

Stellar wind collision and dust formation in long-period, heavily interacting Wolf–Rayet binaries

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SUMMARY

I estimate the rate of mass loss in the form of cold dense gas from a wide Wolf–Rayet binary like WR 140. At some distance from the binary, this gas can form a dust shell and reradiate the UV radiation in the IR region. In the case of WR 140 which has a high eccentricity the observed IR outbursts may be caused by the strong increase of the cold dense gas outflow from WR 140 at the periastron.

1 INTRODUCTION

Recently a new class of astronomical object, namely long-period, heavily interacting Wolf–Rayet (WR) binaries was separated from WR stars by Williams *et al.* (1990). The prototype of this class is WC7+O4-5 WR system HD 193 793 (WR 140). Anomalously strong infrared, X-ray and radio emission was observed from WR 140 [see Williams *et al.* (1990) for a summary of observed properties]. Striking variations were evident in all three regions. The most complete coverage is in the infrared where two strong outbursts were observed (in 1977 and 1985). The 1985 outburst was investigated in detail by Williams *et al.* (1987, 1990). This outburst was interpreted in terms of the formation of $2.8 \times 10^{-8} M_{\odot}$ of amorphous carbon in the wind of the WC star and the subsequent cooling of the dust as it was carried away in the wind. The dust shell was formed at the distance $r_d \approx 2.3 \times 10^{15}$ cm from the star at a steady rate $\dot{M}_d \approx 2 \times 10^{-3} \dot{M}_{WR}$ for about 0.33 yr from 1982.21 (here $\dot{M}_{WR}$ is the mass-loss rate of the WC star). The wind travel time from WR 140 to distance r_d is ~ 0.2 yr. If the dust formation was a consequence of gas compression between the WC and O stars, then the maximum compression occurred some time between 1985.0 and 1985.3 when the WC star passed through its periastron (1985.26 ± 0.10). Here the gas compression in the region of stellar wind collision is discussed and the mass-loss rate of a long-period WR+OB binary in the form of dense cold matter is estimated.

2 STELLAR WIND COLLISION IN A WR + OB BINARY AND COOLING OF GAS IN THE SHOCK LAYER

If the distance D between the components of a WR+OB binary is large enough, the stellar wind of the OB star is not suppressed by the ram pressure of the gas outflowing from a

WR star and the winds flowing out of WR and OB stars can collide (Usov 1990, 1991). The collision of two spherical winds with the terminal velocities was considered by Galeev, Pilyugin & Usov (1989) and Usov (1991).

The distances r_{WR} and r_{OB} from the WR of OB star, respectively, to the region of stellar wind collision are

$$r_{WR} = \frac{1}{1 + \eta^{1/2}} D, \quad r_{OB} = \frac{\eta^{1/2}}{1 + \eta^{1/2}} D \quad (1)$$

(see Fig. 1), where

$$\eta = \frac{\dot{M}_{OB} V_{\infty}^{OB}}{\dot{M}_{WR} V_{\infty}^{WR}}, \quad (2)$$

$\dot{M}_{WR}$ and $\dot{M}_{OB}$ are the mass-loss rates of the WR star and the OB star, respectively, and V_{∞}^{WR} and V_{∞}^{OB} are the terminal velocities of the winds.

Behind the shock front the gas of the stellar winds is heated up to temperatures $\sim 10^7$ to 10^8 K and X-ray emission via bremsstrahlung is generated (Prilutskii & Usov 1975, 1976). Most probably, the X-ray emission of WR 140 is enhanced strongly by the radiation from the shock layer, i.e. the region between the shock front and the contact surface.

In the shock wave the gas of stellar winds is compressed but not more than ~ 4 times. If during the gas motion through the shock layer the main part of the thermal energy of the hot gas is radiated, the degree of the gas compression can increase significantly. However, in the case of long-period binaries like WR 140 even near the periastron passage the fraction of the thermal energy of the hot gas lost by emission is small. At first sight in this case the hot gas outflowing in the shock layer has to expand quasi-adiabatically and the essential cooling and compression of the gas due to the stellar wind collision is impossible. But it is not so. Indeed the main part of the hot gas in the shock layer expands quasi-adiabatically. However, as we can see below, near the contact

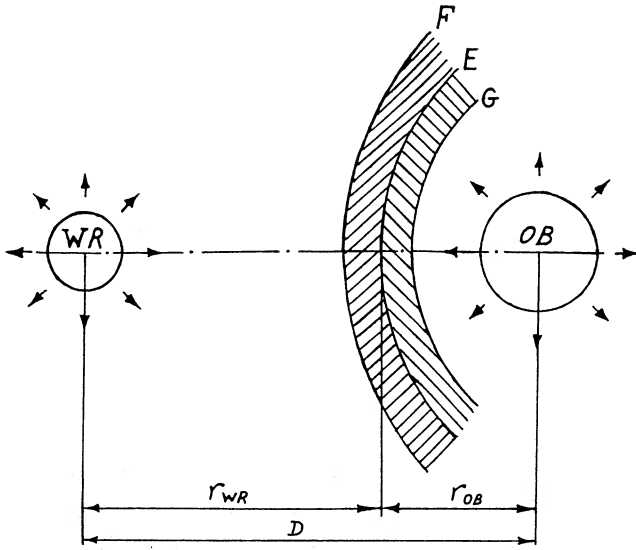


Figure 1. The collision of two stellar winds. *F* and *G* are shock waves and *E* is the contact surface.

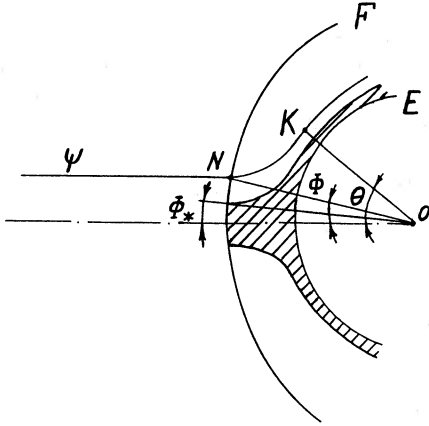


Figure 2. The gas flow in the shock layer. Here, *N* is the point where the current line Ψ with *K*-point on it intersects with the shock front. *O*-point is the centre of the OB star. The region of gas cooling is hatched.

surface there is the region (hatched in Fig. 2) where the energy losses are important and the gas may cool and compress very strongly. Let us estimate the fraction of the WR star wind which flows from WR + OB binary in the form of dense cold matter.

The temperature of gas in the shock layer is given by

$$T(\theta, \Phi) =$$

$$T_s(0) \left\{ \cos^3 \Phi - \frac{\Gamma}{\sin \Phi} [\theta - \Phi + \frac{1}{2}(\sin 2\theta - \sin 2\Phi)] \right\}^{2/3} \quad (3)$$

(Galeev *et al.* 1989; Usov 1991), where

$$T_s(0) \approx 3 \times 10^7 \left(\frac{V_\infty^{\text{WR}}}{10^8 \text{ cm s}^{-1}} \right)^2 \text{ K} \quad (4)$$

is the temperature at the frontal point and

$$\Gamma \approx 0.8 \left(\frac{\dot{M}_{\text{WR}}}{10^{-5} M_\odot \text{ yr}^{-1}} \right) \left(\frac{D}{10^{13} \text{ cm}} \right)^{-1} \left(\frac{V_\infty^{\text{WR}}}{10^8 \text{ cm s}^{-1}} \right)^{-3} \times (1 + \eta^{1/2}) \eta^{1/2} \quad (5)$$

is the dimensionless parameter which describes the cooling of gas in the shock layer due to radiation. When $\Gamma \ll 1$, the fraction of the thermal energy of hot gas lost by emission is small.

In the shock layer the angles Φ and θ are used as coordinates of an arbitrary point *K* (see Fig. 2). In this figure *N* is the point at which the current line (where *K* is located) intersects the shock front. Thus, the angle Φ fixes the current line passing through *K*, and the angle θ determines the location of *K* on this line.

To estimate the part of the matter which is cooling significantly in the shock layer let us rewrite equation (3) for $\Phi \ll 1$ and $\theta \sim \pi/2$:

$$T\left(\frac{\pi}{2}, \Phi\right) \approx T_s(0) \left(1 - \frac{\pi \Gamma}{2 \Phi} \right)^{2/3}. \quad (6)$$

It follows that the wind of a WR star which crosses the shock front at points with $\Phi < \Phi_* = \pi\Gamma/2$ is strongly cooled before it leaves the vicinity of the binary (before reaching $\theta = \pi/2$). The strong cooling in this region is caused by the slow motion of the gas along the contact surface, such that the gas has ample time to cool. The external pressure of the hot gas compresses the cooling gas ($\rho \propto T^{-1}$).

The fraction of the WR wind which is strongly cooled and compressed in the shock layer is

$$\alpha \approx \frac{\pi(r_{\text{OB}}\Phi_*)^2}{4\pi r_{\text{WR}}^2} \approx \frac{1}{4} \left(\frac{\pi}{2} \right)^2 \eta \Gamma^2. \quad (7)$$

Since the characteristic cooling time of the hot plasma via the bremsstrahlung depends on the temperature and the density as

$$\tau_c \approx 1.5 \times 10^{11} n^{-1} T^{1/2} \text{ s}, \quad (8)$$

the cooling near the contact surface is accelerating (thermal instability).

From equation (3), the gas entering the shock front with $\Phi < \Phi_*$ is cooled essentially to $T \approx 0$ in the process of leaving the vicinity of the binary. However, equation (3) is not applicable at relatively low gas temperatures in the shock layer, because it is deduced under the following assumptions: (1) the cooling is done by the thermal bremsstrahlung radiation of a fully ionized plasma; and (2) the radiation generated in the shock layer propagates freely, i.e. it does not interact with the stellar wind.

As to the first assumption, it breaks down at the gas temperature $T \lesssim 3 \times 10^6$ K and the line emission becomes the main mechanism of plasma cooling (Gaetz & Salpeter 1983). At $T \sim 10^5$ – 10^6 K, the total radiative cooling coefficient increases 10– 10^2 times in comparison with the value used by Galeev *et al.* (1989) and Usov (1991), whereas at $T \lesssim 10^4$ K the cooling is sharply reduced.

If only the first assumption were broken, the gas near the contact surface would cool down to $\sim 10^4$ K. However,

violation of the second assumption can reduce the cooling at higher temperatures. There is the additional heating of the cool gas by the X-ray radiation from the shock layer and by the UV radiation from the OB star. In addition, there is some heating from the diffusion of hot electrons from the main part of the shock layer. It is worth noting that the heating by electronic thermoconductivity can be much suppressed if the shock layer contains some (even weak) magnetic field parallel to the gas flow. A detailed study of the cooling and heating processes near the contact surface are beyond the framework of this paper and will be addressed elsewhere.

The density of the cold gas near the contact surface is (Galeev *et al.* 1989; Usov 1991)

$$\rho_c \approx 4\rho_* \frac{T_s(0)}{T_c} \quad (9)$$

and, at cold gas temperature $T_c \approx 10^5$ K and $T_s(0) \approx 3 \times 10^7$ K it can be as large as $\sim 10^3 \rho_*$, where ρ_* is the density of the WR star wind before the shock front. In the outflow, the cold gas as well as the hot gas is cooled by the expansion.

3 GAS COOLING IN COLLISION OF STELLAR WINDS AND DUST FORMATION IN WR 140

In the case of WR 140, the parameters of the binary system and the stellar winds are the following: the orbital period $P = 2900 \pm 10$ d (7.94 yr), the semimajor axis $a = 14.7$ AU, the eccentricity $e = 0.84 \pm 0.04$, $D_{\min} = (1 - e)a = 3.5 \times 10^{13}$ cm, $D_{\max} = (1 + e)a = 4 \times 10^{14}$ cm, $\dot{M}_{\text{WR}} = 5.7 \times 10^{-5} M_{\odot} \text{ yr}^{-1}$, $V_{\infty}^{\text{WR}} = 2860 \text{ km s}^{-1}$, $\dot{M}_{\text{OB}} = 1.6 \times 10^{-6} M_{\odot} \text{ yr}^{-1}$, and $V_{\infty}^{\text{OB}} = 3200 \text{ km s}^{-1}$ (Williams *et al.* 1990).

Let us note that these parameters characterize the stellar winds on the average and there are large uncertainties in their determination. The density and the velocity of the outflow can vary from one direction to another. In addition, the WC stellar wind can be slowed down by the O star radiation pressure. For instance, in the case of the close binary V444 Cygni, this effect reduces the WR wind velocity by factor ~ 3 , by the time it enters the shock (Usov 1990). Therefore it is useful to introduce dimensionless parameters β and δ to characterize the mass loss rate $\dot{M}_*$ of the WC star in the direction of the O star, and the gas velocity V_* of the WC stellar wind before the shock front: $\dot{M}_* = \beta \dot{M}_{\text{WR}}$ and $V_* = \delta V_{\infty}^{\text{WR}}$. Another advantage of the parameters β and δ is that it will be possible to determine them quite precisely from the X-ray spectrum and X-ray luminosity of WR 140 (Usov 1991).

Substitution of these parameters in equations (2), (5) and (7) and replacement of $\dot{M}_{\text{WR}}$ and V_{∞}^{WR} by $\dot{M}_*$ and V_* yields

$$\Gamma \approx 0.013 \left(\frac{D}{D_{\min}} \right)^{-1} \beta^{1/2} \delta^{-7/2}, \quad (10)$$

$$\alpha \approx 2 \times 10^{-5} \left(\frac{D}{D_{\min}} \right)^{-2} \delta^{-8}. \quad (11)$$

We see that the fraction of the WC wind, α , which is strongly cooled and compressed in the shock layer does not depend on $\dot{M}_*$, but it depends strongly on the gas velocity V_*

before the shock front. Some estimates (Usov 1991) show that the mass loss from the shock layer in form of cold and compressed gas is roughly the same ($\sim \alpha \dot{M}_{\text{WR}}$) for the winds from the O star and from the WC star.

The relative abundance of carbon by number in the WC wind is ~ 0.06 (Williams *et al.* 1990). Let us assume that most of the carbon in the cold compressed gas outflowing from WR 140 condenses into dust. Then, in order to explain the observed rate of the dust formation, $\dot{M}_d \approx 2 \times 10^{-3} \dot{M}_{\text{WR}}$, it is necessary that $\delta \approx 0.6$ at $D \approx D_{\min}$.

The mass-loss rate of WR 140 in the form of dense cold gas is maximal at the periastron ($D = D_{\min}$), whereas the time-scale of the intense outflow is about

$$\Delta t \approx \pi \left(\frac{D_{\min}^3}{GM_0} \right)^{1/2} \approx 10^7 \text{ s} \approx 0.3 \text{ yr}, \quad (12)$$

where G is the gravitational constant, $M_0 \approx 38 M_{\odot}$ is the mass of the O star and Δt is the time during which D varies by factor 2. The time-scale Δt is in good agreement with the observed duration of the dust shell formation.

As we noted above, the parameter δ can be determined from observations of the WR 140 X-ray spectrum. For $\delta = 0.6$, this spectrum must be nearly the bremsstrahlung radiation from an optically thin plasma with $kT \approx 4.6$ keV ($kT \approx 12.7$ keV for $\delta = 1$) (Usov 1991).

There are already some indications that the value of δ is nearly 0.6 at the periastron. Indeed, the gas of the shock layer in the WC wind loses only a small part of its thermal energy for radiation. Therefore its velocity far from the binary, after expansion, must be $\sim V_* \approx \delta V_{\infty}^{\text{WR}} \approx 1700 \text{ km s}^{-1}$. This value is about the same as the velocity of the dust shell, $\sim 1600 \text{ km s}^{-1}$ (Williams *et al.* 1990).

4 DISCUSSION

A WR+OB binary can belong to one of the following classes, depending on the distance D between its components.

(1) A very close binary in which the OB wind is suppressed by the ram pressure of the WR wind, on the side facing the WR star: $r_{\text{OB}} \leq R_{\text{OB}}$, where R_{OB} is the OB star radius.

(2) A close binary in which the WR wind is strongly slowed down by the OB star radiation pressure before it collides with the OB wind: $R_{\text{OB}} < r_{\text{OB}} \leq r_{\text{ter}}$, where $r_{\text{ter}} \sim 5 R_{\text{OB}}$ is the distance from the OB star centre at which the OB wind reaches the terminal velocity V_{∞}^{OB} .

(3) A wide binary in which the WR and OB winds collide with the terminal velocities V_{∞}^{WR} and V_{∞}^{OB} , and the temperatures of ions and electrons in both the winds coincide in the shock layers: $r_{\text{OB}} > r_{\text{ter}}$ and $D < D_{\text{eq}}$, where (Usov 1991)

$$D_{\text{eq}} \approx 10^{15} \eta^{1/2} \left(\frac{\dot{M}_{\text{WR}}}{10^{-5} M_{\odot} \text{ yr}^{-1}} \right) \left(\frac{V_{\infty}^{\text{WR}}}{10^8 \text{ cm s}^{-1}} \right)^{-5} \text{ cm}. \quad (13)$$

(4) A very wide binary in which the gas densities in the stellar winds at the collision region are so small that the electron and ion temperatures do not have enough time to equilibrate in the shock layers: $D > D_{\text{eq}}$.

WR 140 is a unique object for studying stellar wind collisions. Its large orbital eccentricity endows it with remarkable

properties. The distance between the stars D varies by more than an order of magnitude and WR 140 moves from one class to another: it is a very wide binary at $D \sim D_{\max}$, whereas at $D \sim D_{\min}$ it is something intermediate between a close binary and a wide binary. In the latter case, WR 140 realizes nearly the most favourable conditions for a strong compression of the gas in the vicinity of the contact surface. Indeed, at $D \approx D_{\min}$ the slowing down of the WC wind by the O star radiation pressure becomes considerable. The parameter δ is reduced and the cold gas outflow from WR 140 is sharply increased (see equation 11). At the same time, δ is not as small as, for instance, in V444 Cygni (Usov 1990) and the gas is strongly compressed near the contact surface [see equation (9) in which the temperature $T_s(0)$ decreases and the temperature T_c increases with the decreasing of parameter δ].

The long-period, heavily interacting WR binaries (WR 48a, WR 137, WR 140, and possibly WR 19) are distinguished among the rest of the WR binaries in that they experience the intermediate state between the close binaries and the wide binaries ($r_{\text{OB}} \sim r_{\text{ter}}$). In this state there is a strong outflow of cold gas, which leads to an IR outburst. Long-period, heavily interacting binaries must have hard X-ray spectrum similar to the observed WR 140 spectrum (Pollock 1987a,b). The X-ray luminosity must be maximal and the X-ray spectrum must become softer during the strong outflow of the cold gas.

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