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MASS-LOSING PULSATING STARS AND THEIR CIRCUMSTELLAR MATTER

Observations and Theory

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OPTICAL AND MICROWAVE SPECTROSCOPY OF LONG-PERIOD VARIABLE STARS

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Abstract The results of multiwavelength studies (optical spectroscopy, H_2O maser line, radio continuum) of a sample of long-period variable stars are presented. For some of the stars studied (R Aql, RR Aql, W Hya, U Ori) the H_2O maser emission has been detectable throughout the monitoring interval, for more than 20 years. A comparison of the H_2O maser monitoring of these stars with their visual light curves suggests a correlation of their maser and optical brightness. There is a phase lag $\Delta\varphi \sim 0.1 - 0.4P$ (P is the star's variability period) of the H_2O maser variations relative to the optical variability. There are also stars ('transient masers', R Leo, R Cas, U Aur) that have exhibited short-duration flares in the H_2O maser line with several years of no detectable emission between them. The H_2O maser flares were preceded by flares of the Hα emission line. The common cause of such sequence of events can be the consecutive impact of a shock wave on different layers of the stellar atmosphere and circumstellar envelope.

Keywords: Miras, spectroscopy, emission lines, masers

Since 1980 we have been performing radio spectral observations of the maser emission of late-type variable stars in the $\lambda = 1.35$ cm rotational line of the H_2O molecule (6_{16}–5_{23}, 22235.08 MHz) on the 22-meter radio telescope, Pushchino Radio Astronomy Observatory, Russian Academy of Sciences, with a helium-cooled FET amplifier ($T_{\rm noise} = 150$ K), 128-channel filter-bank spectrometer, resolution 7.5 kHz ($\Delta V_R = 0.1$ km/s). The 3σ sensitivity of the H_2O observations is about 10 Jy. The interval between the H_2O observational sessions is on the average 1–1.5 months. The sample includes M-type long-period variables (Miras and semireg-

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ulars R Leo, R Aql, R Cas, U Ori, W Hya and others) as well as M-supergiants (VX Sgr, VY CMa, S Per).

In 1994 we began regular optical spectroscopic observations of the stars on the 125-cm telescope of the Crimean Observatory, Sternberg Astronomical Institute, with a diffraction spectrograph and CCD camera, $\Delta\lambda = 0.25$ Å/pixel (Esipov et al. 1999). Main attention has been paid to the Balmer emission lines (Hα and others).

In November 1995 34 stars were observed on the Australia Telescope Compact Array at $\lambda\lambda = 6$ and 3 cm for a systematic search of radio continuum emission. The program included o Cet, U Ori, U Her, R Aql and some southern-hemisphere Mira and semiregular variables. The result was negative with upper limits typically ~0.1–0.3 mJy (Chapman and Rudnitskij 2002).

The H_2O maser monitoring has allowed us to divide the stars into two groups.

1. Stable masers, emitting throughout 22 years (R Aql, RR Aql, RS Vir, S CrB, X Hya).

2. Transient masers, displaying strong flares intermitting with long quiescent intervals without detectable H_2O emission (R Leo, R Cas, U Aur).

For stable, permanently emitting stars we could trace a correlation between their visual light curves and H_2O maser variations. The H_2O line flux usually followed the visual brightness with a phase delay $\Delta\varphi$ of 0.1–0.4 stellar periods (P). For RS Vir ($P = 354^d$) the cross-correlation function between the visual light curve and H_2O maser variations shows maximum correlation for a delay τ of 4–5P (Lekht et al. 2001).

A special case is U Ori. This star was undetectable in the H_2O line in June 1980, but by October 1980 it flared and has remained since a 'permanent' (Group 1) maser, displaying, too, light-curve-correlated maser variations with some delay $\Delta\varphi$. The value of $\Delta\varphi$ was changing itself with a 'superperiod' of 9 years, i.e, almost 9 light cycles of $P = 372^d$ (Rudnitskij et al. 2000).

For three 'transient' (Group 2) masers (R Leo, R Cas, U Aur) the Hα flares were followed in 1–1.5 years by an H_2O maser flare (Esipov et al. 1999). In between R Leo showed also a SiO maser flare. Such sequence of the flares can be explained by a consecutive action of a moderate-strength shock ($v_{sh} \sim 6 - 10$ km s^{-1}) on various layers of the stellar atmosphere and inner circumstellar envelope.

We connect the flaring events (observed once per several stellar light cycles) with the effect of a shock wave propagating through the stellar atmosphere and then through the inner layer of the circumstellar envelope, hosting the masers (Fig. 1, *left*). The cross-correlation function

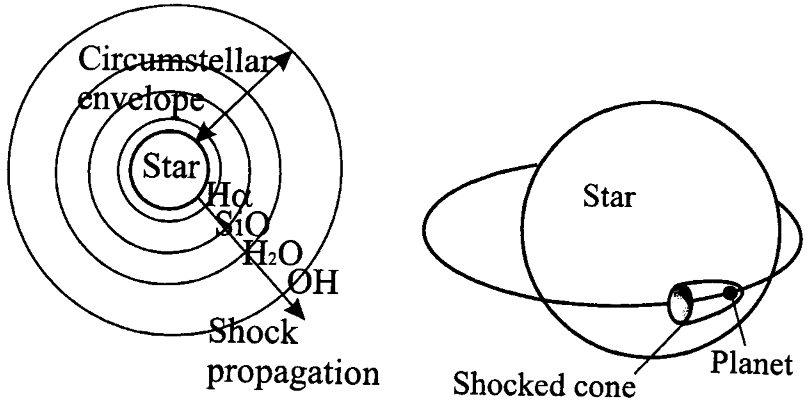

Figure 1. *Left:* Consecutive excitation by an outward propagating shock of the layers responsible for the Hα, SiO, H_2O and OH emission. *Right:* A shock induced by a planet revolving in a close orbit near the stellar photosphere.

for RS Vir, peaking at $\tau \sim 4 - 5P$, suggests the travel time of a shock from the stellar surface to the H_2O masering layer in the circumstellar envelope (at $r_m \sim 10^{14}$ cm) of about this interval. Then we estimate the mean shock velocity as $v_{sh} \sim r_m/\tau \sim 7$ km s^{-1}, i.e., not a strong shock.

The rare occurrence of such episodes of the Hα emission followed by an H_2O maser flare can be explained by the following mechanisms.

1. Merging shocks (Wood 1979). Overtaking and merging of consecutive stellar-pulsation-driven shocks is possible. Merged shocks can produce stronger Balmer and maser emission once per several stellar cycles.

2. Appearing and disappearing quasi-stationary spherical layer (Hinkle et al. 1984) at a distance $r \sim 10^{14}$ cm from the stellar surface. This layer has physical conditions favourable for the H_2O maser generation, when pumped by a relatively slow shock with v_{sh} just about the value estimated for RS Vir, 7 km s^{-1} (Rudnitskij and Chuprikov 1990).

3. A low-mass companion in an elliptical orbit (Rudnitskij 2000; Struck et al. 2002; Fig. 1, *right*). This model does not imply a 'global' spherical shock, engendered by the stellar pulsation. Shocks in Miras may be intrinsically weak, as suggested above by the lack of associated radio continuum, though this continuum should accompany the observed strong Balmer line emission. An alternative may be a local hot spot, connected with the shocked tail behind a planetary (or brown dwarf) companion to the red giant. This spot can emit sufficiently strong optical hydrogen lines, remaining very weak in the radio continuum because of its small angular size. If the planet is revolving in an eccentric orbit

with a period of several years, the Hα–H_2O events are connected with the periastron passages of the planet. Details are given in Rudnitskij's poster (this volume).

Thus, our long-term observations have shown that some effects connected with Miras' light variations, 'superperiods' in the delay $\Delta\varphi$ and in the appearance of Balmer emission lines and molecular maser flares, can be understood only if monitored on a sufficiently long time interval, covering at least 10 to 20 light cycles of the stars.

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Discussion

Sandra Etoka: A comment about the time scale in the occurrence of similar events at different wavelengths: superperiods and flare events in H_2O and OH, in particular found in both of our works on long-period monitoring of AGB stars, might be connected.

Georgij Rudnitskij: Indeed, in R Leo we have two examples of such chains of flare events: SiO$\rightarrow H_2O\rightarrow$OH in 1980s, H$\alpha\rightarrow$SiO$\rightarrow H_2O$ in 1990s (similar single chains in U Aur and R Cas). It would be interesting if R Leo flares also in OH within a couple of years, this would strengthen the evidence.