MODELS OF CIRCUMSTELLAR MASERS IN BIPOLAR OUTFLOWS

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ABSTRACT. Sources of molecular maser radio emission in envelopes of late-type variable stars (red giants and supergiants) are considered. Radio and optical data on asymmetry of mass loss process in red giants are briefly reviewed. Main attention is paid to maser emission in the H_2O rotational transition $6_{16} - 5_{23}$ ($\lambda = 1.35\,\mathrm{cm}$) of M-type supergiants (VX Sgr, VY CMa). Results of single-dish and interferometric studies of H_2O maser emission of these stars are discussed. It is shown that circumstellar H_2O masers in VX Sgr fit in a model of a rotating circumstellar gas-dust disc and a bipolar outflow of matter directed along the disc axis.

Key Words: Stars: Late-Type, Stars: Mass Loss, Stars: Circumstellar Envelopes, Maser Sources, Bipolar Outflows, Stars: Individual: VX Sgr, VY CMa.

At present, several hundreds of late-type stars of spectral types M, C, and S (most of them are Mira-type or semiregular variables) are known to emit maser or thermal radio emission in spectral lines of molecules (Cesaroni et al. 1988; Engels and Heske, 1989; Benson et al. 1990; Loup et al. 1992). Oxygen-rich (M-type) stars emit maser lines of the oxygen-bearing molecules OH, H_2O, and SiO. Carbon stars emit thermal lines of CO and HCN; a few carbon stars are also HCN masers. CO radio emission appears in many oxygen-rich stars as well. A small number of S-type stars emit maser lines of SiO.

Maser emission of late-type stars is observed at the evolutionary stage of intense mass loss when the stars are on the asymptotic giant branch (AGB). At this stage, the stars are surrounded by extended gas-dust envelopes formed by outflowing material. Physical conditions in the circumstellar envelopes are favourable for nonequilibrium excitation of molecules, resulting in maser effect.

The AGB stage is critical in evolution of stars, because stars lose a considerable part of their masses. This results, on one hand, in a quick transition of a star from the red-giant stage to that of "white dwarf + planetary nebula", and, on the other, in enrichment of interstellar medium with stellar ejecta (dust and gas with heavy elements).

Masers in different molecular lines originate in different layers of the circumstellar envelopes. OH molecules emit from the outer parts of the envelopes ($r \sim 10^{16}$ cm), H_2O – at closer distances to stellar surfaces ($r \sim 10^{14} - 10^{15}$ cm). SiO and HCN maser emission comes from vibrationally excited states of these molecules and requires much more energy for excitation. Therefore, SiO masers in M- and S-type stars, and HCN masers in carbon stars are located in the innermost parts of the circumstellar envelopes, at $r \sim$ a few $\times 10^{13}$ cm, near stellar photospheres.

In this contribution, I consider circumstellar maser emission in the rotational transition $6_{16} - 5_{23}$ of the H_2O molecule ($\lambda = 1.35\,\mathrm{cm}$). The maser pair of H_2O rotational levels is located high enough above the ground level, $T_{exc} = 644\,\mathrm{K}$. The H_2O maser is thus of intermediate degree of excitation among other circumstellar masers. The H_2O maser is of interest for studies of mass loss process, because it probes those layers of circumstellar envelopes,

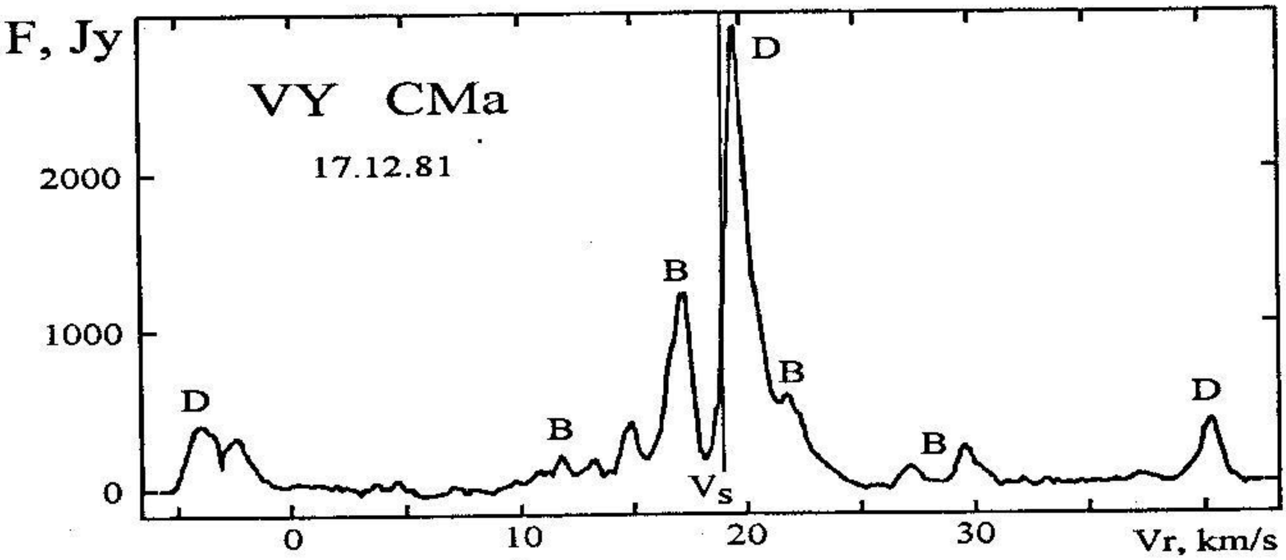
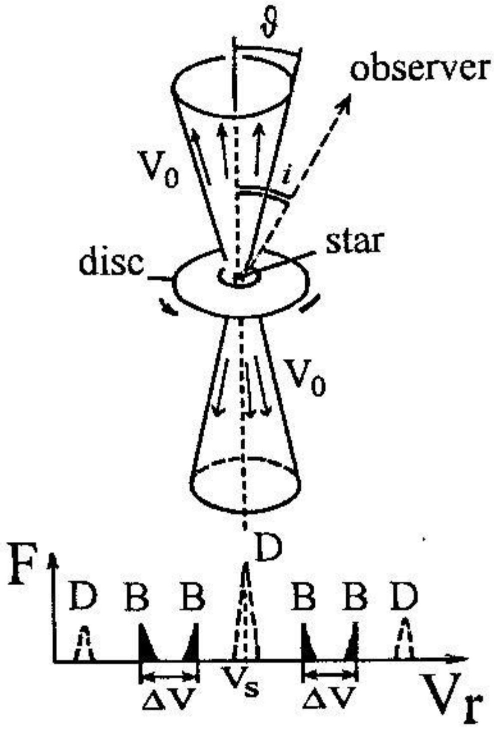


Figure 1: Profile of the H_2O line $\lambda = 1.35$ cm of the supergiant VY CMa, observed on the Pushchino 22-meter radio telescope of the Lebedev Physical Institute, Russian Academy of Sciences (flux density in Janskys *vs* radial velocity with respect to the local standard of rest in km/s). Radial velocity of the star $V_s = 19$ km/s (Loup et al. 1992).



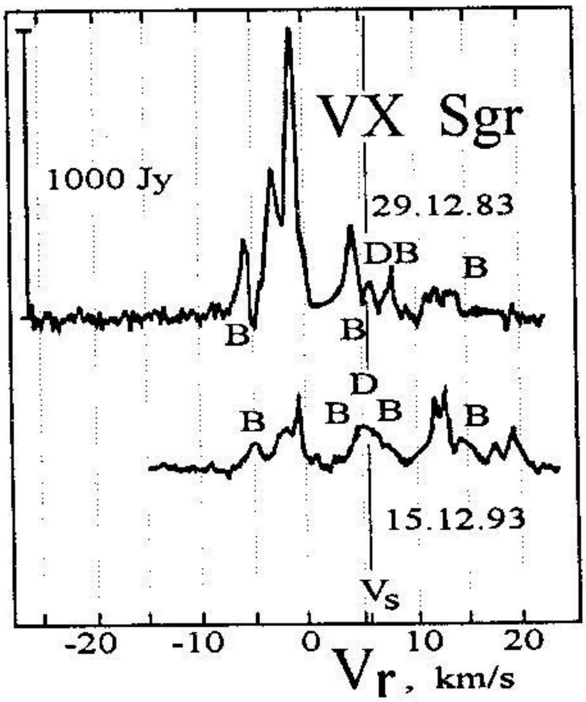


Figure 2: *Left:* Bipolar geometry is shown together with the expected line profile (see text). Separation between spectral features within each pair $\Delta V = 2V_0 \sin\vartheta \sin i$. *Right:* Same as Fig. 1, for VX Sgr, observed in 1983 and 1993; $V_s = 5.3$ km/s (Chapman and Cohen 1986).

in which main acceleration of the outflowing material takes place.

There are much data indicating that mass loss from AGB stars is not a smooth, spherically symmetric flow of gas and dust. These data include optical and infrared interferometry of circumstellar envelopes (e.g., Haniff et al. 1992; Tuthill et al. 1994), radio interferometry in molecular lines, both maser (Bowers et al. 1993) and thermal (Planesas et al. 1990). The results obtained suggest that many circumstellar envelopes have elongated shapes. This is also supported by variety of nonspherical structures (bipolar, elliptical) observed in planetary nebulae - descendants of AGB stars (Balick 1993). Several mechanisms can cause the asymmetry of mass loss: (1) stellar rotation (rather improbable for red giants, although plausible for absolutely younger red supergiants); (2) magnetic field; (3) star's nonradial pulsations; (4) presence of a companion star. Anyway, asymmetry in the shapes of planetary nebulae and their precursors - circumstellar envelopes - is laid early at the AGB stage. Viewing the lucky position of H_2O masers at the crucial levels of circumstellar matter acceleration, H_2O masers are useful tools for studies of mass loss asymmetries on the AGB. H_2O masers are strong and easily accessible for both interferometric and single-dish radio observations. Therefore, much information can be gained from systematic studies of circumstellar H_2O masers.

The most straightforward evidence for asymmetric geometry of circumstellar H_2O masers is got from interferometric (in particular, VLA and VLBI) observations. Circumstellar H_2O masers have been more than once studied interferometrically (Spencer et al. 1979; Lada et al. 1981; Johnston et al. 1985; Chapman and Cohen 1986; Lane et al. 1987; Reid and Menten, 1990; Bowers et al. 1993). Maps of distribution of circumstellar H_2O maser emission for the stars U Ori, W Hya, VX Sgr, VY CMa, R Aql, RR Aql, NML Cyg, IK Tau, RT Vir, RX Boo were obtained, for some of them (VX Sgr, W Hya, R Aql) - repeatedly. The maps show complex structure, with numerous spots of maser emission scattered in regions with sizes ranging between $\sim 10^{14}$ cm for giants and $\sim 10^{15}$ cm for supergiants. Shapes of visible distributions are in many cases far from circular. Generally, the authors of the above-mentioned works on H_2O interferometry are careful in their interpretation of the H_2O maps. However, in my opinion, the maps for at least two supergiant stars (VX Sgr and very much similar to it VY CMa) do show clear signatures of bipolar mass loss outflows.

In this contribution, I discuss only the case of the M-type supergiant VX Sgr, because the features of the bipolar model are most readily seen in this star. I show that even single-dish observations, if done systematically, can provide evidence for bipolarity in maser structure.

In my earlier work (Rudnitskij 1993), I considered a model of circumstellar masers with a circumstellar disc and a bipolar outflow directed along the disc axis. Here I apply this model to some more recent data on H_2O emission of VX Sgr.

Disc geometry is quite common in maser sources. Such a model was first suggested for masers in star-forming regions by Elmegreen and Morris (1979). A rotating disc of masering gas, when observed edge-on, produces a characteristic three-peak line profile with a central peak at approximately stellar radial velocity V_s and two satellite features arranged symmetrically with respect to V_s. Satellites come from disc's limb parts, while the central peak is generated in the gas moving perpendicular to the line of sight, at the near and far sides of the disc. Figure 1 shows an example of such a profile, observed in the H_2O maser emission of the M-supergiant VY CMa. Features coming from the disc are labeled with D's.

Proceeding from this, it is natural to assume that outflowing matter will be stopped by the disc in the equatorial plane, but will be free to expand in the polar directions, producing two oppositely directed flows. Figure 2 shows the geometry of the model. The maser emission from the disc yields a three-peak spectral pattern (as in Fig. 1) with some superposed features originating in the polar jets. I assume the masering gas to be concentrated at the walls of the two polar cones with opening half-angle

ϑ. Cones' axis is inclined to the line of sight at an angle i. Gas velocity along cones' walls is V_0. Such a model, when viewed at a moderate angle, produces two pairs of additional spectral peaks, shown on the model profile in Fig. 2. Probable corresponding features in the H_2O line profiles of VY CMa and VX Sgr are labeled with B's on Fig. 1 and 2. The picture described is supported by the H_2O interferometric maps of VX Sgr and VY CMa (Chapman and Cohen, 1986; Bowers et al. 1993), on which the disc and the jets can be distinguished, although these authors do not go such far in their interpretation of the data. The 'B' features can be seen on both H_2O profiles of VX Sgr, separated by almost ten years (Fig. 2), and, thus, are persistent structures, despite of the general flux variations.

Note that Likkel et al. (1992) came to similar conclusions on bipolar nature of H_2O masers in three evolved stars (probable planetary–nebula precursors) IRAS 16342–3814, W 43A, and IRAS 19134+2131. Likkel et al. also based upon single–dish H_2O observations. Thus, we can expect that repeated observations of maser line profiles for a number of late–type stars can help to reveal some long–living pairs of features that fit into the above model of circumstellar disc + bipolar flow. At present such a work on Pushchino H_2O data is in progress (for earlier results, see Berulis et al. 1983).

A complete set of our H_2O data on VX Sgr and VY CMa together with the details of the model will be published elsewhere (Berulis et al. 1996).

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