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Applications of precision astrometry to studies of massive YSOs

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Abstract. We present VLBI observations of the H_2O maser emission towards a selection of massive young stellar objects (YSOs). In one of these sources, IRAS20126+4104, the measured proper motions confirm that the H_2O masers spots are tracing the very root (~ 100 AU) of a conical bipolar outflow emerging near the position of the embedded YSO, and are an excellent tool to investigate the structure and kinematics of the outflow/jet. We also present preliminary results of a first epoch EVN observations of a selection of 5 high-mass YSO to assess the precise association of maser spots and molecular outflows in these sources.

1. Introduction

There is still much to learn about the role played by molecular outflows in the context of star formation processes. This phenomenon presents many interesting aspects ranging from the possible role in supporting molecular clouds against gravitational collapse, to the collimation mechanism, to the velocity structure of the outflows on different scales. From an observational point of view, answering these questions is equivalent to attaining the best possible picture of an outflow in space and velocity. Since the outflowing material is mostly molecular, normally the means used to image these objects are the transitions of molecules such as CO, HCO^+, and a few others (see e.g. Bachiller and Pérez Gutiérrez, 1997), which usually lie in the millimeter range. However, these tracers can be used only to map the large scale structure of the flow (0.1-1 pc) and not the very root of it, which is likely to convey the most important information on the ejection mechanism, being very close to the central engine. Such a region has a size of a few 10 AU, not accessible even with the most powerful millimeter interferometers, but easy to study with VLBI techniques at centimeter wavelengths. The molecular transitions commonly used to map outflows lie in the millimeter range; however, molecular outflows from high-mass YSO are often associated with H_2O maser emission at 22 GHz (Felli et al. 1992), which hence represents the best tracer for studies of the flow at a small scale. Water masers have very large brightness temperatures, which make them ideal targets for VLBI studies.

With this in mind we have carried out VLBI observations of H_2O masers in a selection of high-mass young stellar objects which belong to the list studied by Tofani et al. (1995) with the VLA in the most extended configuration, to take one step further in the analysis of spatial distribution and kinematics of the masers. The case of IRAS20126+4104 deserves special mention due to the numerous studies of different molecular tracers on scales ranging from 100 AU to 1 pc (Cesaroni et al. 1997; Zhang et al. 1998; Cesaroni et al. 1999a; Hofner et al. 1999; Zhang et al. 1999) that resulted in the detection of a rotating Keplerian disk around the YSO and a detailed analysis of the jet/outflow, with the large scale outflow being fed by a narrow jet, which is ionised on a scale of $\sim 1''$ (1700 AU) and becomes neutral on $\sim 20''$ (0.16pc). IRAS20126+4104 is considered to be the most convincing case of a disk-outflow system in a massive YSO. Moreover, our VLBI observations of H_2O maser emission (Moscadelli et al. 2000) showed a very good agreement with a jet model which assumes that the masers arise on the surface of a conical bipolar jet, at the interaction zone between the ionised jet and the surrounding neutral medium. Hence the spots are tracing the very root (~ 50 AU) of a bipolar outflow. Follow up proper motion measurements of the H_2O maser spots with new multi-epoch VLBI observations have proved the uniqueness of this interpretation. Throughout this paper we assume a distance to IRAS20126+4104 equal to 1.7 kpc.

The encouraging results found for IRAS20126+4104 provided the ground for more VLBI observations towards other sources from the Tofani et al. (1995) sample, aiming to assess the precise association of maser spots and molecular outflows. Table 1 lists the selected sources on the basis of the following criteria: (i) to be deeply embedded in dense molecular clumps; (ii) to be undetected in the free-free radio continuum (i.e. *not* associated with HII regions); (iii) to have luminosities above 1000 $L_\odot$; (iv) to lie close to a compact (in VLBI scales) continuum reference source (for observations in phase referencing mode). The third condition guarantees that one is dealing with high-mass YSOs,while the first two bias the sample towards the youngest, least evolved star-forming regions. For all selected sources Cesaroni et al. (1999b) detected high density molecular clumps around the H_2O masers.

2. Observations and data reduction

We carried out VLBA 22 GHz observations of the young massive (proto)star IRAS20126+4104 on November 21-22, 1997,for a total of 12 hours. The analysis of these observations proved the association of the maser spots with the bipolar outflow and provided an estimate of the velocity field on a scale of $\sim$ 100 AU. A complete description can be found in Moscadelli et al. (2000).

The study of the source was followed up with 3 VLBA+EVN (global) astrometric observations to measure H_2O maser spot proper motions. The multi epoch observations were scheduled in the course of 4 months to match the mean lifetime of maser lines, estimated on the basis of our single dish monitoring. The global campaign included all VLBA, and 8 EVN antennas: Effelsberg (100m, Germany), Medicina (32m, Italy), Noto (32m, Italy), Onsala (20m, Sweden), Jodrell Bank (25m, UK), Metsahovi (14,Finland), Sheshan (25m, China) and DSS63 (70m, Spain) observing on Nov. 9th and 26th, 2000, and March 1, 2001, for a total of 18 hours, at 22 GHz. During the observations, the antennas switched every 30 s between IRAS20126+4104 and the continuum calibrator source J2007+4029, $1^0.5$ apart. The quasar J2007+4029 belongs to the list of sources used to define the International Celestial Reference Frame (ICRF) and has very accurate coordinates (uncertainties in RA and DEC < 1 mas). All stations recorded an aggregate of 16 MHz bandwidth in each (left and right circular) polarization for each scan, centered at the LSR velocity of -3.5 km s^{-1} (based upon a rest frequency of 22235.0798 MHz), using 2-bit sampling (mode 128-2-2). The correlation was made at the VLBA correlator in Socorro (New Mexico) using 1024 spectral points which led to a channel separation of 0.21 km s^{-1}.

The data reduction was done using the NRAO AIPS software package. The information on system temperatures (T_{sys}), gain curves and telescope gains measured at the individual array elements was used to calibrate the raw correlation coefficients of the line and reference sources. The application of standard fringe-fitting, amplitude and phase (self-)calibration techniques produced a hybrid map of the reference source.

The phase calibration of the line source involved a temporal interpolation between adjacent scans on the reference source. This strategy preserves the signature of the relative separation, between the target and reference source pair, present in the calibrated phase. In our series of observations the rapid antenna switching matched the requirements for a succesfull astrometric analysis and the Fourier Transformation of the calibrated visibility function of the line source produced multiple "phase referenced" maps, corresponding to different spectral channels with line emission. At each epoch, the offsets of the maser spots from the center of the map are estimates of the absolute position parameters in the astrometric analysis. Moreover, a multi epoch comparison (at least 3 different epochs in the course of $\leq$ 1 year) leads to proper motion estimates. Fig. 1 shows the displacements, in RA and DEC coordinates, for a galactic source 1.7 kpc away due to the Galactic rotation, the annual parallax and the solar motion, for a time span equal to 2 years. We have implemented this "galactic motion" effect in the calculus of the maser proper motions. A more detailed description of the analysis of the multi epoch observations will be given in Moscadelli et al. (2004).

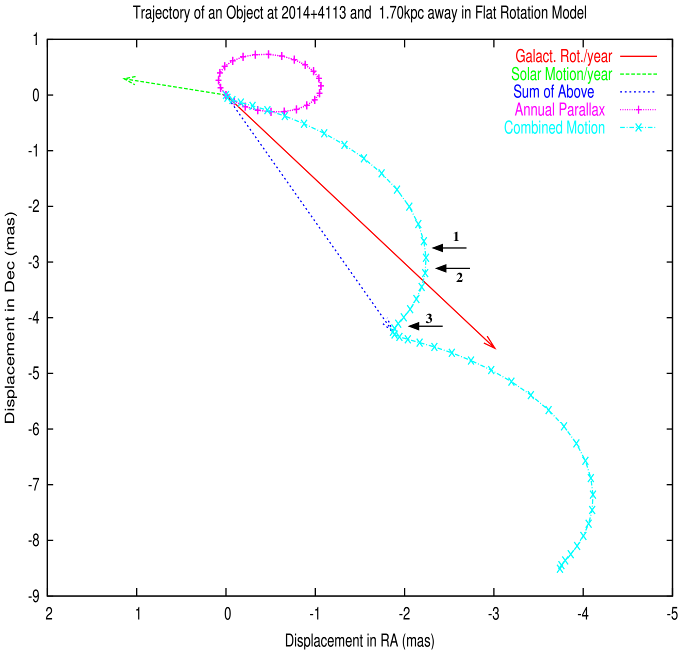

Fig. 1. Simulation of the trajectory of an object 1.7 kpc away due to the Galactic rotation (solid line), the annual parallax (dotted line) and the solar motion (long dashes line). The Galactic rotation is assumed to follow the simple Flat Rotation Model(FRM). The combined motion follows the "x" line, for a time span of 2 year. The VLBI multi-epoch observing dates are indicated with labels 1,2, and 3, corresponding to first, second and third campaigns, respectively.

Also, EVN observations of H_2O maser emission towards other 5 high-mass young stellar objects, along with nearby ($< 3^o$ apart) continuum calibrator sources, were carried out on February 10-11, 2004. We observed with an array of 9 antennas for a total duration of 15 hours, at 22 GHz. The observing network was composed of the following antennas: Cambridge (32m, UK), Jodrell Bank (25m, UK), Effelsberg (100m, Germany), Noto (32m, Italy), Onsala (20m, Sweden), Metsahovi (14m, Finland), Sheshan (25m, China) plus 2 other antennas wich failed to produce interferometric fringes. At the observations, all stations used a similar configuration as the one described above for IRAS20126+4104. For a given pair of line/continuum calibrator sources the recorded bandwidth was centered at the LSR velocity of the line source (based upon a rest frequency of 22235.0798 MHz), derived from single dish observations obtained with the Medicina radiotelescope few days before the VLBI run. The processing of the data was done at the JIVE correlator, in Dwingeloo, using 1024 spectral channels. For most of the time the antennas were switching, with 3 minutes duty cycles, between the 2 sources at each pair. This sequence was interrupted every 2 hours with 3 minutes scans on the continuum calibrator sources 3C84 and 0528+134. Our preliminary analysis of the EVN observations does not implement phase referencing techniques, and follows the standard procedure for the analysis of spectral line data within AIPS.

3. The interesting case of IRAS20126+4104

Our previous single epoch VLBA observations (Moscadelli et al. 2000) detected 26 H_2O maser spots spread over a region of $\sim 0''.7$ (1200 AU). The VLBI data are in excellent agreement with the predictions of a model which assumes that the H_2O masers lie on the surface of a conical bipolar jet, and expand radially away with constant velocity from a common centre coincident with the position of the YSO. Figure 5 in Moscadelli et al. (2000) show a map with the spatial distribution of the H_2O maser spots and a comparison between the spot LSR velocities observed and computed from the best fit of the free parameters of the model (vertex position, opening angle of the cone, inclination of the cone axis with respect to the line of sight, and velocity of the spots).

Fig. 2 shows the map of the H_2O maser spots for the new multi epoch global observations, along with measured proper motions. The best fit of model parameters to the data from multi epoch global observations is obtained for a well collimated (semi opening angle=17^0) conical bipolar jet model with the vertex near the peak of the 3.6 cm and 7 mm continuum emission recently observed with the VLA (Hofner personal comm.), and its axis closely aligned to the plane of the sky (the angle between the jet axis and the line of sight is 96^0) and with the direction of measured proper motions (position angle north-to-east=122^0). The fit of the multi epoch observations implements a Hubble velocity outflow, with a variation of the velocity proportional to the distance to the vertex of the cone. Fig. 3 shows a comparison between the observed maser velocity components and those obtained from the best model fit. Given the goodness of the fit, the new results prove the uniqueness of the interpretation proposed by Moscadelli et al. (2000), thus validating the use of H_2O masers as excellent tools to investigate the structure and kinematics of the jet/outflows in massive YSOs.

The combination of the proper motion measurements, from the astrometric analysis of the multi epoch observations, and the velocities along the line of sight, allows us to compute total velocities. We stress that this is completely independent of the conical model. The measured total velocities of the H_2O maser spots are in a range between 11 km s^{-1} and 113 km s^{-1}, with most of them with velocities around 60 km s^{-1}. This value is larger than our previous estimate (23 km s^{-1}), from the best fit of the single VLBA observations to the conical model (Moscadelli et al. 2000). Interestingly, the new velocities are closer to the values estimated by Cesaroni et al. (1999a) from the SiO jet, between 60 and 200 km s^{-1}, on a much larger scale.

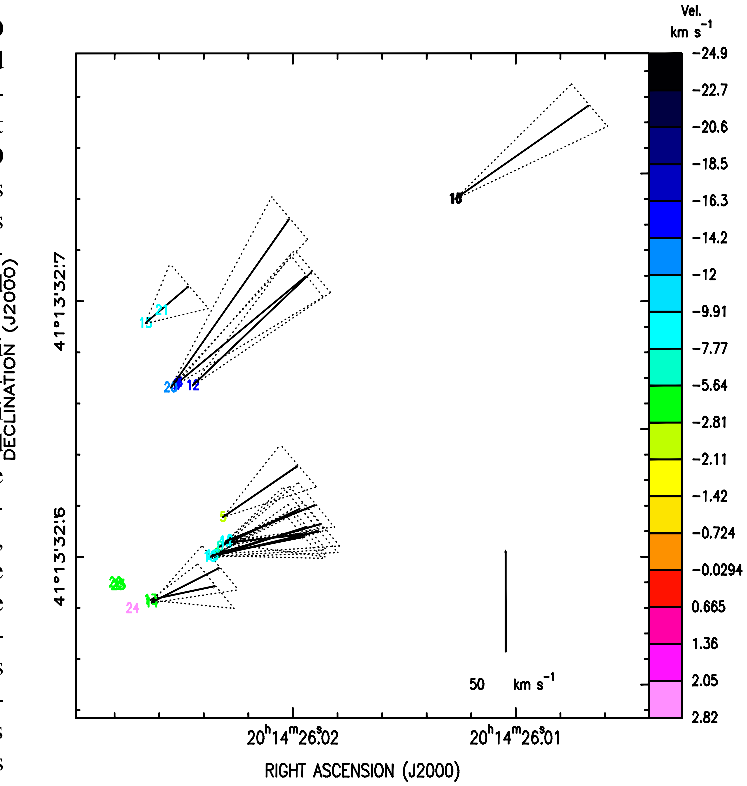

Fig. 2. Map of H_2O maser spots and measured proper motions, measured from global VLBI multiepoch observations.

4. Preliminary Results on other YSOs

In this section we present very preliminary results of a H_2O maser survey performed by us towards a sample of 5 massive YSOs similar to IRAS 20126+4104 (see Table 1). All of our maser sources are associated with molecular outflows, have luminosities in excess of 2000 $L_\odot$, and are not associated with a detectable HII region (see Tofani et al. 1995). Although the data reduction is still in progress and only maps for the most intense spectral features have been produced so far, we may summarize the results obtained for two of the sources: NGC281-W and GGD 12-15.

Table 1. VLA H_2O Maser Properties of YSO observed with EVN.

Source Component	Radio Coordinates (B1950) R.A.	 Decl.	Peak Flux (Jy)	Integ. Flux (Jy km s^{-1})	velocity (km s^{-1}) v_{peak}	 v_{min}	 v_{max}
NGC281-W	00 49 28.233	56 17 26.408	9.38 ± 0.48	17.66 ± 0.46	-27.9	-39.8	-25.9
S233	05 35 51.199	35 44 12.975	5.39 ± 0.27	12.29 ± 0.29	-16.9	-18.9	-14.3
S235 B	05 37 31.864	35 40 17.775	165.73 ± 8.29	257.51 ± 6.38	-61.2	-69.1	-55.3
GGD 12-15	06 08 25.662	-06 10 49.60	104.67 ± 5.24	240.48 ± 4.71	-22.6	-31.8	-11.4
NGC2264	06 38 25.385	09 32 14.459	44.18 ± 2.21	60.55 ± 1.89	7.1	6.5	9.1

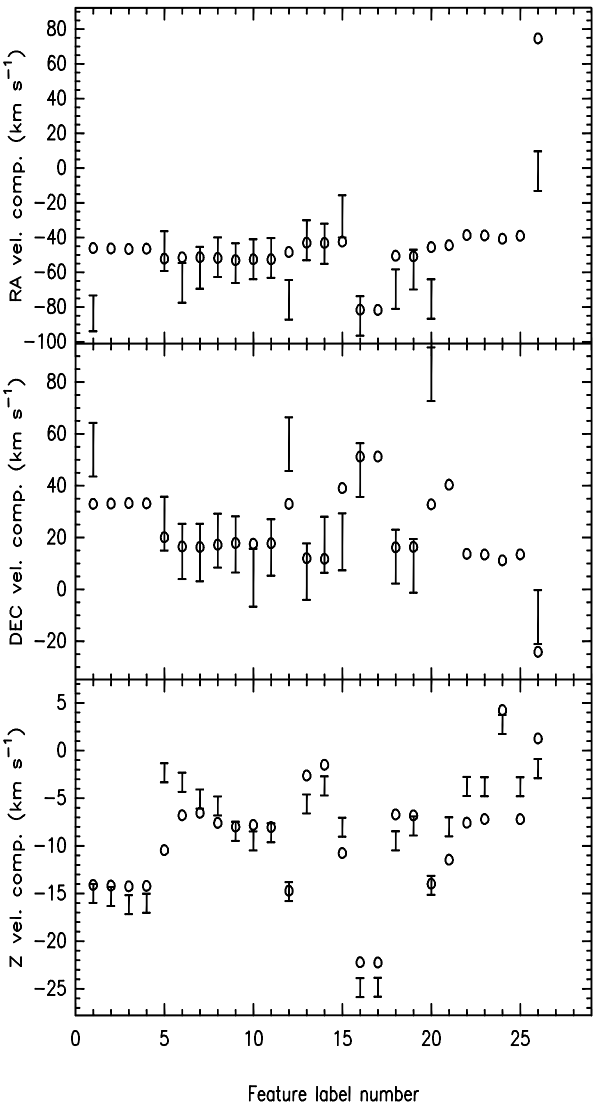

Fig. 3. Comparison between the observed maser velocity components and those obtained from the best model fit, for data from global multiepoch VLBI observations.

NGC281-W

Fig. 4 (*upper*) shows the total power spectrum obtained with the Effelsberg radiotelescope. The systemic LSR velocity, derived from single dish observations is indicated with a dotted line. The labels on top of the most prominent features correspond to the velocities of the channels, in units of [km s^{-1}], for which we have produced maps.

The *lower* plot in Fig. 4 shows the distribution of H_2O maser spots corresponding to the most prominent features in the total spectrum shown above. The location of the spots is given by the crosses, whose size is proportional to the square root of the peak flux in the individual maps for the velocities indicated aside. The channel containing the most prominent peak of emission (velocity -31.5 km s^{-1}) was selected as reference in the analysis, and corresponds to the spot with null righ ascension and declination offsets in the map. The other spots correspond to emission from secondary peaks in the total spectrum, with red-shifted emission with respect to the systemic LSR velocity of the bulk material (velocities -6.3,-0.6 and -20.6 km s^{-1}). The spots in the map appear aligned along NW-SE direction. This direction does not seem to coincide with that from larger scale structures seen in observations of other outflow tracers (Cesaroni et al. 1999b, and references herein). On the other hand, large scale structures can also be affected by the presence of multiple outflows arising from a common star forming region.

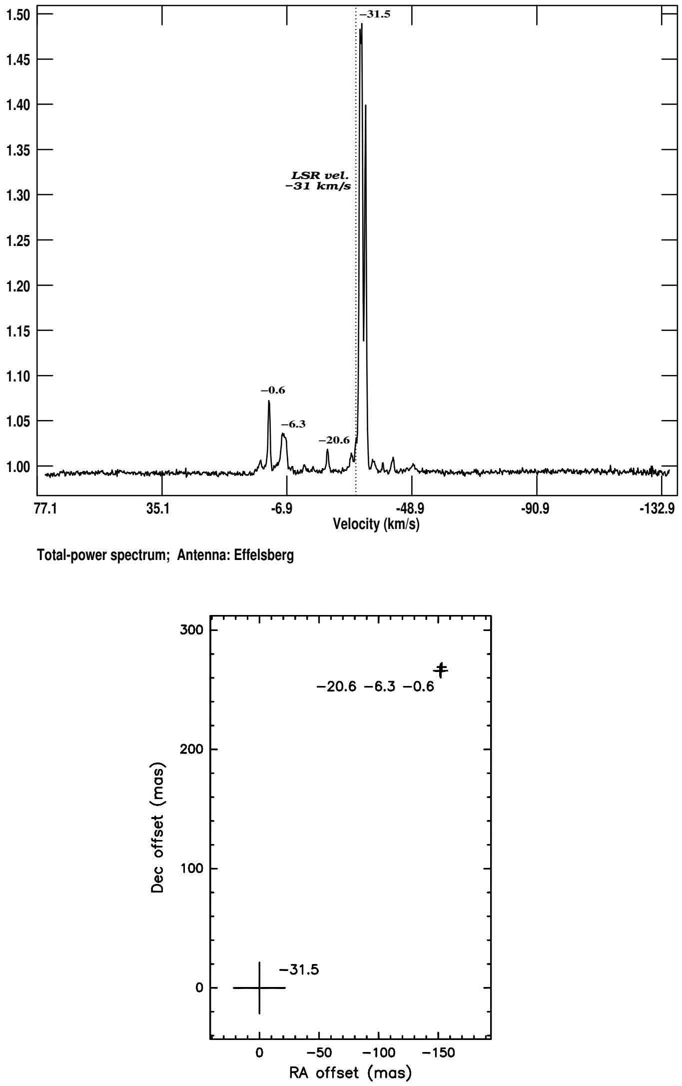

Fig. 4. *Upper*: Effelsberg total power spectrum for NGC281-W. The vertical dotted line indicates the systemic LSR velocity. The labels indicate the velocities in [km/s] of the most prominent features, for which we have made maps. *Lower*: Distribution of H_2O maser spots corresponding to the dominant emission features in the total power spectrum. The channel with the highest emission (vel. -31.5 km s^{-1}) was used as reference in the astrometric analysis. The labels in the plot indicate the velocities corresponding to each spot, in [km/s]; the size of the crosses is proportional to the square root of the peak flux in the maps.

<u>*GGD 12-15*</u>

Fig. 5 (*upper*) shows the total power spectrum obtained with the Effelsberg radiotelescope, along with the systemic LSR velocity obtained from single dish observations (dotted line). Also, it includes labels indicating the velocity of the dominant features in the spectrum, for which we have produced maps.

The *lower* plot in Fig. 5 shows the distribution of H_2O maser spots corresponding to the most prominent features in the total spectrum shown above. The sizes of the crosses, and the labels in the plot have the same meaning as explained for the other source. In the analysis, the channel with the most prominent peak of emission (velocity -30 km s^{-1}) was selected as reference. The spots corresponding to secondary peaks of emission in the total spectrum are located on opposite sides of the reference maser feature, but the fact that all spots are blue-shifted does not seem to support an association of the H_2O maser emission with a bipolar outflow, although this cannot be ruled out (see the case of IRAS20126+4104). In fact, the (NW-SE) direction of H_2O maser emission in our phase referenced maps is in agreement with that of J=2-1 CO line emission from the bipolar outflow detected by Little et al. 1990.

5. Conclusions

We have used global VLBI multiepoch observations to study the H_2O maser emission towards IRAS 20126+4104, using phase referencing techniques. The map of the H_2O maser spots, along with the measured proper motions, prove that the water masers are clearly tracing a well collimated outflow. Hence, are excellent tools to investigate the structure and kinematics of molecular jet/outflows in massive YSO.

We aim to extend the observations to a larger sample of protostars, selected from the Tofani et al. (1995) catalog. With that in mind, we have observed a first epoch EVN observations of a selection of 5 YSOs, and preliminary results have been presented in that paper. We must wait for a more detailed analysis before drawing any conclusion.

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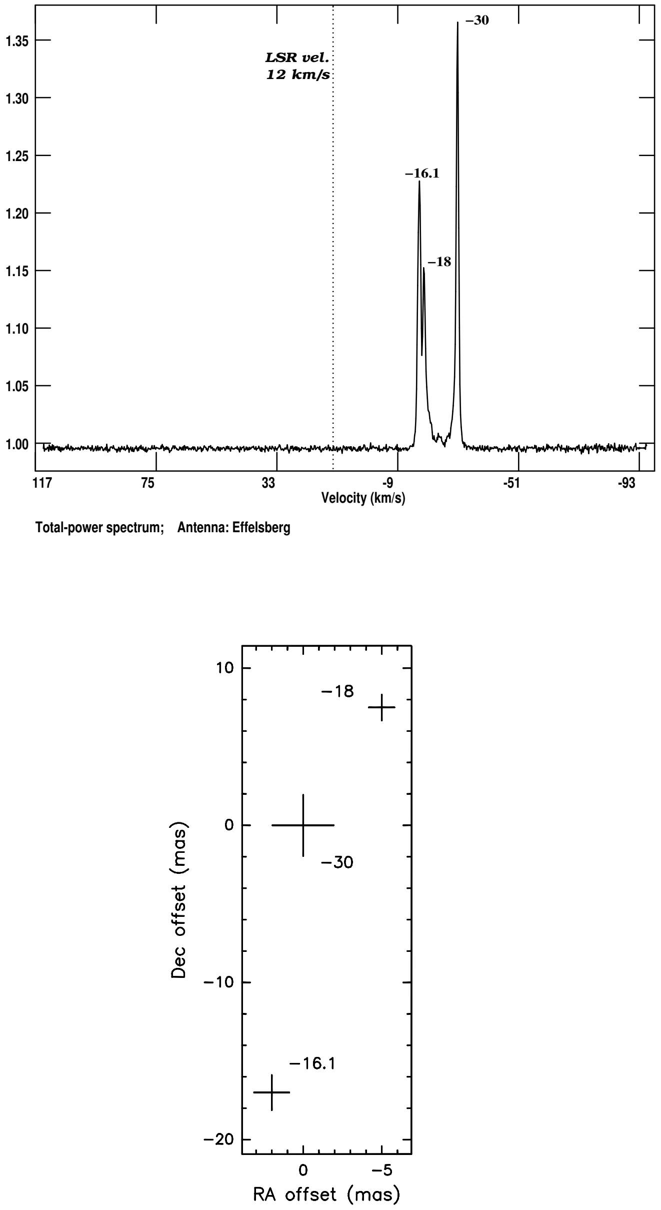

Fig. 5. *Upper*: Effelsberg total power spectrum for GGD12-15. The vertical dotted line indicates the systemic LSR velocity. The labels indicate the velocities in [km/s] of the most prominent features, for which we have made maps. *Lower*: Distribution of H_2O maser spots corresponding to the dominant emission features in the total power spectrum. The channel with the highest emission (vel. -30 km s^{-1}) was used as reference in the astrometric analysis. The labels in the plot indicate the velocities corresponding to each spot, in [km/s]; the size of the crosses is proportional to the square root of the peak flux in the maps.