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A general catalogue of 6.7 GHz methanol masers

II. statistical analysis

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ABSTRACT

Context. Methanol masers at 6.7 GHz are recognised markers of high-mass star formation regions. The study of their distribution in the Galaxy gives important insights into the star formation activity of the Milky Way. We present a statistical analysis on the General Catalogue of 6.7 GHz methanol masers in the Galaxy with the aim of extracting global properties of the masers.

Aims. We provide constraints on the luminosity function of 6.7 GHz methanol masers and on their total number in the Galaxy.

Methods. We model the spatial distribution of the masers in the Milky Way by using their distribution in galactocentric distance which is unambiguous once a rotation curve for the Galaxy is assumed. This is the starting point for determining the luminosity function of the masers.

Results. The luminosity function of 6.7 GHz methanol masers is modelled as a power-law with sharp cutoffs and having an index lying between −1.5 and −2. We also predict the number of detections of methanol masers assuming different sensitivity limits in the observations.

Key words. stars: formation – masers – ISM: HII regions – ISM: molecules

1. Introduction

Since its discovery by Batrla et al. (1987) and Menten (1991) the bright maser emission from methanol (at 12.2 and 6.7 GHz respectively) has become a reliable tool for detecting and studying regions where (massive) stars form and are in their very early stages of evolution (see e.g. Ellingsen 2006). Methanol masers were divided into two empirical classes, I and II (Menten 1991). Class II masers are detected close to strong Infrared sources (as e.g. Ultra Compact (UC) HII regions), while class I are observed offset from these objects, in the shock regions of their outflows. Theoretical modelling was able to identify class I masers as collisionally pumped masers, while class II as radiatively pumped ones (e.g. Sobolev et al. 1997; Cragg et al. 2001, 2005).

Observations of methanol maser sites at other wavelengths support the paradigm of methanol masers as one of the first signposts of massive star formation (e.g. Walsh et al. 1999; Goedhart et al. 2002; Pestalozzi et al. 2002a). Being very bright, methanol masers are ideal for high spatial resolution observations using interferometers where very detailed positioning as well as mapping of the finest spatial and dynamical maser features gives important insights into the nature of some known sources (e.g. Minier et al. 2001, 2003; Pestalozzi et al. 2004). Nevertheless, the question of whether these masers trace discs or outflows in young protostars still remains open to debate (e.g. DeBuizer 2003).

Their association with youthful and massive star birth opens up the possibility of using methanol masers as a new and reliable tracer of that rapid stage of evolution prior to the development of UC HII regions. For more than a decade now, searches for new methanol maser sources have been undertaken by a number of authors, e.g. MacLeod et al. (1992); Schutte et al. (1993); Caswell et al. (1995); Ellingsen (1996); Szymczak et al. (2000, 2002); Pestalozzi et al. (2002b). All together, this brought the number of known methanol masers to 519 (Pestalozzi et al. 2005). This represents a statistically significant sample which, for this paper, motivates us to study their spatial distribution throughout the Galaxy with the aim of determining their luminosity function.

To date, most statistical work has focused on finding correlations between the physical characteristics of the maser and the associated IRAS source. In general, 6.7 GHz methanol masers seem to be more efficiently detected towards bright IRAS sources, having $F_{60} > 100$ Jy (van der Walt et al. 1996; Szymczak & Kus 2000), with a clearly higher detection rate in the inner than in the outer Galaxy (Szymczak & Kus 2000). Early attempts to find a correlation between the associated IRAS flux density with the maser flux density gave no positive results. In van der Walt et al. (1995) the authors are left with the fact that the maser flux densities are smaller than the 100 μm ones, suggesting that the masers could be pumped by the 100 μm photons. The lack of correlation between maser flux density and IR flux density is not explained in that work. IRAS sources associated to 6.7 GHz methanol masers seem to be concentrated in a small region of the [25−12]−[60−25] colour−colour diagram, indicating that the maser arises in specific environments

(Szymczak & Kus 2000). Based on the same conclusions, Xu et al. (2003) claim that the methanol maser phase must be short and occurs in the early stages of star formation, where the IR luminosity is high enough that the IR radiation itself might be responsible for the maser pumping, in accordance with theoretical modelling (Sobolev et al. 1997; Cragg et al. 2005). One should note, however, that the association of methanol masers with IRAS sources is not a reliable one, as several studies at high resolution have confirmed (e.g. Ellingsen 1996; Minier et al. 2002; Pestalozzi et al. 2002b): methanol masers are often seen offset from all IRAS or centimetre continuum sources.

The range of velocities and the linewidths of methanol masers have also been used to try to deduce some intrinsic characteristics for these objects. For instance, Slysh et al. (1999) found that methanol masers show a clear velocity difference relative to the velocity of the parent cloud (a comparison made with the velocity of CS). This could suggest an origin for methanol masers in discs seen edge-on. Alternatively, Szymczak & Kus (2000) suggested that the velocity dispersion seen in maser spectra could be used as an evolutionary tool, arguing that the early stages of the formation of an UC HII region would be traced by narrow line masers because of the low number of masing clouds and the lower velocity dispersion within them. Once the UCHII region begins to disperse the surrounding circumstellar matter, larger linewidths are expected. All such hypotheses which appeal to linewidths or the radial velocities of spectral features are subject to the caveat that spectral feature blending could falsify the measurement of the linewidth resulting in, for example, a false evolutionary sequence.

Comparisons have also been made between masers at different frequencies. Slysh et al. (1999) find that in those sources where 6.7 and 44 GHz masers coexist, the ratio of their flux density can be used to discriminate class I from class II masers. On the other hand, no correlation was found when comparing 6.7 with 12.2 GHz counterparts, except for the clear fact that 6.7 GHz masers are always found to be stronger in flux and in brightness temperature when assuming a constant source size (Malyshev & Sobolev 2003).

More recent studies have concentrated their efforts in characterising the sources hosting methanol masers (e.g. Hill et al. 2005; Purcell et al. 2006). Methanol masers seem to be always associated with 1.2 millimetre dust continuum emission as well as CH_3CN emission. Maser-hosting sources are in general more massive and hotter than sources showing 1.2 mm continuum emission but no maser. Also, sources hosting methanol maser show hot core characteristics and most of them pass the Lumsden MSX criterion for massive protostars in the Galactic plane (Lumsden et al. 2002). Finally, methanol masers have been detected toward dark mid-IR clouds, clearly indicating that star formation is ongoing in those regions.

The luminosity function of 6.7 GHz methanol masers has been studied using different approaches. The main problem is in determining the heliocentric distance for every source. Because of the high correspondence of 6.7 GHz methanol masers with OH masers, Caswell et al. (1995) assume that the luminosity function of 6.7 GHz methanol masers should be similar to the one for OH masers (see Caswell & Haynes 1987) from which they conclude that there must be some 500 methanol maser sources in the Galaxy. In van der Walt et al. (1996), the ambiguity of kinematic distances is solved in a probabilistic way. When the decision was not clearly made on the basis of the total luminosity of the IRAS source hosting the maser, the source was assigned a probability for it to lie at the near heliocentric distance. Repeating this assignment in a random way (and for different probabilities) and averaging over the results the authors obtained a spatial distribution from which the luminosity function was estimated. For their sample of about 240 sources, the authors fit a power-law luminosity function with an index of ≈ -2 (the fitting was done on the distribution of sources per unit luminosity interval). This index is expected to flatten in the low-luminosity end of the distribution as otherwise the total number of methanol masers in the Galaxy would be far too high. Ellingsen (1996) refrained from any luminosity function estimate, invoking the problem of determining the distance to every source. More recent studies of large samples of 6.7 GHz methanol masers by Szymczak & Kus (2000); Szymczak et al. (2002) have not directly addressed the study of the luminosity function of methanol masers.

The most recent statistical study of methanol masers in the Galaxy has been presented by van der Walt (2005) in which estimates for the lifetime of the methanol maser phase and the total number of methanol masers are made. The model uses a combination of the initial mass function, (local) star formation rate, a synthetic distribution of these sources in the Galaxy and a constant detection limit of 1.5 Jy in some template regions to conclude that methanol masers should last between $2.5{-}4.5 \times 10^4$ years and that there should be around 1100 in the Milky Way.

The aim of this paper is to present a statistical analysis of the population of 6.7 GHz methanol masers in the Milky Way. We aim to constrain the luminosity function, and begin by modelling the spatial distribution of methanol masers in our Galaxy. This approach is different from the one presented in van der Walt et al. (1996) and van der Walt (2005), where the authors apply a *random choice* algorithm to solve the heliocentric distance ambiguity for sources on galactic orbits internal to the Sun. Our starting point is the distribution of methanol masers in (kinematic) galactocentric distance, which is unique once a rotation curve for the Galaxy is assumed. We then assume that that distribution is the azimuthally averaged surface density of sources in the Galaxy. In this way we are not compelled to solve the distance ambiguity for every source lying on galactic orbits internal to the Sun, as the decision is made by the surface density itself.

Nevertheless, the estimate of the total number of sources in van der Walt (2005) will be used as check for consistency in this work. Furthermore, the present study represents a study of principles with fewer assumptions than van der Walt (2005). Finally, the physical meaning of the luminosity function of the maser emission is not addressed in this paper.

2. Modelling the maser distribution and luminosity function

The determination of the luminosity function for astronomical sources requires an accurate knowledge of their distance from the observer. In the case of galactic sources, kinematic distances from spectral line observations are becoming more accurate thanks to improved modelling of the Galactic rotation curve (e.g. Brand & Blitz 1993 as well as Russeil 2003). The difficulty resides in the discrimination between *near-* and *far-*heliocentric distances for all sources on orbits *internal* to the Solar orbit around the Galactic Centre.

Beside the probabilistic approach presented in van der Walt et al. (1996), another way to solve the heliocentric distance ambiguity is the observation of HI self-absorption. The method relies on the fact that molecular clouds have an outer layer of neutral hydrogen which can absorb the ubiquitous background

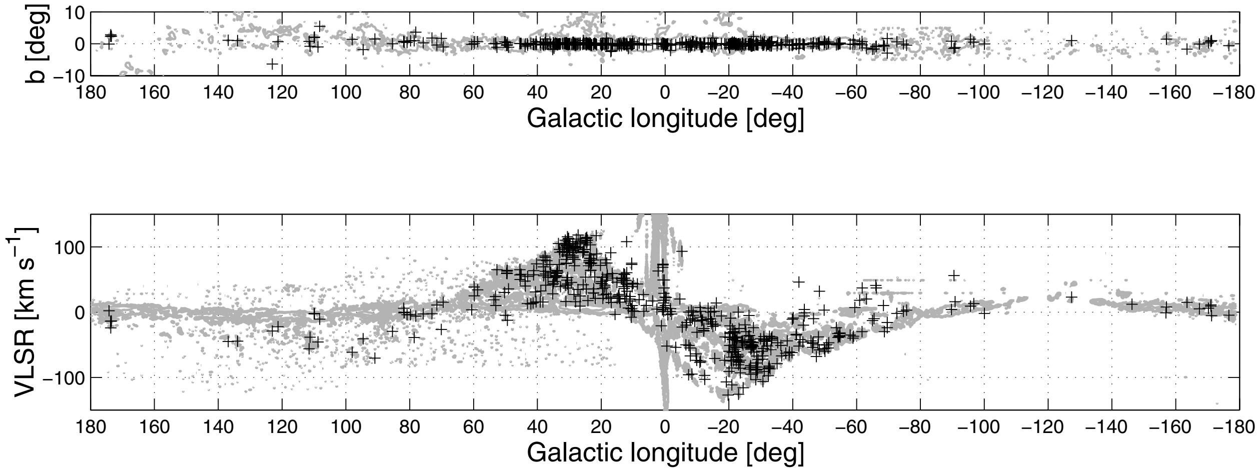

Fig. 1. Distribution of methanol masers in Galaxy, superposed on the CO contours from Dame et al. (1987), in space (*top*) and LOS velocity (*bottom*). The methanol masers seem to accurately follow the overall structure of the Galaxy, both in space and LOS velocity. Particularly visible in the bottom panel is the fact that methanol masers are tracing the spiral arms ($150° > l > 80°$ and $-40° > l > -90°$) and the high rotational velocity of the nuclear ring ($l \approx 0°$).

galactic HI emission. Sources lying on the near side of the galactic centre would have more HI emission to absorb than sources on the far side, making it straightforward to solve the ambiguity (Jackson et al. 2002; Liszt et al. 1981). As the previous one, this method still relies on the calculation of kinematic distances, which requires a good knowledge of the rotation curve of the Galaxy. Recently, Busfield et al. (2006) used this method to successfully determine the distances of a number of massive young stellar object candidates in the fourth quadrant of our Galaxy. The authors succeeded to resolve the distance ambiguity for 80% of their targets, the main limitations being the coarse spatial resolution of the archival HI data as well as the inability to apply the method for sources at galactic longitudes $\ell < |15°|$.

The main idea of the present study is to avoid solving the distance ambiguity for every single source and adopt a global approach instead. This approach starts with a model of the spatial distribution of methanol masers in the Galaxy. We then model the observability of sources with different luminosities at different detection limits and estimate their real total number.

The sample of methanol masers used for the present study is the General Catalogue of 6.7 GHz Methanol Masers (GCMM) published by Pestalozzi et al. (2005), available on the CDS website[1]. This sample is far from complete, but allows a good study of principles and a first test for the formalism we adopt. The outcomes of this study will be compared to the ones from the Methanol MultiBeam Survey (MMB Survey)[2]. The MMB Survey is expected to probe the whole Galaxy at a depth of 0.1 Jy at 1σ, and will probably reveal the complete population of 6.7 GHz methanol masers in the Galaxy.

2.1. Spatial distribution of the masers

For a given observational sensitivity, the *observed* spatial distribution of a certain type of object in the Galaxy is strongly dependent on the luminosity function of those objects. If, for instance, the luminosity function is strongly peaked towards low luminosities, all searches for those objects at a certain detection limit will select the majority of sources in the solar neighbourhood and miss those lying further away. This will give an observed spatial distribution of sources which will probably not reflect the real distribution of sources. If on the other hand the spatial distribution is known to a high degree of confidence it is then possible to estimate both the luminosity function as well as the *real* total number of those sources.

A general view of the methanol masers known to date superimposed on the CO emission in the galactic plane both in space and LOS velocity is presented in Fig. 1. The masers clearly follow both the structural and dynamical features of the CO gas in the Milky Way. There is a clear concentration of sources at longitudes close to $\pm 50°$ which also follows the dynamical signature of the molecular ring. Also, the masers seem to be concentrated in the galactic plane (see also Pestalozzi et al. 2005). Finally, there are some masers that seem to mark the nuclear ring ($l \approx 0°$), and hence lie within 1 kpc from the Galactic Centre. This is not the first time that masers are detected within 1 kpc of the Galactic Centre (see e.g. the detection of OH masers, Caswell & Haynes 1983). The discussion on this point goes beyond the scope of this paper, but it is nevertheless interesting to note that, being methanol masers exclusively associated with star formation activity, these detections are strong indications of recent star formation very close to the Galactic Centre.

The starting point in our analysis is the distribution of masers against their galactocentric distance, as this does not suffer from any distance ambiguity. The distance of every source from the galactic centre is uniquely determined by its galactic longitude and LOS velocity, once a rotation curve for the Galaxy is assumed (we adopt the rotation curve of Brand & Blitz 1993)[3]. Figure 2 shows the surface density of methanol masers in the Galaxy (main panel) and the surface densities of methanol masers and molecular gas (inset, histogram and dashed line respectively) normalised to the integral under the curves. The

[1] `http://vizier.cfa.harvard.edu/viz-bin/VizieR?-source=J/A+A/432/737/`

[2] The MMB Survey aims at surveying a strip of $b = |2°|$ across the galactic plane and at all longitudes, searching for 6.7 GHz methanol masers. It has started in January 2006. See also `http://www.jb.man.ac.uk/research/methanol/`

[3] Note that for the calculation of the galactocentric distance we use the line-of-sight velocity of the brightest spectral component. As mentioned in Pestalozzi et al. (2005), the error of that calculation is about 1 kpc when taking into account the inaccuracies in the position and in LOS velocity.

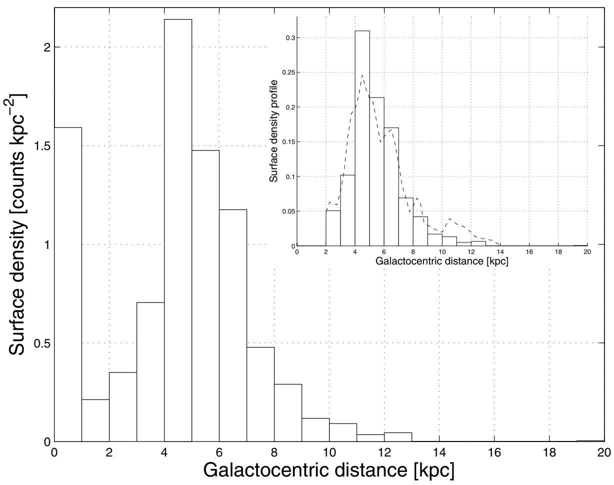

Fig. 2. *Main panel*: spatial density of methanol masers in the Galaxy as a function of galactocentric distance. *Inset*: normalised profile of the surface density of the masers (histogram) compared with the surface density profile of the H_2 gas (dashed line, from Blitz 1996). See Table 1 for the results of the fits to the histogram in the main panel (excluding the first bin).

ratios between the values at 5 kpc (peak, or molecular ring) and the values around the Sun (≈8–9 kpc) are 6:1 and 5:1 for masers and gas respectively. Knowing that methanol masers are associated exclusively with star formation regions, this fact could support the idea that star formation is more efficient in the molecular ring than in the outer Galaxy. We do not draw this conclusion, as this effect could be due to a lower maser detection rate coming from an uneven observational coverage of the outer Galaxy. Another interesting empirical fact is given by the ratio of the gas surface density to the maser surface density. This ratio is an estimate of solar masses of gas per methanol maser and it has values between 1.5×10^6 and 9.7×10^7 for peak and solar neighbourhood, respectively. These values are comparable to the gas content in large molecular clouds ($\approx 10^7$ $M_\odot$, see e.g. Knapen et al. 1993), which means that in the ring we are expecting ≈10 methanol masers per large molecular cloud, while in the outer Galaxy this number drops to approximately one maser every 10 clouds. In the same line of thought we can do an order of magnitude comparison of these numbers with the total content of gas in the Milky Way ($\approx 10^9$ $M_\odot$, see e.g. Dame 1993) and obtain an empirical estimate of the total number of methanol masers in our Galaxy, which should be of the order of 10^3 sources.

We consider the histogram in the main panel of Fig. 2 to be a sufficiently reliable signature for the shape of the spatial distribution of methanol masers in the Galaxy. We support our assumption with the fact that the masers seem to accurately follow the distribution of CO in the Milky Way both in space and LOS velocity (Fig. 1). We make two assumptions: that the surface density of methanol masers in the Galaxy, $F(x, y)$, can be projected onto the Galactic plane ($|b| = 0°$), and that the masers are distributed axisymmetrically, i.e. the surface density distribution depends only on the galactocentric radius, R. The total number of sources in an annulus of thickness dR is then $F(R)\, 2\pi R\, \mathrm{d}R = H(R)\mathrm{d}R$, where $H(R)$ is the function fitted to the histogram in Fig. 2. We support our two assumptions with the following arguments: a) the distribution of methanol masers in galactic latitude has a very small FWHM (about 1.0°, see Pestalozzi et al. 2005); and b) axisymmetry is assumed by noting that the clear peak in the histogram in Fig. 2 is at a galactocentric distance where the spiral pattern of the Galaxy is not yet clearly visible (molecular ring, see e.g. Russeil 2003). The latter argument is also supported in Fux (1999), where it is shown that the existence of a bar in our Galaxy does not significantly affect the dynamics outside the molecular ring. The total number of observed sources in the Galaxy $N_{\mathrm{tot-obs}}$ is given by the integral from 0 to $R_{\max}$ of the function $H(R)$. The Gaussian profile used for the fitting is parametrized by the integral under the curve N, the mean R_{peak} and width σ. The results of the fit are shown in Table 1.

Table 1. Results of the best fit to the histogram in Fig. 2. The values of $r_{\mathrm{max-obs}}$ indicate a truncation of the function F due to sensitivity. A large value of $r_{\mathrm{max-obs}}$ (as e.g. 40 kpc) is equivalent to no truncation (see text for an explanation). The column N lists the *real* total number of sources. The mean and width for the Gaussian distribution are 5.08 and 1.42 kpc respectively.

Profile	$r_{\mathrm{max-obs}}$ [kpc]	N
Gauss	40	483
	12	668
	10	907
	8	1228

2.2. Luminosity distribution of methanol masers

2.2.1. Step 1: equal luminosity for all masers

We use the assumption of the masers having all the same luminosity in order to better understand the basic trends and behaviour of the model within a simple framework.

If we assume that all methanol masers have the same luminosity, the sensitivity limit of the observations translates into a maximum heliocentric distance $r_{\mathrm{max-obs}}$, within which masers will be detected (dashed arcs a, b and c in Fig. 3). We fit $H(R)$ to the histogram of Fig. 2 when applying different $r_{\mathrm{max-obs}}$, i.e. with a spatial distribution which is *truncated* due to sensitivity. Recalling our basic assumption that the histogram in Fig. 2 is a reliable signature for the shape of the galactic distribution of masers, we fix R_{peak} and σ of the function $F(R)$ found from the original fit to the histogram (Table 1) and fit only for N. This will be the total number of sources in the Galaxy. We have then:

$$N_{\mathrm{tot-obs}} = \int_{-\theta_{\max}(R')}^{+\theta_{\max}(R')} \int_{R_{\min}}^{R_{\max}} F(\theta, R')\, R'\, \mathrm{d}R' \mathrm{d}\theta \tag{1}$$

where $R_{\mathrm{min/max}}$ are defined by the heliocentric radius $r_{\mathrm{max-obs}}$ and the function $\theta_{\max}(R)$ ensures that masers are only counted if they lie within $r_{\mathrm{max-obs}}$. Note that if $r_{\mathrm{max-obs}} > R_0$ (i.e. the depth of the observations reaches beyond the Galactic Centre) then $\theta_{\max} = \pi$ for $0 < R < r_{\mathrm{max-obs}} - R_0$ (arc a in Fig. 3). The results of the fits are summarised in Table 1 and in Fig. 4. We choose 7 kpc as minimum value for $r_{\mathrm{max-obs}}$, as shorter distances would be strongly inconsistent with the observed distribution of masers in the Galaxy. This is visible from Fig. 2, where the histogram shows that there are sources close to the galactic centre, i.e. at 8.5 kpc from the Sun. The fits are indicative of how many sources there should be in the Galaxy if the sample was severely limited by sensitivity.

Increasing $r_{\mathrm{max-obs}}$ to large values (e.g. 40 kpc) is equivalent to stating that the sample in GCMM does not depend on the luminosity distribution of the masers, and hence that all masers in the Milky Way are detected. There are several reasons to believe that GCMM does not contain all methanol masers sources in the Galaxy: not only is there a bias due to the unknown luminosity

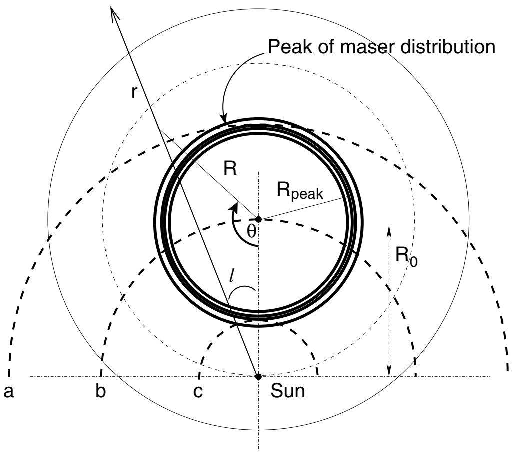

Fig. 3. Geometry of the modelled methanol masers in the Galaxy. R_{peak} is the radius at which the maser distribution peaks, R_0 the radius of the solar orbit around the galactic centre, θ the central angle, r the heliocentric distance and ℓ the galactic longitude. The dashed arcs a, b and c are equidistant curves from the Sun, described in the text.

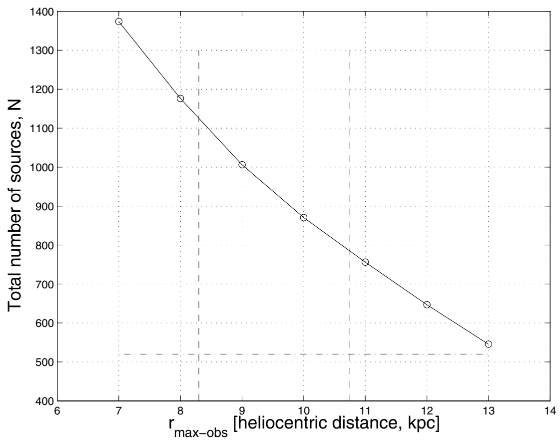

Fig. 4. Dependence of the real total number of sources N inferred by fitting a distribution F truncated at different values of $r_{\mathrm{max-obs}}$ to the histogram in Fig. 2, using the assumption of equal luminosity for all masers. The range of $r_{\mathrm{max-obs}}$ defined by the vertical dashed lines corresponds to the range for N estimated in van der Walt 2005. The horizontal dashed line indicates the total number of sources in GCMM, 519.

function but also the catalogue is biased due to non-uniform coverage of the galactic plane. The present study is meant to make predictions on the basis of the data available.

Note that, by introducing a sensitivity limit, i.e. $r_{\mathrm{max-obs}}$, we define a minimum luminosity for all detected masers. For a detection limit of 1 Jy over 0.2 km s^{-1} or 5.56 kHz at the rest frequency of 6.668519 GHz (Müller et al. 2004), we get minimum luminosities of the masers of 2.85×10^{-6}, 1.91×10^{-7} and 7.33×10^{-8} $L_\odot$ for $r_{\mathrm{max-obs}}$ equal to 40.5, 10.5 and 6.5 kpc, respectively.

Comparing these results with recent estimates of the total number of methanol masers in the Galaxy (as e.g. in Sect. 2.1 and van der Walt 2005), and retaining our assumption that all masers have the same luminosity, we conclude that GCMM contains sources up to the galactic centre and just beyond (see dashed vertical lines in Fig. 4).

The conclusions we can draw at this point of the paper are:

– from fitting the histogram in Fig. 2 with *truncated* models of the spatial distribution (Eq. (1)) we see that GCMM has a considerable number of sources missing (up to a factor of about 2–3);
– this suggests that the luminosity function of 6.7 GHz methanol masers is not a delta function (i.e. all masers do not have the same luminosity) and it is most likely dominated by intrinsically weak emitters, potentially young high-mass star formation regions;
– the large number of missing sources is mostly due to the shallow sensitivity limit of most of the observations which contribute to the GCMM (see Pestalozzi et al. 2005). Only a very small part of the Galaxy was observed with a sensitivity limit better than 2 Jy.

2.2.2. Step 2: introducing a distribution of luminosities

The general distribution of luminosities of methanol masers is the link between the real spatial distribution and the observations. The observability of a source depends on a combination of its luminosity and the sensitivity of the survey used to detect it. High-sensitivity observations (e.g. 0.1 Jy at 1σ) can detect low-luminosity sources far away from the Sun, reaching a high level of completeness. Deep surveys guarantee that one probes most, if not all, of the Galaxy: this is the aim of the MMB Survey.

By discarding the assumption of equal luminosity for all masers and introducing a luminosity distribution $G(L)$, $r_{\mathrm{max-obs}}$ no longer defines any sharp spatial cutoff point. The physical depth of the observations will scale as $\sqrt{L/\Phi}$, where L is luminosity and Φ is the detection limit in the observations. It is therefore not possible to define an absolute value for the largest distance probed by the observations, as this will vary within the same combination of luminosity function and sensitivity of the observations. For every sensitivity limit Φ, the scaling of the spatial cutoff becomes smaller increasingly quickly toward low luminosities. This means that if low luminosity sources are concentrated around some particular heliocentric distance r, these will be missing from the counts unless the sensitivity is set accordingly. An order of magnitude in sensitivity implies a factor of $\sqrt{10}$ in $r_{\mathrm{max-obs}}$. Assuming masers lie in a ring-like structure around the galactic centre (with some known radial profile as e.g. a Gaussian), such a difference in $r_{\mathrm{max-obs}}$ could mean either including or not a factor ≈ 2 sources in the final counts, as $r_{\mathrm{max-obs}}$ could either include only the near peak or both the near *and* the far peaks of the distribution.

To better understand the influence of the luminosity function in the present study we follow the following procedure:

1. Prescribe a functional form for the luminosity function $G(L)$. We require that this is normalised so that $\int S(\ln(L))\,\mathrm{d}(\ln(\mathrm{L})) = 1$, where $S(\ln(L))$ is the distribution of luminosities sampled in equal logarithmic intervals. From this function, we construct a discrete set of probabilities P_j, centered on luminosities L_j, such that $\sum_j P_j(L_j) = 1$.
2. Set a sensitivity limit Φ for the observations. For every luminosity L_j, Φ sets a maximum heliocentric distance $r_{\mathrm{max-obs}}(L_j, \Phi)$ to which the observations will detect sources of that particular luminosity;
3. For each luminosity bin we then:
   – Multiply the spatial distribution $F(R)$ (without any distance cutoff) with $P(L_j)$, i.e. the probability which corresponds to that luminosity. In this way we are left with the distribution of sources of luminosity L_j in the Galaxy;
   – Apply the distance cutoff $r_{\mathrm{max-obs}}(L_j, \Phi)$ and count the number of sources in each galactocentric distance bin (this is equivalent to integrating over θ and R as Eq. (1)).

In this way we count how many sources of the luminosity L_j we are able to detect with the sensitivity Φ.

The total number of *observed* sources $N_{\text{tot-obs}}$ is given by the sum of all (detected) sources at all luminosities:

$$N_{\text{tot-obs}} = \iint \left[\sum_{L_j} P(L_j) \times F_{j\text{-trunc}}(R) \right] R \, \mathrm{d}R \, \mathrm{d}\theta \tag{2}$$

where $F_{j\text{-trunc}}(R)$ is the spatial distribution of sources within $r_{\text{max-obs}}(L_j, \Phi)$ and the integration limits of both integrals are the same as in Eq. (1).

Once the shapes of the spatial distribution $F(R)$ and of the luminosity function $G(L)$ are chosen, the fit to the histogram in Fig. 2 has the following free parameters: the total number of sources in the Galaxy N, the parameters defining $G(L)$ and the sensitivity Φ. Note that we assume that the mean and width of the spatial distribution are fixed.

To keep the number of free parameters to a minimum, we choose the luminosity function to be of the simplest kind, a power-law with sharp cutoffs $L_{\min}$ and $L_{\max}$:

$$G(L) = A\, L^{\alpha} \tag{3}$$

where A is determined by the normalisation condition, and the only free parameter defining $G(L)$ is its power α. We take the range of luminosities from the literature, $L_{\min} = 10^{-8}\, L_{\odot}$ and $L_{\max} = 10^{-3}\, L_{\odot}$ (Walsh et al. 1997), as our best estimate.

2.2.3. Results

From Eq. (2) it is not possible to determine N and α simultaneously. Nevertheless, this method is still able to provide important insights and predictions on both the total number of sources in the Galaxy (N) as well as on the slope α of the maser luminosity function.

We can attempt to answer two different questions:

- Knowing the mean detection limit in GCMM and how many sources GCMM contains, how many sources should there be in total in the Galaxy and how does this number depend on the slope of the luminosity function?
- What fraction of N do we expect to detect depending on the detection limit and the slope of the luminosity function?

The answer to the first of these questions is shown in Fig. 5. The curves in the graph were obtained by fitting Eq. (2) to the histogram in Fig. 2, excluding the integral over R. For example, if we assume the mean detection limit of GCMM to be 1 Jy, N would lie between ≈520 and ≈5000, depending on the power of the luminosity function. If we are to constrain our range for N by taking into account the prediction made in Sect. 2.1 ($N \approx 1000$) and of van der Walt 2005 ($N \approx 800{-}1200$), we can state that the luminosity function has a slope between ≈−1.2 and ≈−1.5. At the detection limit of the MMB Survey (0.5 Jy) the total number of sources is expected to lie between 519 and more than 2500, depending on the slope of the luminosity function.

The answer to the second question is shown in Fig. 6. In this approach the absolute number of sources N and $N_{\text{tot-obs}}$ are irrelevant, and only the shapes of the spatial and luminosity distributions are important. From the graph we can say that by taking the mean sensitivity of GCMM to be 1 Jy, the total number of sources in that catalogue (519) represents between 10 and 80% of the total depending on the chosen luminosity function. Again, if previous estimates of the total number of methanol masers in the Galaxy are correct, we can state that GCMM contains 30−50% of N, and this would constrain the slope of the luminosity function α to be ≈−1.5. The detection limit of the MMB Survey (0.5 Jy) will produce a catalogue containing between 15 and 85% of the real total number of sources in the Galaxy, depending on the slope of the luminosity function.

Figure 6 indicates that deeper observations have the effect of reducing the dependence of the fraction $N_{\text{tot-obs}}/N$ from the luminosity function. A detection limit of 0.1 Jy would allow to detect 60−95% of the total number of sources, which is a more favourable range than the one provided by a mean detection limit of 1 Jy. Assuming a power-law with slope −1.5, a 0.1 Jy detection limit would yield the detection of 85% of the total number of existing methanol masers in the Milky Way.

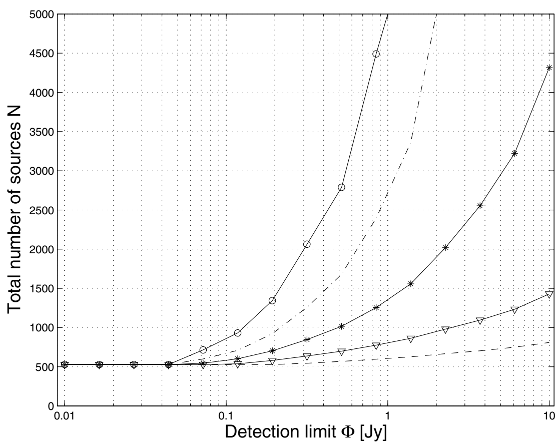

Fig. 5. N versus detection limit at several values of α, the slope of the luminosity function (dashed −1; triangles −1.2; stars −1.5; dash-dot −2.0; circles −3.5). The spatial distribution profile used here is a Gaussian. The detection limit is defined as Φ spread over $0.2\,\mathrm{km\,s^{-1}}$. N is the result of fitting Eq. (2) to the histogram in Fig. 2. This explains the convergence to $N = 519$ at low detection limits.

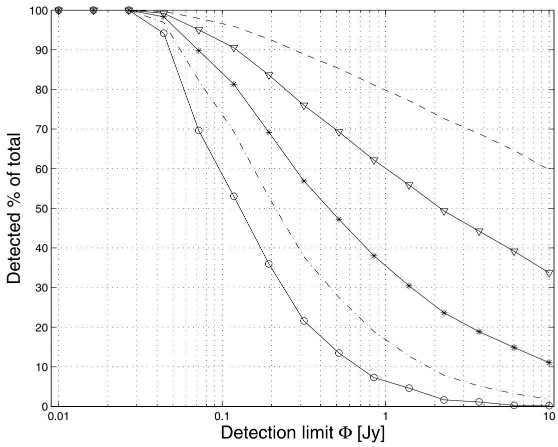

Fig. 6. $N_{\text{tot-obs}}$ as percentage of N versus sensitivity limit at different values of α, the slope of the luminosity function. The curves are labeled as in Fig. 5. Note that an order of magnitude in sensitivity implies a factor of $\sqrt{10}$ in $r_{\text{max-obs}}$. The spatial distribution profile used here is a Gaussian. The detection limit is defined as Φ spread over $0.2\,\mathrm{km\,s^{-1}}$.

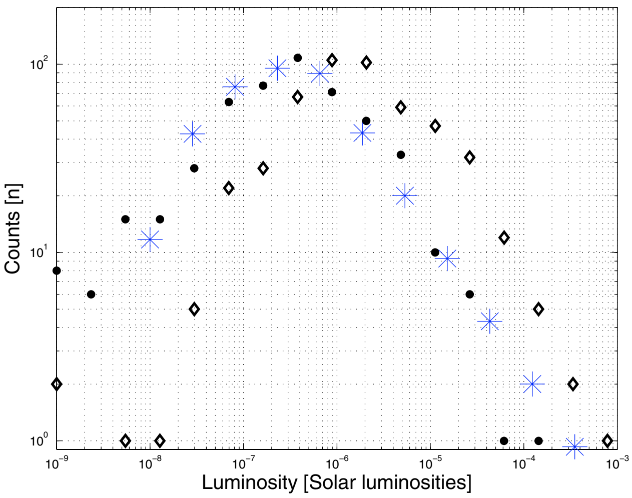

Fig. 7. Distribution of the luminosities of all masers in GCMM, assuming, for all ambiguous sources, either the near (dots) or the far (diamonds) heliocentric distance. The luminosities were calculated by assuming that the peak flux is spread over 0.2 km s^{-1}. The difference in the peak position is of about 1 order of magnitude. Stars show the results obtained by the observation at 2 Jy sensitivity of the modelled maser population in the Galaxy. The model is defined by a total number of sources equal to 5000, a spatial distribution as in Fig. 2 and a luminosity function expressed as a single power-law of index −1.7 between 10^{-8} and 10^{-3} $L_\odot$.

3. Can we constrain the luminosity function from GCMM?

Figure 7 shows the distribution of luminosities of the masers in GCMM. Dots and diamonds represent the two extreme cases where all *ambiguous* sources have been assumed to lie at the near and far heliocentric distance, respectively. Since the sources suffering from distance ambiguity are about 90% of the catalogue, the two curves in Fig. 7 show a relative shift of about one order of magnitude in luminosity.

As GCMM is a highly heterogeneous sample (different sensitivities, non-uniform area coverage), we cannot conclude that the plots in Fig. 7 are indicative of the shape of the *real* luminosity function of the masers. Nevertheless, if GCMM does not contain most of the faint methanol masers in the Galaxy (<1−3 Jy), we expect the counts of a large scale deep search of methanol masers in the Milky Way (as e.g. the MMB Survey) to populate the lower part of the luminosity range in Fig. 7. This is due to the fact that a 1 Jy source is intrinsically fainter than the peak luminosity in those distribution, as calculated in Sect. 2.2.1. The detection of many sources at the 1 Jy level or below will change the shape of the luminosity distribution in Fig. 7 closer to one of a power-law.

Maintaining the assumption of the luminosity function of methanol masers to be a single power-law between sharp cutoffs and observing it with a sensitivity of e.g. 2 Jy we obtain best similarity to the data as shown in Fig. 7. The synthetic data points (stars) seem closest to the data curve obtained when putting all ambiguous sources at the near heliocentric distance (dots). This strongly suggests that most of the ambiguous sources in GCMM probably lie at the near heliocentric distance. It is to notice that the last points toward lower luminosities could be considered to be the only few sources at the far distance, what would bring them within the range of luminosities assumed in the model ($10^{-8} < L < 10^{-3}$ $L_\odot$).

It is in principle possible to eliminate the near-far distance problem by selecting appropriate subsamples of sources from GCMM. We have then two possibilities: either we select the sources in the outer Galaxy ($90° \leq l \leq 270°$) or we select all sources at the tangent point of the molecular ring ($\pm 50° \leq l \leq \pm 20°$). The luminosity distributions resulting from these selections were not better defined than the ones shown in Fig. 7. This is mainly due to the fact that the number of sources we are left with after the selection (≈90) is severely reduced as compared to the total. Also, the selection of sources at the tangent points does not completely eliminate the near-far ambiguity, because of the difficulty of unambiguously defining the tangent point.

It is important to notice that our estimates of the index of the luminosity function of methanol masers ($-1.5 \geq \alpha \geq -2$) is in slight disagreement with what found in previous studies (≈−2). The difference in index could probably be reduced assuming a more complex luminosity function, as e.g. a broken power-law. We still consider the luminosity function presented here to be the best estimate with the least number of assumptions and free parameters, and, most importantly, obtained without any selection of sources. The definitive shape of the luminosity function of methanol masers in the Galaxy will be found once the MMB Survey is completed.

4. Conclusions

Using the General Catalogue of 6.7 GHz Methanol Masers in the Milky Way, we have modelled their spatial distribution in the Galaxy and estimated their luminosity function. We conclude the following:

– methanol masers are distributed in a ring of some 5 kpc in radius around the Galactic centre;
– most of the sources in GCMM are probably confined in an area of heliocentric radius equal to R_0 or slightly larger. This also means that the sources showing heliocentric distance ambiguity lie probably at the near distance;
– the luminosity function of methanol masers in our Galaxy is modelled as a power-law between sharp cutoffs having an index α between −1.5 and −2;
– given a uniform survey which is able to define a methanol maser luminosity function, the approach presented here will allow us to estimate the total number of sources in the Galaxy. As an example, a large scale survey with a sensitivity limit of 0.5 Jy will be able to detect ≈50% of the total number of sources or more, if the power of the luminosity function is −1.5 or lower. This is what is expected from the MMB Survey.

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