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Variability of the H_2O maser associated with U Orionis

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Abstract. H_2O line observations at $\lambda = 1.35$ cm of the Mira Ceti-type variable star U Ori are reported. The observations cover the time interval from March, 1980, to September, 1999. Variations of the integral flux and velocity centroid of the H_2O line are analysed. The flux in general correlates with the visual light curve, following it with some phase delay $\Delta\varphi \sim 0.2 - 0.4P$ (P is the period of the star). The maser emission is generated in a quasi-stationary layer of gas and dust at a distance of about 10^{14} cm from the stellar centre. The maser variability is explained by the action of periodic shocks, driven by stellar pulsation and arriving to the maser in each stellar cycle. The shocks provide the maser pumping, whereas the sink of the waste energy is controlled by the dust, periodically heated by the stellar radiation near the light maximum; this accounts for the correlation of the maser radiation maximum with the descending branch of the light curve. Temporary weakness of the maser emission may be due to decay of the quasi-stationary layer, which is then rebuilt by a powerful shock, carrying away from the star a portion of the lost mass, once per a few stellar periods – the "superperiod". In its turn, the superperiod may reflect multiperiodic pulsation of the star or the presence of a long-term activity cycle, connected with restructuring of the stellar magnetic field, which is known to be strong in U Ori.

Key words: stars: variables: Miras — circumstellar matter — stars: individual: U Ori — radio lines: stars — masers — shock waves

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1. Introduction

U Orionis is one of the brightest long-period variables belonging to the Mira Ceti type. According to GCVS (Kholopov et al. 1985) its period is $368.3^{\rm d}$, the extreme limits of its visual brightness variations are $4.8 - 13.0^{\rm m}$, the spectral type varies between M6e and M9.5e. It has a rather asymmetric light curve with a steep ascending branch, $(M - m)/P = 0.38$. The revised light elements (Kudashkina 1989) are

$$\mathrm{Max} = 2445275.20 + 369.0^{\rm d}E.$$

U Ori is known to be a source of maser radio emission of OH (Wilson & Barrett 1970), H_2O (Wilson et al. 1972) and SiO (Kaifu et al. 1975). The star also displays thermal lines of CO (Knapp et al. 1998); the mass loss rate, determined from the thermal CO line, is $2.9\ 10^{-7} M_\odot\ {\rm yr}^{-1}$, the star's radial velocity $V_{\rm LSR} = -38.1 \pm 1.3$ km s^{-1}. A recent distance estimate for U Ori, using the $P - M_{\rm K}$ dependence and the *Hipparcos* data, is ~ 300 pc (Knapp et al. 1998).

The molecular maser emission of U Ori is highly variable, with peculiar changes, sometimes vanishing in some lines. In particular, in mid-1970s U Ori changed its type of the OH emission from IIb to I (Cimerman 1979; Jewell et al. 1979, 1981). In 1980 U Ori experienced a strong flare in the H_2O line $\lambda = 1.35$ cm (Lekht et al. 1981), the flare lasted almost 1 year. All this indicates that the star may had been in a peculiar state, which is reflected in nonstationary processes in its circumstellar envelope, resulting in strong variations of the maser emission.

U Ori has been repeatedly studied by interferometry in the maser lines of OH (Reid et al. 1979; Fix et al. 1980; Bowers et al. 1981; Chapman & Cohen 1985; Bowers & Johnston 1988; Chapman et al. 1991) and H_2O (Lada et al. 1981; Bowers & Johnston 1994).

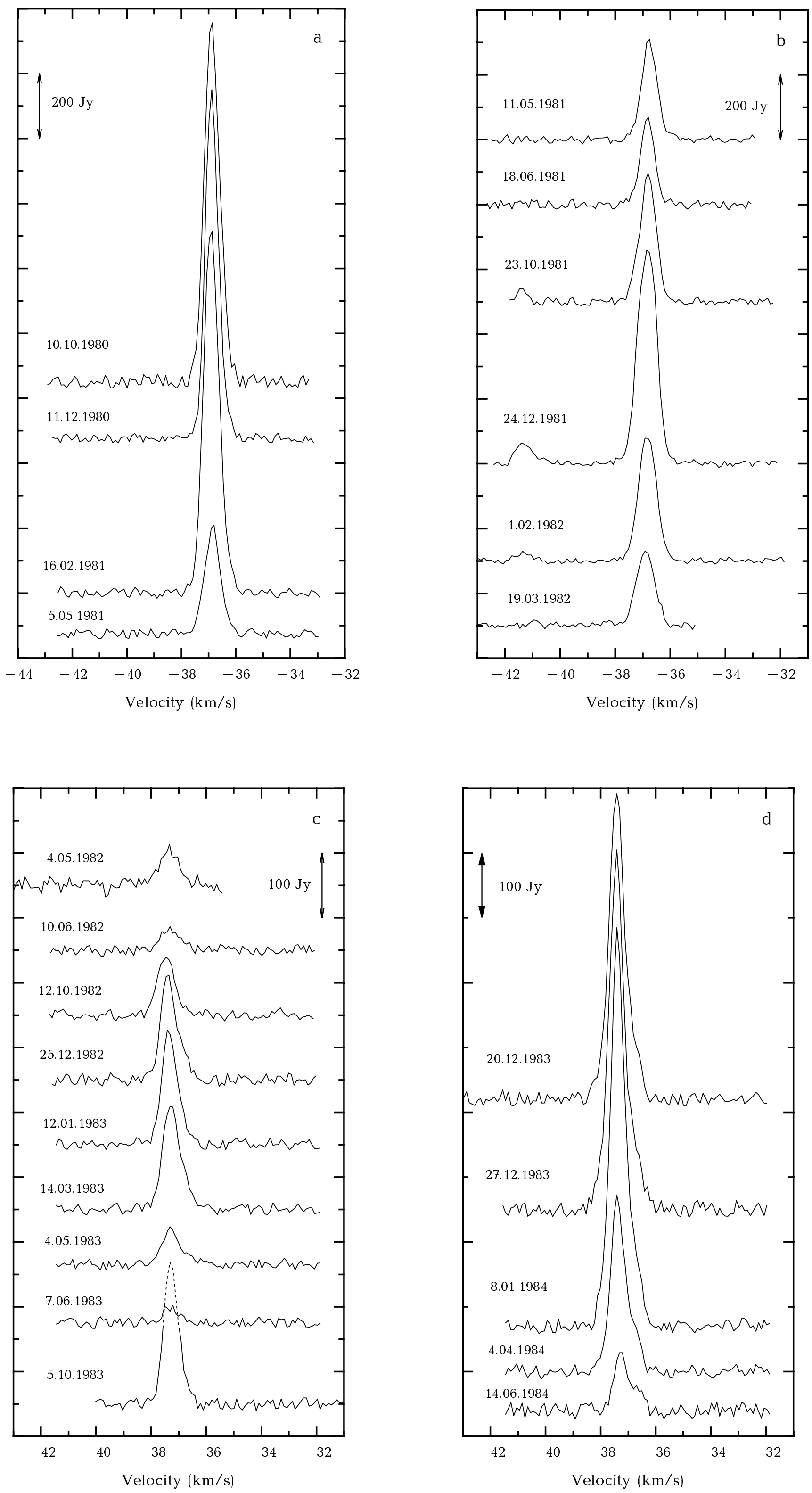
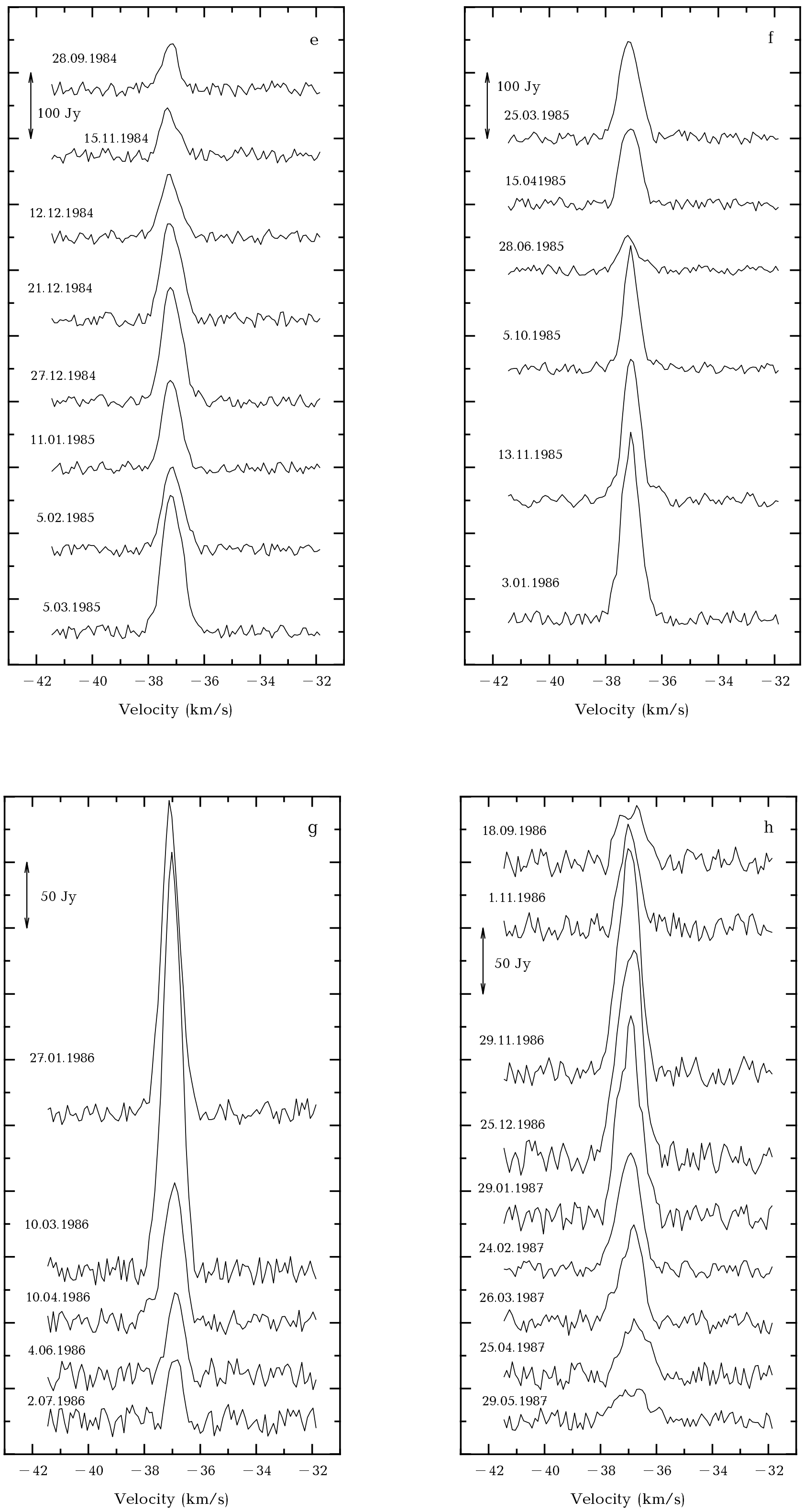


Fig. 1. The profiles of the H_2O line emission of the star U Ori. Vertical scale (flux density in Janskys) is common to all the graphs on the same panel. Horizontal axis is the radial velocity with respect to the Local Standard of Rest



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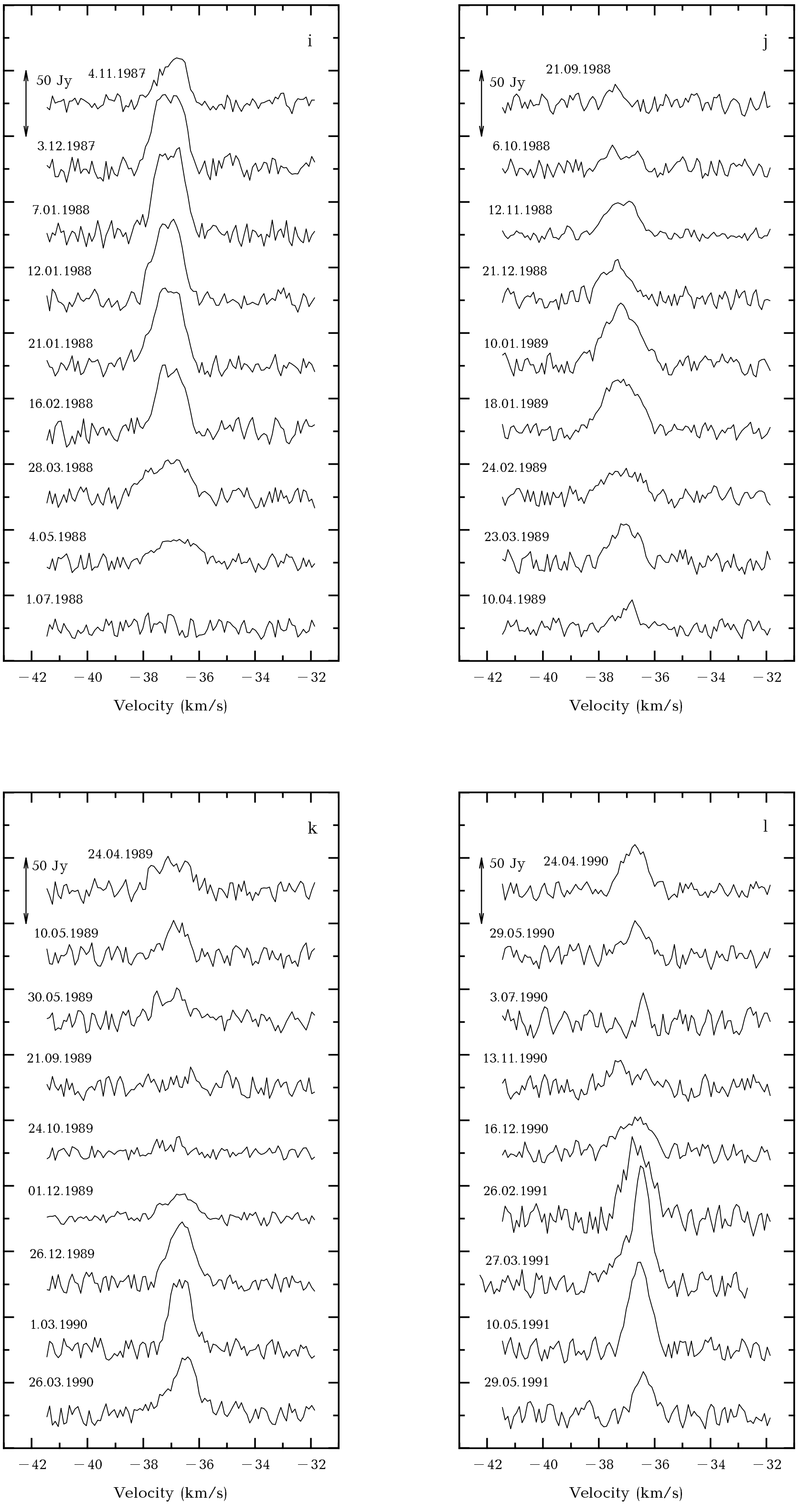

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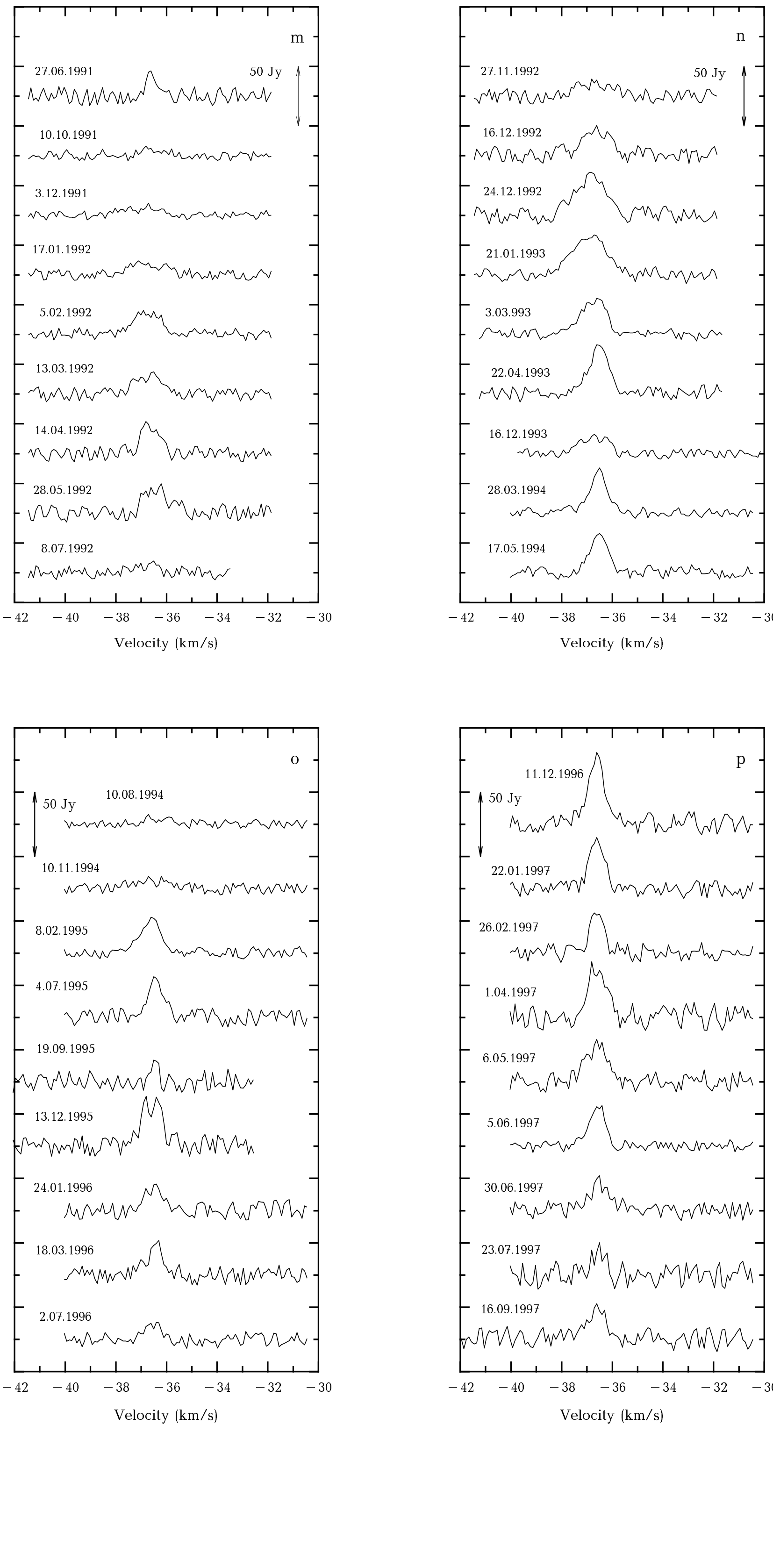

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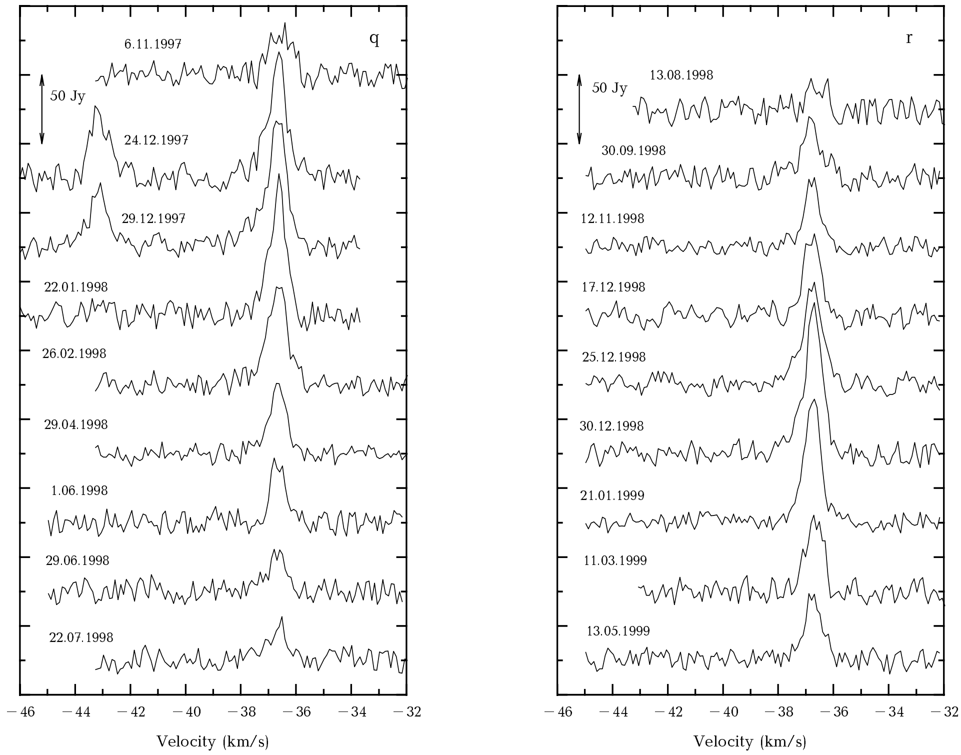

Fig. 1. continued

U Ori is one of the Mira Ceti-type stars that are included into our program of long-term monitoring of H_2O maser sources (Berulis et al. 1984; Esipov et al. 1999). We have been observing U Ori in the 1.35-cm H_2O line since 1980. Some intermediate results on this star were published in Lekht et al. (1981), Berulis et al. (1983, 1984, 1987, 1990, 1994), where we discussed earlier studies of other authors on the H_2O maser variability of U Ori. In this paper we present the complete sample of all the H_2O spectra we obtained in 1980–1999, together with an analysis of the H_2O maser variability, comparison with the light curve of U Ori and with variations in other maser lines.

2. Observations and data presentation

Our H_2O observations were carried out on the RT-22 radio telescope of the Pushchino Radio Astronomy Observatory (Russia). The details of the observational techniques and equipment were given by Lekht et al. (1995). The problem of radiowave absorption in the terrestrial atmosphere at the frequency of the H_2O line was discussed by Lekht et al. (1999) and Rudnitskij et al. (1999).

Figures 1a–r present the profiles of the H_2O line of U Ori. To get a more vivid idea of the overall maser activity, the same profiles are presented in the three-dimensional form in Fig. 2. To construct them, we used the method described in our previous work on the H_2O maser star RT Vir (Lekht et al. 1999). The sensitivity at the 3σ level is on the average 10 Jy. The radial-velocity resolution of the spectra is 0.101 km s^{-1}. We used a 96-channel filter bank spectrum analyser which allowed us to measure simultaneously a $V_{\rm LSR}$ interval of 9.7 km s^{-1}. Since July 1997 the number of channels was increased to 128, yielding a one-time velocity coverage of 12.9 km s^{-1}. Most H_2O spectra of U Ori were taken in the range from -32 km s^{-1} to -42 or to -46 km s^{-1}. Unfortunately, for technical reasons and tight observational programme, it was not always possible to observe the more blueshifted part of the spectrum at -42 to -46 km s^{-1}; therefore, our data on the very interesting, transient maser features in this interval are not complete, see next section.

Our observations cover a time interval from March 6, 1980, to September 29, 1999 (JD 2444305–2451451). The profiles of March and June, 1980, as well as those of June, August and September, 1999, when the peak flux density of U Ori in the H_2O line was below 10 Jy, are not shown.

Figure 3 shows the variation of the integrated flux for the entire timespan of our observations. Vertical bars in the upper part of Fig. 3 denote the epochs of visual maxima of U Ori. These epochs are based on the visual light curves from the associations of variable star observers, French (AFOEV) and American (AAVSO). The maxima of the H_2O maser emission are obviously correlated with the visual light maxima and follow them with some phase delay $\Delta\varphi$. In Fig. 4 the values of $\Delta\varphi$ (expressed in fractions of the stellar light period P) are plotted versus time.

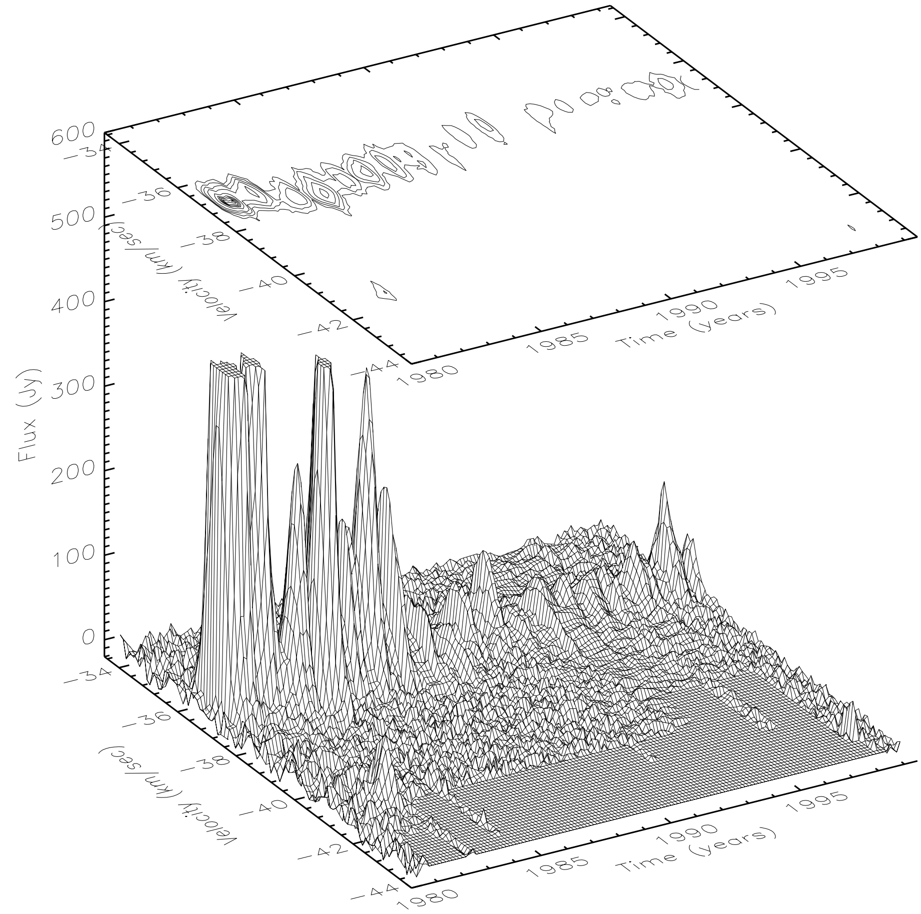

Fig. 2. Same as in Fig. 1, but in the three-dimensional presentation

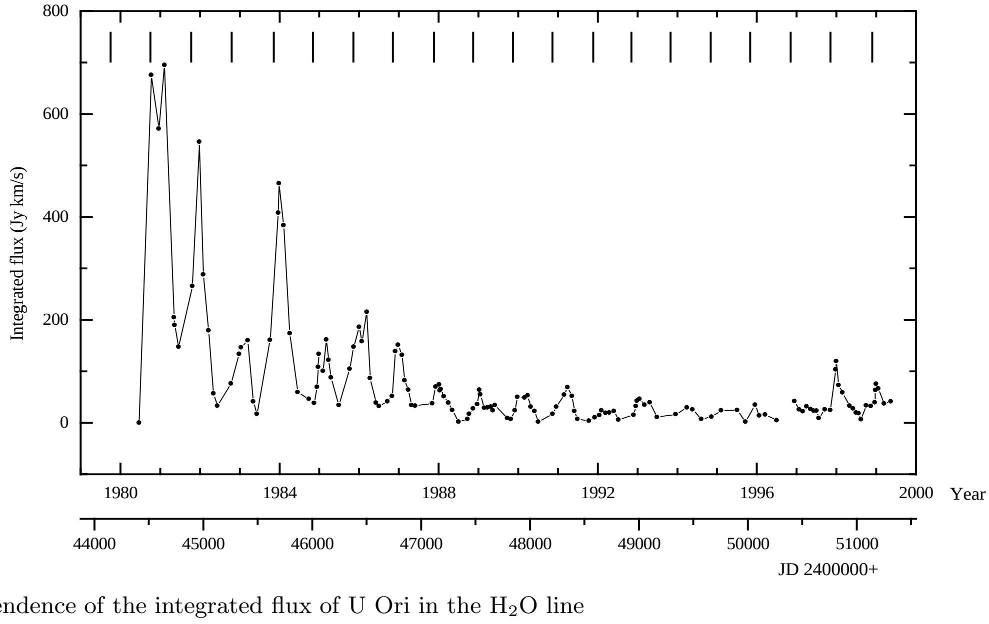

Fig. 3. Time dependence of the integrated flux of U Ori in the H_2O line

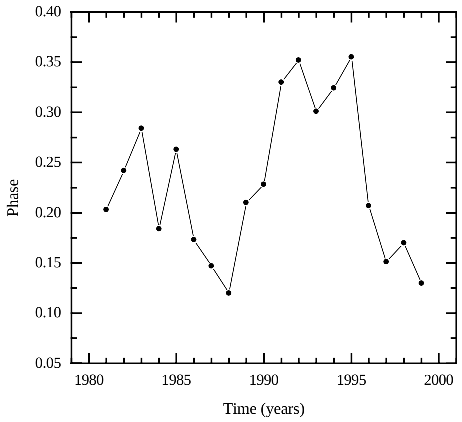

Fig. 4. Phase delay (in units of the stellar variability period) between the visual maximum and the H_2O maser maximum immediately following it

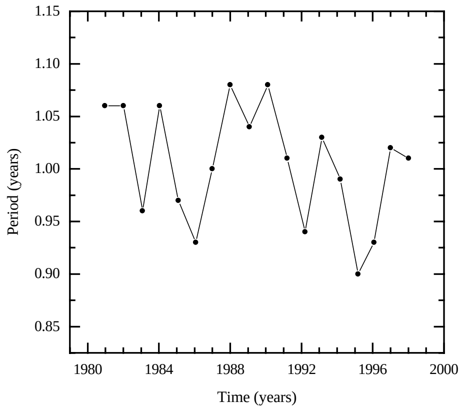

Fig. 5. Time dependence of the "radio period" (time interval between two consecutive maxima of the H_2O maser emission)

The most conspicuous event, as it is visible from Figs. 2 and 3, was the flare of 1980–1981, when the integrated flux density reached $\sim$ 900 Jy km s^{-1}. Then there were two weaker bursts, and again a stronger burst of up to 450 Jy km s^{-1} at the end of 1983. By the beginning of 1988 the maser activity calmed down, with bursts' amplitudes of $30-100$ Jy km s^{-1}, and remains such until now (late 1999).

The periods of both visual-light and H_2O-maser variations are subject to fluctuations. Figure 5 presents the lengths of consecutive "radio periods" of U Ori, i.e., time intervals between pairs of consecutive radio maxima in the H_2O "radio light curve".

We have also found systematic radial-velocity variations of the H_2O maser emission in U Ori. Figure 6 shows the weighted mean radial velocity for the main group of the H_2O maser features. A long-term drift of the H_2O velocity centroid is obvious. In our early observations (1980–1981) the radial velocity was between -36.8 and -36.9 km s^{-1}. By the end of 1981, there was an abrupt change to ~ -37.4 km s^{-1}. Then, until 1995 the mean velocity had been drifting to more positive values.

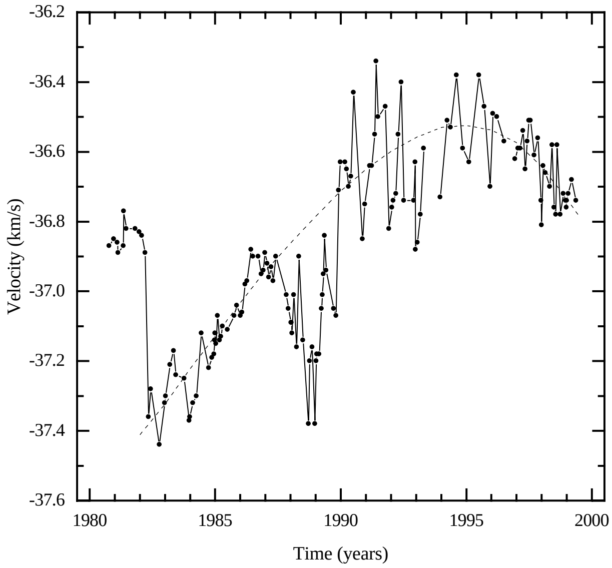

Fig. 6. Weighted mean radial velocity for the main group of the H_2O maser features in U Ori

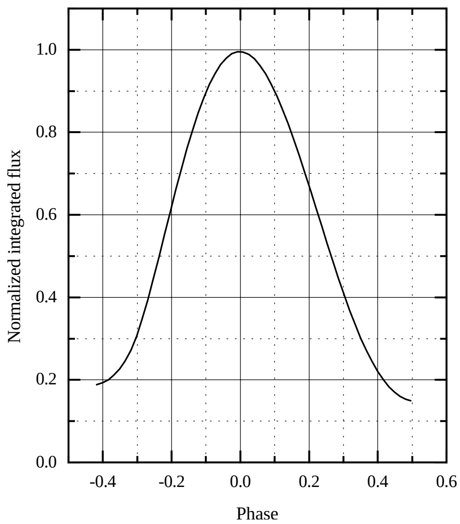

Fig. 7. Averaged and normalised "light curve" of the H_2O maser U Ori

The extreme value was -36.5 km s^{-1}, and then a turnover toward negative velocities followed. The curve in Fig. 6 may resemble a section of a sine wave.

Finally, in Fig. 7 the averaged and normalised "radio light curve" of the H_2O maser U Ori is presented. This curve looks quite smooth, in contrast to the analogous H_2O curve for the semiregular variable W Hya (Rudnitskij et al. 1999). For W Hya the curve is sharp-peaked, with a steep ascending branch and a slower, nearly exponential decline.

3. Discussion

The variability of the H_2O maser emission is most probably due to impact of shock waves on the maser generation region, located at distances of about 10^{14} cm from the star's centre (Rudnitskij & Chuprikov 1990). The circumstellar masers in the SiO and OH lines are also affected by the shock. The SiO masers, closest to the stellar surface, display an outburst first, then there is a rise in the H_2O and main OH lines, and after that the OH 1612-MHz satellite line may rise. This sequence was traced by us for the star R Leo: after its strong flare in the Hα line in May, 1996 (Esipov et al. 1999) there was a rise in SiO (Cho et al. 1998; Herpin et al. 1998) and H_2O (Esipov et al. 1999). A similar sequence of the SiO and H_2O line events in early 1980s in R Leo was followed by an OH flare in 1985 (Etoka & Le Squeren 1997), when the shock reached the OH maser generation region.

U Ori showed dramatic variations in the OH lines in 1974, when the type of its OH emission changed (Cimerman 1979; Jewell et al. 1979, 1981). The events consisted of the sudden appearance of strong 1612-MHz radiation, coinciding with the disappearance of the 1667-MHz radiation. Then the 1612-MHz radiation declined and the 1667-MHz line reappeared. Unfortunately there are no data on systematic SiO or H_2O line monitoring at nearby previous epochs. However, it is known that at least in September, 1976 the H_2O emission in U Ori was quite weak, below ~ 12 Jy (Spencer et al. 1979).

The next activity cycle of U Ori started in late 1970s. The exact date of its onset is not known, since there are no Hα or SiO data available. As mentioned above, the H_2O maser flared between June and October, 1980. Wallerstein (1985) notes that the H_2O flare we observed in 1980 may be related to the emission-line activity, observed by him in the preceding star's cycles, and hence to shocks emerging from the star. Another, weaker flare of up to ~ 450 Jy km s^{-1} at the end of 1983 is probably connected with the SiO flare of the end of 1982, observed by Nyman & Olofsson (1986).

In the intervals between the sequences of the superactivity events (Hα − SiO − H_2O − OH(main) − OH(1612)) the H_2O maser U Ori is weak. In addition to the absence of the shock-wave pumping, the cause for this may be the lack of an appropriate H_2O maser medium.

Rudnitskij & Chuprikov (1990) proposed a model, in which the H_2O maser emission is generated within a "quasi-stationary layer" (QSL) of gas (the term is due to Hinkle et al. 1982), which is located at $r \sim 10^{14}$ cm from the star's centre and has an approximately zero velocity with respect to the star. The gas temperature T_g in QSL is on the average about 800 K, the density n_H may be 10^{11} cm^{-3}. QSL represents a temporary stop of the mass lost by the star, the matter is infalling toward the stellar surface from the QSL inner boundary and outflowing from the outer one. The physical conditions at the QSL radius are favourable for dust formation and H_2O maser effect in the above scheme.

In the model of Rudnitskij & Chuprikov (1990) the H_2O maser is pumped by a moderate-strength shock ($v_s \sim 6 - 10$ km s^{-1}) reaching QSL and creating nonequilibrium conditions in the postshock matter, where the gas is heated promptly and the dust remains cooler for some time. Thus, a collisional-radiative pumping on rotational H_2O transitions (*CRr* in the classification of Strel'nitskij 1984) can operate. The effectiveness of the mechanism is proportional to the difference of T_g and T_{dust}. In the absence of a shock the dust temperature is controlled mainly by stellar radiation. After the shock passage the temperature rises, and as $T_{dust} \rightarrow T_g$, the efficiency of the H_2O pumping decreases.

The above model of a thin H_2O masering shell, expanding outward behind a shock front, is supported by the H_2O interferometry data of Lada et al. (1981) and Bowers & Johnston (1994). Their maps of U Ori indicate that the maser emission at the most negative ("bluemost") velocities is approximately centred on the stellar position, thus being located at the near side of the circumstellar envelope, approaching the observer, whereas the emission at velocities close to V_* is distributed (though nonuniformly, in several clumps) over a wider region, probably outlining the entire H_2O shell. The emission redshifted with respect to V_* is spread in a smaller region, also within the expectations of the same model. Furthermore, the entire velocity set of the H_2O shell is visible in the high-sensitivity H_2O line profiles of Bowers (1992) as a tail of faint emission ($F_\nu \sim 100$ mJy), extending from V_* to as far as $V_{blue} \sim -49.5$ km s^{-1}, marking the bluemost boundary of the profile and yielding an estimate of the shock velocity $v_s \sim V_{blue} - V_* \sim 11.4$ km s^{-1}, in agreement with the value accepted in our model (10 km s^{-1}). Stronger shocks may mark some light cycles of the star when occasional higher-intensity emission, accessible to our observations (less sensitive than those of Bowers 1992) appeared at blueshifted velocities. This emission is seen in Fig. 2 as "ripple" at velocities of -41 to -43 km s^{-1}, especially in 1981 (soon after the giant flare) and in 1997. Unfortunately, our velocity coverage of this portion of the spectrum is not complete enough.

An independent confirmation of a thin-shell model for H_2O masers in long-period variables may come also from Colomer et al. (2000) who mapped several Miras and SRs in the 1.35-cm H_2O line on VLA (among them, U Ori was observed, too, but unfortunately not resolved). A 3D model fit by Colomer et al. showed that at least for some stars they observed (U Her, R LMi, R Cas and others) the H_2O maser structure can be best represented as a thin expanding shell, in agreement with our above reasonings.

Note, however, that the actual shape of the circumstellar envelope of U Ori may be not so simple as the spherically-symmetrical structure we have assumed. The results of the OH interferometry, referring to the regions of the envelope slightly outward from the H_2O shell (Reid et al. 1979; Fix et al. 1980; Chapman & Cohen 1985; Bowers & Johnston 1988; Chapman et al. 1991), indicate that mass loss (and hence the distribution of circumstellar matter in U Ori) may have a form of a bipolar outflow, though with some element of spherical symmetry. The same is testified to by detailed modelling of the OH masers around U Ori (Bowers 1991). This asymmetry should be taken into account in further modelling.

QSL hosting the H_2O maser may temporarily vanish and then reappear as a result of an episode of enhanced mass loss by the star (Hinkle et al. 1984). This explains the observed lack of the H_2O maser emission in U Ori and some other Miras during several cycles of light variations (Esipov et al. 1999 and references therein). The flare of the H_2O maser U Ori in 1980–1982 may be associated with rebuilding of QSL after the period of maser absence and weakness in 1976–1980. Infrared data (Danchi et al. 1994) and an analysis of OH data (Etoka & Le Squeren 1997) show that the circumstellar envelope of U Ori is indeed a peculiar one, with little dust located close to the star, and with mass loss in isolated episodes, separated by a decade or so. Hence we can associate this information with temporary disappearance of QSL and of the H_2O maser.

In our model, the phase delay $\Delta\varphi$ between visual and subsequent H_2O maximum is different for different light cycles of U Ori (Fig. 4). Accordingly, the interval between consecutive H_2O maxima varies (Fig. 5). As said above, the dust is not abundant in the shell of U Ori. Since the *CRr* pumping we assume in our model is quite sensitive to the amount of dust available, then small variations of the dust content and displacements of the inner boundary of dust formation in separate light cycles affect both the maser intensity and phase delay $\Delta\varphi$.

Of interest is also the long-term drift of the H_2O maser velocity centroid (Fig. 7). Note that the dominant maser emission is mainly *redshifted* with respect to the stated above stellar centre-of-mass velocity -38.1 km s^{-1}, though, with an account of the probable error of this figure (±1.3 km s^{-1}) it may fall within the velocity range shown in Fig. 6. The general trend is a sinewavelike variation with some jumps "blueward", superimposed onto it, for instance, in 1989–1990, with more blueshifted ripple, see also Fig. 2. However, the flare of 1980–1981 took place at a *redshifted* velocity (-36.8 km s^{-1}). This may be due to longer amplification paths, extending from the far, receding side of the expanding shell just after rebuilding of QSL, whereas the sinewave probably reflects the long-term dynamics of QSL: QSL, while present, is as if "breathing", sometimes infalling, sometimes expanding outward. A detailed discussion of this phenomenon will be given elsewhere.

The correlation of the H_2O maxima following visual maxima with some delay $\Delta\varphi$ is explained as follows. The shock propagating within QSL at $v_s \sim 6 - 10$ km s^{-1} pumps the H_2O molecules, serving as the source of energy. At the same time the dust, which is a sink of energy, is heated mainly by stellar radiation. The latter, peaking in the infrared, varies lagging behind the visual light by $\Delta\varphi$ of up to $0.4P$ (Lockwood & Wing 1971). As the infrared radiation is increasing, the pumping effectiveness is falling, the maser emission is going down, too. Thus, the peak of the maser radiation takes place at $\Delta\varphi \sim 0.2$ after the visual maximum.

The variability curve of the H_2O maser emission is a result of interplay between the direct shock-wave pumping and heating of dust by stellar radiation; the latter thus indirectly damps the maser by reducing the efficiency of the sink. The shock may be constantly present within the molecular zone coinciding with QSL, while the sink has variable efficiency depending on the infrared stellar irradiation of dust. This scheme (Berulis et al. 1998) is a modification of the model of Rudnitskij & Chuprikov (1990), which included only direct effects of a shock on QSL. It was applied to the H_2O maser RR Aql (Berulis et al. 1998) in an attempt to reconcile obvious correlation of the H_2O maser emission, mimicking with a delay of $0.2 - 0.3P$ the visual brightness, with a long travel time of the shock: for a shock front with $v_s \sim 10$ km s^{-1} it may take about two years to reach QSL and to produce the required pumping; the shock then arrives to QSL at an arbitrary stellar phase. The visual-H_2O correlation may still persist, though $\Delta\varphi$ may be quite arbitrary. For instance, in the case of the H_2O maser associated with the semiregular M-type supergiant VX Sgr $\Delta\varphi$ in the course of our observations (1981–1998) was progressively increasing from zero to $\sim 1P$ ($P = 732^{\rm d}$) (Esipov et al. 1999). However, in distinction from the giant U Ori, the circumstellar envelope of VX Sgr is much larger, with the H_2O maser region located at $\sim 10^{15}$ cm from the stellar centre. Similar estimates for VX Sgr show that for this star $\Delta\varphi$ may in reality be as long as $10 - 15P$. In this case, only constructing a correlation function of the H_2O maser variations and visual light curve at a time interval of a few decades may help to test the model with more confidence.

4. Conclusions

We have been monitoring the maser emission of the Mira Ceti-type variable star U Ori in the 1.35-cm H_2O line during 19 years (1980–1999). The star was quite active in the H_2O line in 1980–1988, with a giant flare that took place between June and October, 1980. Then the curve of the integrated H_2O flux variability of U Ori went on in the mode of damped oscillations and finally stabilised in the form of repeated outbursts to a level of $50 - 100$ Jy km s^{-1}, following the visual light maxima of the star with some phase delay $\Delta\varphi$. The phase delay did not remain constant, varying from one variability cycle to another. These results confirm the main conclusion we drew earlier (Berulis et al. 1994) about quasi-periodic variations of $\Delta\varphi$ with a certain "superperiod" of the star's activity, about 9 years long.

Once per each "superperiod" the star sends a powerful shock, which consecutively excites emissions in the Hα, SiO, H_2O, and OH lines. Such a sequence of events was traced by us in the Mira R Leo (Esipov et al. 1999).

The star's "superperiod" may reflect, on the one hand, the multiperiodicity of the pulsations themselves, namely a presence of a long period, found in the long time series of visual observations in some Miras (Percy & Bagby 1999), or, on the other hand, some kind of a long-term activity cycle, similar to the solar 11/22-year cycle; the latter possibility may be due to general stellar mass-loss variations, connected with restructuring of the stellar magnetic field, which is found to be quite strong in U Ori, up to 10 G near its surface (Reid et al. 1979; Fix 1979; Fix et al. 1980; Claussen & Fix 1982).

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