Origin and Propagation of Shocks in the Atmospheres of Mira-Type Stars

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Results of long-term studies of Mira-type variables are analysed. Data on the maser emission of H_2O molecules (λ =1.35 cm) and on the Balmer-line emission are considered. Shocks are assumed to be a common cause for the H α and H_2O maser variations. Two groups of the stars are revealed.

In some Miras the Hα emission was detected rather frequently, while the H_2O maser was permanently present, with some variations, which correlated with the visual light curve. In these Miras, the shock waves may be driven by stable, large -amplitude pulsations. These pulsations also enhance stellar mass -loss rate and build a thick circumstellar envelope; in its inner layers, physical conditions are favourable for the H_2O maser generation.

A group of the stars (`transient emitters') displays brief episodes (lasting not more than a couple of months) of H α emission. Such episodes appear only in one of a few visual light cycles; in other cycles the Balmer emissions are undetectable. These stars may be intrinsically weaker pulsators, with lower mass -loss rates, accordingly thinner circumstellar envelopes and fainter, unstable masers. Once per several periods (`superperiod'), a stronger shock departs from the stellar surface. The visual light curves suggest that this is probably connected with brighter maxima of the stars. Another possibility for the `transients' is connected with relic planetary systems around red giants. Moving at a supersonic velocity within the atmosphere, a planet produces a conic shock wave, visible a hot spot. This spot is a source of Balmer emission lines, it may also account for changing asymmetries in the infrared brightness distributions, observed interferometrically in some Miras. If the companion orbit has a sufficient eccentricity and a period of several years, then the episode of strong H α (and following H_2O maser) flare may be due to the periastron passage of the companion.

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1 Observations

Since 1980, our team has been monitoring a sample of about 20 Miras in the H_2O maser line at $\lambda = 1.35$ cm (Berulis et al. 1983). Beginning from 1994 we have also been doing optical spectroscopy of these stars (Esipov et al. 1999 and references therein). In this poster I give special emphasis for the Balmer-line emission and H_2O circumstellar masers, for which we have traced a long-term variability.

Two Groups of Masers

- *'Stable' masers,* which have been displaying H_2O maser emission (however, with varying intensity) throughout our observational interval, never falling below our detection threshold (~ 10 Jy). Examples: R Aql, U Her, RS Vir. For these stars the H_2O maser variations correlate with the visual light curves, following them with a certain delay $\Delta\varphi$ of about 0.3–0.4P (P is the brightness variation period). For U Ori this delay, analysed on a time interval of $\sim 12P$, probably varies itself with a 'supeperiod' of $\sim 9P$ (Rudnitskij et al. 2000). A cross-correlation analysis between the visual light curve and H_2O maser variations for the Mira RS Vir (Lekht et al. 2001) shows that actually the correlation is maximum for a delay between the visual and H_2O light curves of 4–5P. These stars also frequently show Balmer emission lines in their spectra, nearly in every light cycle.
- *'Transient' masers*, which sometimes disappeared from our view, falling below 10 Jy for certain intervals. Some of them (R Leo, R Cas, U Aur) remained 'H_2O-silent' for more than 15 years, but then episodically reappeared. The Hα emission was seldom observed in these stars, usually in the form of short epsiodes, lasting a couple of weeks, near selected light minima (Esipov et al. 1999).

The H_2O masers from both groups flare from time to time. In particular, U Ori, which to some extent may be classified as a 'transient', because in early 1980 (and prior to this, during several years, as can be found in the literature) it was 'H_2O-silent'), but between June and October 1980 bursted to more than 1000 Jy (Rudnitskij et al. 2000). A similar event happened in the H_2O maser associated with the miralike semiregular variable W Hya in 1981 (Berulis et al. 1983) and in 2001.

2 Shocks as a Common Cause of Variations of the Optical Emission Lines and H_2O Masers

The correlation between the visual light curve and the H_2O maser variations can be explained by the model of shock impact on the masering region (Rudnitskij & Chuprikov 1990, Fig. 1).

Shock waves, departing from the stellar surface under the action of pulsations, reach some time after the layers of the circumstellar envelope containing the H_2O molecules. At this, collisional maser pumping is enhanced, and maser line flux increases. The visual–H_2O correlation function for RS Vir suggests that this delay may be as long as a few stellar periods (Lekht et al. 2001), corresponding to a shock velocity of ~ 10 km s^{-1}.

In the star R Leo (Esipov et al. 1999, see Fig. 2) — and, to a smaller scale, in R Cas and U Aur — we have observed short events of an Hα line flare, followed a year and a half later by a flare in the H_2O radio line. We have assumed a shock as a common cause of these two events. If such an event is rare and takes place once per 10–15 stellar light cycles, there can be various explanations.

The main problem may be that shocks in Miras are not so strong as it has been believed. Basing on the Hα emission line profiles in o Cet, Gillet et al. (1983) inferred shock velocities v_s of up to 90 km s^{-1}. However, other data of optical spectroscopy (Fox, Wood, & Dopita 1984) and weakness or lack of microwave continuum, which should accompany the Hα emission (Reid & Menten 1997, Chapman & Rudnitskij 2002) suggest v_s values not higher than $\sim$20-25 km s^{-1}. This is difficult to reconcile with the intense Balmer emission.

- *Merging shocks.* Wood (1979) made calculations of consecutive shocks leaving the mira's surface and showed that shocks that leave the stellar surface later propagate in the gas 'prepared' by previous shocks. The 'later' shocks can overtake the 'earlier' ones, merge with them and produce a stringer effect, both on Balmer emission and H_2O maser.

- *Quasi-Stationary Layer.* Rudnitskij & Chuprikov (1990) have explained the 'superperiod' by building and disruption of a quasi-stationary circumstellar layer hosting the masering H_2O molecules. This layer may appear in a stronger mass-loss episode once per several stellar cycles. Another cause may be that pulsation-driven shocks, consecutively departing from the stellar surface, can overtake their predecessors and merge with them, thus producing, again once per several cycles, a stronger-than-average shock (Wood 1979), also resulting in a maser flare.

3 A Low-Mass Companion as a Source of Shocks

As a basis of a discussion, I propose another explanation for the lack of radio continuum and for the rare Hα–H_2O episodes in the 'transient' H_2O source, namely, impact of a shock provoked by a low-mass companion (a planet?) to the Mira star.

If a star possessed a planetary system during its main-sequence life, at the red-giant stage the closer-by planets, revolving at $R \sim 1-3$ A.U., will be embedded within the star's atmosphere. The more massive ones of them will probably survive the red-giant phase (Struck-Marcell 1988, Rybicki & Denis 2001).

Evolution of a red giant having a compact stellar companion (a brown/black dwarf with a mass of $\geq 0.02M_\odot$ or possibly a neutron star) was analysed in a series of papers on the 'double-core evolution' (Soker 1999 and references therein). The fate of a lower-mass companion [$(0.001$–$0.01)M_\odot$ – a planet], embedded in the atmosphere of a star that has become a red giant, was also considered in a number of works. In particular, Soker (1999) proposed to search for Uranus–Neptune-like planets in planetary nebulae, formed in course of the post-AGB evolution.

Until recently considerations about exosolar planetary systems might be purely speculative. However, systematic observations of the last decade have led to discoveries of several tens of planets orbiting solar-type stars in the solar vicinity. Most of them have been detected by the Doppler technique, involving precise measurements of stellar radial velocities on a time interval of several years, aiming to find small velocity shifts, caused by the orbital motion of a low-mass companion. Depending on the planet's mass and semimajor axis, amplitudes of such velocity variations are from several meters per second to several scores of m s^{-1}. A complete list of these detections is maintained by Schneider (2002) at the Paris–Meudon Observatory.

The Doppler technique, used on a limited time interval, selects in the first turn more massive planets in orbits closer to the central stars. The planets detected so far can be divided into two groups:

- 'hot Jupiters', planets of one to a few Jupiter masses, revolving in circular very closely to their stars, at 0.05–0.5 A.U.;
- planets in eccentric orbits (with e up to 0.6) with revolution periods up to a few hundred days.

Certainly, further observations will find lower-mass and longer-period planets, perhaps planetary systems similar to the Solar System.

A planet orbiting around a $1M_\odot$ star at a distance of 1 A.U. would move at velocity $V_p \sim 30$ km s^{-1}. If the star is a red giant, then the planet is embedded in the star's atmosphere, having a temperature $T \sim 2000$ K and particle number density of $\sim 10^{12} - 10^{13}$ cm^{-3}. The velocity of sound a_s there would be about 3.4 km s^{-1}. Thus, the planet's motion is supersonic, the Mach number $\mathsf{M} = V_p/a_s$ being about 9. This motion is similar to a motion of a large meteoritic body in the Earth's atmosphere (Tsikulin 1969). A strong conical shock wave, ionising gas and heating it to 10,000–15,000 K, is formed.

We consider a simple model, in which a perturbing body with diameter d is moving along a rectilinear trajectory at velocity $V_p > a_s$ through a medium with mass density ρ_0. Quantity E is the energy released at a unit path of the body's motion; E is numerically equal to the drag force exerted on the body by the medium:

$$F = \frac{\pi d^2}{4} \rho_0 V_p^2. \tag{1}$$

Owing to the drag, the planet is gradually spiraling into the red giant's atmosphere. The rate of decrease of its semimajor axis a is (see, e.g., Taam, Bodenheimer & Ostriker 1978):

$$\frac{\dot{a}}{a} = -\frac{F V_p a}{G M_* M_p}. \tag{2}$$

Using (1) and substituting $a = 1$ A.U., $M_* = 1 M_\odot$, $V_p = 30$ km s^{-1} and Jupiter's parameters $M_p = 1 M_\mathrm{J} = 1.9 \times 10^{30}$ g, $d = d_\mathrm{J} = 1.4 \times 10^{10}$ cm, we have $\dot{a}/a \sim -8 \times 10^{-8}$ year^{-1}. Thus, during the red giant stage, which lasts not longer than 10^6 years, the semimajor axis of the planet's orbit decreases by $\leq$8%. For a larger planet ($13 M_\mathrm{J}$, $2.35 d_\mathrm{J}$), braking is still smaller, $\leq$3.2%.

The motion of the planet through the stellar atmosphere is similar to the case of propagation of a shock wave from a detonating cylindrical charge (Tsikulin 1969). That is, in any plane perpendicular to the trajectory of the body, the propagating shock can be considered as a cylindrical one (see Fig. 3). The shock front radius in this plane is

$$r_f = \left(\frac{E}{\rho_0}\right)^{1/4} t^{1/2} \tag{3}$$

with $t = z/V_p$. The front equation in the $(r,\, z)$ coordinates (Fig. 3, *left*) is

$$\frac{r_f}{d} = \left(\frac{\pi}{4}\right)^{1/4} \left(\frac{z}{d}\right)^{1/2} \tag{4}$$

Shock velocity D in the direction perpendicular to the trajectory is decreasing with time as

$$D = \frac{1}{2}\left(\frac{E}{\rho_0}\right)^{1/4} t^{-1/2}. \tag{5}$$

For a planet with $d = 2.35 d_{\rm J}$, velocity D will fall to the velocity of sound a_s at a distance $z_{\rm max} = d(\pi/4)^{1/2}(\mathsf{M}^2/4) \sim 5.6 \times 10^{11}$ cm behind the body. There will be no emission at greater z's. The corresponding maximum front radius $r_{f\rm max} = 1.3 \times 10^{11}$ cm. The maximum projected area of the shocked 'cone' (for a side view, as in Fig. 3, *right*) is

$$S_{\rm sh} = \frac{1}{3}\left(4\pi\right)^{1/4} d^{1/2} z_{\rm max}^{3/2} \sim 4.8 \times 10^{22}\ {\rm cm}^2\ \sim 1.6 \times 10^{-5} S_*, \tag{6}$$

where $S_* = \pi R_*^2 \sim 3 \times 10^{27}$ cm^2 is the stellar disc area for $R_* \sim 3 \times 10^{13}$ cm. Observations and model calculations of the Balmer emission lines in Miras (e.g., Fox & Wood 1985) show that, for the above-mentioned parameters, the shock front yields up to 10^{20} Hα photons ${\rm cm}^{-2}\,{\rm s}^{-1}$; with source area $S_{\rm sh}$, this can account for the total Balmer line fluxes observed from a star at a distance of about 300 pc, a few $\times 10^{-12}$ ${\rm erg\,cm^{-2}\,s^{-1}}$ (Fox, Wood & Dopita 1984). The side-view observations of the cone shock also naturally explain doubling and large linewidth (~ 60 km s^{-1}) of the Balmer lines, observed in Miras (e.g., Gillet et al. 1983, Udry et al. 1998). The lack of radio continuum is explained by the small angular size of the planetary source, which is though hot enough to produce the observed Balmer emission.

Another effect of the planetary shock is enhanced H_2O maser pumping by the mechanism proposed by Rudnitskij & Chuprikov (1990); the delay may be similar to the case of a spherical shock.

As mentioned above, some stars (R Leo, R Cas and U Aur) displayed isolated bursts of the Hα emission, followed (about a year and a half later) by a flare of the H_2O maser radio emission. This may be due to a periastron shock-wave episode of a planet in a highly eccentric orbit with a period $P \sim 15$ years. Some other stars (e.g., U Ori, Rudnitskij et al. 2000) have already shown some hints to H_2O maser 'superperiodicity' of ~ 9 years — which could be associated with planetary revolution periods.

One of the main objections to the model proposed is that the drag of the surrounding medium tends to circularise the planet's orbit. However, Soker (2000) has shown that in the case of a mass-losing central star the passage of the periastron by a planet enhances the mass-loss rate, and this effect can support, and even increase the orbit eccentricity.

4 Observational Tests

- Repeated mapping of the H_2O masers throughout the light. This would allow us to trace the propagation of a shock across the maser layer, igniting sequentially maser spots more and more distant from the stellar surface.
- Optical and infrared interferometry of miras, aiming to detect hot spots (eventual planets) migrating across the stellar discs — like the one probably observed in R Cas by Lopez et al. (1997).
- Further radio continuum observations of red giants at shorter wavelengths (short centimetre and millimetre), similar to those performed on ATCA at $\lambda = 6$ and 3 cm by Chapman & Rudnitskij (2002). For a thermal spectrum, $F_\nu \propto \nu^2$, and shorter-wave observations are more promising for detection. In the millimeter continuum flux densities of about a millijansky from red giants are expected, due to photospheric emission. Episodes connected with shocks can also happen, in this case parallel monitoring in optical spectroscopy is useful for shock diagnostics.

References

Berulis, I.I., Lekht, E.E., Pashchenko, M.I., & Rudnitskij, G.M. 1983, SvA, 27, 179

Chapman, J.M., & Rudnitskij, G.M. 2002, PASA, submitted

Esipov, V.F., Pashchenko, M.I., Rudnitskij, G.M., & Fomin, S.V. 1999, Astron. Lett., 25, 672

Fox, M.W., Wood, P.R., & Dopita, M.A. 1984, ApJ, 286, 337

Gillet, D., Maurice, E., & Baade D. 1983, A&A, 128, 384

Lekht, E.E., Mendoza-Torres, J.E., Rudnitskij, G.M., & Tolmachev, A.M. 2001, A&A, 376, 928

Reid, M.J., & Menten, K.M. 1997, ApJ, 476, 327

Rudnitskij, G.M., & Chuprikov, A.A. 1990, SvA, 34, 147

Rudnitskij, G.M., Lekht, E.E., Mendoza-Torres, J.E., Pashchenko, M.I., & Berulis, I.I. 2000, A&AS, 146, 385

Rybicki, K.R., & Denis, C. 2001, Icarus, 151, 130

Schneider, E. 2002, http://www.obspm.fr/planets/

Soker, N. 1999, MNRAS, 306, 806

Soker, N. 2000, A&A, 357, 557

Struck-Marcell, C. 1988, ApJ, 330, 986

Taam, R.E., Bodenheimer, P., & Ostriker, J.P. 1978, ApJ, 222, 269

Tsikulin, M.A. 1969, Shock Waves Induced in the Atmosphere by Motion of Large Meteoritic Bodies (in Russian) (Moscow: Nauka)

Udry, S., Jorissen, A., Mayor, M., & Van Eck, S. 1998, A&AS, 131, 25

Wood, P.R. 1979, ApJ, 227, 220

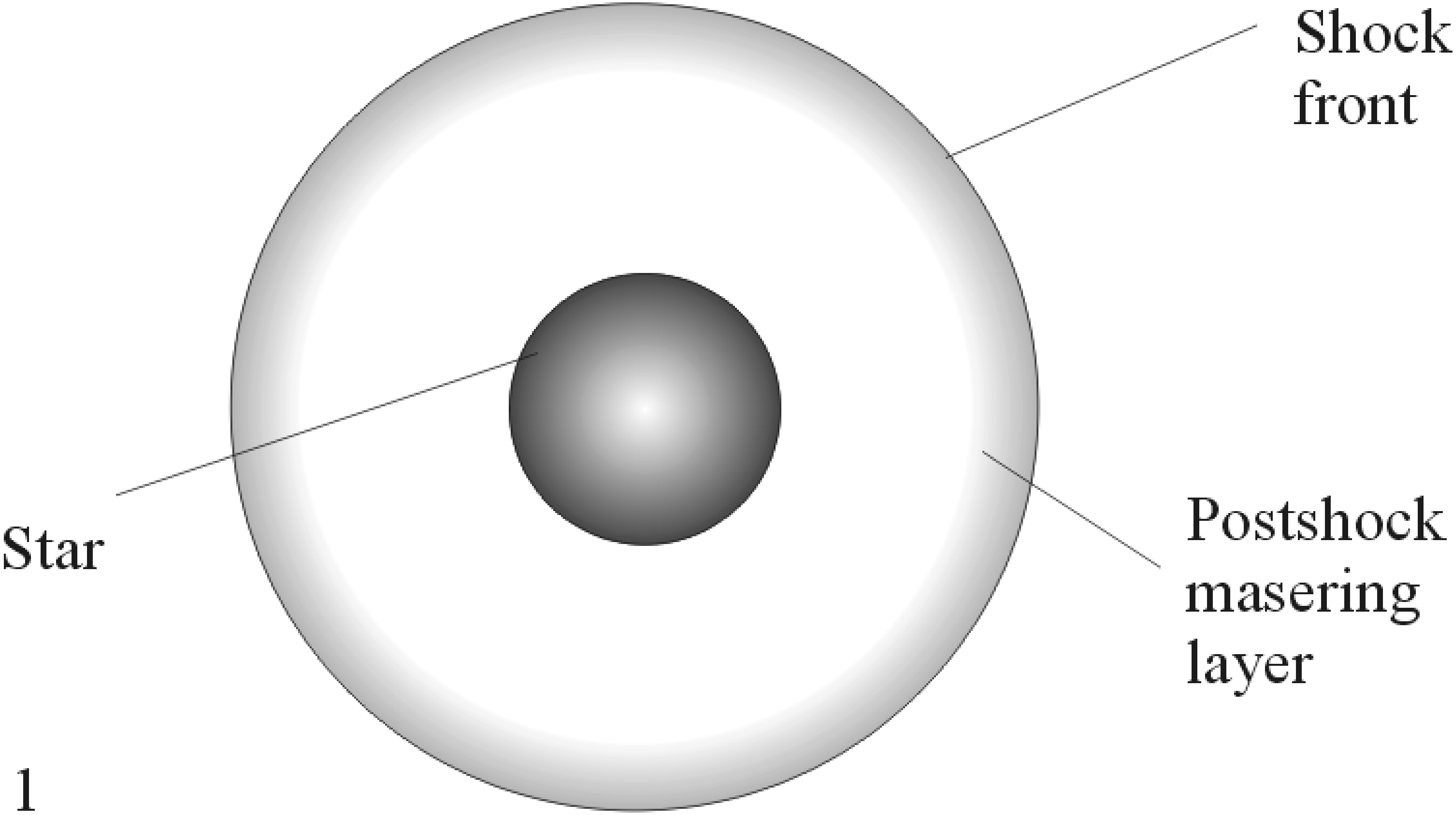

Figure 1

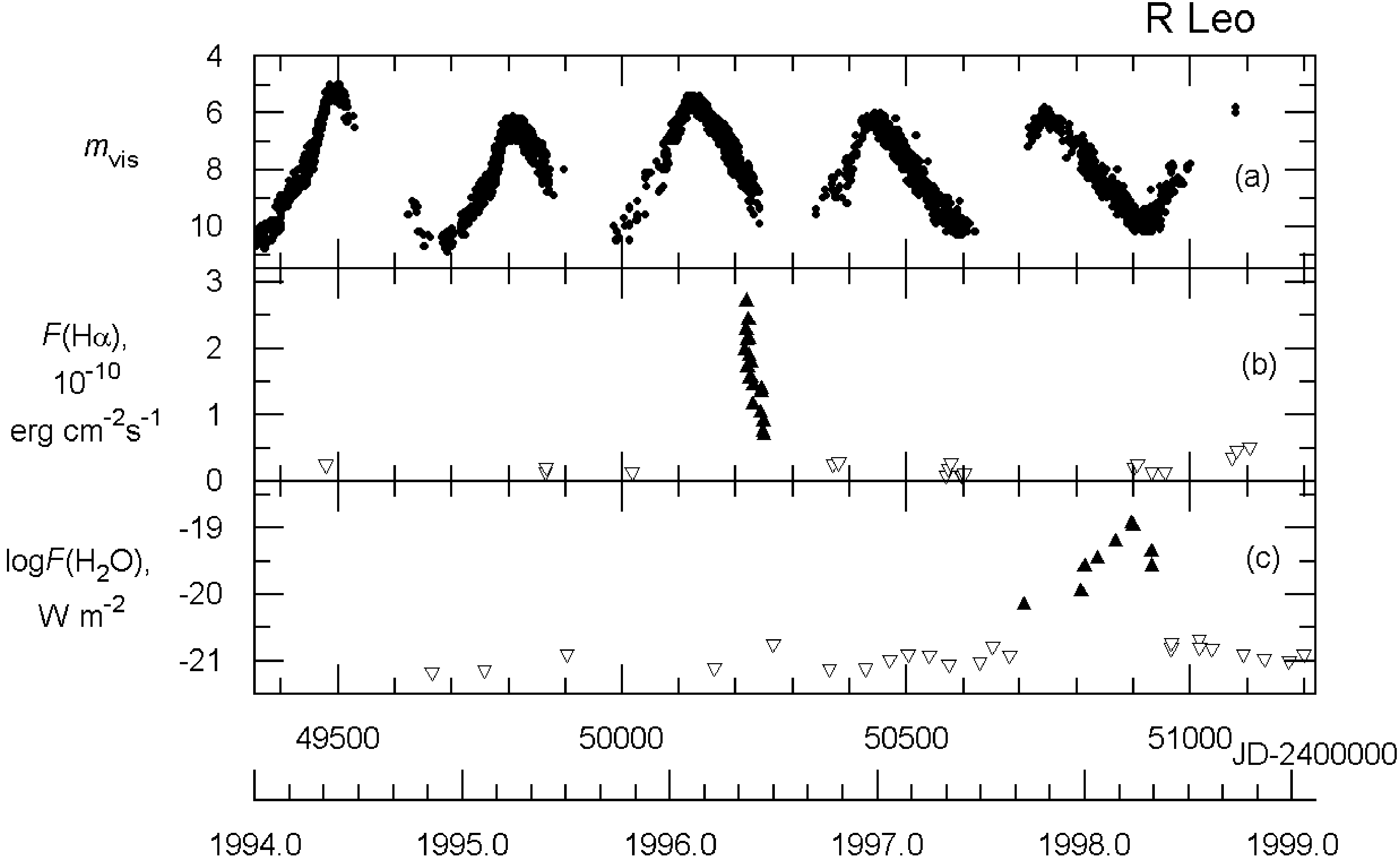
R Leo
m_{vis}
4
6
8
10
(a)
F(Hα),
10^{-10}
erg $cm^{-2}s^{-1}$
3
2
1
0
(b)
log$F(H_2O)$,
W m^{-2}
-19
-20
-21
(c)
49500
50000
50500
51000
JD-2400000
1994.0
1995.0
1996.0
1997.0
1998.0
1999.0

Figure 2

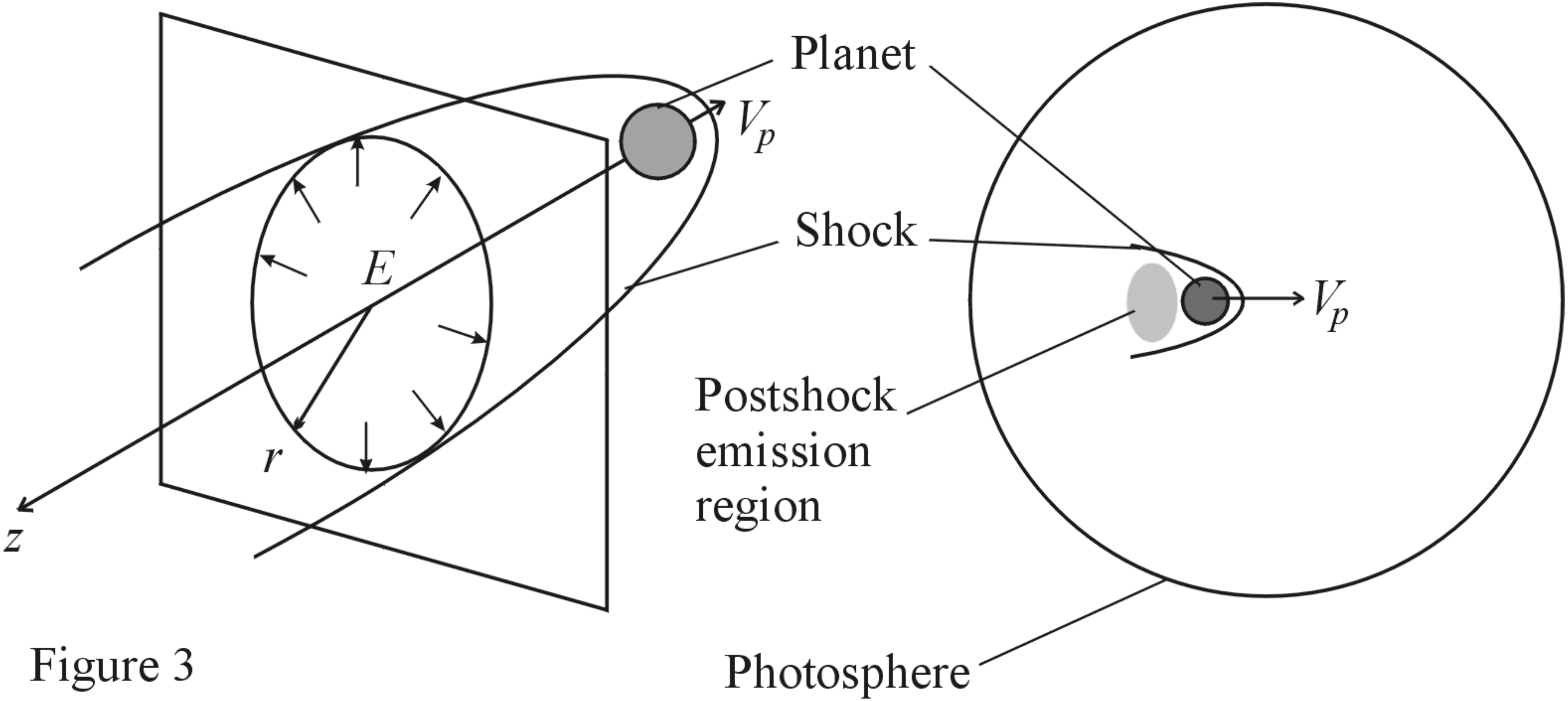
Planet
V_p
Shock
E
r
z
V_p
Postshock emission region
Photosphere

Figure 3