HYDRODYNAMICS AND HIGH-ENERGY PHYSICS OF WOLF-RAYET COLLIDING WINDS

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Abstract. The stellar winds flowing out of the components of WR+OB binaries can collide and shock waves are formed. Stellar wind collision, particle acceleration by the shocks and generation of X-ray, γ-ray, radio and IR emission in WR+OB binaries are discussed.

Key words: stars: Wolf-Rayet – colliding winds – particle acceleration

1. Introduction

One of the main properties of Wolf-Rayet (WR) stars is their very intense outflow of gas. The mass-loss rate for WR stars, $\dot{M}_{WR}$, and the terminal velocity of the matter outflow, v^{∞}_{WR}, far from the star amount to $\sim (0.8-8)\times 10^{-5}$ M$_{\odot}$yr^{-1} and $\sim (1-5)\times 10^{3}$ km s^{-1}, respectively. No less than 40% of the WR stars belong to binary systems. Young massive O and B stars are the other components of such systems. OB stars also have an intense stellar wind: $\dot{M} \sim 10^{-6}$ M$_{\odot}$yr^{-1} and $v^{\infty}_{OB} \sim v^{\infty}_{WR}$. The winds flowing out of WR and OB stars can collide and shock waves are formed. In the shock the gas is heated to temperature $\sim 10^{7}$ K and generates X-ray emission (Prilutskii & Usov 1975, 1976; Cherepashchuk 1976; Cook, Fabian & Pringle 1979; Bianchi 1982; Luo *et al.* 1990; Usov 1990; Stevens *et al.* 1992; Usov 1992; Myasnikov & Zhekov 1993; Nussbaumer, these proceedings).

Until now X-ray emission from a few tens of WR stars has been detected (Pollock 1987 and these proceedings). From the observational data it follows that the WR binaries are significantly brighter in X-rays than single stars (Pollock 1987), and the WR stars detected in X-rays have a much higher than usual incidence of binaries (Abbott & Conti 1987). These two facts can be naturally explained if the X-ray emission of WR binaries is enhanced essentially by the radiation of the gas heated in the shock. Besides, the analysis of the energy spectra of the X-ray emission and the time variability indicates that the X-rays are generated in the outer regions of the stellar wind near the OB star (Moffat *et al.* 1982; Pollock 1987; Williams *et al.* 1990), as expected in models of stellar wind collision (see Section 2).

Stellar wind collision may be responsible not only for the X-ray emission of WR+OB binaries and for their radio, IR and γ-ray emission as well (Prilutskii & Usov 1976; Williams, van der Hucht & Thé 1987; Williams *et al.* 1990, 1992, 1994; Usov 1991; Eichler & Usov 1993).

K. A. van der Hucht and P. M. Williams (eds.), Wolf-Rayet Stars: Binaries, Colliding Winds, Evolution, 495–503.

2. Stellar wind collision in WR+OB binaries

2.1 GEOMETRY OF THE REGION OF STELLAR WIND COLLISION

The winds from the binary components are highly supersonic, the Mach number $\xi \simeq 10^2 \gg 1$, and flow nearly radially out to the shocks. In the shock the gas is heated to the temperature $T \sim 10^7$ K. Behind the shock the hot gas outflows from the region of stellar wind collision nearly along the contact surface (for details see Usov 1992; Eichler & Usov 1993).

In the case of the collision of two spherical winds at terminal velocity the distances $r_{\rm WR}$ and $r_{\rm OB}$ from WR or OB stars, respectively, to the region where these winds meet is

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

(see Fig. 1), where $\eta = (\dot{M}_{OB}v^{\infty}_{OB})/(\dot{M}_{WR}v^{\infty}_{WR})$. Since $\dot{M}_{OB} \simeq (0.01 - 0.1)\dot{M}_{WR}$ and $v^{\infty}_{OB} \simeq v^{\infty}_{WR}$, the dimensionless parameter η is small ($\eta \ll 1$). Hence, the region of stellar wind collision is much nearer to the OB star than to the WR star. The form of the contact surface C near the OB star ($r \simeq r_{OB}$) is given by

$$|\mathbf{R}_c(\chi)| \simeq r_{OB}\frac{\chi}{\sin\chi} \qquad (2)$$

for $\chi \le \pi/2$ (here χ is the angle between the radius vector $\mathbf{R}_c(\chi)$ from the center of the OB star to the point at the contact surface and the line connecting the components of the binary). At intermediate distances ($r_{OB} \ll r < (P/2)v^{\infty}_{WR}$) from the OB star the contact surface C approaches the conic surface $\tilde{C}$ with angle

$$\theta \simeq 2.1\left(1-\frac{\eta^{2/5}}{4}\right)\eta^{1/3} \quad \text{for } 10^{-4} \le \eta \le 1 \qquad (3)$$

The shock fronts S_1 and S_2 are near the conic surfaces $\tilde{S}_1$ and $\tilde{S}_2$ at $r_{OB} \ll r < (P/2)v^{\infty}_{WR}$ as well. In the case of wide WR+OB binaries, like WR140, when the fraction of thermal energy of the hot gas lost by emission in the shock layers is small, the angle $\Delta\theta$ between these conic surfaces is $\sim \theta$. In the other case the value of $\Delta\theta$ is smaller than θ and asymptotically approaches zero if this fraction goes to unity. The contact surface C and two shock fronts S_1 and S_2 are twisted at a distance more than $\sim (P/2)v^{\infty}_{WR}$ due to the orbital rotation and have spiral form (see Fig. 1).

For an OB star the velocity of the matter outflow $v_{OB}(r)$ at distance r from the center of the OB star varies from almost zero on the OB star surface, $r = R_{OB}$, to v^{∞}_{OB} for $r > r_{ter}$, where R_{OB} is the radius of the OB star, and r_{ter} is approximately equal to (3-5) R_{OB}. If $r_{OB} > r_{ter}$, we have

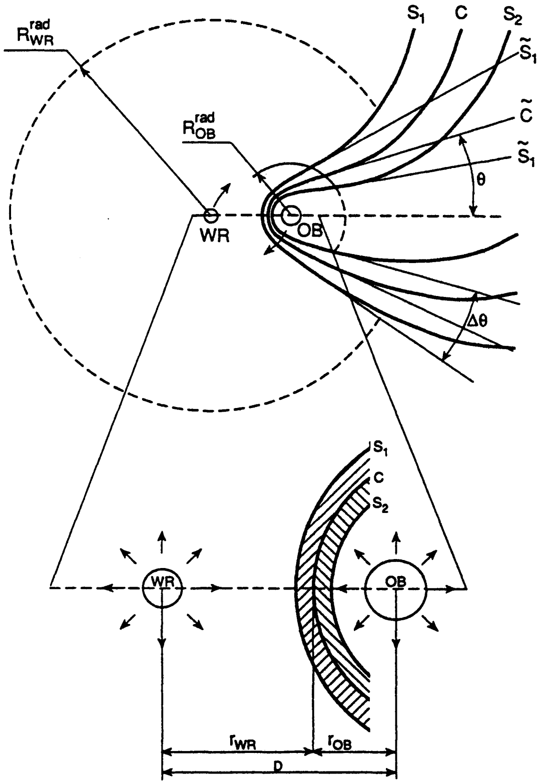

Fig. 1. The collision of two stellar winds in a WR+OB binary. S_1 and S_2 denote the shock waves and C is the contact surface. R_{WR}^{rad} and R_{OB}^{rad} are the radii of the radio photospheres of the WR and OB star. The directions of the orbital motion of the binary components are shown by arrows. The region of stellar wind collision is hatched at the lower part of the figure at which the collision region is enlarged.

the collision of two winds with terminal velocities and values r_{WR} and r_{OB} are determined by equation (2). If $R_{OB} < r_{OB} < r_{ter}$, the gas flowing out of the OB star does not reach the terminal velocity by the time it enters the shock. In turn, the stellar-wind gas of the WR star is decelerated by the radiation pressure of the OB star while approaching the OB star. In this case, the gas velocities ahead of and near the shocks drop, and the gas temperature behind the shocks drops too (Usov 1990, 1992; Stevens *et al.* 1992). If $r_{OB} \leq R_{OB}$, the OB wind is suppressed by the ram pressure of the WR wind, on the side facing the WR star.

2.2 EQUATIONS, BOUNDARY CONDITIONS AND METHOD OF SOLUTION

The set of equations which describes the steady gas flow in the shock layers between the shock fronts S_1 and S_2 and the contact surface C will be

the continuity equation : $$\operatorname{div}(\rho \mathbf{v}) = 0\,, \tag{4}$$

the momentum equation : $$\rho(\mathbf{v}\nabla)\mathbf{v} = -\nabla p\,, \tag{5}$$

and the energy equation : $$\rho \mathbf{v}\nabla(H + |\mathbf{v}|^2/2) = -Q\,, \tag{6}$$

where ρ is the density of the gas and Q is the rate of the energy losses per unit gas volume by radiation. Since the gas in the shock layer is practically totally ionized, its pressure p and its specific enthalpy H can be expressed as

$$p = \frac{\rho k T}{m_p \mu}, \qquad H = \frac{\gamma}{\gamma - 1}\frac{p}{\rho} = \frac{5}{2}\frac{kT}{m_p \mu}\,, \tag{7}$$

here γ is the ratio of heat capacities at constant pressure and at constant volume, μ is the mean molecular weight, k is the Boltzmann constant and m_p is the proton mass.

Gas parameters ahead of the shock front (index 1) and behind the shock front (index 2) are related via the Rankin-Hugoniot relations

$$\rho_1 v_1^{(n)} = \rho_2 v_2^{(n)}, \qquad p_1 + \rho_1 (v_1^{(n)})^2 = p_2 + \rho_2 (v_2^{(n)})^2\,,$$

$$v_1^{(\tau)} = v_2^{(\tau)}, \qquad H_1 + \frac{1}{2}(v_1^{(n)})^2 = H_2 + \frac{1}{2}(v_2^{(n)})^2\,. \tag{8}$$

Indices n and τ denote the normal and tangential components of the vector $\mathbf{v}$. The condition $v^{(n)}=0$ is met on the contact surface. This condition and the Rankine-Hugoniot relations (8) are the full set of boundary conditions for the set of equation (4)-(7) needed to find the parameters of hot gas in the shock layers.

The set of equations (4)-(7) with the boundary conditions (8) was solved by Bairamov, Pilyugin & Usov (1990) and Usov (1992) analytically, using the method of Chernyi (1961) in which the ratio of the density of the gas, ϵ, ahead of the shock to that behind it was considered small.

The problem of stellar wind collision was solved in the following way. First, the parameters of the hot gas in the external and internal shock layers were obtained as a function of the form of unknown contact surface. Then the form of the contact surface was found from the equality of the gas pressure on both sides of contact surface. To calculate both the parameters of the hot gas in the external and internal shock layers and X-ray emission from the shock layers equation (2) for the contact surface was used (Usov 1992).

3. X-Rays from colliding winds

If a WR+OB binary is wide enough, $r_{OB} > r_{ter}$, the WR and OB winds collide with the terminal velocities, and the fraction of the thermal energy of the hot gas lost by emission in the shock layers is, as a rule, small. In this case, the expected X-ray luminosity is (Usov 1992)

$$L_{ext} \simeq 8 \times 10^{34} \left(\frac{\dot{M}_{WR}}{10^{-5}\mathrm{M_\odot yr^{-1}}}\right)^{1/2} \left(\frac{\dot{M}_{OB}}{10^{-6}\mathrm{M_\odot yr^{-1}}}\right)^{3/2} \left(\frac{v^{\infty}_{WR}}{10^3\,\mathrm{km\,s^{-1}}}\right)^{-5/2} \times \left(\frac{v^{\infty}_{OB}}{10^3\,\mathrm{km\,s^{-1}}}\right)^{3/2} \left(\frac{D}{10^{13}\,\mathrm{cm}}\right)^{-1} \mathrm{ergs\ s^{-1}} \tag{9}$$

from the external shock layer between the shock front S_1 and the contact surface (see Fig. 1), and

$$L_{int} \simeq 1.3 \times 10^{35} \left(\frac{\dot{M}_{WR}}{10^{-5}\mathrm{M_\odot yr^{-1}}}\right)^{1/2} \left(\frac{\dot{M}_{OB}}{10^{-6}\mathrm{M_\odot yr^{-1}}}\right)^{3/2} \left(\frac{v^{\infty}_{WR}}{10^3\,\mathrm{km\,s^{-1}}}\right)^{1/2} \times \left(\frac{v^{\infty}_{OB}}{10^3\,\mathrm{km\,s^{-1}}}\right)^{-3/2} \left(\frac{D}{10^{13}\,\mathrm{cm}}\right)^{-1} \mathrm{ergs\ s^{-1}} \tag{10}$$

from the internal shock layer between the shock front S_2 and the contact surface. The total power of X-ray emission from the region of stellar wind collision is $L_x = L_{ext} + L_{int}$. The accuracy of equations (9) and (10) is of the order of $(\epsilon^2 + \eta)^{1/2}$, *i.e.*, the accuracy is several tens of percent for $\eta \leq 0.1$ which is typical for WR+OB binaries. Equations (9) and (10) for the expected X-ray emission from colliding winds did not take into account the absorption of X-rays in the stellar winds. We can do it only if WR+OB binaries are wide enough, $D > 10^{13}$ cm (Usov 1992).

In a close binary, $r_{OB} < r_{ter}$, both the WR stellar wind and the OB stellar wind have velocities, v_{WR} and v_{OB}, near the shock waves which are less than their terminal velocities (see Section 2.1). Therefore, at first the X-ray luminosity L_x may increase a few times in comparison with the sum of equations (9) and (10), $L_x \propto (v_{WR,OB})^{-1}$. In turn, the gas temperature in the shock layers drops, $T \propto (v_{WR,OB})^2$, and the spectrum of the X-ray emission shifts to the soft region (Usov 1990). Then, if the value of r_{OB} is a few times smaller than r_{ter}, the main portion of this soft X-ray emission is absorbed in the WR and OB stellar winds and the X-ray luminosity is decreased (Luo *et al.* 1990; Usov 1990, 1992; Stevens *et al.* 1992). Hence, it is expected that the X-ray luminosity of a WR+OB binary is as high as possible when $r_{OB} \simeq (0.5 - 1)r_{ter}$ or $D \simeq (0.5 - 1)\eta^{-1/2} r_{ter}$.

4. Gas cooling and dust formation

In the shocks the gas of stellar winds is compressed but not more than ~ 4 times. If a WR+OB binary is close enough and 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, *i.e.*, a cold dense gas may be formed.

In the case of long-period binaries like WR140 even near 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 in the region of 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, near the contact surface there is the region where the energy losses may be important and the gas may cool and compress very strongly (Usov 1991). 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. In this case the fraction of WR wind which may be strongly cooled and compressed in the shock layers is (Usov 1991)

$$\alpha \simeq \eta^2 \left(\frac{\dot{M}_{WR}}{10^{-5}\,\mathrm{M_\odot yr^{-1}}}\right)^2 \left(\frac{D}{10^{13}\,\mathrm{cm}}\right)^{-2} \left(\frac{v_{WR}^{\infty}}{10^3\,\mathrm{km\,s^{-1}}}\right)^{-6} \tag{11}$$

The characteristic cooling time of the hot plasma via the bremsstrahlung depends on the temperature, T, and the density, n, as $\tau_c \simeq 1.5 \times 10^{11} n^{-1} T^{1/2}$ s. Taking into account that the external pressure of the hot gas compresses the cooling gas ($N \propto T^{-1}$), we have $\tau_c \propto T^{3/2}$, i. e. the process of cooling near the contact surface is accelerating (thermal instability). The gas near the contact surface may be cooled down to ~ $10^4 - 10^5$ K, and the density of the cold gas may be as large as ~ $10^3 - 10^4 \rho_*$, where ρ_* is the gas density before the shock (Usov 1991). At the distance $r_d \simeq$ a few $\times 10^{15}$ cm from the binary, the cold dense gas can form a dust shell and re-radiate the UV radiation in the IR region (Williams *et al.* 1990, 1992, 1994; Usov 1991).

The value of α is, as a rule, very small at $r_{OB} > r_{ter}$ because of high velocity of the stellar winds and increases very sharply at $r_{OB} < r_{ter}$. When r_{OB} is comparable with R_{OB}, the dynamical gas pressure of both winds ahead of the shocks is decreased, and the gas compression in the shock layers is decreased too. In addition, in close WR+OB binaries with $r_{OB} \sim R_{OB}$ the X-ray absorption inside the shock layers is high, and it can prevent strong gas cooling in the layers. Therefore, when the value of r_{OB} is somewhere between ~ r_{ter} and ~ $0.3 r_{ter}$ (say, $r_{OB} \simeq 0.5 r_{ter}$), the most favourable conditions for a strong compression of the gas in the shock layers are realized (Usov 1991).

Long-period WR binaries like WR48a, WR125, WR137, WR140, and possibly WR19, with a large enough value of orbital eccentricity, distinguish themselves from the other WR binaries in that they experience a state with $r_{OB} \sim 0.5 r_{ter}$ in the process of their orbital motion. In this state there is a strong outflow of cold gas, which leads to an IR outburst (Williams *et al.* 1992, 1994). The cold gas may consist of a few components which move with different velocities. As a result of this, the maximum of the IR light curve may be split.

5. Particle acceleration and radio and γ-ray emission

It is well known that plasma shocks in an astrophysical setting can and do accelerate charged particles to high energies (for a review, see Blandford & Eichler 1987). Therefore the strong shocks formed by the colliding stellar winds in WR+OB binaries are very promising as particle accelerators. Necessary conditions for particle acceleration by a shock wave include the following (Eichler & Usov 1993): (1) *The shock must be collisionless in the absence of an external injection mechanism.* This is typically satisfied if the strength of the magnetic field ahead of the shock is $B \gg 10^{-6}$ Gauss; (2) *The Ohmic damping rate of Alfven waves must not exceed the maximum growth rate*; and (3) *For primary electron acceleration, the shock velocity must considerably exceed the phase velocity of whistler waves propagating normal to the shock.* The last two conditions holds for WR+OB binaries if $B \ll$ a few Gauss. All of these constraints on B are typically satisfied by colliding winds in WR+OB binaries (see, *e.g.*, Usov & Melrose 1992). Hence the region of stellar wind collision in these binaries may be a strong source of both high energy particles and nonthermal radiation generated by these particles. The maximum Lorentz factor of electrons, $\Gamma_{\max}$, is limited by inverse Compton losses and may be as high as $\Gamma_{\max} \simeq 3 \times 10^3 (B/\text{Gauss})^{1/2}$ for a quasi-parallel shock geometry (Eichler & Usov 1993). Given the constraints of B discussed above, the energy of electrons $E_{\max} = \Gamma_{\max} mc^2$ is enough to generate synchrotron radio emission at the frequencies of which nonthermal radio emission from WR+OB binaries has been observed (Becker & White 1985 and these proceedings; Abbott *et al.* 1986).

Stellar winds outflowing from WR and OB stars are opaque to free-free absorption. A typical radius of the radio photosphere at the frequency of a few GHz for WR stars is $R^{rad}_{WR} \simeq$ a few times 10^{14}cm (Wright & Barlow 1975). Radio emission from the colliding wind region may be observed at the frequency ν only if the time $R^{rad}_{WR}/v^{\infty}_{WR}$ during which the gas outflowing from the WR star with the velocity v^{∞}_{WR} reaches the radius of the radio photosphere R^{rad}_{WR} is of the order of or smaller than the time which is necessary for the WR+OB binary to turn on the angle $2\theta + \Delta\theta \simeq 3\theta$ (see Fig. 1), *i.e.*,

$$\frac{R^{rad}_{WR}}{v^{\infty}_{WR}} \leq \frac{3\theta}{2\pi} P \quad \text{or} \quad P \geq P_{cr} = \frac{2\pi}{3\theta} \frac{R^{rad}_{WR}}{v^{\infty}_{WR}} \simeq 13 \eta^{-1/3} \left(\frac{\nu}{5\,\text{GHz}} \right)^{-2/3} \text{d}. \quad (13)$$

For a typical WR+OB binary the value of P_{cr} is of the order of a month when the frequency of observation is a few GHz (Eichler & Usov 1993). If $P < P_{cr}$ nonthermal radio emission from the region of stellar wind collision in the WR+OB binary cannot be observed because it is screened by the WR wind.

Gamma-ray emission can be attributed to either inverse Compton emission or $p - p$ collisions followed by pion decay. In the former case, the seed photons would presumably be the processed UV radiation from the OB stars. A high-energy tail of the inverse Compton spectrum of γ-rays may exist up to $\sim 10^3$ MeV (Eichler & Usov 1993).

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DISCUSSION:

Nussbaumer: Your analytical approach is of great importance and the resulting agreement with observation is impressive. In contrast to your method the full hydrodynamic treatment is loaded with numerical booby-traps, and it is very demanding on computer resources. Nevertheless, there are physical phenomena which need the full hydrodynamic treatment. Where do you see the connection and possible interaction between your analytical approach and the full hydrodynamic treatment?

Usov: In my analytical approach I have calculated both all parameters of the hot gas in the shock layers and the X-ray luminosity of WR + OB binary for the case when the outflowing gas has the terminal velocities ahead of the shock. The accuracy of these calculations is several tens of percent. The full hydrodynamic treatment of the stellar-wind-collision problem is needed for compact WR + OB binaries, like V 444 Cyg, for which the accuracy of my analytical calculations decreases.

Zubko: At what distances from the star in stellar radii may a gas be cooled down to the temperatures for dust to create?

Usov: These distances may be estimated from the theoretical conditions when the gas velocities become very small because of intensive losses of energy.

Zubko: What about the thermal stability of the cooled gas where the dust could be created?

Usov: Now it is very difficult to calculate this precisely. But some estimations evidence in favour of the stability of the cooled gas.

Marchenko: About the interpretation of the IR observations. You told about 4 subpeaks on the IR light curve. In my opinion it should be only two, taking into account the different chemical composition of the O star and WR star winds. Do you expect to see any dust formation from the aftershock cooling zone of the O star?

Usov: My reply is yes, in principle. From my consideration, it follows that the masses of the cold dense gas which are ejected from the external and internal shock layers are more or less the same. You are right that the efficiency of the dust formation depends on the chemical composition of the winds. If the aboundance of carbon in the OB wind is high enough, dust formation from the cold dense gas outflowing from the aftershock cooling zone of the internal shock layer may be observed.