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On the selection of ultra-compact HII regions from the IRAS Point Source Catalogue: What the 6.7-GHz methanol maser surveys tell us

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Abstract. The detection rate of 6.7-GHz methanol masers in IRAS based surveys is discussed within the framework of a model for the distribution and far-infrared characteristics of embedded ionizing stars in the Galaxy. It is shown that the fainter IRAS sources selected with the Wood & Churchwell (1989) criteria have a distribution in Galactic latitude that is completely different from what is expected for embedded ionizing stars. It is concluded that a significant fraction of the fainter sources selected with the Wood & Churchwell criteria are most probably not embedded ionizing stars. The model also predicts that a significant fraction of embedded ionizing stars, primarily the less massive ones, are not expected to be exceptionally bright in the far-infrared and are also expected to be located at very small Galactic latitudes.

Key words: masers – HII regions – ISM: clouds – radio lines: ISM

1. Introduction

The number of known ultra-compact (UC) HII regions in the Galaxy has increased rapidly over the last couple of years due to a number of radio continuum and maser surveys. The maser surveys that have contributed mostly to this increase are the 6.7-GHz methanol maser surveys. These include surveys of known OH-maser sources (Menten 1991; MacLeod et al. 1992; MacLeod & Gaylard 1992; Gaylard & MacLeod 1993), of colour selected sources from the IRAS Point Source Catalogue (PSC, IRAS 1985) (Schutte et al. 1993; van der Walt et al. 1995; Walsh et al. 1995; van der Walt et al. 1996) and also some blind surveys (Caswell et al. 1995; Caswell 1996; Ellingsen et al. 1996).

The IRAS based searches mentioned above were all completely, or to a large extent, based on the far-infrared (FIR) selection criteria for UCHII regions proposed by Wood & Churchwell (1989) (WC). From an analysis of the 6.7-GHz methanol masers with IRAS counterparts known at that time, van der Walt et al. (1995) found that there seems to be a colour dependence of the detection rate: the "redder" sources are more likely to have associated 6.7-GHz maser emission. More recently van der Walt et al. (1996) found that the detection rate of 6.7-GHz methanol masers seems to decrease towards fainter sources selected with the WC criteria and may become very small, or perhaps even zero, for sources for which $F_{25-60} \equiv \int_{25\mu m}^{60\mu m} S(\nu)d\nu < 10^{14}\mathrm{Jy} \cdot \mathrm{Hz}$, while the WC sources extend down to $F_{25-60} \simeq 10^{13}\mathrm{Jy} \cdot \mathrm{Hz}$. As pointed out by van der Walt et al. (1996) this decrease cannot be solely a sensitivity effect only since the IRAS counterparts of the sources detected by Walsh et al. (1995) in an IRAS based survey which has a lower detection limit than that conducted by van der Walt et al. (1996), all have values of $F_{25-60} > 10^{14}\mathrm{Jy} \cdot \mathrm{Hz}$.

Ellingsen et al. (1996) recently compared the detection of 6.7-GHz methanol masers in their blind survey and IRAS based surveys. They pointed out that they could not find IRAS counterparts (satisfying the WC criteria) for more than 50 per cent of the 6.7-GHz masers that they detected, and concluded that the number of UCHII regions in the Galaxy may be a factor of two greater than that estimated by Wood and Churchwell (1989).

Thus, from both the IRAS based as well as the blind surveys there are questions as to the nature of the WC sources. Since, as pointed out by Ellingsen et al.(1996), the 6.7-GHz methanol masers may yield one of the most accurate determinations of the number of UCHII regions in the Galaxy, it is necessary to try to understand what the 6.7-GHz methanol masers possessing IRAS counterparts can tell us about the selection of UCHII regions from data bases such as the IRAS Point Source Catalogue.

A further need for understanding the nature of the sources selected with the WC criteria, comes from the study of H_2O masers. Recently Codella et al. (1996) studied the occurrence of H_2O masers towards 39 young stellar objects (YSO's). The majority of the 39 YSO's satisfies the WC criteria and are presumably embedded ionizing stars. On the basis of the fact that radio continuum emission is not observed from a number of the YSO's, these authors concluded that H_2O maser activity may start even before an HII region has developed. If, how-

Send offprint requests to: D.J. van der Walt ever, some of the sources without radio continuum emission are not very young embedded ionizing stars but rather embedded non-ionizing stars, one would come to a somewhat different conclusion regarding the evolutionary phase during which H_2O masers occur. Since it is known that H_2O masers are also found towards non-ionizing YSO's, it certainly is necessary to address the question of the nature of the WC sources.

The aim of this paper is to investigate, within the framework of a simple model, the question of whether all the sources selected with the WC criteria are embedded ionizing stars and why the detection rate of 6.7-GHz methanol masers seems to decrease towards fainter WC sources. We argue, on the basis of the model, that the majority of the fainter WC sources are most likely not embedded ionizing stars. The model furthermore predicts that the majority of embedded ionizing stars are not as bright in the FIR as expected.

2. The model

The aim of the model is to simulate the distribution as well as the FIR fluxes of embedded ionizing stars in the Galaxy in a simple but realistic way. The components of the model will now be described in more detail.

For the radial distribution of embedded ionizing stars in the Galactic plane we used the distribution of molecular gas given by Burton (1988) but corrected for the Sun to be at a distance of 8.5 kpc from the Galactic center rather than 10 kpc. The close association between the molecular gas and the 6.7-GHz methanol maser sources has already been demonstrated by van der Walt et al. (1995). Burton (1992) gives the thickness of the molecular gas perpendicular to the Galactic plane in terms of a Gaussian distribution with a dispersion of five parsec at $R/R_{\odot}$ = 0.2 and which increases to about 50 pc at $R/R_{\odot}$ = 0.6. For $R/R_{\odot} > 0.6$ the dispersion stays constant at about 50 pc. van der Walt et al. (1996) have shown, however, that the scale height for 6.7-GHz methanol maser sources is significantly smaller than that of the molecular gas. Here we will assume the maser sources to have an exponential distribution perpendicular to the Galactic plane and a constant scale height of 27 pc, which is the average between the smallest and largest scale heights estimated by van der Walt et al. (1996). For the spiral structure we used the four-armed model of Vallée (1995). The spiral arms were assumed to have a thickness of 400 pc (Dickel et al. 1970) in the Galactic plane. We assumed that only single embedded ionizing stars are the sites of 6.7-GHz masers. The masses of individual stars were assigned according to the initial mass function (IMF) of Miller & Scalo (1979). The corresponding luminosities were obtained from the mass-luminosity relation of Mihalas & Binney (1981).

We furthermore assumed that all the radiant energy of an embedded ionizing star appears in the IR and that the FIR flux distribution is given by the observed average FIR flux distribution of the methanol maser sources. With this assumption and using Boulanger's formula (Casoli et al. 1986) to estimate the total IR luminosity from the IRAS data, it is possible to show that

$$F_{25-60} = 8.67 \times 10^{11} L/d^2, \quad (1)$$

where L is the luminosity (in units of $L_{\odot}$) of the star and d is the distance, measured in kiloparsec, between the star and the observer. The observer was assumed to be at a distance of 8.5 kpc from the Galactic centre and to be located on the inside edge of a spiral arm. Star formation was taken to end at a galactocentric radius of 13 kpc although it seems to extend to galactocentric distances of about 20 kpc in the Galaxy (see eg. Brand & Wouterloot, 1991). The reason for limiting this distance is merely practical since the number of massive stars beyond this distance is much smaller than the number at smaller distances as a consequence of the radial distribution of molecular gas. Inclusion of these stars will not influence our results since it will only contribute more sources at very small galactic latitudes.

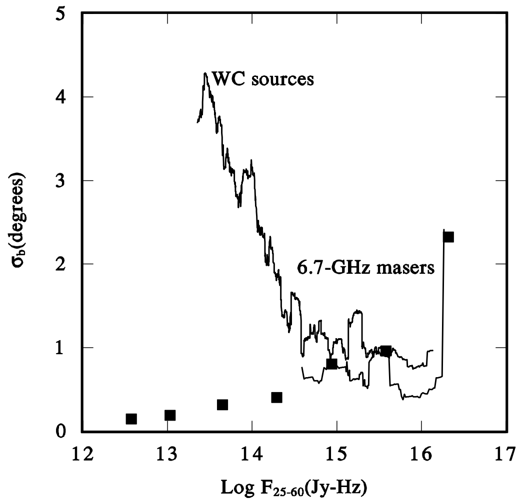

Fig. 1. σ_b vs. F_{25-60} for the WC sources, the 6.7-GHz methanol maser sources and the model prediction (solid squares).

3. Model predictions and comparison with observations

We first consider the dispersion in Galactic latitude, σ_b , as a function of F_{25-60}. This comparison is made in Fig. 1 where σ_b is plotted as a function of F_{25-60} for the WC sources, the methanol masers and the model prediction. The values of σ_b and F_{25-60} for the WC and methanol maser sources were calculated from running means. For the WC sources it is seen that $\sigma_b \simeq 4°$ at the smallest values of F_{25-60} and that it decreases to about 1° at $\log F_{25-60} \simeq 14.5$ after which it fluctuates around 1°. For the methanol maser sources σ_b is seen to be less than 1° over the range of values of F_{25-60} covered by these sources, except for the last group where σ_b is seen to increase rapidly to slightly more than 2°. This increase is due to IRAS 06053-06022 (Mon R2) which has a Galactic latitude of -12°.6 and longitude of 213°. This source is clearly associated with the local spiral arm.

No comparison between the methanol maser and WC sources can be made for $\log F_{25-60} < 14$ since the smallest value of $\log F_{25-60}$ for the maser sources with IRAS counterparts is 13.98. We therefore used the model to extrapolate to values of $\log F_{25-60} < 14$. The model prediction is shown as the solid squares in Fig. 1. Although there is not exact agreement with the data, the model follows the data reasonably well

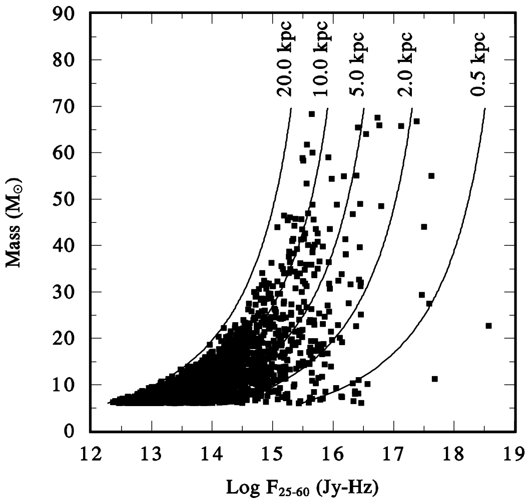

Fig. 2. Mass of the embedded ionizing star as a function of F_{25-60}. The solid lines are the relation between the mass of the ionizing star and F_{25-60} for d = 0.5, 2.0, 5.0, 10.0, and 20 kpc from the observer. The solid squares are the model prediction.

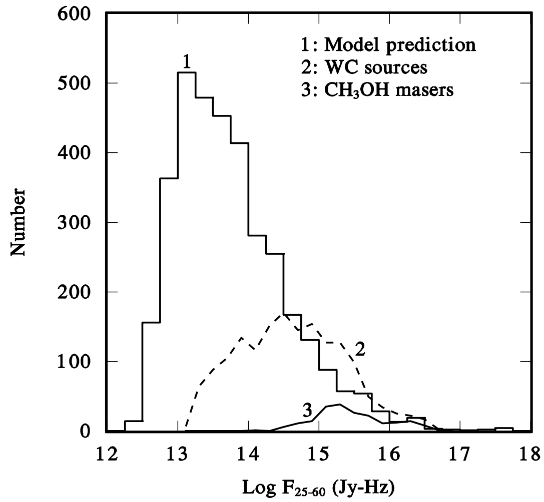

Fig. 3. Comparison of the distributions of F_{25-60} for the WC sources, the 6.7-GHz methanol masers, and the model prediction.

for $\log F_{25-60} > 14.5$. The sharp increase in σ_b at the largest value of F_{25-60} is also seen to be reproduced fairly well by the model.

For $\log F_{25-60} < 14$ the model predicts σ_b to decrease slowly with decreasing F_{25-60}. This is in sharp contrast with the WC sources for which σ_b increases very rapidly as F_{25-60} decreases. Although it is possible to further improve the model, we believe it is sufficiently realistic that the real behaviour of σ_b as a function of F_{25-60} cannot be much different from that predicted by the model. The significant difference in the behaviour and absolute values of σ_b of the WC sources and what can be expected for young embedded ionizing stars, strongly suggests that the majority of the fainter WC sources does not belong to the population of UCHII regions.

The prediction that σ_b decreases with decreasing F_{25-60} for embedded ionizing stars is a direct consequence of their mass distribution and their distribution in the Galaxy. To illustrate this we plotted in Fig. 2 the mass of the ionizing star against F_{25-60} for 3000 embedded ionizing stars. Also shown as solid lines is the relation between the mass of the star and F_{25-60} for a number of distances, d, between the star and the observer as derived from (1).

Assuming for argument sake that the greatest distance between the observer and a source is 20 kpc, it is seen that the relation for d = 20 kpc gives the smallest value that F_{25-60} can have for a given mass. For example, for a $30M_\odot$ star $F_{25-60} > 10^{14.5}$Jy·Hz and for a $20M_\odot$ star $F_{25-60} > 10^{14}$Jy·Hz. Fig. 2 shows therefore that the faintest objects are also the least massive embedded ionizing stars and they are also at the greatest distances. Due to the small scale height of these sources they have to be at very small Galactic latitudes which explaines the decrease of σ_b towards smaller values of F_{25-60}.

What is also apparent from both Figs. 1 and 2 is that the model predicts a large number of sources with F_{25-60} weaker than the WC sources. In Fig. 3 the predicted distribution of F_{25-60} is compared with that of the WC sources and the methanol maser sources. The predicted distribution is seen to have a maximum at $\log F_{25-60} \simeq 13.1$ while for the WC sources the distribution peaks at about $\log F_{25-60} = 14.5$. For the methanol maser sources the distribution has a peak at about $\log F_{25-60} = 15.25$. The model therefore suggests that the distribution of F_{25-60} for the methanol maser sources is not representative of the population of embedded massive stars. What is even more important is that the model predicts that a significant fraction of the embedded ionizing stars is not any brighter than the fainter WC sources but is in fact fainter.

4. Discussion

With the results presented above we can now address some of the question raised in the Introduction. We first consider the nature of the faint WC sources.

Using the relation $F_{25-60} = 8.67 \times 10^{11} L/d^2$, taking $F_{25-60} = 10^{13}\mathrm{Jy\cdot Hz}$, then for an embedded ionizing star of B3 type ($\log L/L_\odot = 3.02$) it is found that d = 9.5 kpc. Assuming that the source is located at a Galactic latitude of four degrees (equal to the dispersion in Galactic latitude for $F_{25-60} \simeq 10^{13}\mathrm{Jy\cdot Hz}$) it follows that it should be at a distance of about 660 pc above the Galactic plane. If it is assumed that the embedded star is more massive than a B3 type star it will have to be located at an even greater distance above the Galactic plane. Given the fact that the molecular gas is strongly concentrated to the Galactic plane, it is highly unlikely that large numbers of embedded ionizing stars occur at such distances above the Galactic plane. We are therefore led to the conclusion that a significant fraction of the faint WC sources, especially those at large Galactic latitudes, is most probably not embedded ionizing stars but perhaps relatively nearby embedded less massive stars. If this is the case then the decrease in detection rate towards smaller values of F_{25-60} can be explained as being due to an increasing level of contamination of sources that are not embedded ionizing stars.

Ellingsen et al. (1996) noted that confusion may be the reason why the IRAS based surveys are more successful in directions away from the Galactic plane than close to or in the Galactic plane. In fact, the model result in Fig. 1 is in support of this view. Since for embedded young ionizing stars the dispersion in Galactic latitude decreases with decreasing F_{25-60} and is about 0.2° for $\log F_{25-60} = 12.5$, it can be expected that the effect of confusion will become even more serious towards the fainter sources. Because of this behaviour, it would seem as if it will be very difficult, if not impossible, to devise selection criteria that are able to select all the embedded ionizing stars from the IRAS PSC.

Apart from the reasons mentioned above, the decrease in the detection rate of 6.7-GHz masers towards fainter sources may also be due to a decrease in the efficiency of exciting 6.7-GHz methanol masers by less massive ionizing stars. As is evident from Fig. 2, the average mass of the ionizing stars becomes smaller towards smaller values of F_{25-60}. On current evidence, none of the 6.7-GHz methanol masers are associated with objects other than embedded ionizing stars. If this is generally true, then one might expect the efficiency of exciting methanol masers to have a mass dependence in such a way that the efficiency decreases with decreasing mass of the ionizing star. Due to the relation between the mass of the embedded ionizing star and F_{25-60} as shown in Fig. 2, this behaviour will also manifest itself as a decrease in the detection rate towards smaller values of F_{25-60}.

The distribution of F_{25-60} for methanol maser sources as shown in Fig. 3 applies to the combined population of those 6.7-GHz methanol masers detected towards previously known OH masers and those towards colour selected IRAS sources. To investigate whether this is also true for sources detected in blind surveys, we calculated the values of F_{25-60} for the 6.7 GHz methanol maser sources detected by Ellingsen et al.(1996) for which they identified IRAS counterparts. Amongst the 26 sources which they list, only one source (G331.42+0.26) has a value of F_{25-60} that is less that 10^{14}Jy · Hz viz. $F_{25-60} = 10^{13.69}$ Jy · Hz. The remaining 25 sources all have $F_{25-60} > 10^{14}$ Jy · Hz. The second faintest source in the list of Ellingsen et al.(1996) is G334.65-0.02, for which $F_{25-60} = 10^{14.11}$ Jy · Hz. The mean of $\log F_{25-60}$ for these sources is 15.24 and the standard deviation 0.72. The range of F_{25-60} for these sources is therefore no different from that of the sources detected in the IRAS based surveys. It would seem therefore as if $F_{25-60} > 10^{14}$ Jy · Hz for the majority of methanol maser sources for which IRAS counterparts can be identified.

5. Conclusions

We have used a simple model to investigate some of the properties of embedded ionizing stars in the Galaxy. Our conclusions are as follows:

1. The model predicts that the dispersion in Galactic latitude decreases towards smaller values of F_{25-60}. The model also predicts that a significant fraction of the embedded ionizing stars are fainter than previously expected (by WC) in the FIR. It is therefore unlikely that all the embedded ionizing stars in the Galaxy can be selected with criteria that are simple as the WC criteria.
2. From a comparison of the dependence of the dispersion in Galactic latitude as a function of F_{25-60} for the WC sources with that of the model prediction it is concluded that a significant fraction of the fainter WC sources are most likely not embedded ionizing stars. The decrease in the detection rate of 6.7-GHz methanol masers towards smaller values of F_{25-60} for the WC sources may be partly due to an increase in the level of contamination by sources that are not embedded ionizing stars.
3. Due to the expected decrease in dispersion in Galactic latitude towards smaller values of F_{25-60} the best way to detect new 6.7-GHz methanol masers sources seems to be through blind surveys. Efforts should be made as far as possible to get additional information on the spectral class of the ionizing star(s) associated with the masers. Such information is necessary to investigate a possible mass dependence of the excitation of methanol masers.

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