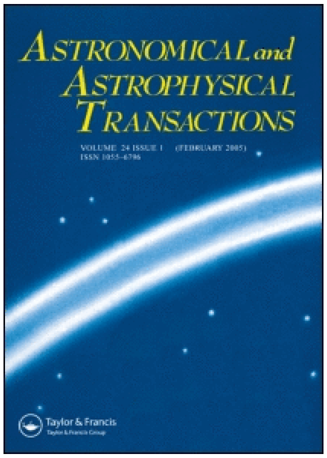

Astronomical & Astrophysical Transactions

The Journal of the Eurasian Astronomical Society

Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713453505

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Online Publication Date: 01 August 1999
To cite this Article: Berulis, I. I., Pashchenko, M. I. and Rudnitskij, G. M. (1999) 'H_2O maser emission of the M-type supergiant VX Sgr', Astronomical & Astrophysical Transactions, 18:1, 77 - 82
To link to this article: DOI: 10.1080/10556799908203038
URL: http://dx.doi.org/10.1080/10556799908203038

Astronomical and Astrophysical Transactions, 1999, Vol. 18, pp. 77–82
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H_2O MASER EMISSION OF THE M-TYPE SUPERGIANT VX Sgr

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(Received January 9, 1997)

We present the results of observations of the M-type semiregular supergiant VX Sgr in the water-vapour line at $\lambda = 1.35$ cm. The observations were carried out on the 22-metre radio telescope RT-22 in Pushchino in 1981–1996. The profiles of the H_2O line have a complex structure typical for H_2O masers associated with late-type supergiants. We reveal some features persistent during the last 15 years; we suggest that they arise from masering H_2O molecules located in the circumstellar disk and the bipolar outflows from the disk poles. The parameters of the outflow are estimated.

KEY WORDS Late-type stars, supergiants, semiregular variables, circumstellar envelopes, molecular lines, masers

Among several hundreds of late-type stars, known to possess circumstellat maser emission in the H_2O rotational line 6_{16}–5_{23} ($\lambda = 1.35$ cm), there is a relatively small group of M-type supergiants (VY CMa, VX Sgr, NML Cyg, IK Tau, S Per, and some others). All of them are classified as slow variable stars – long-period or semiregular variables. Their variability differs from that of late-type giants by having much longer light cycles. The H_2O maser emission of the supergiants is also variable; the H_2O line flux density may vary by more than one or two orders of magnitude.

Beginning in 1981, we have been systematically monitoring some M-type giants and supergiants in the $\lambda = 1.35$ cm line of H_2O (Berulis *et al.* 1983). In this work, we present the results of our H_2O line observations for the M-supergiant VX Sgr (IRC–20431), obtained in 1981–1996.

In the Fourth Edition of the General Catalogue of Variable Stars (Kholopov *et al.*, 1987), VX Sgr is classified as a semiregular variable of type SRc. Its light cycle is 732^{d}, maximum range of visual-brightness variations is $6\overset{\mathrm{m}}{.}52$–$14\overset{\mathrm{m}}{.}0$, and the spectral type varies between M4e and M10e (Ia). The light curve of VX Sgr at a timespan of more than fifty years was studied by Mayall (1970), Dinerstein (1973), Celis (1975), and Smith (1977). There were some "quiescent" intervals, when light variations were virtually absent (Dinerstein, 1973); this indicates the beating of pulsations with several different periods P. In other time intervals, the amplitude of brightness variations increased and eventually exceeded 5^{m}; this is typical of Mira-type variables. The latest interval of VX Sgr activity began at the end of 1984.

The light elements from GCVS, in their turn taken from Mayall (1970), are

$$\mathrm{Max} = \mathrm{JD}\,2436493 + 732^{\mathrm{d}}E. \tag{1}$$

Lockwood and Wing (1982) note that these elements fit well their light curve obtained in 1974–1976; therefore, we, too, adopt $P = 732^{\mathrm{d}}$. However, since then VX Sgr has undergone a "quiescent" stage, and the phase of its light variations has shifted by approximately $\frac{1}{2}P$ (see below).

The distance to VX Sgr is estimated to be from 1.5 kpc (Lockwood and Wing, 1982) to 2 kpc (Humphreys, Strecker and Ney, 1972).

The star VX Sgr is a source of maser emission in the molecular lines of OH (Caswell and Robinson, 1970; Paschenko *et al.*, 1971), H_2O (Dickinson, Bechis and Barrett, 1973), and SiO (Kaifu, Buhl and Snyder, 1975). Thermal emission in the lines of SiO (Engels and Heske, 1988), CO and HCN (Loup *et al.*, 1992) was also observed.

The H_2O line observations were carried out on the 22-metre reflector radio telescope (RT-22) at the Radio Astronomy Observatory (Astrospace Center of the Lebedev Institute of Physics, Russian Academy of Sciences) in Pushchino, Moscow Region. The receiving-system front-end was a liquid-helium-cooled maser amplifier of the 22-GHz frequency band, yielding a system noise temperature of 200–300 K. In our observations of 1993–1996, we used a cooled FET amplifier. For the line spectrum analysis, we constructed a 96-channel filter bank with a frequency resolution of 7.5 kHz (or 0.101 km s^{-1} in the radial velocity at the H_2O line frequency, covering a 9.7-km s^{-1} velocity range in a single observational run).

Figure 1 shows some sample profiles of the H_2O line in VX Sgr as the flux density F_ν (in Janskys) *versus* the radial velocity V_{LSR} (km s^{-1}) referred to the Local Standard of Rest. The maximum V_{LSR} range covered by our observations is from −25 to +35 km s^{-1}.

In M-type supergiants, the structure of the H_2O $\lambda = 1.35$-cm line profile is by far more complicated and varied than in M-giants. In M-supergiants, the H_2O line profile may contain scores of emission peaks scattered within a V_{LSR} interval of up to 30 km s^{-1}. In many cases, H_2O line profiles possess a prominent symmetry in the distribution of emission features. Below, we will discuss a model of the circumstellar maser region in VX Sgr explaining the profile structure. M-giants usually have only one or two emission features in their H_2O line profiles, and the V_{LSR} range, as a rule, is not broader than 5 km s^{-1}.

In VX Sgr, the emission feature at $V_{\mathrm{LSR}} = -1$ km s^{-1} is present (although with somewhat differing flux densities) in almost all the spectra obtained between 1981 and 1996. Note also two pairs of lower-intensity emission peaks at $V_{\mathrm{LSR}} = (-5, +4.5)$ and (+6, +13) km s^{-1}. Between the features at $V_{\mathrm{LSR}} = +6$ and +13 km s^{-1}, there is a gradual fall-off of the emission toward the mid-point of

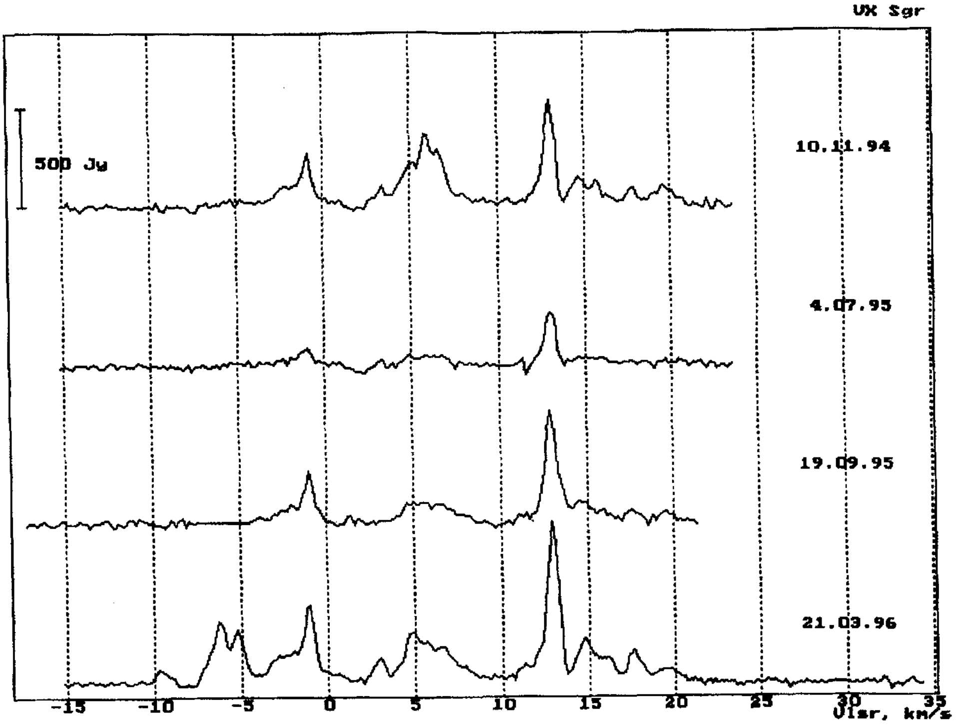

Figure 1 Profiles of the H_2O spectral line $\lambda = 1.35$ cm of the star VX Sgr, observed in 1994–1996.

the pair. This profile is reminiscent of an expanding maser structure, similar to that observed in OH/IR stars in the OH 1612–MHz line (Kwok, 1976). It is more difficult to trace this structure between the peaks at $V_{\rm LSR} = -5$ and $+4.5$ km s^{-1}, because this $V_{\rm LSR}$ interval is filled with the intense peak $V_{\rm LSR} = -1$ km s^{-1}. Some profiles show also an additional peak at $V_{\rm LSR} = -3$ km s^{-1}, which was especially strong in 1985, when its density exceeded that of the -11 km s^{-1} feature.

The emission pairs at $V_{\rm LSR} = (-5, +4.5)$ and $(+6, +13)$ km s^{-1} are present in VX Sgr spectra starting from our early observations of this star in 1981–1982; they can be traced also in the spectra of 1994–1996 (see Figure 1). However, on the latter spectra, there is also a broad feature (with $\Delta V \sim 2.5$ km s^{-1} at half-intensity) at $V_{\rm LSR} = +5.5$ km s^{-1}. Such a large ΔV is not typical for most of the maser peaks observed, which usually have $\Delta V \lesssim 1$ km s^{-1}. Note that the broad-feature velocity coincides with V_*, the radial velocity of VX Sgr, measured from thermal molecular radio lines (Loup *et al.*, 1992). The feature blends with the above-mentioned peaks at $V_{\rm LSR} = +4.5$ and $+6$ km s^{-1}.

We compared the variability curves of VX Sgr in the H_2O line and in the visual spectral region. The correlation between these curves, together with accompanying variations in the H_2O line profile structure, is indicative of the physical processes

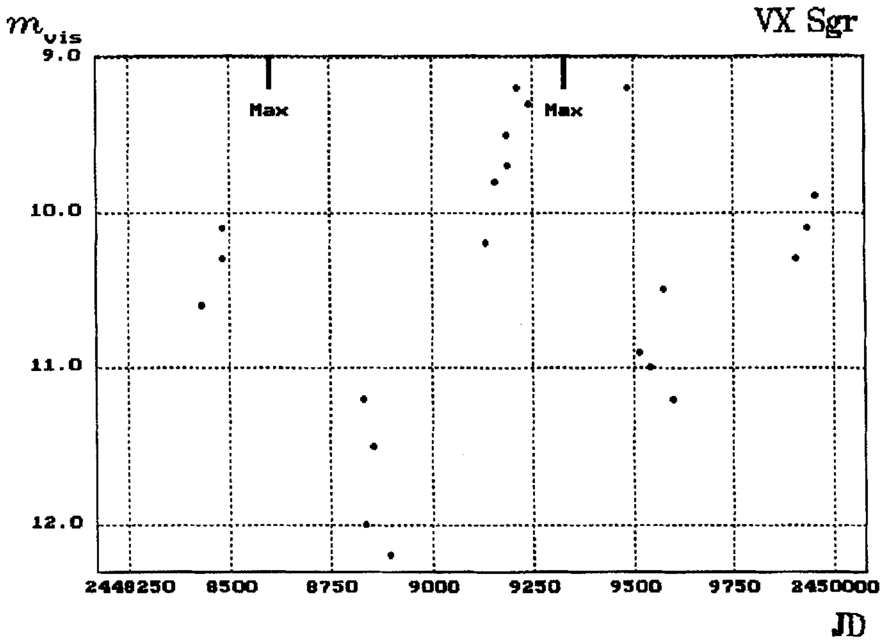

Figure 2 Visual light curve of VX Sgr.

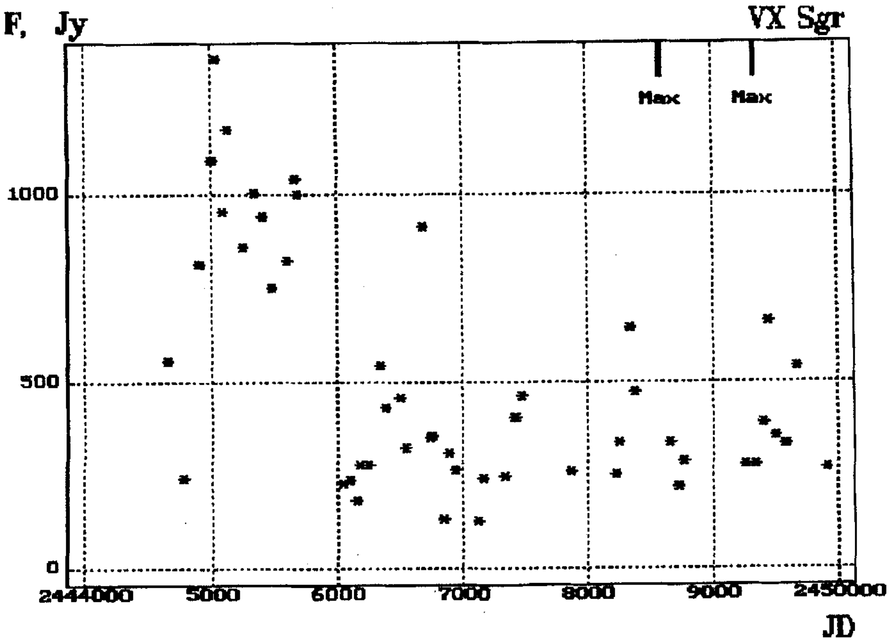

Figure 3 Time dependence of the peak flux density of the H_2O line feature at *V*LSR = -1 km s^{-1} in VX Sgr.

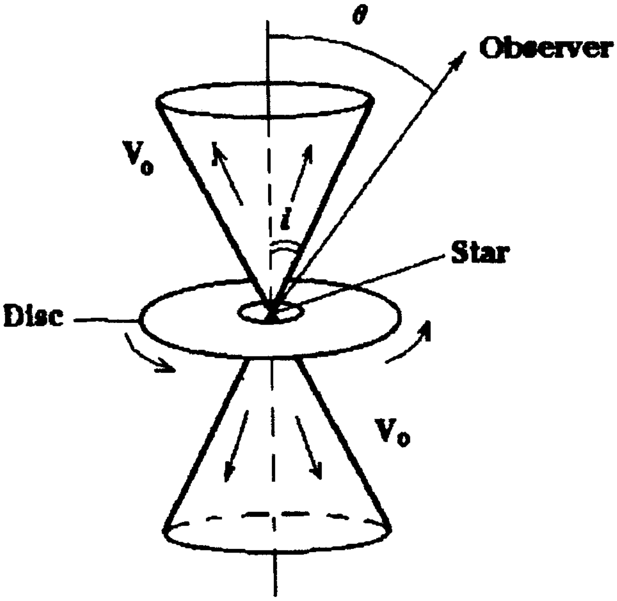

Figure 4 Bipolar outflow model of the H_2O maser in VX Sgr.

in the inner parts of the circumstellar envelope. For the years 1990–1996, we used visual observations obtained by the associations of variable star observers: American (AAVSO), French (AFOEV), and Japanese (VSLOJ). These data were retrieved via Internet. Figure 2 presents a composite visual light curve based on these data. We find that the period $P = 732^d$ is present, but, as noted above, the phase of the light variations has shifted since the observations of Lockwood and Wing (1982) [consistent with light elements (1)] by $\sim 1/2P$, yielding the new elements:

$$\text{Max} \approx \text{JD}\,2448600 + 732^d E. \quad (2)$$

Figure 3 shows the variability curve of the peak flux density of the H_2O feature $V_{\rm LSR} = -1$ km s^{-1} during the entire interval of our observations (1981–1996). This feature was chosen as the most intense one that was present on each of the H_2O spectra obtained. Vertical bars in the upper part of the graph mark the latest two light maxima of VX Sgr, computed with elements (2). A correlation of the flux density of the -1 km s^{-1} feature with the visual light curve during the last years is evident. It is also interesting to note that enhanced H_2O maser activity of VX Sgr with high values of F_ν took place at interval JD = 2445000–2446000, i.e. when the star visual-light variations almost stopped.

The presence of three groups of spectral features in the $V_{\rm LSR}$ intervals (–5, 0), (2, 7), and (10, 15) km s^{-1} can be explained by the model of bipolar outflow (Rudnitskij, 1995) – see Figure 4. The star is losing mass at a constant velocity V_0 within two oppositely directed cones with the apex at the star centre. The central spectral peak (near $V_{LSR} \approx V_*$, i.e. the stellar velocity) is generated in a turbulent circumstellar disk, observed almost face-on. The inclination angle i of the outflow axis to the line of sight is of the order of the outflow cone opening angle θ (Figure 4). Two side groups of spectral fetures arise in the approaching and receding jets of the bipolar outflow. The $V_{\rm LSR}$ spacing between the centres of the groups is $2V_0 \cos i$. The maximum velocity spread (absolute values) within one group is $V_0 \cos(i+\theta) \rightarrow V_0$. According to H_2O VLBI data (Bowers, Claussen and Johnston, 1993), $\theta \sim 60°$, $i \sim 0$. From the extreme in $V_{\rm LSR}$ points of the H_2O line profile, we get $V_0 \sim 10$ km s^{-1}, in agreement with the analysis of the circumstellar envelope of VX Sgr based on OH lines (Chapman and Cohen, 1986).

A complete set of our H_2O observational data, together with the model analysis, will be published in the Astronomicheskii Zhurnal (translated in English as Astronomy Reports).

Acknowledgments

This work was supported by the International Science Foundation (grant J4U100) and Russian Foundation for Basic Research (project codes 94–02–05763 and 96–02–18867). This research made use of the SIMBAD database, operated at Centre des données astronomiques (CDS), Strasbourg, France, and of the AAVSO and VSLOJ data.

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