maser distributions in the bottom panel of Fig. 3 gives confidence in the robustness of the maser counts and the adopted uncertainty.

Finally, the trends in Fig. 3 consist of ratios between observed parameters rather than the absolute values of the parameters themselves. The distance-dependence on expected source flux is the same for all observed parameters, so the trend itself will not be affected by systematic differences in distance between the GC-only and non-GC regions. We conclude that there is no evidence that our results may be strongly affected by observational biases.

5.2 Potential systematic biases in the dense gas and SF tracers

Many mechanisms can affect assumption (i) above, the most important of these being: the emission optical depth (assumed to be optically thin); ammonia abundance and gas excitation conditions; dust properties (composition, temperature) and gas-to-dust ratio. These properties will certainly vary from one molecular cloud to another and undoubtedly cause much of the scatter seen in Fig. 3 as well as the non-linear slope in the $\text{NH}_3(1, 1)$ integrated intensity versus $500 \mu\text{m}$ flux. The variation in these properties must be understood before interpreting differences between individual clouds or deriving physical properties of the gas directly from one of these tracers. However, we are averaging over many molecular cloud complexes and are interested in order-of-magnitude variations across the Galaxy so focus on systematic differences between GC-only and non-GC regions.

5.2.1 Potential systematic biases in the dense gas mass estimates

Regarding the mass estimates, the emission optical depth will on average likely be much higher towards the GC-only regions, leading to a substantial underestimate of the dense gas mass towards the GC. This only accentuates the difference between the Galactic Centre and the rest of the Galaxy. However, many observations show the GC excitation conditions and dust temperature are on average higher. The most relevant temperature measurements for this work are those derived directly from NH_3 . Targeted observations of multiple NH_3 inversion transitions towards GC GMCs show these have at least two kinetic temperature regimes – a cool (25 K) component which dominates the column density and a warm (200 K) component which accounts for ~ 25 per cent of the column density (Huettemeister et al. 1993). Beam-averaged temperature measurements at the HOPS resolution results in an average T_K of ~ 50 K for GC clouds (J. Ott, private communication). Compared to ~ 20 K for typical GMCs, this would lead to an overestimate of the GC dense gas mass by a factor of 2–3.

As the average gas kinetic temperature is higher in the GC, the $\text{NH}_3(1, 1)$ effective critical density will be lower. Given the uniform sensitivity of the HOPS observations, this means the GC $\text{NH}_3(1, 1)$ integrated intensity will include emission from lower density gas. As the ultimate goal is to compare the amount of gas across the Galaxy above a single density threshold, including lower density material will lead to a systematic overestimate of this value towards the GC. The magnitude of the overestimate will depend on both the difference between the effective critical density probed towards the GC and the rest of the Galaxy, and how much additional gas in the GC lies between these two effective critical density limits. The $\text{NH}_3(1, 1)$ effective critical density changes by less than a factor of 2 for gas with kinetic temperatures between 10 K and 100 K (Evans 1999). The line brightness temperature of 1 K used in these calculations corresponds to five times the HOPS rms sensitivity and so is a sensible limit. As the average gas kinetic temperature difference between the GC and the Galaxy is much less than this (see above), the effective critical density probed will be very similar. In Section 6 we estimate the average density of gas in the CMZ to be $\sim 5 \times 10^3 \text{ cm}^{-3}$, so most of the gas will be close to or above the effective critical density. We conclude that systematic differences in the effective critical density probed between the GC-only and non-GC regions will not affect the result.

Extrapolating the observed metallicity gradient in the disc of -0.03 to $-0.07 \text{ dex kpc}^{-1}$ (Balser et al. 2011), one would expect the metallicity to increase by a factor of 3–4 from the Sun to the Galactic Centre. While some studies do find an increased metallicity towards the Galactic Centre, others find close to solar values (Shields & Ferland 1994; Najarro et al. 2009). Using the commonly adopted assumption that the Galactic Centre metallicity is twice solar (Ferrière et al. 2007), the gas-to-dust ratio in the Galactic Centre is likely lower by the same value. This means the $500 \mu\text{m}$ flux towards the Galactic Centre systematically overestimates the dense gas mass by a factor of ~ 2 compared to the disc. Similarly, the NH_3 abundance gradient in the disc (Dunham et al. 2011) implies an average factor of ~ 2 relative overestimate in the Galactic Centre NH_3 -derived mass estimate. Both the $500 \mu\text{m}$ and NH_3 dense gas mass estimates therefore overpredict the Galactic Centre mass by a factor of ~ 2 . No systematic effects are known regarding dust composition with Galacto-centric radius.

Another potential worry is related to beam dilution. The $\text{NH}_3(1, 1)$ emission from the GC covers a large angular area on the sky and thus fills the 2 arcmin beam of the HOPS observations. If

the molecular clouds outside of the GC systematically had angular sizes much smaller than the 2 arcmin beam, the measured $\text{NH}_3(1, 1)$ surface brightness would be affected by beam dilution and the integrated intensity would be systematically underestimated. To assess whether this effect is important, we estimated the distance at which molecular clouds of a given mass will be the same angular size as the 2 arcmin HOPS beam. The physical radius as a function of mass was estimated using the Kauffmann & Pillai (2010) empirical mass–size relationship, $M = 870 M_\odot (r/\text{pc})^{1.33}$, for molecular clouds which will proceed to form high-mass stars. Based on this relation, the line in the top panel of Fig. 4 shows the distance at which a molecular cloud of a given mass will have an angular size of 2 arcmin. Molecular clouds below the line will suffer from beam dilution so the observed surface brightness will be reduced, and the integrated intensity underestimated. From this we conclude that beam dilution is undoubtedly an important factor for low-mass clouds at large distances. An implicit assumption in the above anal-

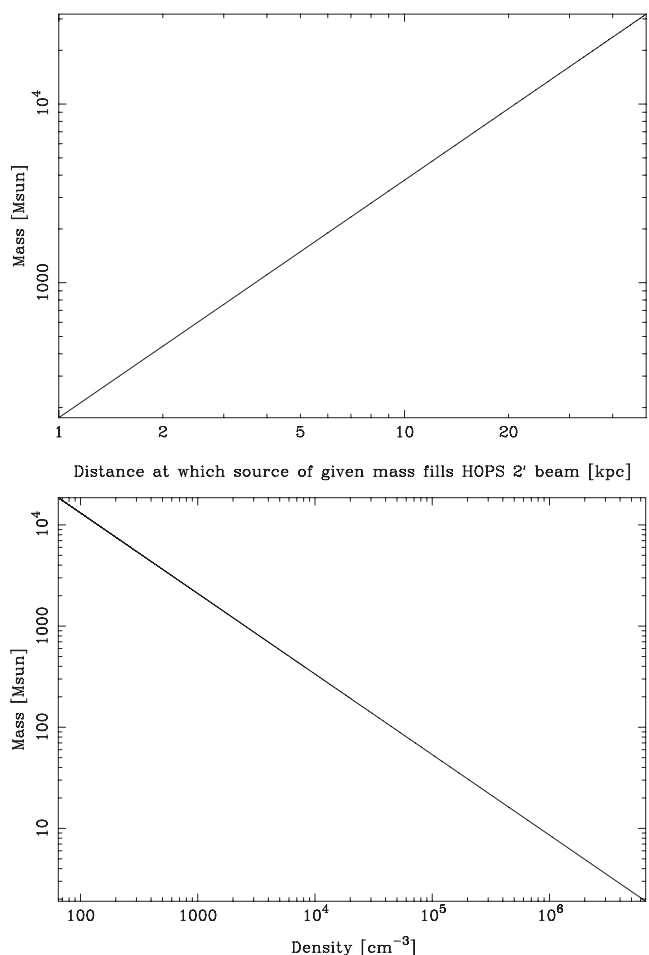


Figure 4. Top: estimating the distance at which molecular clouds of a given mass will be of the same angular size as the 2 arcmin HOPS beam. The physical radius as a function of mass was estimated using the Kauffmann & Pillai (2010) empirical mass–size relationship for molecular clouds which will proceed to form high-mass stars. The line in the plot shows the distance at which a molecular cloud of that mass will have an angular size of 2 arcmin. Molecular clouds below the line will suffer from beam dilution, so the observed surface brightness, and therefore integrated intensity, will be reduced. Molecular clouds above this line will not suffer from this effect. Bottom: density of clouds as a function of their mass, calculated from the Kauffmann & Pillai (2010) empirical mass–size relationship.

ysis is that it is possible to detect the emission from all the gas in the cloud. However, the density fluctuations in molecular clouds mean that some of the gas may lie at low density and not excite NH_3 emission. We can estimate the effect of this by calculating the average density of the gas inferred from the empirical mass–size relation (Kauffmann & Pillai 2010), $n(\text{H}_2) = 3.13 \times 10^3 (r/\text{pc})^{-1.67} \text{ cm}^{-3}$. As shown in the bottom panel of Fig. 4, clouds up to $\sim 1000 M_\odot$ have average volume densities several 10^3 cm^{-3} and above, so we would expect most of the gas to emit in NH_3 . The average density of more massive clouds drops, so the fraction of NH_3 emitting gas will drop too. Although the top panel of Fig. 4 shows HOPS will easily resolve very massive clouds to large distances, the NH_3 emission must come from denser clumps within these clouds. The extent to which beam dilution affects the detected NH_3 emission, if at all, depends on the density fluctuations within the clouds, which will vary from cloud to cloud. However, the fact that in general the larger the cloud, the better it will be resolved, mitigates the fact that less of the gas will be at high density. We conclude that while beam dilution undoubtedly affects low-mass clouds at large distances, it is not an important issue for clouds of a thousand solar masses and greater. It is the clouds in this mass regime that will be forming the high-mass stars traced by methanol maser emission and H II regions.

On balance, the systematic effects would argue that making assumption (i) would overestimate the dense gas mass towards the GC relative to the rest of the Galaxy. However, it seems highly unlikely that these would lead to an overestimate by a factor of ~ 100 . Additionally, as most of these effects are (at least partially) independent between the $500 \mu\text{m}$ and ammonia emission, the fact that no jump is seen in the correlation between the two tracers in Fig. 3 when comparing the GC-only and non-GC regions argues the systematics are not important for the analysis presented here. Based on the above arguments and the observed scatter in the $500 \mu\text{m}$ versus ammonia emission correlation (top panel of Fig. 3), we adopt a factor of 5 uncertainty, which is illustrated by the error bars in Fig. 3.

5.2.2 Potential systematic biases in the maser counts

As water masers are also observed towards evolved stars, contamination may affect the maser number counts. As previously stated, the water masers from evolved stars are found outside the disc plane and the emission is typically two orders of magnitude weaker (Caswell et al. 2010). Therefore, sensitivity-limited, water maser Galactic plane surveys should predominantly trace SF regions. Nevertheless, we are conducting high angular resolution follow-up observations of the HOPS masers to uncover the true nature of each maser detection. Preliminary results show the majority (~ 70 per cent) are associated with SF. Also, no trends in the relative number of masers associated with evolved stars or SF regions are seen with Galactic longitude (Walsh et al., in preparation). In any case, if anything, one might expect more evolved stars towards the bulge and Galactic Centre. Contamination of water masers from evolved stars would lead to an *increase* in number of water masers observed towards the GC. This only strengthens the result. Finally, the similarity of the water maser distribution in the bottom panel of Fig. 3 to the methanol maser distribution (which are not observed towards evolved stars) adds further weight that contamination does not affect the results.

Given the tight constraints on the physical conditions required for masers to exist, another possibility is that maser emission is somehow quenched towards the Galactic Centre region. This seems

plausible given the extreme environmental conditions in the Galactic Centre compared to the rest of the disc (e.g. interstellar radiation field enhanced by 10^3 , external pressure $P/k \sim 10^8$, strong magnetic fields, turbulence, gamma rays: Morris & Serabyn 1996; Ferrière et al. 2007; Crocker et al. 2010). However, masers are formed deeply embedded within GMCs, so they are shielded from the interstellar radiation field. Regarding the effect of turbulence, the coherence path lengths for masers are of the order of au-sized scales, so individual maser emission regions will not be affected by velocity flows or gas kinematics on pc-scales (Mark Reid, private communication). Additionally, extremely bright ‘mega masers’ are known to exist in the circumnuclear discs around supermassive black holes – an even more extreme environment than the CMZ. It is worth pointing out that the pumping mechanisms for water and methanol masers are different. As far as we are aware, no known effect in maser pumping theory can account for the observed factor 100 deficit in the number of both water and methanol masers towards the GC-only region. We conclude there is no evidence that our results are strongly affected by systematic biases in the dense gas and SF tracers.

6 QUANTITATIVE ANALYSIS OF THE SFR AND GAS MASS IN THE CMZ

The previous qualitative analysis strongly points to large differences between the SFR per unit mass of dense gas in the CMZ and the rest of the Galaxy. However, the inability to derive absolute SFRs from first principle for masers and the large uncertainties in deriving masses from $\text{NH}_3(1, 1)$ integrated intensities preclude us from a more quantitative analysis using these tracers. Therefore, we now focus on the CMZ, the region which stands out as potentially discrepant, and aim to directly test the predictions of different SF relations.

6.1 Structure and physical properties of the molecular gas in the Galactic Centre

The Galactic Centre environment has been well studied (Morris & Serabyn 1996; Ferrière et al. 2007). Here we summarize the structure and physical properties of the molecular gas within a Galacto-centric radius (r_{GC}) of 500 pc ($|l| < 3.5^\circ$) – i.e. the CMZ. The CMZ can be decomposed into an outer and inner component, separated at $r_{\text{GC}} \sim 230 \text{ pc}$, and further separated the inner CMZ into a ‘disc’ and torus, with approximate radial ranges of 0 to 120 pc and 130 to 230 pc , respectively (Launhardt, Zylka & Mezger 2002). Based on the far-IR dust continuum emission (Launhardt et al. 2002), the mass of the disc and torus components are derived to be $\sim 4 \times 10^6 M_\odot$ and $\sim 1.6 \times 10^7 M_\odot$, respectively, with a total CMZ mass ($r_{\text{GC}} \leq 500 \text{ pc}$) of $\sim 6 \times 10^7 M_\odot$. Despite the many systematic uncertainties in dust-derived masses, and the notoriously uncertain X-factor affecting CO-derived mass estimates, there is general agreement in the literature that the total molecular gas mass within $r_{\text{GC}} \leq 500 \text{ pc}$ is $2\text{--}6 \times 10^7 M_\odot$ (Ferrière et al. 2007).

Numerous studies have argued for two distinct molecular gas components: a warmer, low-density component ($\leq 10^3 \text{ cm}^{-3}$) of ‘diffuse’ clouds with a large filling factor and comprising ~ 30 per cent of the mass, and a high-density ($\geq 10^4 \text{ cm}^{-3}$) component with a volume filling factor of roughly a few per cent (see Ferrière et al. 2007, for details). Given the effective critical density of the $\text{NH}_3(1, 1)$, it is likely the HOPS observations are tracing the dense component.

The recent far-IR HiGAL survey provides a new, high angular resolution view of the CMZ molecular gas properties (Molinari et al.

2011). We derive the column density maps for the region $-2.5^\circ < l < 3.5^\circ$, $|b| \leq 0.5^\circ$ using well-tested methods (Battersby et al. 2011). A major systematic uncertainty is the assumed dust opacity and we note that we systematically underestimate the mass by a factor of 2–3 compared to the DustEM method (e.g. Molinari et al. 2011) for this reason. Fig. 5 shows the total mass of gas which lies above a range of different column density thresholds. The different curves show the effect on the derived column density of using different wavelength bands and different source-extraction algorithms. From this we conclude the mass derived from the column densities to be robust to the background and source extraction to the 10–20 per cent level.

The vertical lines in Fig. 5 show the Lada et al. (2012) proposed column density threshold of $7.5 \times 10^{21} \text{ cm}^{-2}$, calculated from the Lada et al. (2012) extinction threshold of $A_V = 8 \text{ mag}$ and assuming an $A_V \rightarrow N_{\text{H}_2}$ conversion of $N_{\text{H}_2} = A_V \times 0.95 \times 10^{21} \text{ cm}^{-2}$ (Frerking, Langer & Wilson 1982). This shows that most of the mass in this region lies above an extinction of $A_V = 8 \text{ mag}$. The masses derived from this analysis is reported in Table 2. The total derived mass of the CMZ gas from the HiGAL data is $4.1 \times 10^7 M_\odot$, in good agreement with previous measurements in the literature (Ferrière et al. 2007).

Determining the volume density of the gas from the HiGAL column density maps is not straightforward as it depends on the knowledge of the 3D gas structure. For the most part this is not well constrained towards the Galactic Centre. The region of the CMZ with the best quantified 3D structure is the molecular torus, or ‘100 pc ring’ (Molinari et al. 2011). The volume of gas in a ring of radius R and width ΔR , with a thickness of H , is

$$V = 2\pi R \Delta R H = 4.4 \times 10^{60} \left(\frac{R}{100 \text{ pc}} \right) \left(\frac{\Delta R}{12 \text{ pc}} \right) \left(\frac{H}{20 \text{ pc}} \right) \text{ cm}^{-3}. \quad (1)$$

The fiducial radius of 100 pc is that determined for the ring and the fiducial width of 12 pc is based on the observed column density maps (Molinari et al. 2011). We have used $H = 20 \text{ pc}$ assuming hydrostatic equilibrium ($H/R = v_T / v_c$), the circular velocity $v_c \approx 100 \text{ km s}^{-1}$ while the turbulent velocity $v_T \equiv \sqrt{8 \ln 2} \sigma_v = 20 \text{ km s}^{-1}$ (Oka et al. 2001).

With a mass of $1.8 \times 10^7 M_\odot$ (see Column 5 of Table 2), the volume density for the ring is then

$$n = \frac{M_g}{m_p V} \approx 5000 \left(\frac{R}{100 \text{ pc}} \right)^{-1} \left(\frac{\Delta R}{12 \text{ pc}} \right)^{-1} \left(\frac{H}{20 \text{ pc}} \right)^{-1} \text{ cm}^{-3}. \quad (2)$$

Note that this mass is a factor of ~ 1.7 smaller than reported previously (Molinari et al. 2011) due to the different dust opacities used in that work. The inferred densities in this work are therefore also lower by the same factor. The surface density of the ring is

$$\Sigma_{\text{ring}} = \frac{M_g}{2\pi R \Delta R} \approx 2400 \left(\frac{R}{100 \text{ pc}} \right) \left(\frac{\Delta R}{12 \text{ pc}} \right) M_\odot \text{ pc}^{-2}, \quad (3)$$

or

$$\Sigma_{\text{ring}} = 0.5 \text{ g cm}^{-2}. \quad (4)$$

As the gas in the ring is observed to be clumpy, the density at individual positions along the ring may clearly deviate from these representative values.

The gas in the ring has been modelled as a twisted ellipse with semi-major and semi-minor axes of 100 pc and 60 pc, respectively

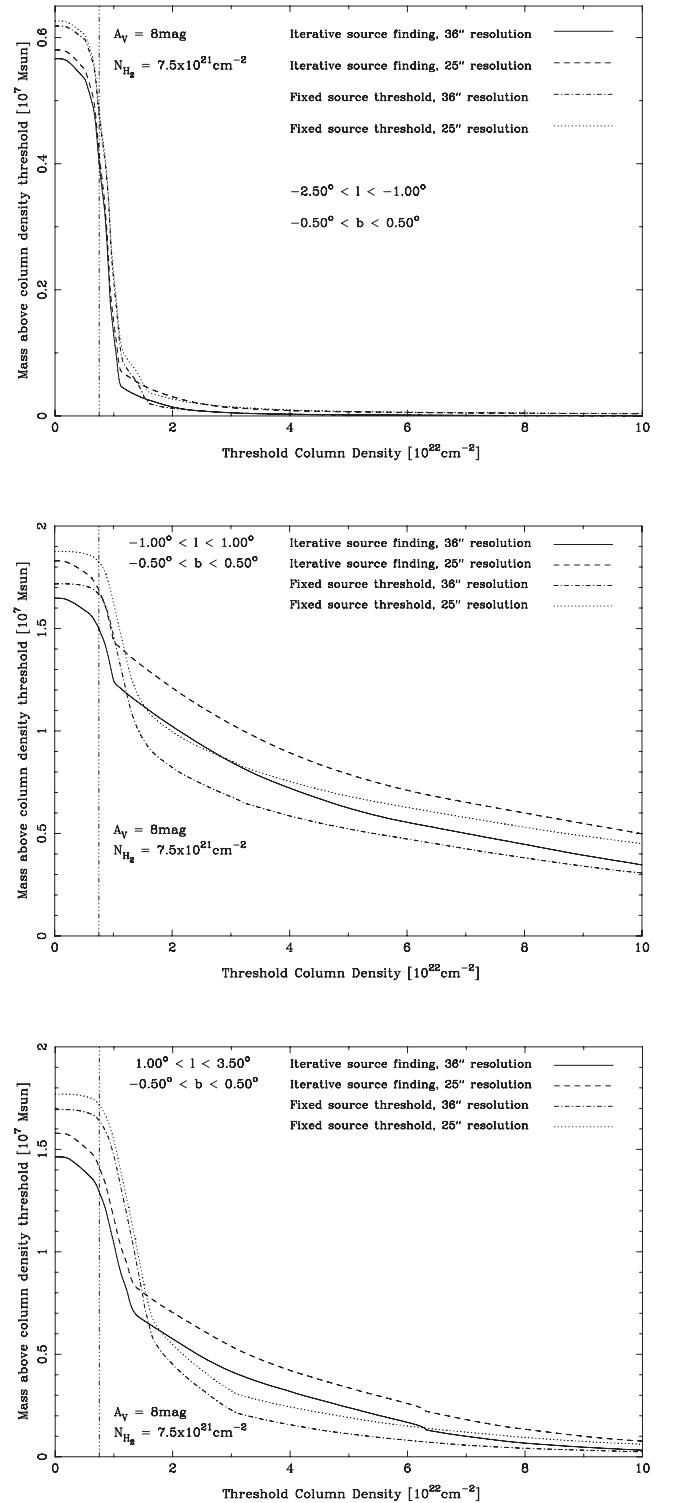


Figure 5. Total mass in various longitude ranges of the CMZ which lies above a range of column density thresholds. The vertical dashed line shows the proposed column density threshold of $7.5 \times 10^{21} \text{ cm}^{-2}$, calculated from the extinction threshold of $A_V = 8 \text{ mag}$ and assuming an $A_V \rightarrow N_{\text{H}_2}$ conversion of $N_{\text{H}_2} = A_V \times 0.95 \times 10^{21} \text{ cm}^{-2}$. The different curves show the effect on the derived column density of using different wavelength bands and different source-extraction algorithms. From this we conclude the column densities are robust to the 10–20 per cent level.

Table 2. Gas mass and ionizing photon rate (Q) for various longitude and latitude ranges of the CMZ. The second row corresponds roughly to the longitude range for the inner ~ 150 pc of the CMZ. The first and third rows correspond roughly to the longitude ranges of the outer ~ 150 to ~ 500 pc of the CMZ, in the negative and positive longitude ranges, respectively. The gas masses are derived from the HiGAL column density maps. The value in Column 5 is the total mass in that longitude and latitude range, whereas Column 6 reports the mass above the column density threshold corresponding to an extinction of $A_V = 8$ mag (see text for details). The range in values in Column 7 corresponds to the total Q assuming near and far kinematic distances, respectively (Lee et al. 2012). Column 8 gives the fraction (in per cent) of the total Galactic molecular gas contained in Column 5, assuming a total Galactic molecular gas mass of $2 \times 10^9 M_\odot$. Column 9 gives the fraction (in per cent) of the total Galactic Q of $2.9 \times 10^{53} \text{ s}^{-1}$ (Lee et al. 2012). Column 10 gives the corresponding SFRs for each of the regions. The values in parentheses in Columns 7, 9 and 10 are the Q values over the same longitude regions if the latitude range is doubled to $|b| < 1^\circ$. Only the $|l| < 1^\circ$ longitude range is affected. The SFRs in Columns 11 and 12 are those predicted from the column density threshold and volumetric SF relations, respectively (see text for details).

b_{\min} ($^\circ$)	b_{\max} ($^\circ$)	l_{\min} ($^\circ$)	l_{\max} ($^\circ$)	Mass ($10^7 M_\odot$)	Mass $_{A_V \geq 8}$ ($10^7 M_\odot$)	Q (10^{51} s^{-1})	Mass/ M_{TOT} (per cent)	Q/Q_{TOT} (per cent)	SFR $_Q$ ($M_\odot \text{ yr}^{-1}$)	SFR $_{A_V \geq 8}$ ($M_\odot \text{ yr}^{-1}$)	SFR $_\rho$ ($M_\odot \text{ yr}^{-1}$)
-0.5	0.5	-2.5	-1.0	0.6	0.4	2–6	0.3	1.3	0.016	0.184	0.14
-0.5	0.5	-1	1	1.8	1.7	3–4(13)	0.9	1.2(4.5)	0.012–0.018(0.06)	0.782	0.41
-0.5	0.5	1	3.5	1.7	1.6	0.1–2	0.85	0.3	0.0036	0.736	0.39

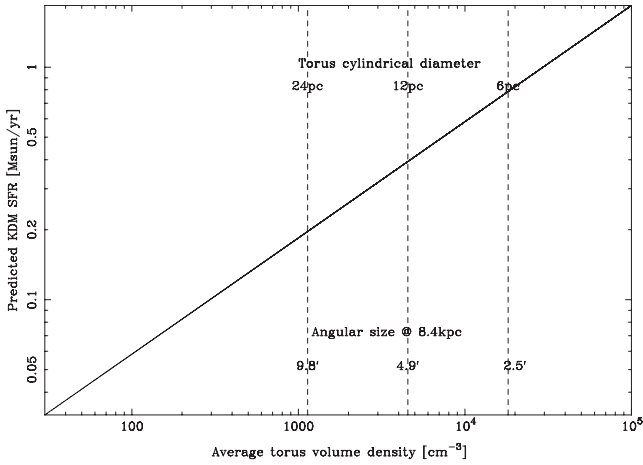


Figure 6. The predicted SFR from the Krumholz et al. (2012) volumetric relation as a function of the average gas volume density. The dashed vertical lines show the average volume density assuming that $1.8 \times 10^7 M_\odot$ of gas in the region $|l| < 1^\circ$, $|b| < 0.5^\circ$ (see Table 2) lies in a cylindrical ring with semi-major and semi-minor axes of 100 pc and 60 pc, respectively, with the diameter specified by the annotation for each line. The observed thickness (and hence the inferred diameter) of the ring varies from ~ 6 pc to factors of several larger. We estimate the average volume density to be $\sim 5 \times 10^3 \text{ cm}^{-3}$, with a corresponding predicted SFR of $\sim 0.4 M_\odot \text{ yr}^{-1}$.

(Molinari et al. 2011). The dashed vertical lines in Fig. 6 show the average volume density assuming the ellipse has the average cylindrical diameter (i.e. $H = \Delta R$) specified by the annotated values. From the measured height of the ring projected on the plane of the sky we estimate the average volume density to be $\sim 5 \times 10^3 \text{ cm}^{-3}$. This agrees well with the analytical estimate above and also volume densities estimated by previous authors for the dense component of the CMZ molecular gas (see above).

We note that the gas volume density and interpretation of the measured column density change considerably if the gas structure is different than assumed above. For example, in the worst-case scenario, if the gas assumed to make up the ring actually lies in a uniform disc with the same radius, the volume density would drop to around a few 10^2 cm^{-3} . Additionally, the measured column density would be highly dependent on the viewing angle, and appear much larger if viewed through the disc plane rather than in a face-on view of the Galaxy. In this case it would not be fair to test the predictions of the column density threshold SF relations using the directly measured column density without taking this into account.

However, several lines of evidence suggest this is not the case. On top of the modelling which successfully reproduces the gas kinematic structure (Molinari et al. 2011), the analysis of emission from many high critical density molecular line transitions shows the majority of the gas in the CMZ is cold, has a density $\gtrsim 10^4 \text{ cm}^{-3}$ and has a volume filling factor of only a few per cent. In addition, if the gas was uniformly distributed, one would expect optically thin emission (e.g. from sub-mm dust emission) to peak along the line of sight with the largest path length, i.e. directly through the centre. In fact, the emission intensity increases towards the edges, directly contradicting what would be expected from a uniform disc, and as expected from the emission arising in a ring.

6.2 Measured CMZ SFR values

Values of the SFR for the CMZ in the literature vary by factors of several, but recent measurements based on number counts of massive young stellar objects appear to converge to a value close to $0.1 M_\odot \text{ yr}^{-1}$ (e.g. $0.14 M_\odot \text{ yr}^{-1}$ and $0.08 M_\odot \text{ yr}^{-1}$; Yusef-Zadeh et al. 2009; Immer et al. 2012).

As an alternative approach, we make use of the recent analysis of *WMAP* data (Murray & Rahman 2010) to determine the fraction of ionizing photons in the Galaxy coming from the GC. This analysis offers many advantages over older estimates of the ionizing photon flux. *WMAP* data has much better absolute flux precision, suffers less from spatial filtering and covers a large frequency range. From this data an accurate spectral index of the emission can be calculated allowing the relative contributions from free-free, non-thermal and spinning dust emission to be determined. Although the *WMAP* beam is large, $\sim 1^\circ$ at the lowest frequencies, the free-free emission in the Galaxy is dominated by the so-called ‘extended low density’ (ELD) H II emission, rather than classical H II regions (Murray & Rahman 2010).

Based on the free-free-only contribution to the 33 GHz flux, corrected for dust attenuation, the rate of ionizing photons, Q , across the Galaxy is measured to be $2.9 \times 10^{53} \text{ s}^{-1}$ (Lee, Murray & Rahman 2012). The SFR, \dot{M}_* , is then given by (Murray & Rahman 2010)

$$\dot{M}_* = Q \frac{\langle m_* \rangle}{\langle q \rangle} \frac{1}{\langle t_Q \rangle}, \quad (5)$$

where $\langle q \rangle$ is the ionizing flux per star averaged over the stellar initial mass function and $\langle m_* \rangle$ is the mean mass per star. The quantity $\langle t_Q \rangle$ is the ionization-weighted stellar lifetime, or time at which the ionizing flux of a star falls to half its maximum value, averaged

over the initial mass function (IMF).⁴ Murray & Rahman (2010) show that

$$\frac{\langle m_* \rangle}{\langle q \rangle} = 1.59 \times 10^{-47} \text{ M}_\odot \text{ s} \quad (6)$$

and

$$\langle t_Q \rangle = 3.9 \times 10^6 \text{ yr}. \quad (7)$$

The reason this time-scale is small compared to the average lifetime of stars in a cluster is because $\langle t_Q \rangle$ is dominated by stars $> 40 \text{ M}_\odot$ (Murray 2011). While stars of $\geq 8 \text{ M}_\odot$ (with lifetimes significantly longer than $\langle t_Q \rangle$) produce ionizing photons, the main-sequence lifetime of stars $> 40 \text{ M}_\odot$ is a slowly varying function of mass, while the ionizing photon output continues to increase rapidly. The *WMAP* observations are therefore sensitive to SF over the past $\sim 4 \text{ Myr}$.

From the total rate of Lyman continuum photons in the Galaxy of $Q = 2.9 \times 10^{53} \text{ s}^{-1}$, the total SFR is calculated to be $1.2 \text{ M}_\odot \text{ yr}^{-1}$ (Lee et al. 2012). Note that this value is sensitive to the form of the IMF adopted, especially the slope of the upper mass end, Γ . A Salpeter (1955) value is adopted for Γ ($\Gamma = 1.35$) and Murray & Rahman (2010) discuss in detail the robustness of the derived SFR when using different commonly used forms of the IMF. The interested reader is referred to their paper for further details.

In Table 2 we show the Q values for the same latitude and longitude regions as the previous gas mass calculations. The range of values in Column 7 show the total Q assuming the near and far kinematic distances. Column 9 gives the fraction of the total Galactic Q that the average of these values corresponds to. Based on this analysis, for the latitude range of $|b| < 0.5$, the longitude ranges $-2.5 < l < -1.0$, $|l| < 1^\circ$ and $1^\circ < l < 3.5$ therefore have SFRs of ~ 0.016 , ~ 0.015 and $\sim 0.0036 \text{ M}_\odot \text{ yr}^{-1}$, respectively. We report these numbers in Table 2.

This means that in total ~ 2.8 per cent of the SF in the Galaxy lie in this l and b range. Although this encompasses the region most people would use to define the CMZ, given the different angular resolutions of the studies used to derive the mass and SFR, we check to make sure the hard l and b boundary imposed is not affecting this result. The *WMAP* data extend to higher latitudes, and we note that including the latitude range $|b| < 1^\circ$ for the $|l| < 1^\circ$ region increases the maximum Q by a factor of ~ 3 . The total SFR over this larger region is $0.06 \text{ M}_\odot \text{ yr}^{-1}$. The Q values over the larger latitude range are shown in parentheses in Columns 7, 9 and 10 of Table 2. The other longitude regions are not affected by increasing the latitude range. As a final check, we note that the total Q in the much larger region $|l| < 4^\circ$, $|b| < 1^\circ$ is $\sim 1.80 \times 10^{52}$, corresponding to ~ 6.1 per cent of the total Galactic SFR.

6.3 Comparing measured CMZ gas mass and SFRs with those predicted from SF relations

We now compare the measured gas mass and SFRs determined for the CMZ above with the values predicted from the column density threshold and volumetric SF relations.

6.3.1 Column-density threshold SF relation: predicted CMZ SFR

The Lada et al. (2012) column density threshold relation proposes the SFR in a molecular cloud is set by the amount of gas above a column density threshold corresponding to an extinction of $A_V = 8 \text{ mag}$. This is parametrized through $\text{SFR} = 4.6 \times 10^{-8} (f_D) M_{\text{gas}}(\text{M}_\odot) \text{ M}_\odot \text{ yr}^{-1}$, where the factor f_D is the fraction of the total gas mass (M_{gas}) above the column density threshold. Table 2 shows the mass of gas above the column density threshold for the three different CMZ regions. Based on these mass measurements, the predicted SFRs for these regions are 0.18, 0.78 and $0.74 \text{ M}_\odot \text{ yr}^{-1}$. These values are listed in Column 11 of Table 2.

6.3.2 Volumetric SF relation: predicted CMZ SFR

Next we consider the Krumholz et al. (2012) volumetric SF relation which is parametrized through:

$$\frac{\text{SFR}}{[\text{volume}]} = \eta \frac{M_{\text{mol}}}{[\text{volume}]} \frac{1}{\tau_{\text{ff}}} = 0.01 \frac{M_{\text{mol}}}{[\text{volume}]} \frac{1}{\tau_{\text{ff}}}, \quad (8)$$

where the SFR in a given volume of gas per free-fall time (τ_{ff}) is determined by the mass of the molecular gas (M_{mol}) in that volume and a global efficiency of gas converted to stars per free-fall time, η , of 1 per cent. The free-fall time is

$$\tau_{\text{ff}} \equiv \sqrt{\frac{3\pi}{32G\rho}} = 3.6 \times 10^5 \left(\frac{10^4 \text{ cm}^{-3}}{n} \right)^{1/2} \text{ yr}. \quad (9)$$

The free-fall time, and hence gas density, for the gas in the GC clearly plays an important role in setting the predicted SFR. As discussed in Section 6.1, the region of the CMZ with the best constrained gas structure is the 100 pc ring (see Section 6.1). From equations (8) and (9), the SFR predicted by the volumetric relation is given by

$$\dot{M}_* = \eta M_g / \tau_{\text{ff}} = 0.53 \left(\frac{n}{8000 \text{ cm}^{-3}} \right)^{1/2} \text{ M}_\odot \text{ yr}^{-1} \quad (10)$$

for $\eta = 0.01$. This is 20 times the observed SFR. The fiducial predicted SFR increases to $0.9 \text{ M}_\odot \text{ yr}^{-1}$ for $\eta = 0.017$ (e.g. Kennicutt 1998).

Given the clumpy nature of the gas in the ring, for illustrative purposes, Fig. 6 plots the predicted SFR as a function of the gas density. The dashed lines show the range in observed thickness (Molinari et al. 2011), or scale height H (and hence the inferred radial extent ΔR if the ring is cylindrical) of the ring from $\sim 6 \text{ pc}$ to factors of several larger.

We note that if instead of using the observed geometry of gas, one assumes the GC gas mass is spread over a uniform disc of diameter $\sim 100 \text{ pc}$, the expected free-fall time significantly increases, and the predicted SFR drops considerably. Using this much larger free-fall time might be appropriate if the time-scale for SF in the GC was set by the time it would take the gas to collapse to the centre of the ring. However, the observed gas dynamics show that the ring is not collapsing towards the centre, but rather rotating around the centre of the ring (Molinari et al. 2011). In addition the gas in the ring clearly fragments, and the free-fall time at the observed local density is much shorter than the time it would take to collapse to the centre (assuming no rotational support). We conclude that the observed local volume density of $\sim 5\text{--}8 \times 10^3 \text{ cm}^{-3}$ is the correct density to use for the purpose of calculating the free-fall time.

We believe the reason our results contradict previous authors who have concluded the CMZ lies on the S-K relation (e.g. Yusef-Zadeh et al. 2009; Kennicutt & Evans 2012) is because they assumed the

⁴ Assuming high-mass stars are well selected from the IMF as expected if their formation is intrinsically linked with the formation of massive stellar clusters (e.g. Smith, Longmore & Bonnell 2009). However, this assumption may be affected if stochastic sampling of the IMF is important (see e.g. Bressert et al. 2012a).

observed CMZ gas lies in a uniform disc and thus had a much lower average volume density.

Assuming the rest of the gas in the outer CMZ is at a similar density to that in the torus (Ferrière et al. 2007), the predicted SFR for the $-3.5 < l < -1^\circ$ and $1^\circ < l < 2.5$ regions are 0.14 and $0.39 \text{ M}_\odot \text{ yr}^{-1}$, respectively. The predicted SFR values are listed in Column 12 of Table 2.

6.3.3 Predicted versus measured SFR values

The predicted SFRs in Table 2 for both the column density threshold and volumetric SF relations agree to within a factor of 2. The measured SFRs are at least a factor of 10 smaller than the predicted values for all three regions. The region of the outer CMZ at positive longitudes (i.e. $1^\circ < l < 3.5$) stands out as extreme in this regard. Despite containing almost the same reservoir of gas as the inner CMZ (i.e. $|l| < 1^\circ$), it has a much lower measured SFR. Both the column density threshold and volumetric SF relations overpredict the SFR in this region by two orders of magnitude.

However, the SFR predictions for the volumetric SF relation in Table 2 rely on the assumption that the volume density of the outer CMZ is similar to that determined for the inner CMZ ‘100 pc ring’. Given the uncertainties in determining the gas density from the measured surface density, we can approach the problem from a different direction and ask what gas densities would be required to produce the measured SFR from the measured gas masses? As shown in Table 2, the $1^\circ < l < 3.5$ region contains 0.85 per cent of the total molecular gas in the Galaxy and 0.3 per cent of the total SF. From equation (8), the density of the clouds in this region should be 0.1 times the density of those in the disc, or $0.1 \times 250 \text{ cm}^{-3} \sim 25 \text{ cm}^{-3}$. This is unfeasibly low.

We conclude the column density and volumetric SF relations overpredict the SFR in the CMZ by an order of magnitude.

7 THE EFFECT OF POSSIBLE VARIATIONS IN THE IMF

Diagnostics of SF activity generally rely on emission coming predominantly from high-mass stars. The observations used to derive the SFRs in Section 6.2 directly measure the number of ionizing photons in a given SF region. From this, a strong constraint can be placed on the number of high-mass stars producing Lyman continuum photons in that region. As discussed in Section 6.2, calculating a SFR from this measurement relies on extrapolating from the determined number of high-mass stars to the total stellar population, using an assumed analytical form of the IMF.

There is no clear observational evidence that the IMF varies strongly and systematically as a function of initial conditions in the Galaxy, including towards the Galactic Centre (see Bastian, Covey & Meyer 2010, for a review). However, if there was some systematic, and as yet unobserved, difference between the stellar mass functions in the Galactic Centre and the rest of the disc this may explain the discrepancy between the predicted and observed SFRs in Section 6.3.3. For example, if the Galactic Centre IMF was substantially bottom-heavy, i.e. more low-mass stars than predicted from standard forms of the IMF, the measured ionizing flux calculated in Section 6.2 would systematically underestimate the SFR.

While a bottom-heavy IMF may potentially reconcile the observed dense gas properties with the SFRs predicted by the relations in Section 6.3, it opens the uncomfortable prospect of an IMF which produces a factor of 10 to 100 more mass in low-mass stars

than expected. Claims have recently been made that external galaxies show evidence for having bottom-heavy IMFs (e.g. Cappellari, McDermid & Alatalo 2012; Conroy & van Dokkum 2012). Cappellari et al. (2012) report this can lead to factor of ~ 3 differences in galactic stellar mass. The gas in the CMZ is known to be very different from that in the rest of the MW disc (see Section 8), and it is interesting to speculate how similar the properties of the gas in the CMZ are to those in the early-type galaxies (in which the claimed IMF variations are seen) when they were forming the bulk of their stars that we observe at the present day. Regardless, even if IMF variation in the CMZ led to a factor of ~ 3 underestimate in the stellar mass determined in Section 6.2, this alone is insufficient to explain the observed factor of 10 to 100 paucity in SF. Variations in the IMF have also been claimed for stellar clusters towards the Galactic Centre (e.g. the Arches), but these claims have been for exactly the opposite scenario – a top-heavy and not bottom-heavy stellar mass function (see Bastian et al. 2010, and references therein).

Claims of observed variations in the IMF are numerous, notoriously difficult to confirm and have a tendency to disappear under scrutiny. However, an extremely bottom-heavy IMF in the CMZ cannot be ruled out as an explanation for the observed dense gas versus SFR relations reported in this work. In future it would clearly be desirable to repeat the measured SFRs towards the CMZ with diagnostics more sensitive to lower-mass stars.

8 SUMMARY AND DISCUSSION

In summary, we find that the dense gas (NH_3 and $500 \mu\text{m}$) and SF activity tracers (masers and H II regions) used in this study are reliably tracing the present-day relative dense gas mass and SF activity distributions, respectively, across the Galaxy. We conclude that the striking difference between the dense gas and SF activity tracers between the GC-only and non-GC regions shows the current SFR per unit mass of dense gas is an order of magnitude smaller in the GC than in the rest of the Galaxy. We directly test the predictions of proposed column density threshold and volumetric SF relations and find that, given the mass of dense gas in the GC, they overpredict the observed SFR in the GC by an order of magnitude. We conclude the current SF relations are incomplete in some way. Any universal column/volume density relations must be a *necessary but not sufficient* condition for SF to occur.

Putting the CMZ in the context of the Galaxy as a whole, the MW contains $\sim 2 \times 10^9 \text{ M}_\odot$ of gas (Kalberla & Kerp 2009), so the CMZ holds roughly a few per cent of this. The *WMAP* analysis shows that the CMZ also contains a few per cent of the ionizing photons, and hence SF, in the Galaxy. Both the volumetric and surface density SF relations predict that a given mass of gas will form stars more rapidly if the respective densities are larger. Yet the gas in the CMZ, which has a much higher surface and volume density than any comparable mass of gas in the disc of the MW, forms stars at a rate proportional to the ratio of gas in the CMZ to that in the MW.

Something is required to slow the rate of SF in the CMZ compared to that in the rest of the MW. An additional support mechanism, not taken into account in either the column density threshold or volumetric SF relations, may be responsible for inhibiting the SF. One potential solution is therefore an additional term or threshold in the proposed SF relations. The most noticeable difference between clouds in the CMZ and the rest of the MW, apart from the 1 to 2 order of magnitude larger volume density, is the order of magnitude larger internal cloud velocity dispersion (Morris &

Serabyn 1996; Ferrière et al. 2007; Shetty et al. 2012a). We thus conclude that it is likely that the relevant term is related to the additional turbulent energy in the gas providing support against gravitational collapse. A simple way to parametrize this is through the linewidth ratio, $\Delta V_{\text{ratio}} = \Delta V / \Delta V_0$, where ΔV_0 is the typical internal cloud velocity dispersion in disc molecular clouds. The Schmidt law could then be re-expressed either in terms of surface density, $\Sigma_{\text{SFR}} \propto (\Sigma_{\text{gas}})^\alpha / (\Delta V_{\text{ratio}})^b$ ($\alpha \sim 1$ to 1.4 ; $b \sim 1$), or mass of gas above the density threshold, M_{dense} , through, $\Sigma_{\text{SFR}} \propto M_{\text{dense}} / (\Delta V_{\text{ratio}})^b$. This would reconcile the SF in the CMZ with that in the rest of the Galaxy. Theorists have wrestled with this before (e.g. Krumholz & McKee 2005; Padoan & Nordlund 2011; Krumholz et al. 2012) and we are currently seeking to test these scenarios.

However, even if the extreme environmental conditions in the CMZ do inhibit SF, they do not stop it entirely. The CMZ contains Sgr B2, one of the most extreme cluster-forming regions in the Galaxy. It also contains high-mass star clusters like the Arches and Quintuplet, and at least one molecular cloud which appears to be the progenitor of such massive stellar clusters (Bressert et al. 2012b; Longmore et al. 2012). Evidence exists of episodic SF events in the CMZ (Sofue & Handa 1984; Bland-Hawthorn & Cohen 2003; Yusef-Zadeh et al. 2009; Su, Slatyer & Finkbeiner 2010) and mechanisms exist to explain how such episodic SF can occur. Gas in barred spiral galaxies like the MW is funnelled from the disc through the bar to the GC (Kormendy & Kennicutt 2004; Sheth et al. 2005). If gas is continually fed from the disc to the GC, and the environmental conditions impose a higher threshold for SF to occur, the gas might build up until reaching a critical point before undergoing a burst of SF.

Although clouds near the Galactic Centre in the MW and other galaxies may only represent a small fractional volume of a galaxy, they can contribute a significant fraction of the total dense molecular gas. In terms of dense gas mass and environmental conditions, the Galactic Centre also acts as a bridge between local SF regions in our Galaxy and SF environments in external galaxies. Understanding why such large reservoirs of dense gas deviate from commonly assumed SF relations is of fundamental importance and may help in the quest to understand SF in more extreme (dense) environments, like those found in interacting galaxies and at earlier epochs of the Universe.

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