1986Ap&SS.124..389S

MASS LOSS FROM WOLF–RAYET STARS

MAHENDRA SINGH and U. S. CHAUBEY
Uttar Pradesh State Observatory, Manora Peak, Naini Tal, India

(Received 5 February, 1986)

Abstract. The observed times of minimum light derived from the photometry of the Wolf–Rayet eclipsing binary stars CQ Cep and V444 Cyg are used to estimate the mass-loss rate of the Wolf–Rayet components in several modes of mass-loss and mass-exchange.

1. Introduction

During the last few years supporting evidence has been given (cf. Hidayat *et al.*, 1984) to Paczynski's hypothesis (Paczynski, 1967, 1968) that the Wolf–Rayet binaries are the evolutionary products of massive close binary systems attained through Case B of mass-exchange. Thus the mass-loss rate of Wolf–Rayet stars is an important quantity in the theoretical studies pertaining to the evolution of massive close binary systems. Interest in this problem has increased with the realization that the mass-loss rate has a direct bearing on the plausibility of some models for galactic X-ray sources (Pratt and Strittmatter, 1976).

Recently, Barlow (1982) has suggested three methods for the determination of mass-loss from the Wolf–Rayet stars, namely (1) analysis of the behaviour of eclipsing Wolf–Rayet binaries, (2) observation of interaction of the Wolf–Rayet wind with the interstellar medium, and (3) the analysis of the continuum emission from the Wolf–Rayet stars. He has also pointed out that the estimated mass-loss rate, in this way, from the Wolf–Rayet stars is to be of the order of $10^{-5}\,M_\odot\,\text{yr}^{-1}$. This estimated mass loss rate value is not very reliable due to the uncertainties in the values of the radii of the emission line regions and the electron densities in the W–R atmosphere. It is, therefore, highly desirable to determine the mass loss rates from the Wolf–Rayet stars based on purely observational data as far as possible.

We are offered such an opportunity by the observations of the changes in the orbital period of the Wolf–Rayet binary systems due to the mass loss and mass exchange between the components. In our opinion, the most reliable and precise estimate of mass-loss rate for the Wolf–Rayet stars may be obtained only from the analysis of period changes of eclipsing Wolf–Rayet binaries. Therefore, in this paper we have estimated the mass-loss rates from the Wolf–Rayet stars in the Wolf–Rayet eclipsing binary systems CQ Cephei (WN7 + O7) and V444 Cygni (WN5.5 + O6) from the observed changes in their orbital period.

Throughout this paper the subscript '1' refers to the Wolf–Rayet star while the subscript '2' to the other companion star.

Astrophysics and Space Science **124** (1986) 389–396.

2. Period Changes

The total orbital angular momentum H for a close binary system with a separation A and eccentricity $e = 0$ can be written as

$$H^2 = G \frac{M_1^2 M_2^2}{M_1 + M_2} A , \tag{1}$$

where M_1 and M_2 are the masses of the systemic components and G is the gravitational constant. By use of Kepler's third law, Equation (1) can be written, in terms of orbital elements, as

$$H = \left(\frac{G^2}{2\pi}\right)^{1/3} \frac{M_1 M_2}{M^{1/3}} P^{1/3} ; \tag{2}$$

or, equivalently,

$$h = \left(\frac{G^2}{2\pi}\right)^{1/3} \frac{M_1 M_2}{M^{4/3}} P^{1/3} ; \tag{3}$$

where h is the orbital angular momentum per unit mass; P, the orbital period; and M, the systemic mass $M_1 + M_2$. Differentiation of Equation (3) with respect to time yields

$$\frac{\dot{P}}{P} = \frac{4\dot{M}}{M} - \frac{3\dot{M}_1}{M_1} - \frac{3\dot{M}_2}{M_2} + \frac{3\dot{h}}{h} . \tag{4}$$

Equation (4) represents the general effects of changes in masses and orbital angular momentum on the orbital period of a binary system. These changes in the mass and orbital angular momentum may occur either by Roche overflow or by stellar wind driven by radiation pressure. Equation (4) has four unknown quantities $\dot{M}_1$, $\dot{M}_2$, $\dot{M}$, and h. Therefore, in order to derive the mass-loss from the Wolf–Rayet component ($\dot{M}_1$) from the observed period variation ($\dot{P}$) it is necessary to have the three other equations among the four unknowns, namely $\dot{M}_1$, $\dot{M}_2$, $\dot{M}$, and $\dot{h}$. This is possible, in our opinion, for the following four idealized cases of mass-loss and mass-exchange:

Case I

Consider the simple mass transfer in which the ejected material from the Wolf–Rayet component is falling onto its companion with no variation in the orbital angular momentum and systemic mass. Then we have

$$\dot{M}_1 = -\dot{M}_2 , \tag{5}$$

$$\dot{M} = 0 , \tag{6}$$

$$\dot{h} = 0 . \tag{7}$$

Thus, from Equations (4), (5), (6), and (7) we obtain

$$\frac{\dot{P}}{P} = -3\left(\frac{M}{M_1} - \frac{M}{M_2}\right)\frac{\dot{M}_1}{M} . \tag{8}$$

Case II

Consider the second possibility of mass transfer in which the ejected material from the Wolf–Rayet star forms the ring which is rotating around the companion star in circular orbit under the gravitational attraction of the companion in the same sense as the binary motion. Then we have

$$\dot{M}_1 = -\dot{M}_2 , \tag{9}$$

$$\dot{M} = 0 , \tag{10}$$

$$\frac{\dot{h}}{h} = \left\{\frac{M}{M_1}\left(\frac{M}{M_2}\right)^{1/2} r^{1/2}\right\}\frac{\dot{M}_1}{M} . \tag{11}$$

In the above equation r is the radius of the ring in terms of semi-major axis of the orbit which will not exceed the radius of the Roche lobe of the M_2 star. This equation is the same as Equation (2) of Hall and Neff (1976). By use of Equations (9), (10), and (11), Equation (4) can be written in terms of $\dot{P}$ and $\dot{M}_1$, as:

$$\frac{\dot{P}}{P} = 3\left\{\frac{M}{M_2} - \frac{M}{M_1} + \left(\frac{M}{M_1}\right)\left(\frac{M}{M_2}\right)^{1/2} r^{1/2}\right\}\frac{\dot{M}_1}{M} . \tag{12}$$

Case III

Consider the third possibility of mass-loss from the Wolf–Rayet star in which the ejected material forms a ring rotating around the entire system and the particles of the ring are moving in the gravitational attraction of the centre of mass of the system in the same sense as the binary motion. If J is the orbital angular momentum of the ring material per unit mass, then we have

$$\dot{M}_1 = \dot{M} , \tag{13}$$

$$\dot{M}_2 = 0 , \tag{14}$$

$$\frac{\dot{h}}{h} = \left(\frac{J-h}{h}\right)\frac{\dot{M}_1}{M} = -\left\{1 - \left(\frac{M}{M_1} + \frac{M}{M_2}\right) r^{1/2}\right\}\frac{\dot{M}_1}{M} . \tag{15}$$

In Equation (9.3) r is the radius of ring in terms of semi-major axis of the orbit. By use of Equations (13), (14), and (15), Equation (4) can be written, in terms of $\dot{M}_1$ and $\dot{P}$, as

$$\frac{\dot{P}}{P} = \left\{1 - 3\,\frac{M}{M_1} + 3\left(\frac{M}{M_1} + \frac{M}{M_2}\right) r^{1/2}\right\}\frac{\dot{M}_1}{M} . \tag{16}$$

Case IV

Consider the fourth possibility of mass-loss from the Wolf–Rayet star in which the ejected material escapes out from the binary system. If J is the orbital angular momentum of the ejecting material per unit mass, then we have

$$\dot{M}_1 = \dot{M}\,, \tag{17}$$

$$\dot{M}_2 = 0\,, \tag{18}$$

$$\frac{\dot{h}}{h} = \frac{J\dot{M}_1}{hM} - \frac{\dot{M}_1}{M} = \left(\frac{M_2}{M_1} - 1\right)\frac{\dot{M}_1}{M}\,. \tag{19}$$

By use of Equations (17), (18), and (19), Equation (4) can be written, in terms of $\dot{P}$ and $\dot{M}_1$, as

$$\frac{\dot{P}}{P} = \left\{1 - 3\,\frac{M}{M_1} + 3\,\frac{M}{M_1}\right\}\frac{\dot{M}_1}{M}\,. \tag{20}$$

Thus, Equations (8), (12), (16), and (20) allow us to estimate the mass loss, $\dot{M}_1$ from the known value of the period change, $\dot{P}$ of a binary star. It is also noticeable that the variation in period for a given $\dot{M}_1$ depends strongly on the mode of mass ejection. We feel that all the four modes of mass-ejections discussed above, may be for the idealized cases. Perhaps the actual mode of mass-ejection is most likely a combination of all the four modes, since the particles ejected from the M_1 star are expected to have a wide range of velocities and orbital momentum per unit mass.

3. Period Variabilities in Wolf–Rayet Binaries CQ Cephei and V444 Cyg

An inspection of the literatures of close binary stars (viz., Wood *et al.*, 1980) reveals that there are only five eclipsing binaries which have their one component as a Wolf–Rayet star. These are CP Cep, CQ Cep, CX Cep, V444 Cyg, and CV Ser. Of these five systems, a series of photometric observations of an adequate length are available only for CQ Cep and V444 Cyg. Therefore, only these two systems are well suited for studying the mass-loss and mass-exchange with respect to their period changes.

Since the period of an eclipsing system is itself constant or variable is based on the relationship O–C = $f(E)$, where O and C are the observed and computed times of minimum light and E is the number of the cycles. Therefore, in order to study the period variations of CQ Cep and V444 Cyg, first we have collected all the times of minimum light available in the literature, and then the cycle numbers and the O–C values of the observed minima have been computed for CQ Cep and V444 Cyg, respectively, with the (heliocentric) ephemerides

$$M(E) = 2\,415\,500.780 + 1\overset{\mathrm{d}}{.}641\,272E \tag{21}$$

and

$$M(E) = 2\,429\,879.230 + 4\overset{\mathrm{d}}{.}212\,38E\,. \tag{22}$$

These O–C values against cycles are given in Figures 1 and 2 for CQ Cep and V444 Cyg, respectively. It is clear from Figure 1 that the O–C curve between 1899 to 1982 gives a downward parabolic segment. It means that the orbital period of CQ Cep

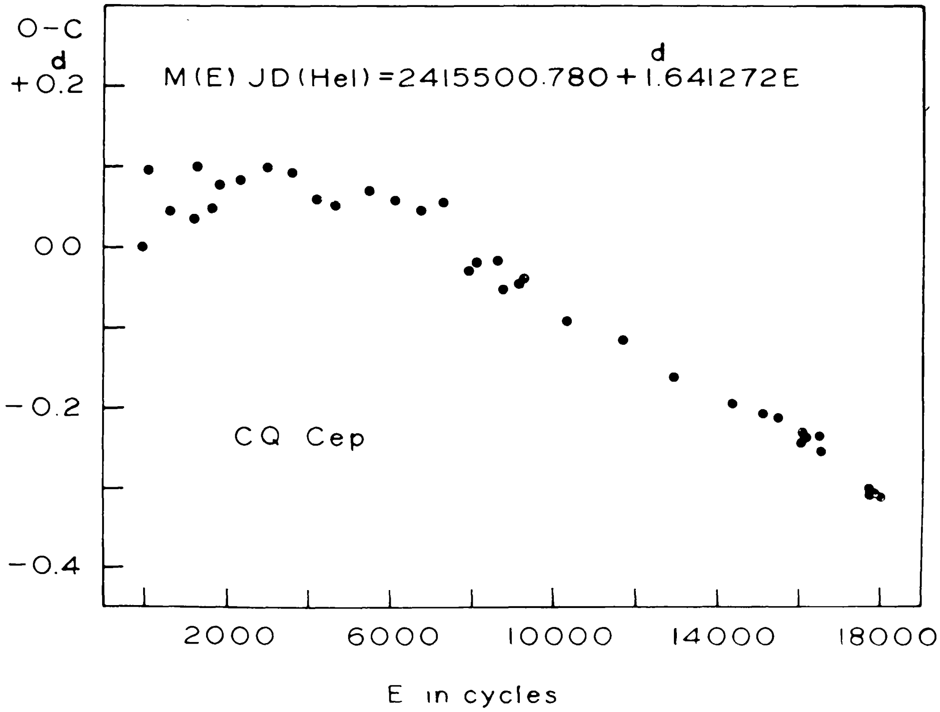

Fig. 1. The O–C curve for CQ Cep between 1899 and 1982. Data are taken from Kreiner and Tremko (1980).

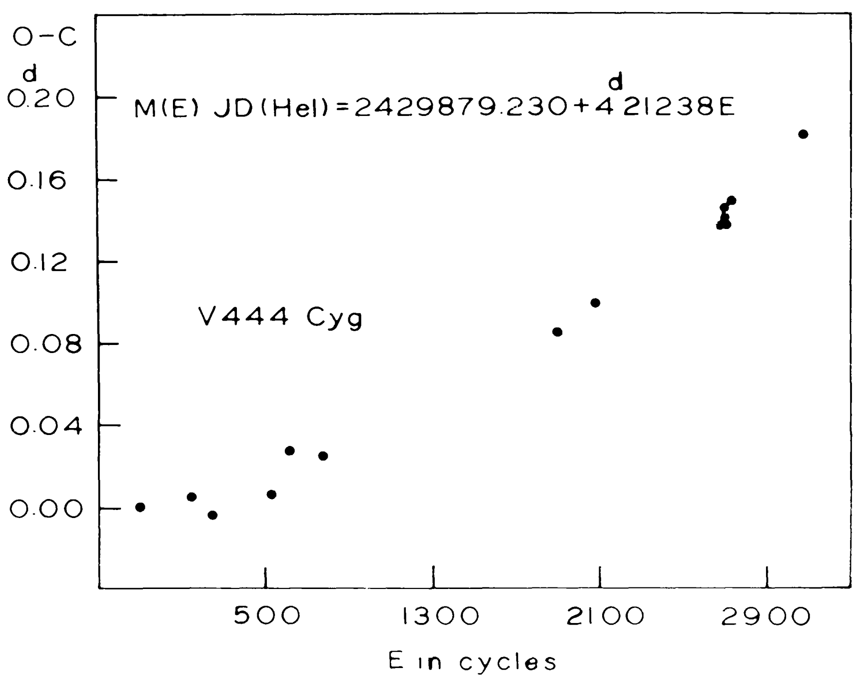

Fig. 2. The O–C curve for V444 Cyg between 1957 and 1981. Data are taken from Cherepashchuk (1982).

is gradually decreasing. The O–C curve (Figure 2) for V444 Cyg between 1957 to 1981 represents an upward parabolic segment which shows that orbital period of the system is gradually increasing.

4. Mass-Loss Rates

From Equations (6), (8), (10), and (12) we have computed the mass-loss rates of the Wolf–Rayet component of the binary stars CQ Cep and V444 Cyg in different models of mass-loss and mass-exchange as described in Section 2. The systemic parameters for both the systems used for computing the $\dot{M}_{\rm WR}$ are given in Table I, wherein masses of the systemic components are taken from Niemela (1980) and Cherepaschchuk *et al.* (1984).

In our calculation the values of the radius of rings are estimated from the Roche model (Kopal, 1978). The $\dot{p}$ with which the orbital period varies with time has been computed from the quadratic terms of Figures 1 and 2. The resulting values of $\dot{M}_{\rm WR}$ for both the stars in all the four models are given in Table II.

TABLE I

Data for the eclipsing binaries CQ Cep and V444 Cyg

	CQ Cep	V444 Cyg
P	$1\overset{\rm d}{.}641$	$4\overset{\rm d}{.}212$
$\dot{P}/P$	1.34×10^{-7} yr^{-1}	6.11×10^{-7} yr^{-1}
Spectral type	WN7 + O7	WN5.5 + O6
$M_1/M_\odot$	31.0	10
$M_2/M_\odot$	25.5	25

TABLE II

Mass loss rates from the Wolf–Rayet components in CQ Cep and V444 Cyg in different models

	CQ Cep	V444 Cyg
Case I	$6.3 \times 10^{-6} M_\odot$ yr^{-1}	$3.4 \times 10^{-6} M_\odot$ yr^{-1}
Case II	$1.2 \times 10^{-6} M_\odot$ yr^{-1}	$10.5 \times 10^{-6} M_\odot$ yr^{-1}
Case III	$1.7 \times 10^{-6} M_\odot$ yr^{-1}	$5.5 \times 10^{-6} M_\odot$ yr^{-1}
Case IV	$3.8 \times 10^{-6} M_\odot$ yr^{-1}	$10.6 \times 10^{-6} M_\odot$ yr^{-1}

5. Discussion of the Results

An inspection of Table II reveals that the values of mass-loss rates of he Wolf–Rayet components computed in different models are different for both the binary stars. We feel that the four models of mass loss from the W–R star may be valid for the idealized cases and perhaps the actual mode of mass ejection is most likely a combination of all the four modes, since the particles ejected from the W–R star are expected to have a wide range of velocities and angular momentum per unit mass. But in order to know the possible dominating mode of mass-loss and mass-exchange, we have to know the basic parameters of the system and also to know whether the ring (envelope) is confined within the critical surface in a dynamical equilibrium or whether it consists of material that is continuously leaving the binary system. One might expect that the light curves of eclipsing the W–R binary star in different emission lines would solve this problem.

The details of our studied W–R binaries are given below:

CQ. Cephei

CQ Cep (WN7 + O7) is an interesting W–R eclipsing binary system. Its orbital period is short ($P = 1\overset{d}{.}6$). The depths of primary and secondary eclipses are $0\overset{m}{.}5$ and $0\overset{m}{.}4$, respectively. Photoelectric photometric light curves, given by Lipunova and Cherepaschchuk (1982), of CQ Cep show that both the components fill their Roche lobes. The extended atmosphere of the system shows up mainly in the form of a common envelope surrounding the entire system and hardly subject to eclipse. The contribution of this extended common envelope to the total luminosity of the system is $L_3(r) = 0.29$. Thus we feel that Case III is the dominating mode of mass-loss and mass-exchange in the system CQ Cep.

V444 Cygni

V444 Cygni (WN5.5 + O6) is one of the best studied eclipsing binaries in which the W–R component has highly extended atmosphere which produces atmospheric eclipse of the O6 star. Kuhi (1968) and Cherepashchuk and Khaliullin (1972) have reported the random photometric variations which are produced by the extended atmosphere located between the components. Recently, Cherepashchuk *et al.* (1984) have suggested that the outflow of material in the expanding atmosphere achieves the velocity $V_0 = 400$ km s^{-1} even at the surface of the thick core, accelerates rapidly between r_0 and 8 $R_\odot$ and slowly approaches the terminal velocity of 2000 km s^{-1} in the region $r > 10\ R_\odot$. Thus we feel that Case II as well as Case IV, as described in Section 2 are the dominating modes of mass loss and mass exchange in the system V444 Cyg.

Acknowledgement

The authors are thankful to Dr M. C. Pande for a critical review of the manuscript and valuable suggestions.

References

Barlow, M. J.: 1982, in C. W. H. De Loore and A. J. Willis (eds.), 'Wolf–Rayet Stars: Observations, Physics, Evolution', *IAU Symp.* **99**, 149.
Cherepashchuk, A. M.: 1982, *Astrophys. Space Sci.* **86**, 299.
Cherepashchuk, A. M., Eaton, J. A., and Khaliullin, K. F.: 1984, *Astrophys. J.* **281**, 774.

Hall, D. S. and Neff, S. G.: 1976, in P. Eggleton, S. Mitton, and J. Whelan (eds.), 'Structure and Evolution of Close Binary Systems', *IAU Symp.* **73**, 283.

Hidayat, B., Admiranto, A. G., and Van der Hucht, K. A.: 1984, in B. Hidayat, Z. Kopal, and J. Rahe (eds.), 'Double Stars: Physical Properties and Generic Relations', *IAU Colloq.* **80**, 175.

Kopal, Z.: 1978, *Dynamics of Close Binary Systems*, D. Reidel Publ. Co., Dordrecht, Holland, p. 312.

Kreiner, J. M. and Tremko, J.: 1983, *Bull. Astron. Inst. Czech.* **34**, 341.

Kuhi, L. V.: 1968, *Astrophys. J.* **152**, 89.

Lipunova, N. A. and Cherepashchuk, A. M.: 1982, *Astron. Zh.* **59**, 944.

Niemela, V. S.: 1980, in M. Plavec, D. M. Popper, and R. K. Ulrich (eds.), 'Close Binary Stars: Observations and Interpretations', *IAU Symp.* **88**, 127.

Paczynski, B.: 1967, *Acta Astron.* **17**, 355.

Paczynski, B.: 1968, in L. Perek (ed.), *Highlight in Astronomy*, D. Reidel Publ. Co., Dordrecht, Holland, p. 409.

Pratt, J. P. and Strittmatter, P. A.: 1976, *Astrophys. J.* **204**, L29.

Wood, F. B., Oliver, J. P., Florkowski, D. R., and Kosh, R. H.: 1980, *A Finding List for Observers of Interacting Binary Stars*, Pennsylvania Press, p. 59.