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Methanol masers as tools to study high-mass star formation

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Abstract. In this contribution I will attempt to show that the study of Galactic 6.7 and 12.2 GHz methanol masers themselves, as opposed to the use of methanol masers as signposts, can yield important conclusions contributing to the understanding of high-mass star formation. Due to their exclusive association with star formation, methanol masers are the best tools to do this, and their large number allows us to probe the entire Galaxy. In particular I will focus on the determination of the luminosity function of methanol masers and on the determination of an unambiguous signature for a circumstellar masing disc seen edge-on. Finally I will try to point out some future fields of research in the study of methanol masers.

Keywords. masers, methanol, star formation, high-mass stars

1. Introduction

The Galactic maser emission of methanol appears to be exclusively associated with sites of high-mass star formation (Minier *et al.* 2003). In particular, the *class II* masers at 6.7 and 12.2 GHz are among the brightest masers in the Milky Way. Since their discovery, a number of extended searches have been put into action with the aim of gathering a potentially large number of objects to be studied in depth. A good list of these searches is presented in Pestalozzi *et al.* (2005). Because of their high brightness, methanol masers are obvious targets for interferometric observations that reveal the finest dynamical and morphological details at large distances (1 AU at 1 kpc).

The census of 6.7 GHz masers in the Milky Way counts to date some 520 sources, all potentially locating a high-mass protostar (Pestalozzi *et al.* 2005). This number is subject to increase as the Methanol MultiBeam (MMB) Survey (see contribution by J. Green in these proceedings) covers more regions of the Galactic Plane. The distribution of the known methanol masers in the Galaxy is shown in Fig. 1.

Research connected with methanol masers can be summarised and organised as shown in Table 1. In the squares, I put some examples of the type of investigation that were undertaken to study methanol masers. Methanol maser studies can be divided into two main categories: studies having the maser emission itself as target of their investigation on the one hand, and studies having the source hosting the maser emission as their target on the other. Both these paths give rise to two subclasses: studies of the maser sources as a group (statistical or global analysis) on the one hand, and deep studies on specific sources on the other. The outcomes from these studies can also be distributed into a similar diagram. The goal is to make the outcomes fall in the most general possible category (bottom left square in Table 1), i.e. to understand high-mass star formation.

The common property of the early searches for 6.7 GHz (and 12.2 GHz) methanol masers was that they concentrated their efforts in the characterisation of the host of the masers (bottom left square of Table 1). This was in fact a natural consequence

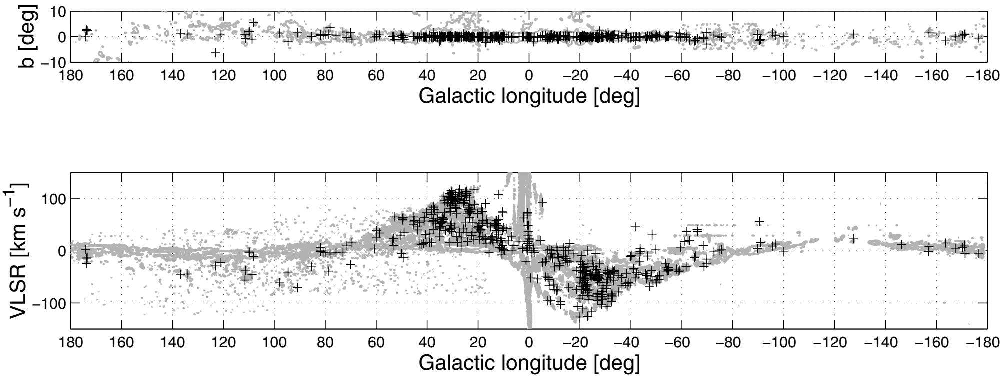

Figure 1. Distribution of methanol masers in Galaxy, superposed on the CO contours from Dame *et al.* 1987, in space (top) and LOS velocity (bottom). The methanol masers seem to accurately follow the overall structure of the Galaxy, both in space and LOS velocity. Particularly visible in the bottom panel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

of the strategy adopted to find new sources, i.e. targetting IRAS sources according to selection criteria corresponding to particular objects, as Ultra Compact (UC) HII regions with more or less red colours (e.g. Schutte *et al.* 1993,Szymczak *et al.* 2000), or known star formation regions hosting OH masers (e.g. Caswell *et al.* 1995). The relatively low detection rate of these surveys revealed the inaccuracy of the definition of methanol maser hosts and called for untargetted searches, where large areas of sky were covered with observations (e.g. Ellingsen *et al.* 1996, Szymczak *et al.* 2002, Pestalozzi *et al.* 2002b, Pandian *et al.* 2007). The main outcome of these studies was that a large fraction of methanol masers at 6.7 GHz were found not to be associated with known bright IR emitters but with very deeply embedded and therefore probably young objects (e.g. Pestalozzi *et al.* 2002a). This conclusion relies on accurate astrometric information both for the masers and for the IR objects, which is only recently starting to become available at a large number of wavelengths and for a large number of targets. More recently, large follow-up campaigns in the millimetre and sub-millimetre bands in continuum and spectral line emission have given further insight into the nature of the hosts of 6.7 GHz methanol masers (Purcell *et al.* 2006, Hill *et al.* 2005). The main outcome from these studies is that methanol masers are probably the first signal for the existence of a high-mass protostar when it is still embedded in its thick primordial dust cocoon.

Studies having the masers themselves as object are more challenging. This is mainly due to the fact that the maser emission is non-thermal in nature and therefore the extraction of information on the physical conditions of the emitting medium is not trivial. Theoretical modelling of the maser emission of methanol faces the challenge of including a larger number of molecular transitions in the calculations, potentially all interacting and producing a large number of masing transitions (e.g. Sobolev *et al.* 1997, Cragg *et al.* 2005). These studies are tightly linked to multi transitional observations of maser-bearing objects, that are starting to include larger samples of targets (see Pestalozzi *et al.* 2005 for a list). In the near future these studies will greatly benefit from the clear improvement of backends that will allow simultaneous observation of different frequency bands covering large regions of the spectrum at once. Polarisation measurements appear to be technically challenging, and from the levels of polarisation obtained, it is not always easy to discriminate between pumping effects and scattering effects (Wiesemeyer *et al.* 2004).

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Table 1. Conceptual division of the study of methanol masers.

	Global studies	Particular studies
Masers	maser luminosity structure of the Galaxy maser theory polarisation	NGC 7538: disc signature Location of new sources proper motions (variability)
Hosts of masers	Associations SEDs follow-up observations	IRAS 20126, S255 Protoclusters

Finally, the quality of the conclusions from variability studies is critically dependent on long time monitoring, and has only recently started to produce interesting results. Some sources show a remarkable regularity, and represent a challenge for modelling (see e.g. Goedhart *et al.* 2004).

In this contribution I will concentrate on the upper row of Table 1 and present one example for each square. In particular I will concentrate on the extraction of the luminosity function of the masers and on the recognition of a unique signature for an edge-on rotating disc marked by maser emission.

2. A global study: the luminosity function of the masers

The distribution of the known methanol masers in the Milky Way is shown in Fig. 1. The majority of the masers are located in a ring, covering Galactic longitudes of ±50°. What is interesting is that a comparison of the Galactic distribution of methanol masers with OB associations (Bronfman *et al.* 2000) shows excellent agreement. This fact reinforces the association of methanol masers with high-mass star formation.

The study of the luminosity function of astronomical objects has to first solve the problem of the distance determination. In the Milky Way, kinematic distances can be attributed to sources observed in spectral line emission (as e.g. masers). Kinematic distances for sources orbiting the Galactic Centre on orbits internal to the Sun's orbit suffer from an ambiguity which can be resolved only on a case-to-case basis. Several methods have been used to solve this ambiguity with varying success (see e.g. Busfield *et al.* 2006 for the HI self absorption method, and van der Walt 2005 for a probabilistic approach). Here I present an approach to the study of the luminosity function of methanol masers that removes the problem of the heliocentric distance determination.

What is needed is to disentangle the spatial distribution of the sources under investigation from their intrinsic luminosity distribution. In fact, the *observed* luminosity distribution of masers (diamonds and circles in Fig. 2) is the convolution of a spatial distribution with an *intrinsic* luminosity distribution after applying an observational sensitivity cutoff. Knowing the spatial distribution of the masers and the sensitivity cutoff leaves the intrinsic luminosity function to be the only unknown in the problem.

The starting point is the distribution of masers in Galactocentric distance. The latter is not affected by any ambiguity, and only assumes a rotation curve of the Galaxy. The inaccuracies of the rotation curve of the Galaxy do not significantly affect the final result, because, as seen in Fig. 2, most of the methanol masers are distributed in a ring with Galactocentric radius ∼5 kpc: at that radius, even the influence of the central bar is not strong enough to produce significant deviations from a circular motion (see e.g. Fux 1999). The distribution of masers in Fig. 2 is assumed to represent with a high level of confidence *the shape* of the true, azimuthally averaged, spatial distribution of methanol masers in the

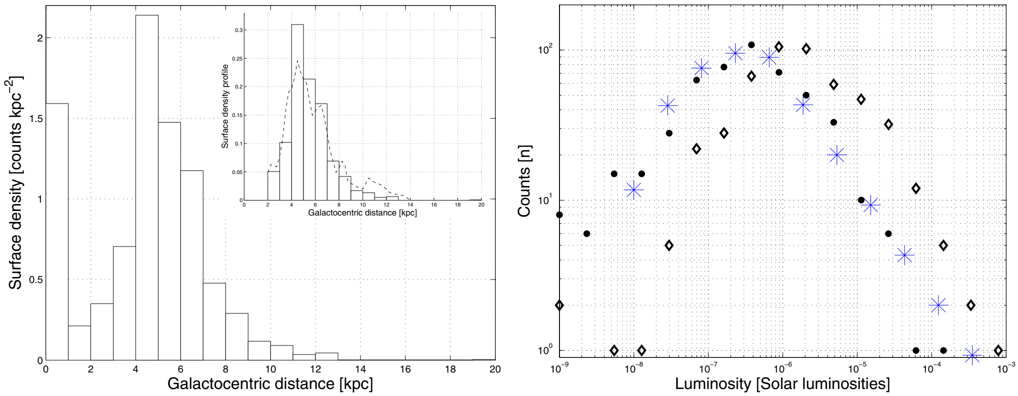

Figure 2. Left: Surface density of the known methanol masers in Galactocentric distance. The distribution shows a peak at the same radius as OB associations. The inset shows a comparison of the surface density of the masers with the molecular gas in the Milky Way. Right: Luminosity distribution of methanol masers in the Galaxy. Diamonds and circles plot all the (ambiguous) sources at the near- and far heliocentric distance, respectively. Stars show a synthetic luminosity distribution obtained by observing with a 2 Jy sensitivity a population of 5000 masers spatially distributed according to a Gaussian and having an intrinsic luminosity distribution as a power-law between cutoffs of index -1.7.

Galaxy, $F(R)$. This will be convolved with the intrinsic luminosity distribution $G(L)$ and "observed" with a certain sensitivity to fit the Galactocentric distribution of observed masers shown in Fig. 2.

The free parameters in the fit are the real total number of masers in the Galaxy (the integral of $F(R)$) and the function $G(L)$. To keep the number of unknowns to a minimum $G(L)$ was expressed as a single power-law between two cutoffs. These cutoffs were fixed by taking a range of sensible luminosities from the literature, so that the only two free parameters in the fit were the index of the luminosity function and the total number of methanol masers in the Galaxy. The two parameters cannot be found simultaneously but a plausible range can be estimated. On the basis of previous estimates of the total number of sources in the Galaxy (van der Walt 2005), the index for the luminosity function was found to lie between -1.5 and -2.0. In Fig. 2 an example of observed synthetic luminosity distribution is shown (stars). The model consists of a total number of 5000 sources distributed in luminosity according to a power-law with index -1.7 and observed with a detection threshold of 2 Jy. The details of this work are presented in Pestalozzi *et al.* 2007a.

The significance of the intrinsic luminosity distribution of the masers is still not clear, both in terms of high-mass star formation and in terms of maser modelling. A major contribution will be given by the completion of the MMB Survey, that is expected to determine with a very high level of confidence how many methanol masers there are in the Milky Way and thus limiting one more parameter in the model presented here.

3. Particular study: the disc signature

NGC7538 is a very well known and deeply studied high-mass star forming region in in the Perseus arm. It contains some 11 catalogued IR sources spanning over a wide range of ages. The centre of the figure is occupied by an UC HII region (IRS 1) that hosts bright 6.7 and 12.2 GHz methanol masers (see the 6.7 GHz spectrum in Fig. 3).

All spectral features have been observed at high angular resolution using MERLIN and the EVN. In particular, positions were recently obtained for features F and G and

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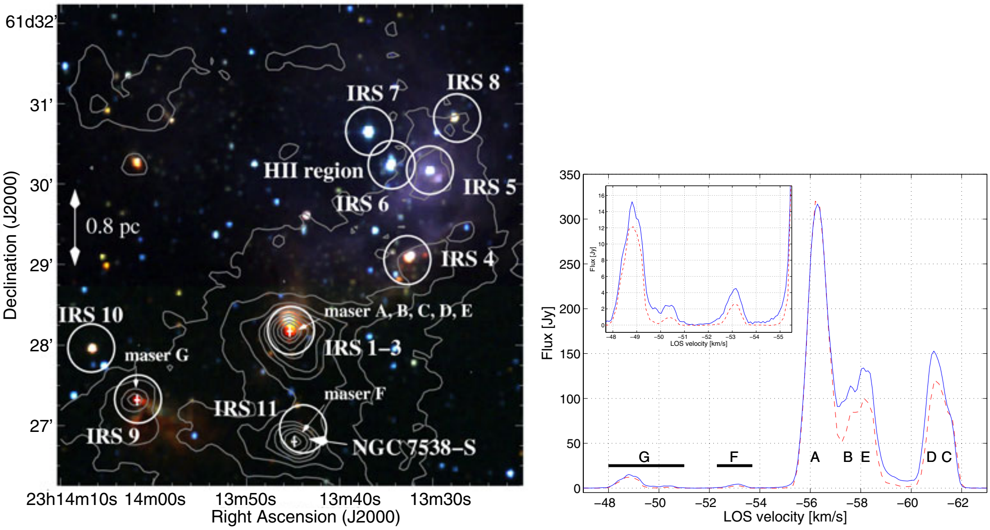

Figure 3. Left: General view of the high-mass star forming region NGC7538. Grey contours of the 1.2 mm dust continuum are overlaid on a JHK 2-mass image. Circles indicate the catalogued IR sources, crosses the methanol masers. The methanol masers appear in association with the youngest and most massive objects. Right: Spectrum of the 6.7 GHz maser emission toward NGC7538. Features A, B, C, D, E are cospatial with IRS 1. The maser disc is feature A. The inset is a zoom of the features F and G. The 12.2 GHz spectrum is similar to the 6.7 GHz one.

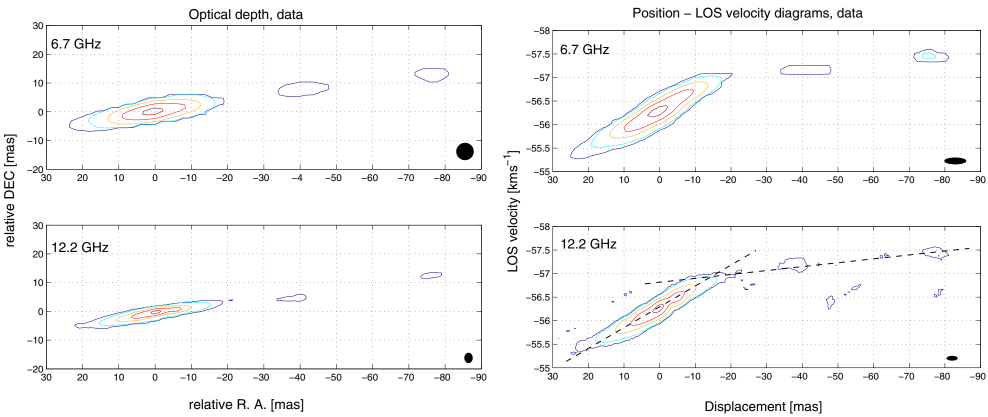

Figure 4. Maps (left) and velocity-displacement diagrams (right) of the main spectral feature of the 6.7 and 12.2 GHz methanol masers toward NGC7538 IRS 1. The beam size is shown in the bottom right corner in all panels. The contours are 1, 5, 10, 30, 50, 70, 90% of the peak in all panels. Dashed lines indicate the change in gradient between the main feature and the outliers.

appear to be cospatial with the youngest and most massive sources in the region, namely NGC7538 S and IRS 9, respectively (Pestalozzi *et al.* 2006). By determining the position of the masers with an accuracy of better than 30 mas, the authors claim to have accurately determined the position of the protostars.

The main spectral feature (A in Fig. 3) reveals a single, smooth spatial feature 6-20 beams across and shows a mainly linear LOS velocity gradient (Fig. 4).

The linear structure in both space and LOS velocity was naturally interpreted as arising from a (Keplerian) rotating disc seen edge-on amplifying a background continuum, and

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where the *maser spots* are orbiting a central object at a fixed radius (Minier *et al.* 1998). The maser emission was subsequently modelled as coming from a uniformly distributed material in a rotating disc seen edge-on and confined between an inner and outer radii. This avoided the assumption of a single radius and produced astonishingly accurate fits to the data (Pestalozzi *et al.* 2004).

Assuming amplification of a background continuum I_B, the optical depth of the maser emission at displacement θ_x and θ_y from the centre of each frequency plane with LOS velocity v is expressed by $\tau(\theta_x, \theta_y, v) = \ln(I(\theta_x, \theta_y, v)/I_B)$. In the case of a thin disc, one spatial dimension can be dropped and the modelling reduces to the study of the position-LOS velocity diagram of the normalised optical depth $F(\theta_x, v) = \tau(\theta_x, v)/\tau_0$, where τ_0 is the optical depth at displacement 0. The function F is then expressed as:

$$F(\theta_x, v) = \int \eta(\rho) \exp\left[-\frac{1}{2}\left(\frac{v - \Omega(\rho)\,\theta_x}{\Delta v_D}\right)^2\right] \frac{\mathrm{d}\rho}{\sqrt{1 - (\theta_x/\rho)^2}} \tag{3.1}$$

where $\Omega(\rho)$ is the angular velocity at every radius and the product $\Omega(\rho)\,\theta_x$ is the LOS component of the rotation velocity. Δv_D is the linewidth at $\theta_x = 0$ and η is the gain of the maser that also defines the limits of integration. Pestalozzi *et al.* (2004) modelled η as a power-law with index 0.5 and with sharp cutoffs at inner and outer radii ρ_{in} and ρ_{out}.

The aim is to reproduce the right panels in Fig. 4. Two features are of extreme importance in this matter: the fact that most of the emission is symmetric around a peak (that we will consider to be the central LOS across the disc) and that there is a significant drop of the overall gradient at displacements larger than 10-15 mas. These two facts greatly constrain the dynamics in the modelling.

The study of F is best summarised by the study of the *spine*, defined by the maximum of F at every LOS, $\partial F/\partial v = 0$. In the case $\Omega(\rho) = constant$, i.e. solid body rotation, the study of the spine becomes very much simplified, as the exponential in eq. 3.1 comes out of the integral. The location of the spine is defined by $v - \Omega\,\theta_x = 0$ and the optical depth on the spine by the integral. The spine is then a straight line with constant slope (Ω). F on the spine will have maxima at displacements tangent to the inner edge of the disc and a local minimum at $\theta_x = 0$. The spectrum will have two features at $v = \pm\Omega\theta_{in}$, where θ_{in} is the LOS tangent to the inner edge. In the special case of $\Omega = 0$ (quiescent disc) the spine will be parallel to the displacement axis, F on the spine will be the same as the previous case and the spectrum will have only one feature, centered at $v = 0$ and of width Δv_D. The above considerations unambiguously show that solid body rotation (and a quiescent disc) cannot reproduce the data in Fig. 4, differential rotation is required.

The study of the spine for $\Omega \neq const$ gives a constraint on the rotation velocity: in order for F to have a maximum at $\theta_x = 0$, the rotation velocity at the inner edge has to be at least some 3–4 times higher than Δv_D (Pestalozzi *et al.* 2007b). Also, in order to account for the drop in gradient (dashed lines in the lower right panel of Fig. 4), the spine analysis indicates that the dynamics has to be Keplerian, i.e. $\Omega \sim \rho^{-3/2}$. Finally, it is important to notice that if the rotation velocity does not meet the above constraint, both spectrum and F-profiles (F on the spine) will have three peaks of emission, in the same way that was predicted by e.g. Ponomarev *et al.* (1994).

The general conclusion at this point is that a maximum of emission in the centre of both map and velocity-displacement diagrams is a strong hint for (fast) differential rotation seen edge-on. This is also supported by the existence of a clear bend of the gradient in the velocity-displacement diagram. These two facts unambiguously exclude

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solid body rotation (and a quiescent disc) as these would produce linear features both in space and velocity but no maximum in the centre, and no bend in the velocity diagram.

4. Summary and future views

In this paper I have tried to show how the study of methanol masers themselves (as opposed to the study of the environment of methanol masers) can lead to important conclusions about the maser emission (luminosity function) and the hosts of the masers (disc signature and accurate localisation of high-mass protostars).

The luminosity function of the maser will be refined in the near future thanks to the outcomes of the MMB Survey, which will also yield the ultimate census of the population of methanol masers in the Galaxy. The study of the accurate luminosity function of the masers will give insights into some characteristics of the maser mechanism, instrumental for extracting the physical conditions of the maser environment from the maser emission itself.

By accurately modelling the maser emission in one source, we were able to unambiguously determine what the signature for a circumstellar (differentially) rotating disc is as opposed to e.g. a bipolar outflow. Such model will be applied to other sources in order to test the existence of thin discs around high-mass protostars. The finding (or not!) of further discs around high-mass protostars will contribute in refining the high-mass star formation scenario.

Furthermore, there is a strong call for studies of the Galactic structure of the Milky Way, as methanol masers seem to represent fairly equally all Galactic longitudes (and latitudes) and carry an important dynamical information. This is unprecedented, as previous studies of the structure of our Galaxy were relying on the observation and positioning of HII regions.

One aspect that will be crucial for the future studies of methanol masers will be the gathering of data on the extended maser emission. As has been observed by Minier *et al.* (2002) and Harvey-Smith & Cohen (2006), it appears that maser emission can probe large surroundings of a high-mass star forming region. The mechanisms of this low brightness maser emission will have to be understood in order to be able to correctly interpret the data and increase our understanding of the physical conditions around high-mass protostars.

Finally it is exciting to keep in mind that the next few years will be characterised by large scale Galactic legacy surveys at a number of wavelengths. In particular, the SCUBA-2 surveys (SASSy and JPS) will yield the most complete catalogue of star forming clouds in the Milky Way detected at sub millimetre wavelengths. The cross correlation of these catalogues with the final MMB catalogue will enable the definition of an evolutionary sequence for the initial stages of the formation of high-mass stars. More in the future, the Herschel survey of the Galactic Plane will give the long waited view of the Galaxy at previously unavailable frequencies. Again, this will allow an accurate characterisation of methanol maser hosts and ultimately the definition of an accurate evolutionary sequence for high-mass star formation.

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References

Bronfman, L., Casassus, S., May, J. & Nyman, L. -Å. 2000 *A&A*, 358, 521

Busfield, A. L., Purcell, C. R., Hoare, M. G., Lumsden, S. L., Moore, T. J. T. & Oudmaijer, R. D. 2006 *MNRAS*, 366, 1096

Caswell, J. L., Vaile, R. A., Ellingsen, S. P., Whiteoak, J. B. & Norris, R. P. 1995, *MNRAS*, 272, 96

Cragg, D. M., Sobolev, A. M. & Godfrey, P. D. *MNRAS*, 360, 533

Dame, T. M., Ungerechts, H., Cohen, R. S., Geus, E. J., Grenier, I. A., May, J., Murphy, D. C., Nyman, L. -Å. & Thaddeus, P. 1987, *ApJ*, 322, 1706

DeBuizer, J. M. 2003, *MNRAS*, 341, 277

De Buizer, J. M. & Minier, V. 2005, *ApJ*, 628, L151

Ellingsen, S. P., von Bibra, M. L., McCulloch, P. M., Norris, R. P., Deshpande, A. A. & Phillips, C. J. 1996, *MNRAS*, 280, 378

Fux, R. 1999 *A&A*, 345, 787

Goedhart, S., Gaylard, M. J. & van der Walt, D. J., 2004 *MNRAS*, 355, 553

Hill, T., Burton, M. G., Minier, V., Thompson, M. A., Walsh, A. J., Hunt-Cunningham, M. & Garay, G. 2005, *MNRAS*, 363, 405

Harvey-Smith, L. & Cohen, R. J. 2006, *MNRAS*, 371, 1550

Minier, V., Booth, R. S., & Conway, J. E. 1998, *A&A*, 336, L5

Minier, V., Booth, R. S. & Conway, J. E. 2002, *A&A*, 383, 614

Minier, V., Ellingsen, S. P., Norris, R. P. & Booth, R. S. 2003, *A&A*, 403, 1095

Pandian, J. D., Goldsmith, P. F. & Deshpande, A. A. 2007, *ApJ*, 656, 255

Pestalozzi, M. R., Humphreys, E. M. L. & Booth, R. S. 2002a, *A&A*, 384, L15

Pestalozzi, M. R., Humphreys, E. M. L. & Booth, R. S. 2002b, in: Migenes, V. and Reid, M. (eds.), *Cosmic Masers: from Proto-Stars to Black Holes*, IAU 206 (ASP Conference Series), p. 139

Pestalozzi, M. R., Elitzur, M., Conway, J. E., & Booth, R. S. 2004, *ApJL*, 603, L113, erratum: 2004, ApJ, 606, L173

Pestalozzi, M. R., Minier, V., & Booth, R. S. 2005, *A&A*, 432, 737

Pestalozzi, M. R., Minier, V., Motte, F., & Conway, J. E. 2006, *A&A*, 448, L57

Pestalozzi, M. R., Chrysostomou, A., Collett, J. Minier, V., Conway, J. E. & Booth, R. S. 2007a, *A&A*, 463, 1009

Pestalozzi, M. R. and Elitzur, M. and Conway, J. E. 2007b, *in prep. for ApJ*

Ponomarev, V. O. and Smith, H. A. and Strelnitski, V. S. 1994, *ApJ*, 424, 976

Purcell, C. and Balasubramanyam, R. and Burton, M. G. *et al.* 2006, *MNRAS*, 367, 553

Schutte, A. J., van der Walt, D. J., Gaylard, M. L. & MacLeod, G. C. 1993, *MNRAS*, 261, 783

Sobolev, A. M., Cragg, D. M. & Godfrey, P. D. 1997, *MNRAS*, 288, L39

Szymczak, M., Hrynek, G. & Kus, A. J. 2000, *A&AS*, 143, 269

Szymczak, M., Kus, A. J., Hrynek, G., Kepa, A. & Pazdereski, E. 2002, *A&A*, 392, 277

Walsh, A. J., Burton, M. G., Hylard, A. R., & Robinson, G. 1998, *MNRAS*, 301, 640

van der Walt, J. 2005 *MNRAS*, 360, 153

Wiesemeyer, H., Thum, C. & Walmsley, C. M. 2004 *A&A*, 428, 479

Discussion

Y. Rodriguez: What is the nature of the outliers in your maps of the NGC7538 maser emission at displacements >30 mas?

Pestalozzi: These are considered to be local enhancements of the optical depth that do not fall on the spine. They helped in constraining the drop of gradient that finally indicated Keplerian rotation.

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