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WHITE DWARF FORMATION IN TWO-BODY SYSTEMS: SIRIUS AB, PROCYON AB, 40 ERI BC AND STEIN 2051 AB

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RESUMEN

Se examinan las historias orbitales de los sistemas Sirio AB, Proción AB, 40 Eri BC y Stein 2051 AB. Se supone que los cambios en los elementos orbitales son el resultado directo de la pérdida de masa de la componente progenitora de la enana blanca.

La suposición de que esta pérdida de masa es isotrópica y que no hay intercambio de masa entre las componentes, junto con las historias orbitales, las abundancias atmosféricas observadas, edades teóricas y tiempos de enfriamiento nos llevan a la conclusión que estrellas tan masivas como $10M_\odot$ pueden ser progenitoras de enanas blancas. En efecto, en el caso de Sirio B hay evidencia que la masa de la progenitora no era menor de $8M_\odot$ y que la estrella no perdió masa en forma explosiva.

ABSTRACT

The orbital histories of the systems Sirius AB, Procyon AB, 40 Eri BC and Stein 2051 AB are examined. It is assumed that the changes in the orbital elements are a direct result of mass loss from the white dwarf precursor component. This loss is considered to be isotropic and no exchange between the components is allowed. These histories, coupled with observed atmospheric abundances, theoretical ages and cooling times lead to the conclusion that stars as massive as $10M_\odot$ can be white dwarf progenitors. Indeed, in the case of Sirius B, there is evidence that the progenitor mass was not less than $8M_\odot$ and that the star did not lose mass in an explosive manner.

The present masses of four white dwarfs are nown because of their membership in visual binary ystems: Sirius B ($1.0M_\odot$), Procyon B ($0.6M_\odot$), 0 Eri B ($0.4M_\odot$), and Stein 2051 ($0.48M_\odot$). tars of initial mass equal to or less than one solar iass have not had sufficient time to complete the on-degenerate phases of their evolution. Hence, ie above white dwarfs must represent the remnants f more massive precursor stars which lost mass in ome manner prior to their present configurations. t is the purpose of this investigation to determine hether or not the possible dynamical histories of hese four systems might place limits on the allowed recursor masses.

Hadjidemetriou (1963) has provided a general nalysis of the behavior of the elements of an lliptical orbit when one component of a two body ystem is losing mass isotropically with no exchange of matter between the two components. The rate of mass loss is not restricted and the analysis applies to orbits with a non-zero initial eccentricity.

The time derivatives of the four relevant orbital elements are given by:

$$\frac{da}{dt} = -a\,\frac{1 + 2e\cos\nu + e^2}{1 - e^2}\,\frac{d}{dt}(\log M_t) \qquad (1)$$

$$\frac{de}{dt} = -(e + \cos\nu)\,\frac{d}{dt}(\log M_t) \qquad (2)$$

$$\frac{d\omega}{dt} = -\frac{\sin\nu}{e}\,\frac{d}{dt}(\log M_t) \qquad (3)$$

$$\frac{d\nu}{dt} = \frac{c(1 + e\cos\nu)^2}{a^2(1 - e^2)^2} - \frac{d\omega}{dt} \qquad (4)$$

with the areal constant

$$c = [GM_t (1 - e^2)]^{1/2}. \quad (5)$$

Where a = semi-major axis,

e = eccentricity,

ω = longitude of periastron,

ν = true anomaly, and

M_t = total mass of the system.

Equations (1) through (4) have been solved numerically using a self-starting predictor-corrector scheme by Hamming (Ralston and Wilf 1960). The overall numerical error has been held to less than 0.01% with the determination of e and ν receiving the greatest weight. Three loss rates were considered: *i*) impulsive at periastron ($\nu = 0°$), *ii*) impulsive at apastron ($\nu = 180°$), and *iii*) slow loss over periods of 10^3 years or more. Impulsive loss is defined to occur in a time interval of 10^{-2} of the initial orbital period. Families of solutions were generated for many initial values of a_i, e_i, ν_i, ω_i, $M_{t,i}$, and the loss rate.

Tables 1 through 3 contain those initial conditions which will give rise to the presently observed orbital and mass parameters for Sirius AB, Procyon AB and 40 Eri BC, respectively. It must be emphasized that there are virtually an infinite number of initial configurations which will result in stable orbits after the postulated mass loss but only those shown will result in the present orbits for the chosen precursor mass ratios m'_B/m_A. In the "slow" loss case T_L is the time interval over which the mass is lost. The initial semi-major axes and eccentricities shown for this case are independent of T_L as long as $T_L \gg$ the orbital period. An increase in the initial semi-major axis accompanies mass loss in every instance. The behavior of the change in orbital eccentricity is more complex with an increase to the precursor value always occuring for impulsive loss at periastron, no change occuring for "slow" loss, and either an increase or decrease allowed for impulsive loss at apastron depending on the value of the initial semi-major axes. Finally, those tabular entries for which an asterisk appears beside the precursor mass, m'_B, should not be considered as possible initial configurations since m'_B is either $\leq 1 M_\odot$ or $\leq m_A$. Our present understanding of the processes of stellar evolution make it unlikely that stars of one sola mass or less will have had time to evolve to th white dwarf stage nor is it likely that the le: massive member of a visual binary system will evolv faster than the more massive component.

The selection of allowed initial configurations fo the system Stein 2051 AB is uncertain since th system has been insufficiently observed to determin the relative orbit. However, while describing a arc of 64° since 1908 (Strand 1977), the separatio has changed very little. For the same reason may be assumed that the present separation, 7".: is very close to the actual angular semi-major axis c the system. Using a parallax of 0".185 yields a = 37. AU. Strand gives the mass of the white dwai primary as $0.48 M_\odot$ if the secondary has a mass c $0.22 M_\odot$ as indicated by its luminosity and spectra type. A third, dark companion of mass $0.01 M_\odot$ als seems to be present but it will have little effect o the dynamical evolution of the AB components an will not be considered further.

The orbital and mass parameters applicable t Stein 2051 AB are thus similar to those of 40 E BC and the allowed precursor states given in Table may be appropriate for both systems. It is, of cours possible that Stein 2051 AB has an orbital eccentri ity significantly less than 0.4. An assumption tha at present, the eccentricity is 0.1 yields no stabl initial values of a_i and e_i for impulsive mass lo: at periastron with the precursor mass, $m'_A \geq 0.$: Impulsive loss at apastron does allow many initi orbital configurations with e_i ranging from 0.45 a 50% mass loss to 0.91 at 90% loss. Over the sar mass loss range a_i goes from 26.9 AU to 17.4 AU Slow loss requires $e_i = 0.1 (e_f)$ at all loss rates an a_i takes nearly the same allowed values as thos shown in Table 3, column 8.

It is of interest at this point to consider wheth the permitted precursor models for the four systen might allow mass to have been exchanged betwee the components. If, during the red giant phase of i evolution, the pre-white-dwarf component expanc to fill its Roche lobe then an orderly transfer matter to its companion may take place. The positio of the inner Lagrangian point will vary with th separation of the two stars as well as with their ma ratio. In an elliptical orbit the separation is co

TABLE 1

SIRIUS A/B

$m_A = 2.2M_\odot$ (Al V) $m_B = 0.96M_\odot$ (DA·) $a = 20.1$AU $e = 0.595$

$\Delta m_T / m_T$	m'_B	Impulsive-Periastron a_i	Impulsive-Periastron e_i	Impulsive-Apastron a_i	Impulsive-Apastron e_i	"Slow" loss T_L	"Slow" loss a_i	"Slow" loss e_i
0.10	*1.31$M_\odot$	14.2AU	0.445	19.2AU	0.635	3.6×10^4 years	17.7AU	0.6
0.20	*1.75	11.3	0.282	18.9	0.676	2.9×10^4	16.0	0.6
0.30	2.31	9.4	0.120	18.5	0.715	2.2×10^4	14.1	0.6
0.40	30.7			18.1 7.5	0.757 0.037	1.7×10^4	12.1	0.6
0.50	4.12	NO STABLE INITIAL VALUES		17.7 6.7	0.797 0.200	1.1×10^4	10.1	0.6
0.60	5.70			17.3 6.0	0.838 0.358	7.2×10^3	7.9	0.6
0.70	8.33			17.0 5.3	0.879 0.518	4.1×10^3	6.0	0.6
0.80	13.60			16.6 4.8	0.917 0.721	1.8×10^3	4.0	0.6
0.90	29.40			16.3 4.2	0.960 0.862	1.1×10^3	1.9(+)	0.58(+)

* Unilikely precurser due to evolutionary considerations.

TABLE 2

PROCYON A/B

$m_A = 1.8M_\odot$ (F4V·) $m_B = 0.6M_\odot$ (DF) $a = 15.8$AU $e = 0.40$

$\Delta m_T / m_T$	m'_B	Impulsive-Periastron a_i	Impulsive-Periastron e_i	Impulsive-Apastron a_i	Impulsive-Apastron e_i	"Slow" loss T_L	"Slow" loss a_i	"Slow" loss e_i
0.10	*0.86$M_\odot$	12.8AU	0.269	15.1AU	0.463	2.9×10^4 years	13.9AU	0.4
0.20	*1.20	10.7	0.130	13.7	0.523	2.3×10^4	12.6	0.4
0.30	*1.63			14.0 9.0	0.582 0.017	1.8×10^4	11.1	0.4
0.40	2.20			13.5 8.2	0.642 0.158	1.3×10^4	9.6	0.4
0.50	3.00			13.0 7.3	0.700 0.300	9.2×10^3	7.9	0.4
0.60	4.20	NO STABLE INITIAL VALUES		12.5 6.6	0.762 0.438	5.7×10^3	6.2	0.4
0.70	6.20			12.0 5.9	0.822 0.579	3.2×10^3	4.7	0.4
0.80	10.20			11.6 5.4	0.882 0.720	1.5×10^3	3.2	0.4
0.90	22.20			11.2 4.8	0.941 0.863	1.0×10^3	1.6	0.39

* Unlikely precurser due to evolutionary considerations.

TABLE 3

40 ERI B/C

$m_B = 0.4M_\odot$ (DA) $m_C = 0.2$ (M6e) $a = 33.6$AU $e = 0.40$

$\Delta m_T / m_T$	m'_B	Impulsive-Periastron a_i	Impulsive-Periastron e_i	Impulsive-Apastron a_i	Impulsive-Apastron e_i	"Slow" loss T_L	"Slow" loss a_i	"Slow" loss e_i
0.10	*0.46$M_\odot$	27.3AU	0.269	32.2AU —	0.463 —	1.8×10^5 years	29.6AU	0.4
0.20	*0.55	22 5	0.130	30.9 —	0.523 —	1.4×10^5	26.7	0.4
0.30	*0.66	NO STABLE INITIAL VALUES		29.8 19.1	0.582 0.017	1.1×10^5	23.6	0.4
0.40	*0.80			28.7 17.2	0.642 0.158	8.2×10^4	20.3	0.4
0.50	*1.00			27.6 15.5	0.700 0.300	5.7×10^4	16.8	0.4
0.60	1.30			26.7 14.0	0.762 0.438	3.5×10^4	13.3	0.4
0.70	1.80			25.6 12.6	0.822 0.579	2.0×10^4	10.0	0.4
0.80	2.80			24.7 11.4	0.882 0.720	9.0×10^3	6.7	0.4
0.90	5.80			23.8 10.3	0.941 0.863	6.6×10^3	3.3	0.39

* Unikely precurser due to evolutionary considerations.

stantly changing and transfer of matter may not take place over the entire orbit. Hence, the average and apastron— using Paczyński's (1971) interpolation radius, r, of the primary star's Roche lobe is calculated at the two extremes of separation —periastron formula

$$\frac{r}{A} = 0.38 + 0.2 \log \frac{m'_B}{m_A}$$

with A = the instantaneous separation of the components,

m'_B = mass of the white dwarf precursor star (primary), and

m_A = mass of the secondary.

Table 4 gives the results of these calculations for Sirius B, Procyon B and 40 Eri B. The entries for the latter star should also apply to Stein 2051A. The instantaneous Roche lobe radii are given in columns three and four for periastron and apastron, respectively, under the assumption that mass was lost in the "slow" mode. The last column gives expected red-giant radii for the precursor masses in column two. These radii are taken from the empirical mass-radius relation for late-type stars by Reimers (1973).

Since the initial orbit calculations did not include effects of mass exchange, a discussion of the entries in Table 4 cannot have a high quantitative accu-

TABLE 4

ROCHE LOBE RADII AND STELLAR RADII FOR PRECURSOR STARS

Star	m'_B ($M_\odot$)	r_p(au)	r_a(au)	R_*(au)
Sirius B ($m_A = 2.2\ M_\odot$)	29.4	0.5	1.9	$\geqq$7.4
	13.6	0.9	3.4	~2.2
	8.3	1.2	4.8	~0.8
	5.7	1.5	5.8	~0.3
Procyon B ($m_A = 1.8M_\odot$)	22.2	0.6	1.3	~7.0
	10.2	1.0	2.4	~1.2
	6.2	1.4	3.2	~0.4
40 Eri B ($m_A = 0.2M_\odot$)	5.8	1.3	3.1	~0.3

acy but some qualitative insight is possible. In he case of Sirius AB, a precursor mass of $29.4M_\odot$ vould have filled its instantaneous Roche lobe at ll points in the orbit and a large quantity of mass night have transferred to Sirius A. This seems unkely since Sirius A could have accepted at most .$2M_\odot$ with the remaining $26.2M_\odot$ of Sirius B being ost in some manner without transfer. The difficulty s eased somewhat for a precursor mass of $13.6M_\odot$ ince mass would only be transferred near periastron assage. For an orbit of eccentricity 0.6 the time luring which transfer could take place would be small portion of the total orbital period. Again ssuming a maximum transfer of $2.2M_\odot$ to Sirius A, total of $10.4M_\odot$ must then be removed from the ystem. Finally, at precursor masses equal to or less han $8.3M_\odot$ the probability of transfer through the nner Lagrangian point becomes quite small at all oints in the orbit. If the observed overabundance f s-process elements in Sirius A (Latham 1970) is nterpreted as an enrichment due to transfer of natter from the precursor of Sirius B, we may conlude that this precursor had a mass greater than $M_\odot$. Such a lower limit would be consistant with cooling time for Sirius B of less than 2×10^8 ears (Koester 1972) and an age for Sirius A rangng from 1.6×10^8 years based on membership in he Sirius group (Eggen 1960) to a maximum of pproximately 4.8×10^8 years based on Iben's (1967) tellar lifetimes for metal-rich stars. Of course, it nay have been the case that the transfer took place n an impulsive mode or that Sirius A has been netal-rich since birth. A detailed investigation of hese alternative explanations is being undertaken.

Studies of elemental abundance in Procyon A (Greenstein 1948, Powell 1970) indicate a comosition like that of the sun. Thus it would seem hat no mass transfer ever took place and a precursor nass of $22.2M_\odot$ for Procyon can be eliminated. Even if m'_B were as large as $10.2M_\odot$ there might ave been some transfer. Hence an upper limit of pproximately $10M_\odot$ may apply to the precursor nass of Procyon B. Powell (1970) shows that Procyon A falls near the 1×10^9 year isochrone n the H-R diagram while cooling times for Procyon B (Koester 1972) would be approximately 1.3×10^9 years for a Mg interior, 2.5×10^9 years for a carbon interior and 4.0×10^9 years for a He interior. The concordance of the age of Procyon A with the cooling time of Procyon B for Mg or C composition would argue for a large precursor mass and is consistant with the upper limit of $10M_\odot$ given above.

In the systems 40 Eri BC and Stein 2051 AB the present white dwarf is the primary component, being twice as massive as the companion in both cases. The small masses of the companions and wide separations of the systems would tend to rule out much, if any, mass transfer between the components at any time in the past for precursor masses up to at least $6M_\odot$.

We may conclude that the dynamical histories of these four systems strongly indicate quite massive ($\leq 10M_\odot$) precursors for the observed white dwarf components. Indeed, in the case of Sirius AB, a lower limit of $8M_\odot$ is applicable if the metal enrichment in the atmosphere of Sirius A is the result of material transfer from a red-giant Sirius B rich in s-process elements. As Latham (1970) points out, the atmosphere of Sirius A is not rich in r-process elements, and thus it is likely that Sirius B evolved from a massive star which did not go through a phase of explosive mass ejection.

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DISCUSSION

King: In the case of Sirius B, you can apply much stronger evolutionary considerations to determine the mass of the precursor uniquely. Sirius is a member of the Ursa Major moving group, and we know its age fairly well. Also from white-dwarf cooling theory we know how long Sirius B has been a white dwarf. (This is not very long, of course). When these numbers are put together, they will give a mass for the Sirius B precursor that is just a little larger than the mass of Sirius A, and you can therefore reduce your Sirius table to a single line. A second remark concerns white dwarfs in general. In considering them, we should keep in mind that Sirius B and Procyon B are not typical cases; they are prominent in our studies presumably because of an observational selection that makes them easier to discover than stars like o^2 Eri B or Stein 2051 A. Statistical studies of evolutionary tracks and of numbers of stars indicate that most of the white dwarfs in the field have middle-main-sequence precursors and therefore belong to older systems than Sirius or Procyon.

Evans: I believe that there is a strong historical condition that Sirius was once red, and it is just conceivable that you could bring this fact in to reduce the range of possibilities you have found.

Huang: I would like to make a comment on the ejection mechanism. What you have said of the fast mode of ejection is only mathematically correct because it means that as soon as the mass has left the star, it is no longer interacting with the system. Physically this is not true, because the physical velocity is limited by the speed of light. There is no such thing as the fast mode, namely, mass loss due to radiation. Consequently, the results derived from the fictional fast mode have little physical meaning. The computer is a very useful thing. I use it frequently. But you must have a physical problem clearly defined before you undertake computation. The electronic computer is fast but has no brain. Sorry for this blunt remark.

Abt: The problem of whether a binary system can survive an evolutionary stage in which one component expanded to a size much larger than its Roche lobe is shared with the common novae which Kraft found to be binary systems with periods of four to six hours; one component in each system is an evolved star, such as a white dwarf, that at one time greatly exceeded its present Roche lobe in size.

Strand: In reference to the orbit of Stein 2051 only a very approximate orbit can be determined, since the change of position angle from the first observations in 1908 to the present is only 65 deg. The separation has remained nearly the same, at 7 arcsec. The most likely orbit has a period of 300 years, a semi-major axis of 7 arcsec, and an eccentricity equal to 0.3.

Scarfe: Have you considered the question of the mechanism of mass loss? In particular, could it be that it is by recurrent nova explosions, and would this fit between your extreme cases of continuous and discontinuous mass loss?

Roark: If the mass lost in an explosion is small, as is usually the case for recurrent novae, and if there are many such small losses, then the situation would closely approach what I have called the "slow" case. Significant loss in an explosion, repeated over many explosions, would probably provide initial configurations somewhere between the results for "slow" loss and impulsive loss at apastron.

Scarfe: An attempt has been made by Lauterborn to interpret Sirius as Case C of mass exchange.

Roark: I am not familiar with the details of this paper, though we should keep in mind that Sirius A/B is widely separated and probably always has been. Thus, unless the precursor mass of the white dwarf was quite large, 20 to 30 solar masses, this paper would tend to rule out the possibility of any mass exchange.

Scarfe: Tinsley has discussed the white dwarfs in the Hyades and has referred to the possibility of there being one in the Pleiades. If true, this sets a high upper limit on the mass of a precursor of a white dwarf. Can you or anyone here confirm the membership of this star in the Pleiades?