ON MASS LOSS FROM LONG PERIOD VARIABLES

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Observations show that long period variables (LPVs) as well as many other giant and supergiant stars are losing mass extensively. As evidence of mass loss one can mention the presence of circumstellar envelopes around LPVs. Such envelopes are inferred from infrared excesses (Gehrz and Woolf, 1971; Reimers, 1975) and maser radiation. P Cyg type profiles are observed in the spectra of some LPVs (Sanner, 1977). The increased brightness of the companion of Mira (a white dwarf) has been interpreted as the result of accretion of matter ejected by the primary (Shklovsky, 1976).

Radiation pressure on molecules or on the dust in the outer layers of the atmosphere is usually assumed to be the main cause of outflow of matter from late type highly luminous stars. The action of periodic shock waves has also been considered an important factor (see, for example, Slutz, 1976).

The presence of shock waves moving in atmospheres of LPVs is confirmed by many observational data. Such a shock wave excites emission line radiation near maximum brightness of the star (Gorbatsky and Minin, 1963). These lines arise from heating of the gas by the shock wave. They are shifted to the violet because the shocks induce gas motion away from the centre of the star. Stratification of an atmosphere under shock wave action causes the observed splitting of the absorption lines.

The shock velocity grows as the brightness increases and maximum velocity is reached at the moment of bolometric luminosity maximum. After this moment the shock wave weakens sharply. Such a shock wave velocity variation follows not only from observations but is corroborated by calculations made with the aid of the Brinkley-Kirkwood method (Klimishin, 1972). However, the cause of shock wave formation is unknown at the present time and there is considerable uncertainty in the results of shock wave calculations. One cannot exclude that shock wave formation might be connected with the oscillations of the core of the star (Fedorova, 1976). Nevertheless shock wave velocities and the dimensions of the region affected by shock waves may be estimated from observational data reliably enough.

A shock wave will expand out to a distance of approximately $3 \cdot 10^{13}$ cm during the time interval between the appearance of emission lines and maximum brightness. Therefore, when the shock weakens the front radius is of the same order as the star radius, and the escape velocity is 25 - 30 km sec^{-1} if the mass of the star $M_* = M_\odot$ and 35 - 40 km sec^{-1} for $M_* = 2M_\odot$. The data on masses of LPVs are very scarce and highly unreliable because of the crudeness of the methods used for their determination. If $M_* = (1 \div 2)M_\odot$ as believed by some authors (the true values are probably less) the gas velocity behind the shock may reach escape velocity. However, even in this case there are no grounds for suggesting that this gas will be lost from a star. One must take into account the considerable mass of gas situated in the outer layers of the stellar atmosphere. This gas does not expand and may even fall towards the star. To correctly determine the mass loss from an atmosphere subjected to shock waves, the exact solution of the gasdynamical problem is necessary. It is not sufficient to know the gas velocities in different layers.

Periodic shock waves may influence the mass loss rate in another way. Due to the action of such waves the dynamic stellar atmosphere becomes considerably more extended than the static one. This circumstance leads to more favourable conditions for outflow of matter under the action of radiation pressure. The solution of the self-consistent gasdynamical problem in order to determine the density distribution in a stellar atmosphere subjected to the action of periodic shock waves results in the following expression for the scale height

$$H = H_o M\gamma \frac{gP}{c} \left(\ln \frac{M + \gamma \frac{gP}{2c}}{M - \gamma \frac{gP}{2c}} \right)^{-1} \qquad (1)$$

Here H_o is the scale height for a static isothermal atmosphere, P is the period, g the surface gravity, γ the adiabatic index and c is the sound velocity. The Mach number M for the shock wave is determined from the following equation

$$(M + \gamma \frac{gP}{2c})\ (M - \gamma \frac{gP}{2c}) = 1. \qquad (2)$$

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Taking values that are plausible for LPVs: $P = 3 \cdot 10^7$ sec, $c \approx 5.10^5$ cm sec^{-1}, $g = 0{,}1 \div 0{,}2$ cm sec^{-2} one has the value $M = 5 \div 10$. The scale height $H = 2 \cdot 10^{13} \div 4 \cdot 10^{13}$ cm is more than one order of magnitude larger than H_o.

The rate of outflow under the action of radiation pressure depends strongly on the ratio

$$\frac{F_{rad}}{F_{grav}} = \frac{L_* \ \kappa}{cg \ 4\pi r_*^2} , \tag{3}$$

where F_{rad} and F_{grav} signify radiation pressure force and gravity force respectively, κ the opacity and r_* the stellar radius. In the case that absorption is due to dust one can assume that κ increases with height in the atmosphere because the dust concentration must grow with distance from the photosphere. Therefore, it is possible that radiation pressure is more effective in this case.

To calculate mass loss more exactly one must solve the corresponding gasdynamical problem. There are no solutions for LPVs at the present. Under the assumption that the position of the sonic point is known, the mass loss rate may be estimated with the aid of the formula

$$\dot{M}_* = 4\pi r_c^2 \ \rho_c \cdot c, \tag{4}$$

where the suffix "c" designates values at this point. Previous calculations (see, for example Maciel, 1976) have shown that the sonic point is situated near the outer boundary of the atmosphere. The sound velocity, c, depends only weakly on the expansion and density in the expanded atmosphere changes slowly. Therefore, the considerable growth of r_c must lead to an increase of $\dot{M}_*$.

Mass loss from LPVs may be important in cosmogonical problems, as the total quantity of stars of this type in our Galaxy is large: $N = (2 \div 5) \cdot 10^5$ (Gorbatsky and Lebedeva, 1976). According to estimates of mass loss with the aid of (4) $\dot{M}_* > 10^{-6}$ $M_\odot$ per year and perhaps $\dot{M}_* \approx 10^{-5}$ $M_\odot$ per year. Thus, the total mass loss from all stars of this type may reach several solar masses per year. This is a large fraction of the total input of matter to the interstellar medium.

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