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ON WOLF-RAYET STARS, BLACK HOLES AND CO-ROTATING BINARY SYSTEMS

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RESUMEN

Se analiza el problema de la formación de agujeros negros en sistemas binarios que corrotan. Se utilizan el valor crítico de a/m de Miller y De Felice y la hipótesis de corrotación para hallar el periodo orbital crítico de un sistema binario con una estrella Wolf-Rayet, justo antes del colapso de ésta. Se comparan estos periodos críticos con datos observacionales para identificar aquellos sistemas WR que puedan engrendrar agujeros negros en el futuro.

ABSTRACT

The problem of black hole formation in a co-rotating binary system is analyzed. The Miller and De Felice critical value of a/m and the co-rotation hipothesis, are used to find critical orbital periods in a Wolf-Rayet system just prior to the collapse of the more evolved star. These critical periods are compared with observational data to find WR binary systems that may produce black holes in the future.

Key words: **BLACK HOLES – STARS-BINARIES – STARS-WOLF-RAYET**

I. INTRODUCTION

The Wolf-Rayet (WR) stars in massive binary sys- :ms are presumed to be progenitors of massive X- ıy binary systems, or systems containing collapsed ɔmpanions (Van den Heuvel 1976). Since some of ıe masses derived for WR members of binary sys- :ms are very large, these stars are good candidates ɔr progenitors of black holes (BH's). Thus, in ad- ition to the interest one may have in the WR phe- omenon itself, an understanding of these stars has ɛlevance to the problem of the existence of BH's in ıassive binary systems.

The general properties and evolutionary scena- .os for the formation of WR stars are described in .bbott and Conti (1987) and Chiosi and Maeder 1986), according to which the massive WR stars volve from O-stars more massive than about 40 $1_\odot$, and consist of He- burning cores with seve- ɛly altered surface chemical abundances: signifi- ant underabundance of H, overabundance of He, nd N or He and C, relative to solar abundances. As ıassive, post- H-main sequence objects their expec- ɛd lifetimes do not exceed a few hundred thousand years, after which they produce a supernova explo- sion.

Black holes are believed to result from the collapse of a massive star, following a supernova explosion. However, there are certain conditions that must be satisfied for the collapse to lead to a BH; in particular, the value of the specific angular momentum at the moment of collapse must be smaller than unity (Abramowicz and Lasota 1980). In itself, this condition does not seem to be a strong restriction for the formation of a BH. However, when one adds to this the generally adopted condition of co-rotation in close binary systems, constraints can be derived that restrict the number of close, massive binary systems in which a BH is allowed to form. In this paper we show that if we assume close binary systems to be co-rotating, and if no more that 40 % of the specific angular momentum of the exploding star is lost (Miller and De Felice 1985), then BH's can form only from binary WR systems with pre-explosion orbital periods larger than 15 days. This would have important consequences on the interpretation of, for example, Cyg X-1, which contains the strongest BH candidate, and where the pre-explosion orbital period has been calculated to be 4.8 days (Sutantyo 1974).

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II. CONSTRAINT ON THE ORBITAL PERIOD IMPOSED BY CO-ROTATION

A corollary of the third law of thermodynamics of black holes (Abramowicz and Lasota 1980) states that the ratio of specific angular momentum to gravitational mass must be less than unity in order for the black hole to form: i.e.,

$$\frac{a}{m} < 1 \quad , \qquad (1)$$

with

$$a = \frac{l}{cm} \qquad m = \frac{Gm}{c^2} \quad ;$$

where

l = angular momentum, c = speed of light, m = rest mass of the BH, and G = gravitational constant.

This restriction applies to the stellar remnant undergoing final collapse following the supernova explosion; i.e., once the ejecta has carried away a fraction of the specific angular momentum and mass. If the assumption is made that the amount of specific angular momentum and mass removed from the immediate progenitor is not constrained, then the condition $a/m < 1$ can always be achieved. However, Miller and De Felice, (MD, 1985) have shown that the pre-supernova value of a/m cannot be reduced by a factor larger than 2.5. This means that, in order for the collapse to lead to a black hole, the following condition on the immediate progenitor star (just prior to the supernova event) must be satisfied:

$$\frac{cl}{Gm^2} < 2.5 \quad . \qquad (2)$$

This restriction applies under the following assumptions (MD):

1. The gravitational collapse is treated as that of a rotating fluid with axial symmetry.
2. The stellar magnetic field, pressure gradients, and energy losses by gravitational radiation are not taken into account.
3. The star is a rigid rotator.
4. Redistribution of angular momentum does not occur during collapse.

Using $l = I\omega$, $\omega = 2\pi/T$, one finds a critical rotation period for the pre-supernova star from (2):

$$T_c > \frac{2\pi Ic}{2.5Gm^2} \qquad (3)$$

Thus, given the MD assumptions, a star rotatin with $T < T_c$ just prior to the supernova explosio cannot engender a black hole.

If we consider a binary system consisting of tw massive ($M_1, M_2 > 40\ M_\odot$) stars, the hypothesis o co-rotation is represented by:

$$\frac{\Omega}{\omega} = 1 \quad , \qquad (4$$

where Ω is the orbital period of the system, and ω is the rotation period of the less massive of the tw stars. If we now identify T_c with the orbital period condition 3 can be used to obtain a lower bound o the orbital periods of potential progenitors of binar systems containing black holes:

$$T_{orb} = T_c > \frac{2\pi Ic}{2.5Gm^2} \quad . \qquad (5$$

III. APPLICATION TO WR BINARY SYSTEMS

Let us consider a binary system consisting o a massive star which has not evolved far beyonc the main sequence, and a less massive star whicl has reached its final evolutionary stages, and whicl we will identify as a Wolf-Rayet star. The latter i assumed to be a star consisting mostly of He.

The moment of inertia, I, in (5) is defined as

$$I = \int \rho r^2 dv \quad ;$$

where $\rho(r)$ is the interior density structure of the H star. Three different density profiles were adopted a constant density, one that decreases linearly fron the center to the surface, and one which decrease exponentially. These density profiles were adoptec so as to be consistent with the assumptions of MI (i.e., rigid rotation) and to illustrate the dependenc of T_c on the interior density distribution. The mos realistic of these $\rho(r)$ distributions is the exponentia one, according to the model of the 8 $M_\odot$ core of 22 $M_\odot$ star just prior to final collapse illustrated b Schramm (Figure 2 in Iben, Renzini and Scharmn 1977). In column 2 of Table 1 we list the moments o inertia derived for each of these density profiles. I column 3 we present the corresponding expression for T_c (in units of days). The values of T_c, as function of the mass are plotted in Figure 1a (th same curves are replotted in Figures 1b-1d), wher we have used the masses and radii of model He star given by Divine (1965) and Langer (1989). Thes curves represent the smallest orbital period a binar system can have, for a given mass of the WR sta and where the post-supernova stellar remnant ca collapse into a black hole. Since the mass of th

TABLE 1

CRITICAL PERIODS FOR THE DIFFERENT INTERIOR DENSITY DISTRIBUTIONS

Density	M.Inertia	T_c (days)
$\rho = \rho_0 = \text{const.}$	$\frac{2}{5}MR_*$	$T_c = 12.76\,(R/R_\odot)^2(M/M_\odot)^{-1}$
$\rho = \rho_0(1 - r/R_*)$	$\frac{8}{90}\pi\rho_0 R_*^5$	$T_c = 63.36\,(R/R_\odot)^2(M/M_\odot)^{-1}$
$\rho = \rho_0^{-\frac{r}{R_*}}$	$\frac{9}{100}\pi\rho_0 R_*^5$	$T_c = 260.36\,(R/R_\odot)^2(M/M_\odot)^{-1}$

TABLE 2

POSSIBLE BH PROGENITOR SYSTEMS ASSUMING AN EXPONENTIAL INTERIOR DENSITY DISTRIBUTION

Number	Name	Mass WR	Ref.	Period (days)
1	CVSer	13–15 $M_\odot$	1,2	29.71
2	γ^2 Vel	18–19 $M_\odot$	1,2	78.50
3	HD 1909	18 15 $M_\odot$	1	112.80

1) Schulte-Ladbeck (1989); 2) Smith and Maeder (1989).

:jecta of Type II supernovae has been estimated o be 5 $M_\odot$, (Chevalier 1977), this means that the ›ossible black hole progenitors must have masses arger than 8 $M_\odot$ given an upper limit of 3 $M_\odot$ to he mass of neutron stars (White 1989). This means hat only in binary systems with $T_c > 15$ days will òrm a black hole, adopting the exponential interior lensity distribution.

The observational data for WR stars are also ›lotted in Figures 1a-1d, each figure containing the lata presented by different authors (1a, De Greve ınd De Loore 1975; 1b, Sutantyo and Dermawan .981; 1c, Schulte-Ladbeck 1989; and 1d, Smith ınd Maeder 1988). The dotted line at 8 $M_\odot$ is the ıbove mentioned lower limit for the BH progenitor nass. The curve corresponding to an exponential nterior density distribution provides the strongest :onstraint on the possible progenitors of BH's, and n Table 2 we list the three WR systems which ›atisfy these conditions. If one adopts a constant nterior density distribution, the number of possible 3H progenitors increases significantly; these are isted in Table 3 according to the data of Smith and Maeder (1989), However, as pointed out above, this lensity distribution is not realistic.

Also plotted in Figures 1a-1d is the position ›f the progenitor of Cyg X-1 as derived by the :alculation of Sutantyo (1974), and which is in ›trong contradiction with the fact that this binary system is the one most likely to contain a black hole, assuming an exponential interior density distribution.

TABLE 3

POSSIBLE BH PROGENITOR SYSTEMS ASSUMING A CONSTANT INTERIOR DENSITY DISTRIBUTION

Number (WR)	Name (HD)	Mass WR ($M_\odot$)	Period (days)
9	63099	10	14.70
11	68273	19	78.50
21	90657	12	8.26
42	97152	11	78.50
47	E 311884	43	6.34
79	152270	7	8.89
127	186943	16	9.56
133	190918	15	112.80
148	197406	60	4.32
153	211853	14	6.69

IV. DISCUSSION AND CONCLUSIONS

Given two assumptions: 1) The maximum value of a/m for the progenitor of a black hole cannot exceed 2.5 and 2) the progenitor binary system is co-rotating, we find that only three WR binary systems

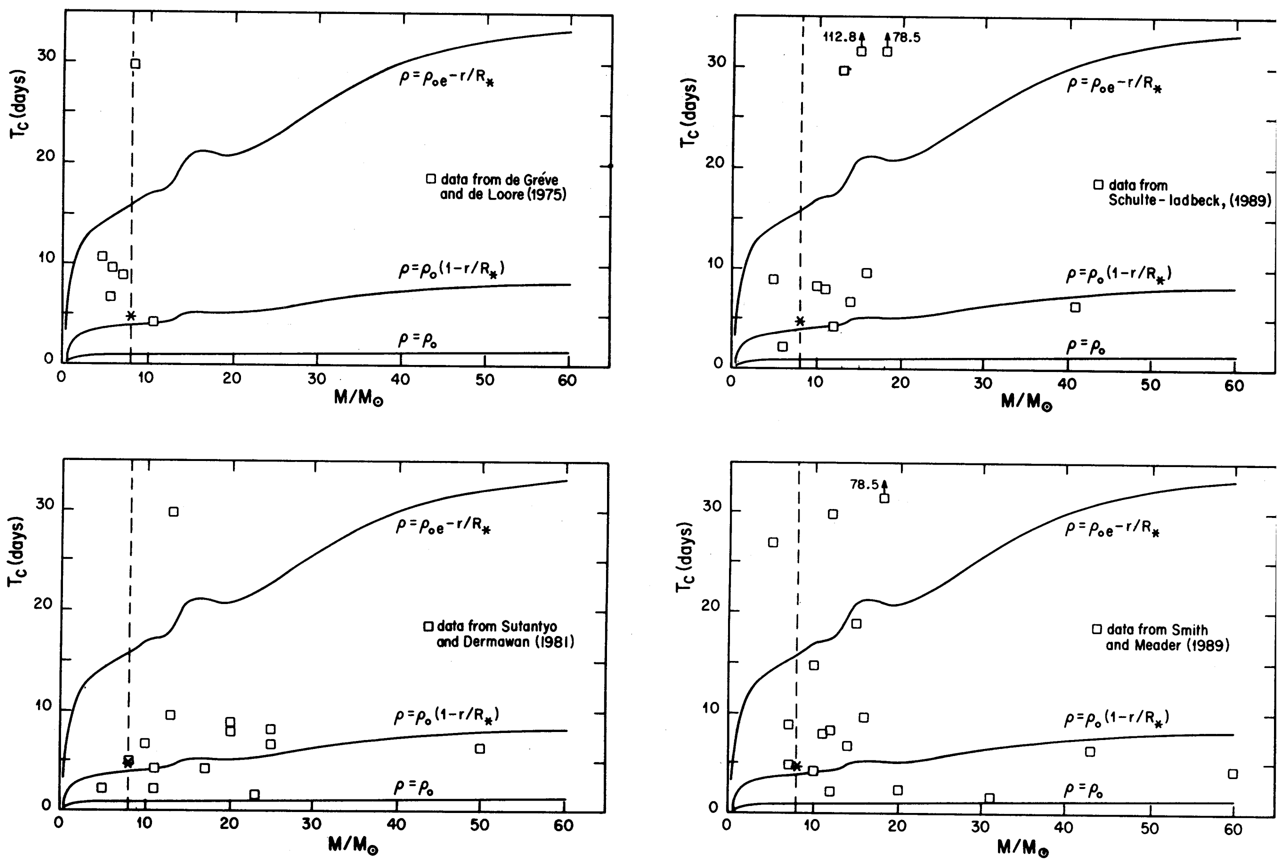

Fig. 1. Curves of critical T_c as a function of the progenitor's mass (i.e., the mass just prior to the final collapse and SN explosion), with the positions of the WR stars according to data of a) De Greve and De Loore 1975; b) Sutantyo and Dermawan 1981; c) Schulte-Ladbeck 1989; d) Smith and Maeder 1989. A * indicates the position of the progenitor of Cyg X-1 (Sutanyo 1974). This figure has been adapted from Mosqueda (1990).

have orbital periods which satisfy the constraint for the formation of a black hole. However, these same constraints lead to a major contradiction when applied to Cyg X-1.

The calculation of the predicted T_c *vs* mass shown in Figures 1 is based on these two assumptions, the weaknesses of which we now point out.

The first assumption is that the MD results for the maximum amount of specific angular momentum lost by the system are realistic. This leads to the adoption of the assumptions used by MD (listed in §II) for our analysis, and in particular, that of rigid rotation. However, if the pre-supernova stellar object is undergoing differential rotation, the redistribution of specific angular momentum during collapse becomes more probable. Although a reanalysis of the MD assumptions and analyses goes beyond the scope of this paper, we find that increasing the critical value of a/m to 12.5 (rather than 2.5) prior to collapse "allows" Cyg X-1 to contain a black hole and most of the WR binaries to form one regardless of the interior density distribution adopted. Indeed, MD note that differential rotation probably would tend to increase the critical a/m and gravitational radiation could decrease this value.

The second assumption is that the binary system is co-rotating prior to the supernova explosion. The hypothesis of co-rotation in close binary systems is based on the work of Zahn (1966a,b,c,; 1975), van den Heuvel (1967), Lea and Margon (1973), and Sutantyo (1974), and applies to stars in or close to the main sequence. The phenomena associated with the evolution of a main sequence star towards a WR star are not yet well understood. In particular, the mechanisms by which an extraordinary fraction of the progenitor's mass is removed in order to expose inner, nuclear processed layers have not been studied in detail (the mass loss by stellar winds, as currently observed, cannot account for the removal of 70 – 80% of a progenitor star's mass). Is is not clear whether the resulting WR star may be rotating with a period shorter than or larger than the orbital period. As pointed out by an anonymous referee, as the helium core contracts from a less dense progenitor that may be have been in co-rotation, its rotation period will tend to speed up. However, as the WR star evolves, the presence of magnetic fields (Maheswaran and Cassinelli 1988) in addition to tidal interaction can lead to an increase of the orbital period. Furthermore, the probable episodic large mass lose events leading to the final stages of the WR phase can carry away angular momentum, slowing it down even more.

We thus conclude that before one can attempt to predict which WR systems can engender a black hole, one must have a better understanding of the evolution of close binary systems, and especially those aspects concerning the way in which the specific angular momentum of the WR component evolves with time.

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