# Part Ia. $H_2O$ MASERs

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*Cosmic MASERs: From Protostars to Blackholes*
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# Water masers and the near-stellar environment in YSOs

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**Abstract.** I present a review of observations of water masers, in particular very high angular resolution of water masers using Very Long Baseline Interferometry, with which it is possible to probe the environment of young stellar objects and forming stars within only a few A.U. of the protostar, its accretion disk, and therefore the base of outflowing material. Although reference is made to some high-luminosity sources, the main thrust of the review are the water masers found toward forming objects whose mass and luminosity will be approximately that of the Sun when they reach the main sequence.

## 1. Introduction

After their discovery in 1969 (Cheung et al. 1969) water masers were quickly discovered to be tracers of early stages of star formation (e.g. Genzel et al. 1978, Norman & Silk 1979) In most cases, the water masers are thought to trace matter flowing away from the protostellar object (e.g. Walker et al. 1977, Rodríguez et al. 1980, Genzel et al. 1980) At first most observations were made toward very high-luminosity (and by implication, high-mass) young stars and protostellar objects, since the water masers in these regions were quite bright. In the early 1980's the group at Harvard-Smithsonian Center for Astrophysics (led by J. Moran and M. Reid) began a systematic set of water maser proper motion observations using the technique of Very Long Baseline Interferometry (VLBI). In the ensuing years, a series of papers (Genzel et al. 1981a; Genzel et al. 1981b; Schneps et al. 1981; Reid et al. 1988; Gwinn et al. 1992) were published on the proper motions of water masers in Orion-KL, W 51, W 49, and Sgr B2. These studies used kinematic models of the velocities of the masers in order to compare the Doppler velocities with proper motions and thus determine the distances to these star-forming regions.

In this review I will try to concentrate on answering or attempting to answer three important questions about the water masers toward young stellar objects (YSOs): 1) Where are the water masers with respect to the environment of the embedded YSO ?; 2) What physical mechanism do the water masers trace ?; and 3) What do the proper motions of water masers tell us ?

## 2. Water Maser Surveys

Surveys of water masers toward regions of star formation (compact HII regions) were made by Genzel & Downes (1977, 1979) using the 100m Effelsberg telescope. These researchers found that the water masers were near but not coincident with the compact HII regions. Rodríguez and his collaborators, using the Haystack 37m telescope, (Rodríguez et al. 1978, 1980) detected a number of water masers toward sources associated with Herbig-Haro objects, thereby extending statistical information of water masers toward low-luminosity objects. Despite several other surveys toward different tracers of star formation (e.g. Jaffe et al. 1981; Henkel et al. 1986) the only blind survey that has been performed was a pilot survey by Matthews et al. (1985), covering two square degrees on the sky, with an approximate sensitivity of 2 Jy. It was very heartening to hear at this meeting that the University of Bristol group is planning a dedicated Galactic plane survey with a new 7 m antenna. Such a blind survey will prove very useful in finding new protostellar objects.

Wilking & Claussen (1987) provided a survey, using the Haystack 37m telescope, of thirty-three infrared sources in the $\rho$ Oph molecular cloud, discovering the strong IRAS 16293-2422 water maser in a low-mass star. More recently, the observations of the Arcetri group (Comoretto et al. 1990) using the Medicina 32m telescope, have provided a reference data base for studies of source variability, a very powerful constraint on the manifestation and duration of the maser phase in the lifetime of the embedded objects. Claussen et al. (1996) present monthly monitoring of some forty-seven low-luminosity YSOs, concluding that the isotropic luminosity of the water masers can vary by more than 2 orders of magnitude in a period of several months. Furuya et al. (2001a), using the Nobeyama 45m telescope, over three years, observed 260 YSOs including all the class 0 sources in the northern sky. This is the most sensitive water maser survey ever conducted, reaching to an isotropic luminosity of $10^{-13}$ $L_\odot$. Finally, a recent survey using the VLA by Healy et al. (2001) has detected water masers toward low-luminosity objects embedded in and around the columns of the Eagle Nebula (M16). These embedded objects are subject to the ionizing radiation of the nearby HII region powered by massive stars, and so are in a much different environment than regions where individual stars form in relative isolation (e.g. Taurus-Auriga).

## 3. Recent VLBI Observations of Both Low-Mass and High-Mass YSOs

Several groups around the world have recently been using the NRAO Very Long Baseline Array (VLBA) to measure the proper motion of water masers toward a number of not-so-famous objects, following the lead of the historical observations mentioned in §1. Most of these observations are listed in Table 1. In the following subsections I briefly describe a selection of these proper motion studies.

### 3.1. IRAS 05413-0104

Claussen et al. (1998) measured the distribution and motion of water masers near IRAS 05413-0104, the YSO driving the outflow of HH 212. Using the VLBA

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| Source | Luminosity | Reference |
|---|---|---|
| IRAS 05413-0104 | 14 L⊙ | Claussen et al. (1998) |
| S106 FIR | <1070 L⊙ | Furuya et al. (2000,2001b) |
| IRAS 16293-2422 | 25 L⊙ | Wootten et al. (1998) |
| IRAS 21391+5802 | 235 L⊙ | Patel et al. (2000) |
| NGC 1333 SVS 13 | 92 L⊙ | Wootten et al. (2001) |
| IRAS 20126+4104 | $\sim 10^4$ L⊙ | Moscadelli et al. (2000) |
| NGC 1333 IRAS 4A | ~20 L⊙ | Marvel et al. (2001) |
| NGC 1333 IRAS 4B | ~20 L⊙ | Marvel et al. (2001) |
| NGC 2071 IRS 1 | ~500 L⊙ | Greenhill et al. (2001) |
| NGC 2071 IRS 3 | ~20 L⊙ | Greenhill et al. (2001) |
| Cep A HW 2 | $\sim 10^4$ L⊙ | Torrelles et al. (2001a, 2001b) |

Table 1. Recent Water Maser Proper Motion Studies

at four epochs over a period of ten weeks, the maser images (see Figure 1) show the detail of a highly symmetric, jetlike structure about 300 mas in extent. Proper motions were detected of numerous maser features, averaging 30±12 mas $yr^{-1}$, implying space velocities of 64±27 km $s^{-1}$. Some of the masers are located within a projected distance of 40 A.U. of the embedded source. In the interest of brevity, I only show in Figure 1 a blowup of the southern bow shock in the masers toward IRAS 05413-0104, and refer the reader to Claussen et al. (1998).

### 3.2. NGC 1333 SVS 13

Wootten et al. (2001) presented water maser proper motions toward NGC 1333 SVS 13, the driving source for the well-known Herbig-Haro objects HH 7-11. Figure 2 shows the water maser distribution associated with NGC 1333 SVS 13 on November 14, 1998, the fourth epoch of VLBA observations. In field C the proper motions correspond to about 32 km $s^{-1}$. The arc of masers in field B exhibits a proper motion of about 16 km $s^{-1}$. The direction of motion is roughly at the same position angle as the Herbig-Haro objects associated with this source. It is likely that the maser arc is associated with a shocked region near the working surface of the YSO jet that also powers the observed Herbig-Haro objects.

### 3.3. S106 FIR

Furuya et al. (2000, 2001b) have discovered a very compact protostellar jet (microjet) from the protostar S106 FIR by using the VLA and the VLBA to observe water masers in this microjet. The VLBA observations showed a U-shaped structure, likely to be a small bowshock located 25 A.U. from the embedded source. There is no large-scale molecular outflow, which suggests that S106 FIR is in a very early evolutionary stage. The bow shock apparently moves forward at speed of about 35 km $s^{-1}$, based on the proper motion of the water masers.

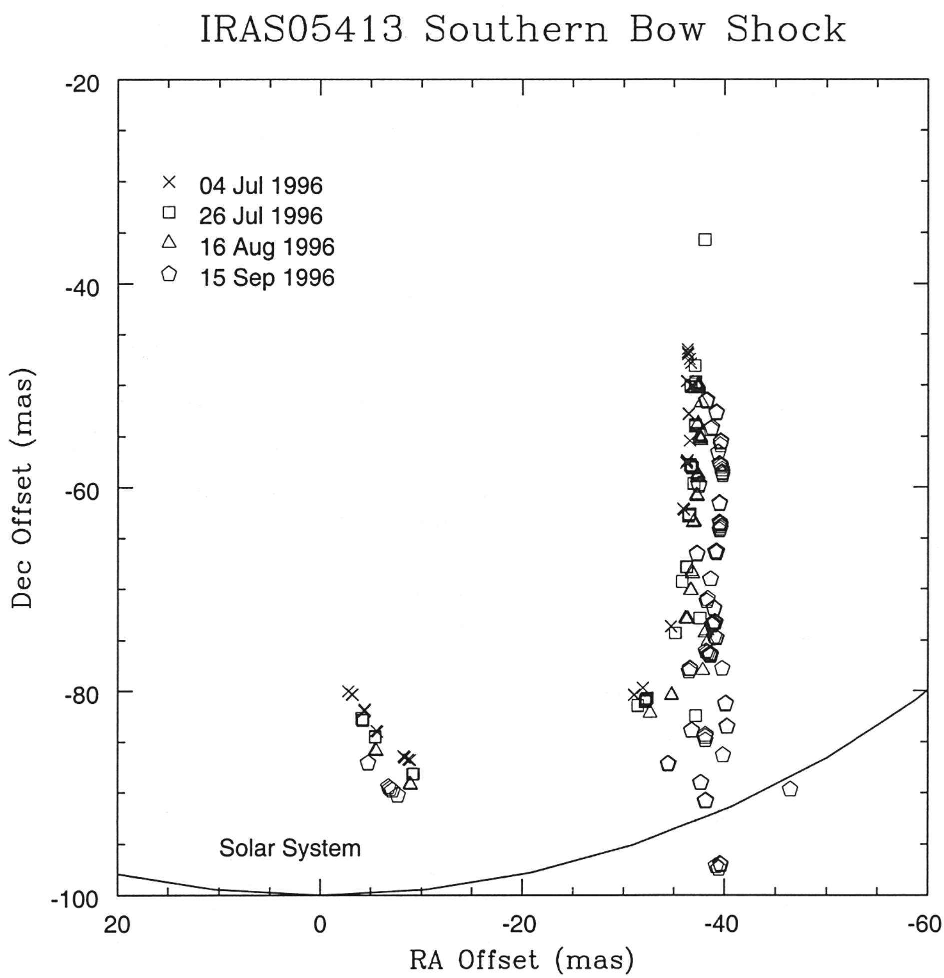


Figure 1. The southern bow shock traced by the water masers toward IRAS 05413-0104. All the VLBA maser spots data from four epochs are shown, and the curved line indicates the size of the solar system.

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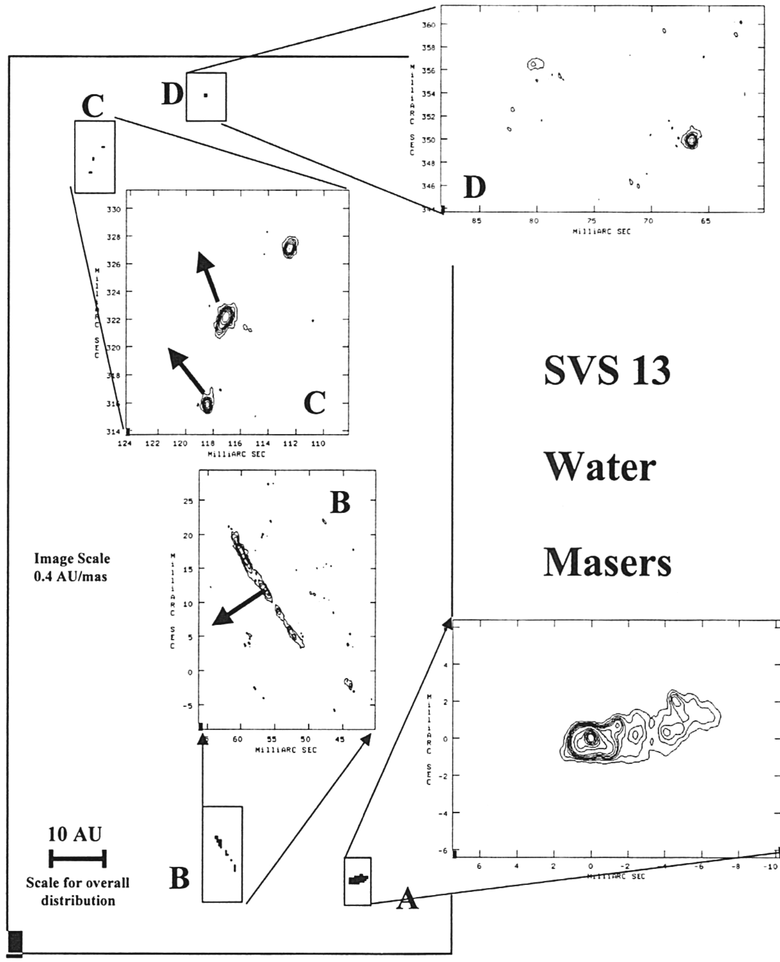


Figure 2. The water maser distribution associated with SVS 13 as it appeared in the fourth epoch of VLBA observations in 14 November 1998. The arrows indicate the direction of the measured proper motions of the masers.

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### 3.4. IRAS 16293-2422

Wootten et al. (1999) and Murphy et al. (2001), using the VLBA over a few months, once again find evidence for a bowshock in the southwest part of the maser distribution toward this strong and highly variable maser source. The bowshock is likely about 60 A.U. away from the embedded YSO. Using VLA data, the $V_{LSR} = 4$ km $s^{-1}$ (at the ambient cloud velocity) water maser feature may be associated directly with the protostar. Thus the fine angular resolution of the VLBA provides us with a probe within 1 A.U. of the YSO.

### 3.5. IRAS 21391+5802

Patel et al. (2000) have measured proper motions of the water masers in this intermediate luminosity source. The masers appear in four groups, aligned linearly on the sky in a rough NE-SW directions. The overall proper motions suggest a bipolar outflow with three-dimensional velocities of about 40 km $s^{-1}$. In a central (20 A.U. extent) cluster of masers, the proper motions show deviations from a radial outflow. An exciting discovery in this source is a loop of masers (radius 1 A.U.) near the center of the cluster, likely at the dust condensation radius.

### 3.6. Cep A HW 2

I cannot conclude without mentioning the fantastic water maser spot maps presented at this meeting by Torrelles et al. associated with Cep A HW 2, and partly just recently published in *Nature*. Though complex, there is evidence once again for the masers tracing bow shocks in outflowing gas. Some of the water masers in this source, however, are distributed in a partial circular ring with radius of about 60 A.U. The deviation from a perfect circular fit to the masers is less than 0.1%. The center of the circle does not, however, correspond to HW 2. Torrelles et al. suggest that the water masers in this ring are tracing a spherical outflow of material which originated in a single, short-lived ejection event, a phenomenon not expected in star formation scenarios.

## 4. Conclusions and Future Prospects

Where are the water masers with respect to the embedded YSO ? The available evidence in these recent observations suggest that water masers trace molecular gas from a few to a few tens of A.U. from the powering source. Of course, previous observations of the most powerful YSOs (e.g. Orion-KL, W49A) show that water masers can trace the outflow much further out. But in the lower-mass star forming regions, the water masers can definitely used as a probe of the very close-in stellar environment.

What physical mechanism do the masers trace ? The masers trace warm, dense molecular gas near the stellar energy source. For the most part, the masers seem to be involved with outflowing gas rather than infalling or gas in an accretion disk. However, in some of the recently observed sources there are masers that don't appear to be tracing outflowing gas, and so some other physical mechanism must also be operating.

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What do the proper motions of the water masers tell us ? All the proper motions discovered in the most recent VLBA observations are on the order of a few tens of km $s^{-1}$. Gas velocities traced by Herbig-Haro object proper motions in similar regions (at much further distances from the energy source) can be up to a few hundreds of km $s^{-1}$. Thus either the gas is accelerated further out in the jet, or the water masers are not necessarily tracing "bullets" or ballistic parcels of gas. Structures in some of these water maser groups are highly suggestive of bow shocks, and so it is likely that, in many cases, the water maser proper motions trace the advance of the shock front into the surrounding medium.

The new capability the VLBA brings, to make multi-epoch observations on short time scales over long periods, has made it easier to observe the proper motions of water masers in many sources. In particular, with short time sampling it is easier to decide if a given maser feature lives from epoch to epoch. Phase referencing and astrometric techniques (already in use) make it possible to observe even weak water masers (e.g. the one toward T Tau). Given the detail found in the distribution of water maser spots, it is now possible to make rather more careful models of the bow shocks, and how the gas flows around them. Finally with the resolution and sensitivity of the VLBA we can now probe within the maser spots and possibly better understand the physics of the maser process.

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