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Authors	MOSCADELLI, Luca, SANNA, ALBERTO, GODDI, CIRIACO, Krishnan, Vasaant, MASSI, Fabrizio, BACCIOTTI, Francesca
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Protostellar Outflows at the Earliest Stages (POETS)

IV. Statistical properties of the 22 GHz H₂O masers

L. Moscadelli¹, A. Sanna^{2,3}, C. Goddi^{4,5}, V. Krishnan^{1,6}, F. Massi¹, and F. Bacciotti¹

¹ INAF – Osservatorio Astrofisico di Arcetri, Largo E. Fermi 5, 50125 Firenze, Italy
e-mail: mosca@arcetri.astro.it

² INAF – Istituto di Radioastronomia & Italian ALMA Regional Centre, Via P. Gobetti 101, 40129 Bologna, Italy

³ Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany

⁴ Leiden Observatory, Leiden University, PO Box 9513, 2300 RA Leiden, The Netherlands

⁵ Department of Astrophysics/IMAPP, Radboud University, PO Box 9010, 6500 GL, Nijmegen, The Netherlands

⁶ South African Radio Astronomy Observatory (SARAO), 2 Fir street, Black River Park, Observatory, Cape Town 7925, South Africa

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ABSTRACT

Context. 22 GHz water masers are the most intense and widespread masers in star-forming regions. They are commonly associated with protostellar winds and jets emerging from low- and high-mass young stellar objects (YSO).

Aims. We wish to perform for the first time a statistical study of the location and motion of individual water maser cloudlets, characterized by typical sizes that are within a few au, with respect to the weak radio thermal emission from YSOs.

Methods. For this purpose, we have been carrying out the Protostellar Outflows at the Earliest Stages survey of a sample (38) of high-mass YSOs. The 22 GHz water maser positions and three-dimensional (3D) velocities were determined through multi-epoch Very Long Baseline Array observations with accuracies of a few milliarcsec (mas) and a few km s⁻¹, respectively. The position of the ionized core of the protostellar wind, marking the YSO, was determined through sensitive radio continuum, multi-frequency *Jansky* Very Large Array observations with a typical error of ≈20 mas.

Results. The statistic of the separation of the water masers from the radio continuum shows that 84% of the masers are found within 1000 au from the YSO and 45% of them are within 200 au. Therefore, we can conclude that the 22 GHz water masers are a reliable proxy for locating the position of the YSO. The distribution of maser luminosity is strongly peaked towards low values, indicating that about half of the maser population is still undetected with the current Very Long Baseline Interferometry detection thresholds of 50–100 mJy beam⁻¹. Next-generation, sensitive (at the nJy level) radio interferometers will have the capability to exploit these weak masers for an improved sampling of the velocity and magnetic fields around the YSOs. The average direction of the water maser proper motions provides a statistically-significant estimate for the orientation of the jet emitted by the YSO: 55% of the maser proper motions are directed on the sky within an angle of 30° from the jet axis. Finally, we show that our measurements of 3D maser velocities statistically support models in which water maser emission arises from planar shocks with propagation direction close to the plane of the sky.

Key words. ISM: jets and outflows – ISM: molecules – masers – radio continuum: ISM – techniques: interferometric

1. Introduction

The 22 GHz water maser $6_{1,6}-5_{2,3}$ rotational transition is the most intense emission line at radio frequency and the most widespread interstellar maser. In star-forming regions, the average isotropic luminosity of detected water masers is $\sim 10^{-5} L_{\odot}$ (Anglada et al. 1996, see Table 5) and in extreme cases, such as in the strong source W49N, it can be as high as $\sim 1 L_{\odot}$ (Elitzur et al. 1989). From the time of its discovery by Cheung et al. (1969), the water maser emission has been surveyed using both single-dish (Furuya et al. 2001; Felli et al. 2007; Urquhart et al. 2011; Walsh et al. 2011) and, more recently, connected interferometers (Beuther et al. 2002; Walsh et al. 2014; Titmarsh et al. 2016; Kim et al. 2019), with angular resolutions ranging from $\sim 1''$ to $\sim 1'$. These surveys have derived the global properties of the emission (luminosity, extent in LSR velocity (V_{LSR}) and the time variability) of the interstellar water masers, in addition to studying the correlation with independent star-formation markers, particularly with other maser types. Very Long Baseline Interferometry

(VLBI) observations of specific sources, achieving milliarcsecond (mas) angular resolution, allow us to resolve the emission and determine the spatial and spectral characteristics of individual maser cloudlets and measure their three-dimensional (3D) motion (Goddi et al. 2006). The VLBI results in most cases indicate a physical association of the water masers with protostellar winds and jets emerging from low- and high-mass young stellar objects (YSO; Torrelles et al. 2003; Moscadelli et al. 2005; Goddi & Moscadelli 2006; Sanna et al. 2012; Burns et al. 2016; Hunter et al. 2018).

Models of the 22 GHz water masers predict that the emission originates in warm and dense, shocked gas. Two different classes of shocks are considered: slow (≤ 40 km s⁻¹) non-dissociative C-type (Kaufman & Neufeld 1996), and fast (≥ 40 km s⁻¹) dissociative J-type (Elitzur et al. 1992; Hollenbach et al. 2013) shocks. The post-shock densities for water maser operation, H₂ number density (n_{H_2}) $\sim 10^8$ – 10^9 cm⁻³, are similar; however, in C shocks molecules are not dissociated and the masing gas attains high temperatures of 1000–2000 K, whereas in J-shocks, the H₂O

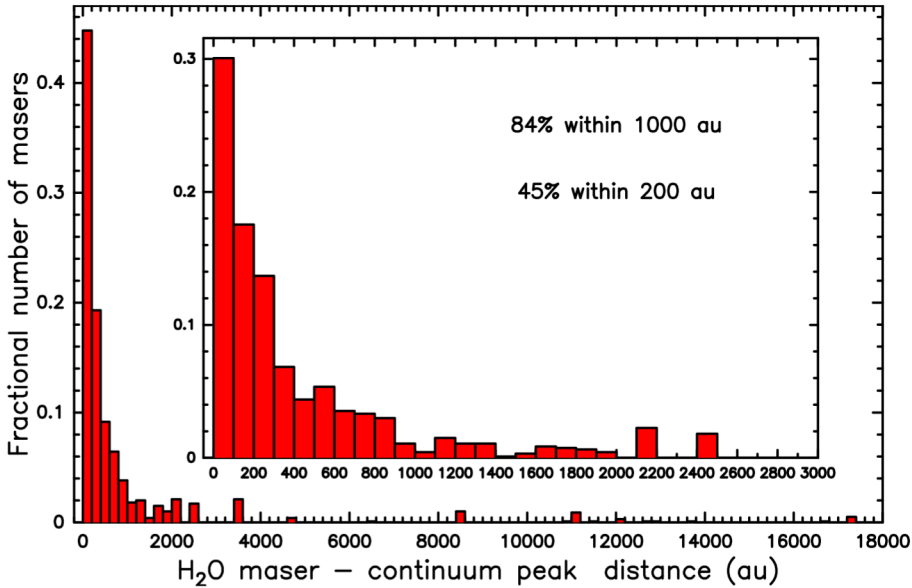


Fig. 1. Histograms of the sky-projected distance of water masers from the radio continuum peak, for all the observed masers in the POETS targets (main) and for a maximum continuum-maser separation of 3000 au (inset). Considering all the observed masers, the target-average distance error and corresponding standard deviation are 182 and 16 au, respectively. Selecting masers within 3000 au from the radio continuum peak, the target-average distance error and corresponding standard deviation are 108 and 17 au, respectively. Correspondingly, we used bins of 200 and 100 au for the histograms in the main plot and in the inset, respectively. The histogram values are normalized by the total number of selected water masers.

molecules reform in a post-shock temperature plateau of 400–500 K. Shocks are a natural by-product of winds and jets, caused either by a velocity or density change internal to the flow, or by interaction of the flow with the surrounding medium. The link between the water masers and the outflows from YSOs provided by the observations is, therefore, consistent with the shock models, although a more quantitative test of the models, in particular discerning between C- and J-shocks, is often hampered by insufficient knowledge about the flow geometry and its speed.

We have been carrying out the Protostellar Outflows at the Earliest Stages (POETS) survey with the goal of imaging the inner outflow scales of 10–100 au in a statistically-significant sample (38¹) of luminous YSOs, targeting both the molecular and ionized components of the outflows. The outflow kinematics is studied at mas scales through Very Long Baseline Array (VLBA) observations of the 22 GHz water masers belonging to the Bar and Spiral Structure Legacy survey (BeSSeL; see below). We have employed the *Jansky* Very Large Array (JVLA) at C- (6 GHz), Ku- (13 GHz), and K-band (22 GHz) in the A- and B-Array configurations (FWHM beams of 0'1–0'4) to determine the spatial structure and the spectral index of the radio continuum emission and to address its nature.

The BeSSeL survey is a key project of the VLBA, whose main goal is to derive the structure and kinematics of the Milky Way by measuring accurate positions, distances (via trigonometric parallaxes) and proper motions (PM) of 6.7 GHz methanol and 22 GHz water masers in hundreds of high-mass star forming regions distributed over the Galactic disk (Reid et al. 2014, 2019). The BeSSeL observations provide absolute positions and velocities of individual maser cloudlets with accuracies of a few mas and a few km s⁻¹, respectively, for hundreds of YSOs. They have an enormous value for star-formation studies since they afford for the first time a VLBI survey of the properties of the most widespread interstellar masers based on a large, homogeneous dataset.

Moscadelli et al. (2016; hereafter Mos16) presented the first results of the POETS survey for a pilot sample of 11 targets, also

¹ This number includes the two YSOs IRAS 20126+4104 and AFGL 5142 studied via multi-epoch VLBI observations by our group in the past, which have been added to the POETS sample of 36 targets (see Table A.1).

describing the target selection, observations, and data analysis. Sanna et al. (2018; hereafter Paper I) reported on and interpreted the radio continuum data of the whole sample, while Sanna et al. (2019a; hereafter Paper II) examined the radio synchrotron jet associated with the high-mass YSO G035.02+0.35. Moscadelli et al. (2019a; hereafter Paper III) completed the combined analysis of the radio continuum and water maser observations for all the targets, with a particular focus on the water maser kinematics. The main result of Paper III is that the 3D-velocity distribution of the water masers near the YSO in all the sources of the sample can be interpreted in terms of a single physical scenario: a disk-wind (DW). The observed masers are produced in the different regions of the DW, from the axial collimated jet portion to the wide-angle outer layers.

In this paper, we report on the statistics of the water maser properties and examine global correlations in the observed physical quantities. The distribution of water maser positions, luminosities, and 3D-velocity orientations and amplitudes is presented in Sect. 2. In Sect. 3, we discuss the use of the H₂O masers as a tool for star-formation studies. Our conclusions are presented in Sect. 4.

2. H₂O maser statistics

2.1. Distance from the YSO

In the POETS survey, on the basis of the spatial distribution of the water masers and their PMs, we could ascertain that 36 out of the 38 water masers observed with the JVLA are clearly associated with a radio continuum source. In Fig. 1, we analyze the linear separation of the detected water masers from the position of the radio continuum peak. In most of our targets, the continuum emission at both 13 and 22 GHz is dominated by a single (unresolved or slightly resolved) source, whose position is determined by fitting a 2D Gaussian profile. For each POETS target, we always select the radio continuum peak of the JVLA observation at the highest angular resolution, that is either 13 GHz or 22 GHz A-Array configuration. The histogram in the main plot of Fig. 1 considers all the water masers associated with the POETS targets, while the histogram in the inset only refers to masers up to a maximum separation of 3000 au from the continuum. Since the error on the linear distance is directly proportional to the distance at large values, the bins of the main and

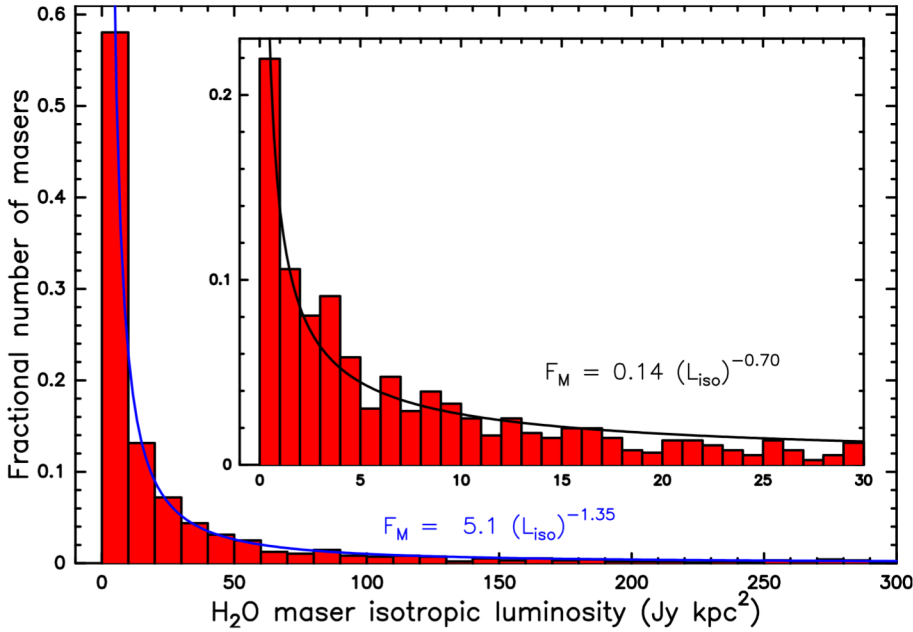


Fig. 2. Histograms of the maser isotropic luminosity for a maximum maser luminosity of 300 Jy kpc² (main) and 30 Jy kpc² (inset). Less than 4% of the observed masers have an isotropic luminosity higher than 300 Jy kpc². The bins are 10 and 1 Jy kpc² for the histograms in the main plot and in the inset, respectively. The histogram values are normalized by the total number of selected water masers. The continuous blue and black lines show the power-law fits of the values of the histograms in the main plot and in the inset, respectively, and the best-fit expressions are also reported using the same colors of the corresponding fits.

inset histograms are chosen 200 and 100 au, respectively, which is comparable with the average distance error of the selected masers. The histogram value is the fractional number of water masers in a bin. From these plots we infer that 84% of the water masers are found within 1000 au from the radio continuum peak and 45% within 200 au.

As discussed in Mos16, the peak of the radio continuum at 13 or 22 GHz is a good proxy for the YSO position, within the absolute position accuracy of ≈ 20 mas of JVLA observations. This belief is supported by several facts ascertained for the large majority of our targets: (1) the peaks of the radio continuum at 6, 13, and 22 GHz coincide in position within the errors and the determined radio spectral index, in the range of $-0.1 - 1.3$, is consistent with thermal bremsstrahlung from a YSO wind; (2) the water masers are distributed across the radio continuum at separations ≤ 1000 au from the continuum peak; (3) the water maser 3D velocities are best interpreted in terms of a DW emerging from the YSO (see Paper III). Therefore, on the basis of the distance distribution from the continuum shown in Fig. 1, we are able to statistically assess for the first time that water masers can be efficiently used to pinpoint the position of a YSO with an uncertainty of a few 100 au. We discuss this result in the context of the relevant literature in Sect. 3.1. Table A.1 lists the POETS targets, reporting distance, bolometric luminosity, YSO position pinpointed by the radio continuum, number of detected maser cloudlets, and the maximum maser separation from the YSO.

2.2. Isotropic luminosity

Most of the water masers detected in the POETS survey have their peak intensity in the range of $0.05\text{--}50$ Jy beam⁻¹. The isotropic luminosity, L_{iso} , of a maser cloudlet is calculated with the product $L_{\text{iso}} = F_p D^2$, where F_p is the (Gaussian-fit) flux of the strongest emission channel, averaged over the different observing epochs, and D is the source distance. The large majority, that is, 96%, of the masers, have $L_{\text{iso}} \leq 300$ Jy kpc², although exceptionally bright masers with $L_{\text{iso}} \sim 10^3\text{--}10^4$ Jy kpc² have also been observed. The histograms in Fig. 2 show that the distribution of maser luminosity is strongly peaked towards low values: in considering masers with $L_{\text{iso}} \leq 300$ Jy kpc², 86%

of them have $L_{\text{iso}} \leq 50$ Jy kpc²; taking the masers with $L_{\text{iso}} \leq 30$ Jy kpc², 56% of them have $L_{\text{iso}} \leq 5$ Jy kpc². The implications of this luminosity distribution for more sensitive water maser observations of the future are considered in Sect. 3.2.

2.3. 3D velocities

Combining the water maser PM and line of sight (LOS) velocity, we derive the maser 3D velocity. We have been searching the literature for the systemic V_{LSR} of our targets from observations of high-density ($n_{\text{H}_2} \geq 10^6$ cm⁻³) thermal tracers and, in most cases, the found values are accurate within a few km s⁻¹. Since PMs are determined with comparable accuracies of a few km s⁻¹ (see Tables 6–16 in Mos16, and Tables B1–B27 in Paper III), we estimate an average error on the 3D-velocity amplitude of 3.3 km s⁻¹. The histogram of the maser 3D-velocity amplitudes is presented in Fig. 3, from which it is clear that a large fraction, 63%, of the water maser speeds falls in the range 10–30 km s⁻¹.

It is also interesting to study the angular distribution of the maser 3D velocities, considering both their projection into the plane of the sky and their inclination with respect to it. In Paper III (see Figs. C1–C3), we produced histograms of the position angle (PA) of the water maser PMs for all the targets with at least two measured PMs and studied the degree of collimation of the maser velocities in the plane of the sky. In searching the literature for high-angular ($\lesssim 1''$) resolution observations in thermal continuum and line tracers of our targets, for several cases we were able to ascertain the PA of the (sky-projected) axis of the YSO jet, referred to as A_{LJ} (see Paper III, Table A.1). Figure 4 presents the histogram of the difference between the maser PM PA and A_{LJ} , cumulating all the 14 POETS targets for which the direction of the protostellar jet is known from the literature (see Paper III, Table A.1). The average error on the PM PA is about half of the histogram bin. We note that 55% of the PMs of the masers is directed on the sky within an angle of 30° from the jet axis.

In Fig. 5 we have plotted the histogram of the inclination of the 3D velocities with the plane of the sky for all the water masers with measured PMs. The histogram bin is comparable with the average error of the inclination. It is clear that most of