Asymptotic Giant Branch Stars
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Multiwavelength Studies of Mira Ceti-type Variable Stars

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Abstract. Since 1994, observations of a sample of about 20 Mira Ceti-type and semiregular variables have been carried out in three spectral ranges: radio (H_2O maser line $\lambda = 1.35$ cm), optical (spectroscopy and *UBV* photometry) and infrared (*JHKLM* photometry). Time series of the Hα emission intensity and H_2O line flux, covering several periods of the stars, have been obtained. Correlation of the intensity variations of the H_2O maser with optical variability in the maser stars RR Aql, U Ori, VX Sgr and others was confirmed. One of the most interesting results is the flare of the H_2O maser emission in R Leo, which happened in autumn 1997, 14 months after a flare of the Hα emission.

1. Introduction

The project of multiwavelength investigation of late-type variable stars grew up from monitoring observations of maser radio sources emitting in the rotational line 6_{16}–5_{23} of the H_2O molecule at $\lambda = 1.35$ cm. We started this program at the end of 1979 and, since then, we have been permanently observing variability of a large sample of H_2O masers, including about 30 late-type giants (Mira stars and semiregular variables).

To get a more complete picture of the stars variability, in 1994 we began a multiwavelength monitoring of a sample of late-type variables with (and without) H_2O maser emission. We were primarily interested in effects of shock waves in the atmospheres and envelopes of the stars. The diagnostics of the shocks is presumably the emission-line spectrum of the stars. Shock waves may influence the intensity of maser emission of OH, H_2O, and SiO in circumstellar envelopes — both directly (by impact of the shock on the maser generation region, Rudnitskij & Chuprikov 1990) and indirectly (through the radio continuum emission of the shock, amplified by masering molecules, Rudnitskij 1990).

There have been a number of studies of the H_2O-line variability in late-type stars (e.g., Schwartz et al. 1974, Cox & Parker 1979, Gómez Balboa & Lépine 1986, Woods et al. 1990); in particular, recently some interferometric monitoring of stellar H_2O masers has been done (Engels et al. 1998; Richards et al. 1998). In our single-dish H_2O observations, we do not attempt to compete with interferometry mapping of the masers. The main advantage of our project is long-term, multiwavelength study of a sample of stars, covering several cycles of their variability. A comparison of these data could yield a new insight on the problems of late-type stars variability, maser emission and shock waves.

In the framework of the project the following programs are carried out.

(1) Regular optical (*UBV*) monitoring of several Mira-type and semiregular variables (R Aql, R Leo, U Ori, U Her, RT Vir, R Cas, IK Tau, R Crt, RX Boo, W Hya).

(2) Optical spectroscopy of the stars.

(3) Radio spectral observations of maser emission of the same stars in 1.35-cm line of H_2O.

(4) IR observations of the stars.

(5) Observations of the stars at centimeter wavelengths for a systematic search for the post-shock radio continuum emission.

2. Observations

Radio observations in the H_2O line at $\lambda = 1.35$ cm are performed on the 22-meter radio telescope of the Lebedev Institute of Physics (Russian Academy of Sciences) in Pushchino, Moscow Region, by means of the 1.35-cm wavelength receiver with a helium-cooled FET amplifier and a 128-channel filter-bank spectrometer with a resolution of 0.1 km/s. Intervals between consecutive observing sessions normally do not exceed 1–2 months.

For optical spectroscopy, we use a diffraction spectrograph with a resolution of 0.25 Å/pixel. An echelle spectrograph with a resolving power of 10 000 has been tested. The spectra are recorded with ST-6 and ST-8 SBIG CCD cameras. This instrumentation is in operation on the 100- and 60-cm telescopes in Crimea.

IR observations are carried out on the Crimean telescopes, equipped with the IR photometer of the Sternberg Astronomical Institute.

In the radio continuum, we have observed a sample of 34 Miras and semiregular variables at $\lambda = 6$ and 3 cm on the Australia Telescope Compact Array (ATCA) in Narrabri (Chapman & Rudnitskij 1999).

3. Results

We have traced the evolution of the Hα emission in several stars (R Aql, R Leo, R Cas, U Her, χ Cyg and others). The appearance of the emission is not regular, not all light cycles are accompanied by it, contrary to the data of previous spectroscopic monitoring with a limited time coverage (e.g., Gillet et al. 1983, Fox, Wood & Dopita 1984, Woodsworth 1995, Castelaz et al. 1997). The emission flared at different light phases φ of the stars, from minimum to maximum, although phases $\varphi \sim 0.4 - 0.5$ seem to be preferred.

Comparing time series of optical and IR photometry, optical and H_2O line spectra, we confirm the correlation of the H_2O maser flux with the optical light curve for many stars studied, in particular, VX Sgr, U Ori and RR Aql (Berulis, Lekht & Pashchenko 1994; Berulis et al. 1998). Among our recent results, the most interesting are: detection of a superperiod in H_2O maser variations of U Ori; Hα-related flare of the H_2O maser R Leo; flare of the H_2O maser RT Vir; redistribution of the H_2O line flux between the groups of blue- and red-shifted

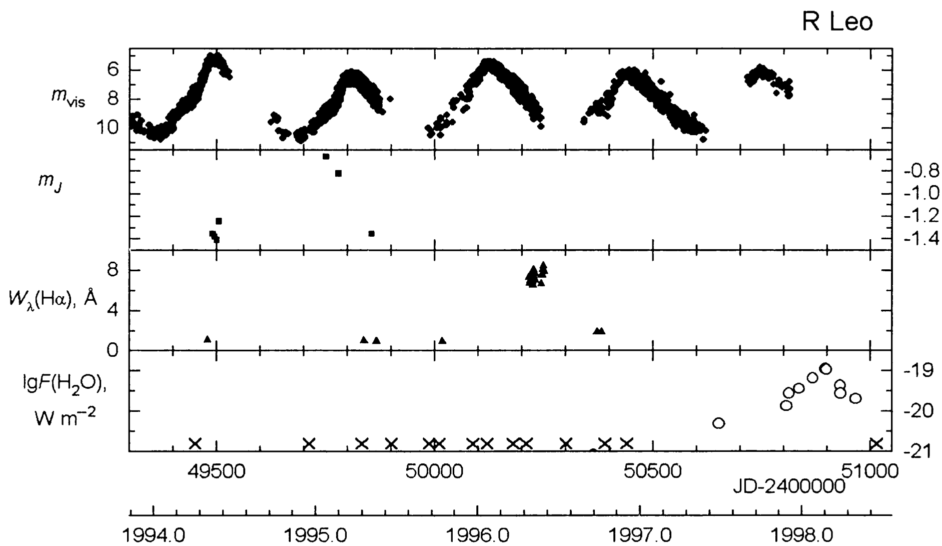

Figure 1. Data on R Leo. From top to bottom: visual light curve (AAVSO and AFOEV data); J-band stellar magnitudes; equivalent width of the Hα emission line; integrated flux of the H_2O maser emission (crosses are upper limits).

spectral features in bipolar outflows from the semiregular variables RT Vir and VX Sgr.

3.1. U Ori

This star was monitored in the H_2O line since March 1980, when it was below our detection limit (< 10 Jy). However, in October 1980 its H_2O peak flux density rose to about 1 000 Jy (Berulis et al. 1983). Since then, the H_2O maser in U Ori has shown flux variations with decreasing amplitude, closely following the light curve with a certain phase delay (Berulis, Lekht & Pashchenko 1994). The delay was not constant, but varied between 0.1 and $0.3P$ in an almost sinusoidal law with a period of about 9 years. We call it 'superperiod' of stellar activity.

3.2. R Leo

R Leo displayed pronounced H_2O flux variations, correlated with its light curve, in the early years of our H_2O observations (1980–1983) (Rudnitskij 1987), but in 1984–1997 we could not detect it at a 3σ level of 10 Jy. In autumn 1997 R Leo flared in the H_2O line, reached a peak flux density of about 150 Jy at the end of March 1998, but then faded again to less than 10 Jy in June 1998. This H_2O flare happened 14 months after the Hα flare observed by us in R Leo during summer 1996 (Fig. 1).

Two other examples of strong Hα flares that occurred when the stars were 'H_2O-quiet' (i.e. below our detection limit) are U Aur (in autumn 1997) and

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R Cas (in September 1998). At present these two stars remain unobservable for us in the H_2O line, but we expect that they may soon flare up, too.

3.3. RT Vir

Our H_2O observations of RT Vir, obtained in 1986–1998 (for earlier spectra see Berulis et al. 1983, 1987, Mendoza-Torres et al. 1997), have shown that the H_2O maser emission is concentrated in three velocity intervals: $V_{\rm LSR} <$ 15.5 km/s, 15.5 km/s$< V_{\rm LSR} <$ 21 km/s, and $V_{\rm LSR} >$ 21 km/s. Stellar velocity, determined from thermal molecular lines, is 18.2 km/s, i.e. close to the middle of the H_2O $V_{\rm LSR}$ interval. An analysis of the character of H_2O integral-flux variations in the above three groups of maser features yields a characteristic variability timescale of 5–6 years, i.e. much longer than typical timescale of optical brightness variations. Thus, a certain 'superperiod' in the maser activity of RT Vir can be distinguished, too. Anticorrelation of the integrated fluxes of the three spectral intervals is observed; it may be due to alternating increase of the intensities in the two jets of the bipolar outflow. In 1998 RT Vir has strongly flared in the H_2O line: the peak flux density in the blueshifted group of maser features reached 1000 Jy, the highest value ever observed in this star.

3.4. VX Sgr

VX Sgr is a semiregular M-type supergiant with a mean period of light variations of 732^d. Its H_2O spectrum is rich with features, numbering up to 15. The spectrum can be divided into three velocity segments, like in the case of RT Vir: $V_{\rm LSR} = -5 \rightarrow 0$, $0 \rightarrow 10$ (this group of features is approximately centered on the stellar velocity $V_* = 5.5$ km/s) and $10 \rightarrow 20$ km/s. The central group remained more or less stable, while the side groups were varying, repeating, with some phase delay, the light variations of VX Sgr. Before 1987, the blueshifted group of features was stronger, but between 1987 and 1993, the red-shifted group increased its integrated flux and almost equaled the blueshifted one. Fig. 2 shows the evolution of the integrated flux of the halves of the VX Sgr H_2O spectrum; H_2O variations generally follow (with some, variable, delay) the light curve. The blue- and red-shifted groups are most probably connected with the two jets of the bipolar outflow (Berulis, Pashchenko & Rudnitskij 1998); the change of their relative intensities may be due to a reversal of the general magnetic field of the star (see discussion in Pashchenko & Rudnitskij 1999).

3.5. The radio continuum

Positive detections of Mira stars in the radio continuum are scarce (Knapp et al. 1995; Reid & Menten 1997). The stars detected were R Aql, W Hya, *o* Cet, χ Cyg, R Cas and R Leo. Typically the fluxes observed were a few tenths of a milliJansky. Jointly with Dr. Jessica M. Chapman we undertook on the ATCA a radio continuum ($\lambda = 6$ and 3 cm) aimed at detecting an eventual correlation between the radio continuum and the H_2O maser intensity. The expected mechanism of the correlation between optical brightness and H_2O maser emission, proposed by Rudnitskij (1990), involves amplification of the post-shock radio continuum by masering H_2O molecules. However, the search we have done yielded negative results for 33 Miras and semiregulars, except for the known source R Aqr (for details see Chapman & Rudnitskij 1999).

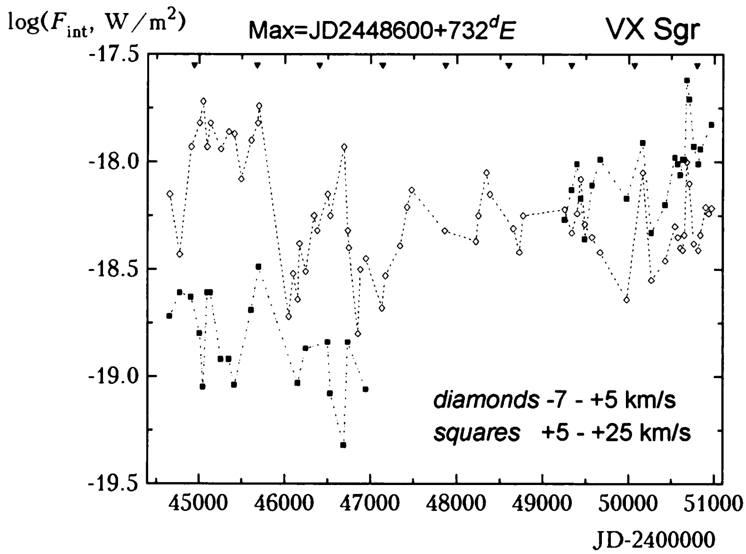

Figure 2. Flux variability of the H_2O maser in VX Sgr. Triangles mark light maxima of the star, computed with the light elements (Berulis, Pashchenko & Rudnitskij 1998), given in the upper part of the graph.

4. Conclusions

The preliminary conclusions we draw from our synchronous monitoring in the H_2O and Hα lines and from our (negative) results on the radio continuum are:

(1) The observed weak radio continuum from Miras must be strongly variable: we could not detect even the stars previously known to be radio continuum sources (o Cet, R Aql, W Hya: Knapp et al. 1995, Reid & Menten 1997), though the sensitivity was sufficient (typically 0.1–0.3 mJy at the 3σ level).

(2) The upper levels obtained imply that strong shocks with front velocities $v_s \geq 15-20$ km/s do not exist in Miras or they may be invisible at microwaves, because they do not propagate above the radius of the 'radio photosphere', $r_{\rm ph} \sim 2R_*$ (Reid & Menten 1997), strongly absorbing the radio emission, but transmitting the optical emission.

(3) The model for H_2O maser variability in late-type giants that involves amplification of the variable post-shock radio continuum by the masering molecules (Rudnitskij 1990) now seems less plausible than that assuming a direct impact of a weaker ($v_s \sim 5-10$ km/s) shock, reaching the masering region in the circumstellar envelope (Rudnitskij & Chuprikov 1990). The delay between the optical and H_2O maxima depends on the shock travel time and may be as long as a few stellar periods.

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