Water Masers Near Herbig Ae/Be Stars

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Abstract Herbig Ae/Be stars are not known to exhibit water maser emission very frequently, but some Herbig Ae/Be stars do exhibit maser emission. Because many other sources have associated water masers, research on Herbig Ae/Be masers has been limited. I present early results from a VLA/VLBA observation campaign to map the water masers near these interesting, sometimes variable, stars.

1. Introduction

Herbig Ae/Be stars have masses of a few to ten solar masses and are in the process of formation. They can be considered the high-mass cousins of the T Tauri stars, both of which show a variety of interesting circumstellar and stellar phenomena (Waelkens and Waters 1998; Bertout 1989).

The central star has become visible and the thick disk formed during the early stages of formation has collapsed significantly. Emission lines are present in the spectrum due to infalling material heating upon contact with the innermost disk and the star itself. The stars are variable, but tend to be faint since they are usually in obscured regions. The Herbig Ae/Be stars have mid-infrared and radio excesses (flux levels beyond that expected from blackbody emission for the star itself) due to emission from dust at a range of temperatures. Less than 10% of these stars exhibit water maser emission.

Water masers are formed when regions of water vapor are excited by either collisions or infrared photons into more energetic molecular states. Although several transitions are observed from the far-infrared into the radio, the transition commonly observed has a frequency of 22 GHz in the radio regime. Because water masers are compact and very bright, they are well-studied using radio interferometry, especially very long baseline interferometry (VLBI), which works best studying compact and high-flux sources.

The Very Long Baseline Array (VLBA), operated by the National Radio Astronomy Observatory, is very well-suited to explore the innermost regions of forming stars, although only recently has this capability begun to be fully exploited.

A number of research teams (e.g. Claussen *et al.* 1998; Furuya *et al.* 2000) have used the VLBA to successfully map and monitor the spatial distributions and kinematics of water masers near young stellar objects. These observations have linked the water maser emission to the jets emanating from these young stars, although the exact structures are not always clear (Marvel 2001).

Groups are also beginning to revisit massive-star forming regions that exhibit water maser emission, which will lead to a greater understanding of the massive-star formation process (Torrelles *et al.* 2001; Imai *et al.* 2000).

Although only a small fraction—6%—of Herbig Ae/Be stars show water maser emission (Palla and Prusti 1993), the masers typically have fluxes in excess of tens of Janskys, sufficient for VLBI observations using self-calibration techniques.

Some connected-element interferometric observations with resolutions as good as 200 mas have been published (Rodriguez *et al.* 1987) for three Herbig Ae/Be stars (and one FU Ori star). These observations show (see Figure 1) that the water masers are associated with the optically detected star, but the exact spatial distribution of the masers is not clear due to the limited resolution of the Very Large Array (or single dish telescopes used for detection experiments).

As can be seen in Figure 1, in some cases the masers lie near the star while in other cases the masers are spatially removed from the star. In one case, (PV Cep) it seems clear that the maser is not associated with the Ae/Be star, but another embedded source due to the large angular separation between the two positions (this could also indicate a position error of some nature).

In preparation for our experiment, we have combed the literature for spectra of all water masers known to be associated with Herbig Ae/Be stars (see Table 1). There are only six sources known currently (five with published spectra). Typically the masers are distributed over relatively narrow velocity ranges, of order 5–10 km/s. This can be indicative of a range of kinematic scenarios, from a high-speed jet moving in the plane of the sky (therefore a small line of sight velocity range) and similar to a number of low-mass Young Stellar Object (YSO) sources such as HH212 (Claussen *et al.* 1998), to a source where the masers reside in a disk with low velocity dispersion (10–20 km/s at maximum), to a situation where only one side of the outflow exhibits maser emission.

It should be noted that in the low-mass YSO case single-dish spectral features covering velocity ranges as small as 5 km/s have been found to have a very complex spatial distribution, in two cases forming nearly complete bow-shock structures (Claussen *et al.* 1998; Furuya *et al.* 2000).

For low-mass YSOs, we are beginning to understand how the masers move and how they change with time. Observations with the VLBA have allowed very accurate determinations of their spatial distributions along with measurements of their proper motions over time (the masers often lie in bow shocks and propagate outward from the star at velocities approaching 75 km/s).

No such observational constraints are currently available for any masers near Herbig Ae/Be stars. Most have not even had accurate positions determined. Since little is known about the water masers in these sources, it is impossible to state whether the masers are associated with an outflow or even if they might actually be associated with as-yet-unknown embedded sources.

Even the VLA observations are not sufficient for answering this question in all cases. This is why we proposed VLBA observations to clearly show whether the water masers are aligned with the outflows already known for these stars, are associated with another source, or even if they are located in a disk or some other distribution.

The key to determining which model may be applicable is the determination of the spatial distributions along with the kinematic information provided by the line of sight velocities. Ultimately, proper motion measurements may be necessary to fully determine the kinematics of the water masers.

2. Observations

In the Fall of 2002, we received both VLA and VLBA time for a project to study the water masers near Herbig Ae/Be stars. Although the VLBA observations have not yet taken place, we have successfully completed the VLA observations.

The sources we observed (using two separate VLA observations) are given below in Table 1. Spectra of detected sources are presented as Figures 2–7. Accurate positions have been determined for those sources detected. Images of the emission show it to be compact given the resolution of the VLA, meaning less than a few hundred milliarcseconds. The two strongest sources, LkHa234 and BD+40°4124, will soon be observed using the VLBA.

Table 1. Table of Observed Sources

Source	*R.A.* (1950.0)	*Dec.* (1950.0)	*Peak 22 GHz Flux (Jy)*	*Reference*
W166	$06^h\,28^m\,22^s\!.8$	+09° 36' 35"	260.	(Mendoza *et al.* 1990)
V1318CygS	20 18 44.9	+41 11 53	13.	(Palla *et al.* 1995)
PV Cep	20 45 23.4	+67 46 36	160.	(Torrelles *et al.* 1986)
BD+40°4124	20 18 42.7	+41 12 18	56.	(Palla and Prusti 1993)
V645 Cyg	21 38 10.6	+50 00 42	54.	(Palla and Prusti 1993)
LkHa234	21 41 53.2	+65 52 42	268.	(Palla and Prusti 1993)

Note: R.A., Dec., and Peak Flux information was obtained from source given in Reference column. [Ed. note: W166 = NGC 2264 D, recently confirmed to be the same source.]

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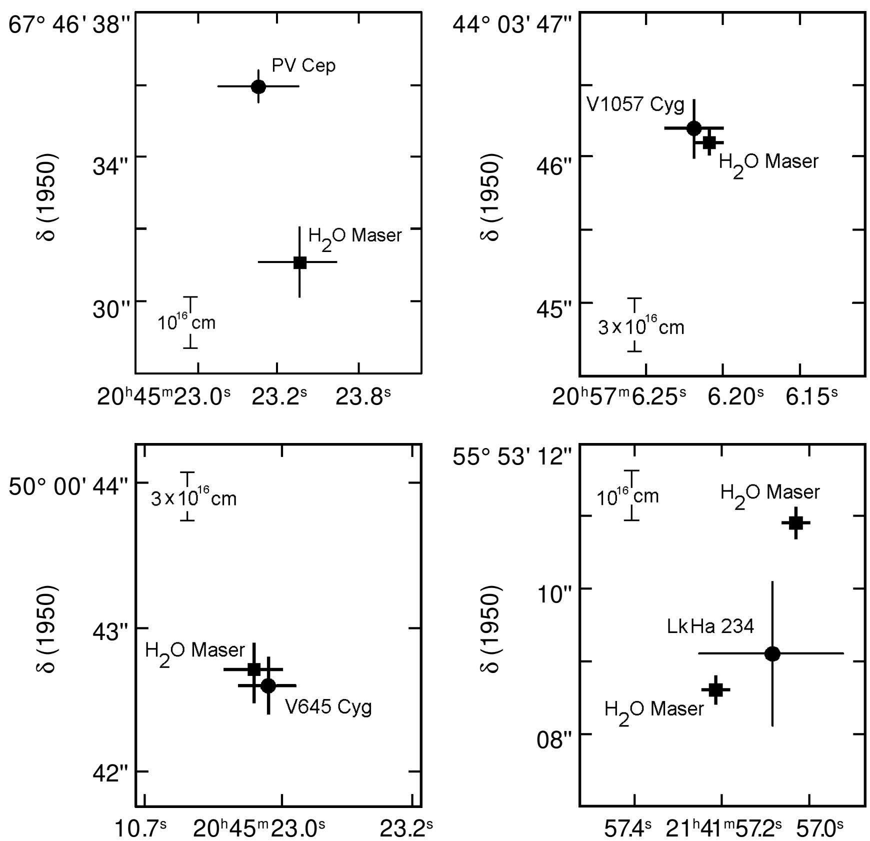

Figure 1. VLA observations by Rodriguez *et al.* 1987. These observations were the only published connected-element observations of water masers near Herbig Ae/Be stars. V1057 Cyg is a FU Orionis star and was not observed for this project.

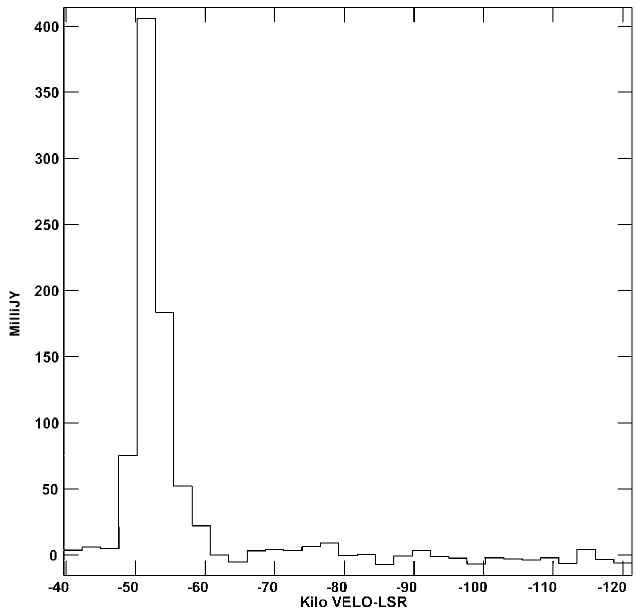

Figure 2. VLA water maser spectrum from this study of V1318 Cyg S. [Note: Kilo VELO-LSR means "km/s with respect to the Local Standard of Rest."]

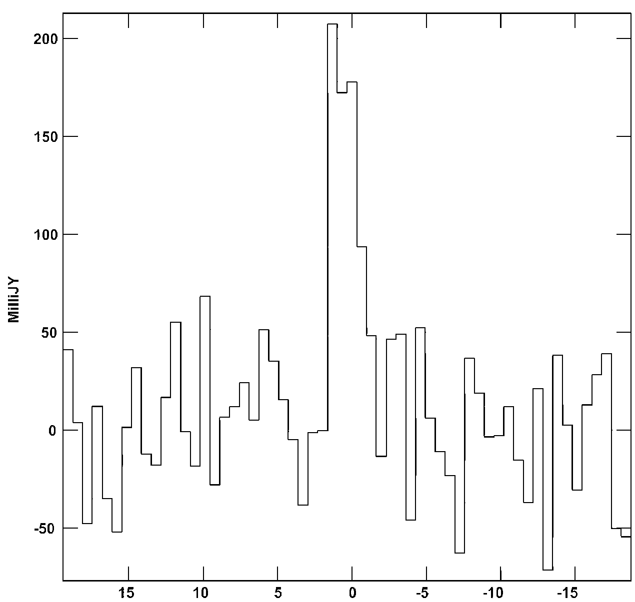

Figure 3. VLA water maser spectrum from this study of PV Cep.

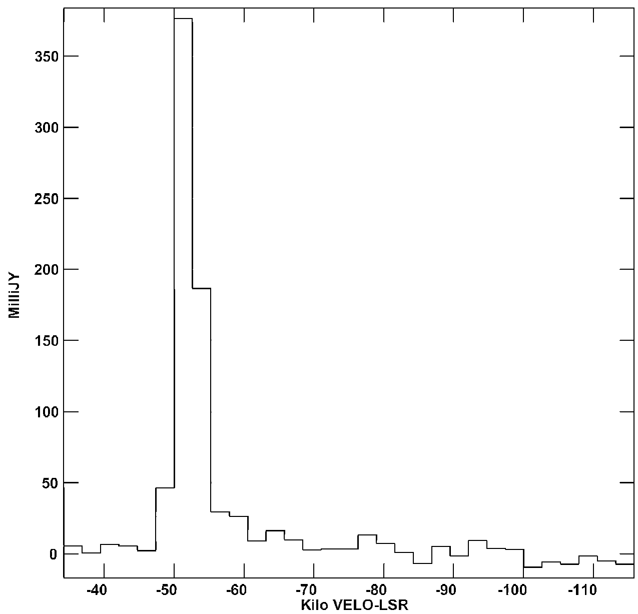

Figure 4. VLA water maser spectrum from this study of BD+40°4124, negative velocity range.

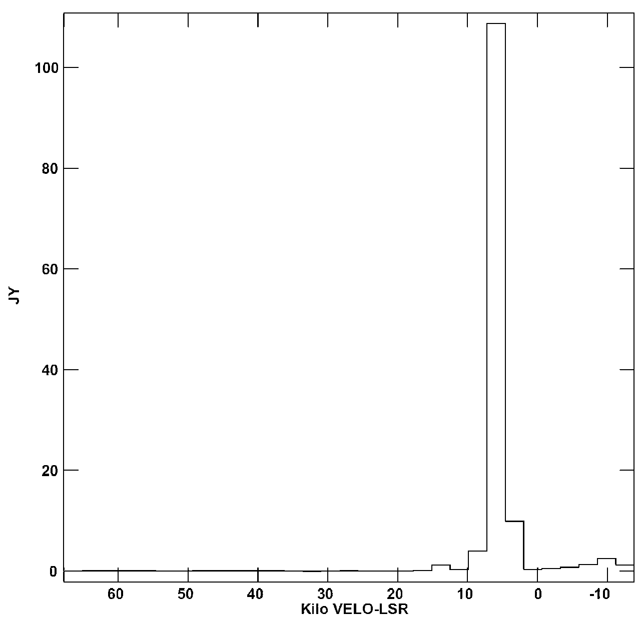

Figure 5. VLA water maser spectrum from this study of BD+40°4124, positive velocity range.

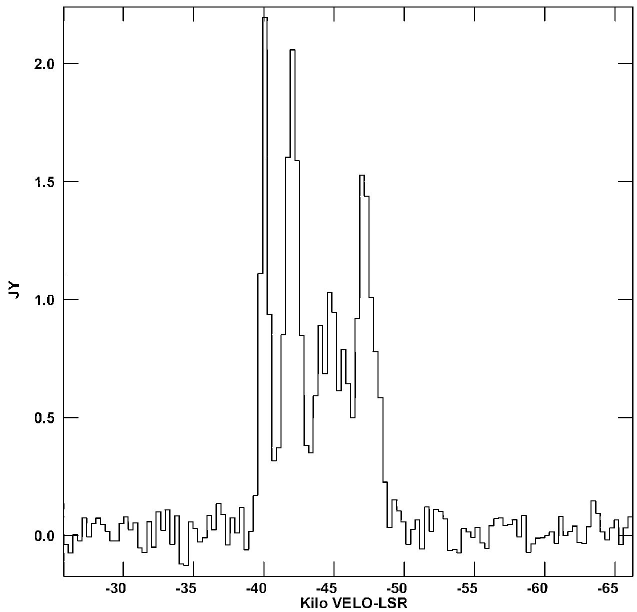

Figure 6. VLA water maser spectrum from this study of V645 Cyg.

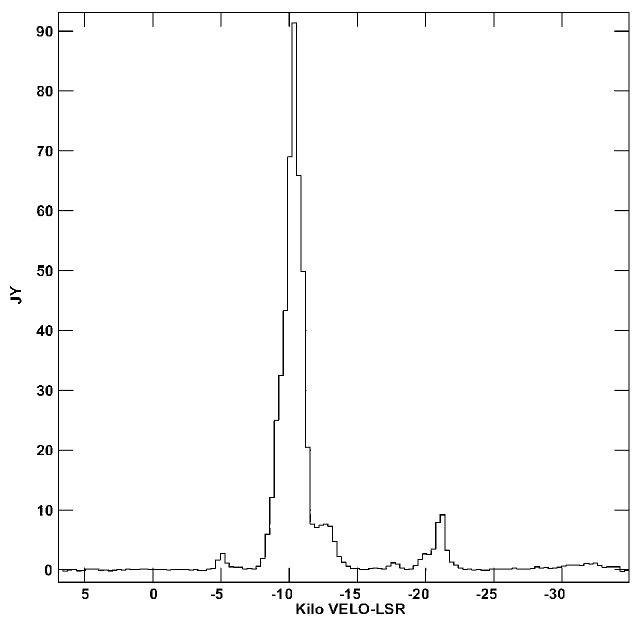

Figure 7. VLA water maser spectrum from this study of LkHa 234.