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MASS LOSS AND THE FORMATION OF WHITE-DWARF STARS

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ABSTRACT

The presence of white dwarfs in the Hyades and a suspected one in the Pleiades indicate that stars with masses greater than 2 5 $M_\odot$, and possibly 7 $M_\odot$, can become white dwarfs Calculations show that the excess mass cannot be lost merely through rotational shedding if the star always rotates like a solid body. Consideration of wide pairs containing a white dwarf indicates that mass is probably lost on a time scale greater than 10^4 years. Nuclear fuel must be the major source of energy for mass ejection, although in the case of too massive stars it will be insufficient to eject enough mass to permit a stable white-dwarf configuration. It is noted that the minimum masses for helium and carbon burning are comparable with the observed mean mass of white dwarfs, indicating that mass loss continues until nuclear burning ceases.

I. INTRODUCTION

It is apparent that at some time prior to the formation of white dwarfs there is substantial mass loss. Theoretically the upper limit to the mass of such a star is 1.4 $M_\odot$, and observationally all white dwarfs with measured masses are less than 1 $M_\odot$. Yet there are white dwarfs in the Hyades cluster, although the stars there presently evolving from the main sequence have a mass of 2 $M_\odot$.

The mass may depart slowly or rapidly. Deutsch (1956) has pointed out that slow mass loss from red giants may be the dominant form of mass loss. On the other hand, Chandrasekhar (1941) and Hoyle (1946) have suggested that mass may be lost rapidly, for example, in a supernova explosion, or possibly by equatorial shedding from a rotationally unstable star.

Supernova explosions are so rare in our Galaxy that only a small fraction of stars initially more massive than white dwarfs could be evolving this way. Furthermore there is some evidence that at least one supernova explosion (the Crab Nebula explosion) has not produced a white-dwarf remnant (Hoyle, Fowler, Burbidge, and Burbidge 1964).

In this paper we discuss several aspects of the mass-loss process as they relate to the formation of white dwarfs. We do not consider the evolution of an interacting binary which has been discussed by Kraft (1963) as a possible stage in the development of a nova.

II. STARS THAT BECOME WHITE DWARFS

There are twelve white dwarfs known to be members of the Hyades cluster, and this total is probably incomplete (Luyten 1964; Eggen and Greenstein 1965). One white dwarf is a suspected member of the Pleiades cluster (Luyten and Herbig 1960).

The twelve white dwarfs and four yellow giants in the Hyades will have previously extended its main sequence by 0.8 mag. Stars presently at the turn-off point have masses of about 2 $M_\odot$, and the initially most massive white dwarf will have been about 1.3 times as massive. If more white dwarfs are found in the cluster this factor will increase. Thus some white dwarfs had initial masses as high as 2.5 $M_\odot$, possibly higher. The Pleiades white dwarf is less certainly a cluster member. The proper motions of nearby field stars are similar to the motions of true cluster stars; however, the white dwarf has an apparent magnitude consistent with it being a member. Stars at present evolving from the main sequence of the Pleiades have masses of 5 $M_\odot$. If the white dwarf is really a cluster member, its initial mass was at least 7 $M_\odot$. On this evidence we assert that stars of 2.5 $M_\odot$ succeed in shedding enough mass to become white dwarfs, and that possibly stars of 7 $M_\odot$ also succeed.

These figures are consistent with the number of stars that do not become white dwarfs but instead become supernovae. Stothers (1963) estimates from the frequency of supernovae in our Galaxy that all stars more massive than 5–18 $M\odot$ become supernovae.

III. ROTATIONAL INSTABILITY

It has been suggested by both Chandrasekhar (1941) and Hoyle (1946) that stars might lose sufficient mass to become white dwarfs because of their high initial angular momentum. A shrinking star will become equatorially unstable and shed mass as its radius decreases. We have determined how the path of a shrinking star would intersect the white-dwarf mass-radius relationship.

TABLE 1

RADII OF GYRATION

Polytropic Index	k^2	$2/k^2-3$
1 5	0 205	7
1 5 with rotational correction	135	12
3 0	076	23
3 0 with rotational correction	0 038	50

TABLE 2

PARAMETERS ASSUMED FOR MAIN SEQUENCE

Spectral type	F0	A0	B8	B5	B3
Radius ($R\odot$)	1 5	2 1	2 4	3 4	4 7
Mass ($M\odot$)	1 7	2 2	2 8	5 0	10 0
Equatorial velocity (km/sec)	100	200	233	233	200
Initial value of k^2	0 075	0 075	0 075	0 075	0 075

The loss of mass from a shrinking, rigidly rotating star has been calculated by Schatzman (1960). A star shrinks until it becomes equatorially unstable, and when it becomes unstable equation (1) is fulfilled.

$$\alpha G M^3 k^4 r_e = \Gamma^2 \; ; \tag{1}$$

M is the mass of the star, Γ is its angular momentum, k is the radius of gyration in units of the equatorial radius r_e, and α is a factor dependent on the stellar model, but calculation shows that it is approximately unity. According to Schatzman (1960), once the star becomes equatorially unstable its mass and radius will decrease in the manner

$$\log (r_e/r_{\text{crit}}) = [(2/k^2) - 3] \log (M/M_0) \, , \tag{2}$$

where M_0 is the initial mass, and r_{crit} is the equatorial radius at which the star just becomes unstable. It is seen that, for a star of given initial mass and angular momentum, both the critical radius at which shedding begins and the subsequent development depend only on the radius of gyration.

The radii of gyration of spherical polytropes have been calculated by Motz (1952), and James (1963) has determined the corrections to those values for stars that are rotationally unstable. The values of k^2 and of $([2/k^2] - 3)$ are given in Table 1.

We have applied these results to determine the path followed by main-sequence stars if they were to contract with solid-body rotation. We assume that a star will first change its polytropic index and then maintain this index during contraction. Table 2 gives the parameters we consider to be typical of main-sequence stars. Figures 1 and 2 show the routes followed for values of k^2 during contraction of 0.205 and 0.076. Real stars cannot while equatorially shedding attain values of k^2 higher than 0.135, if they rotate like solid bodies. Figures 1 and 2 also give the mass-radius relationships for white dwarfs. The upper curve (for $\mu_e = 2$) is due to Chandrasekhar (1938). The lower curve is by Hamada and Salpeter (1961) and is for a white dwarf composed of iron. The curl near 1.1 $M_\odot$ is caused by inverse beta-decay of atoms. The paths reach white-dwarf masses only at radii far smaller than the observed radii. We conclude that if stars evolve with solid-body rotation this mechanism does not lead to the formation of normal white dwarfs.

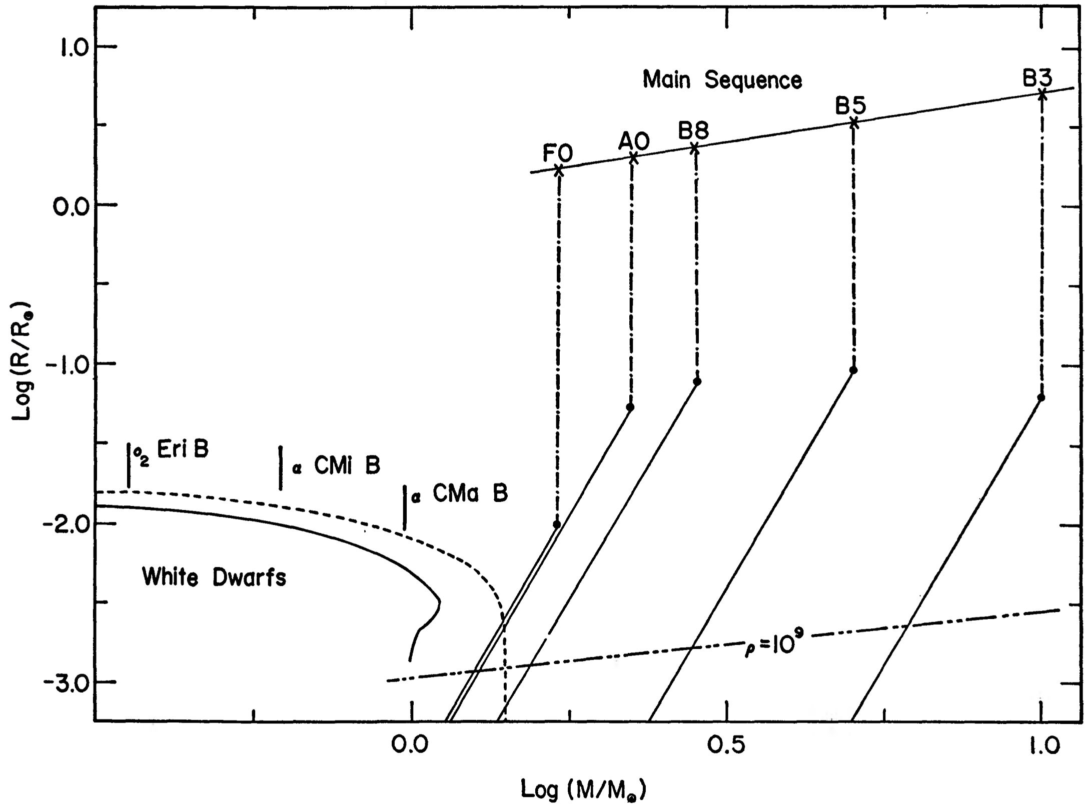

FIG. 1.—The path of contracting stars with solid-body rotation. The initial stars have the rotational velocities of Table 2, and initial polytropic index 3.0. The star is first assumed to change its polytropic index and then to contract. The value of k^2 during contraction is 0.205.

Modest amounts of non-uniform rotation will not change this result. If the total angular momentum is a factor f higher than inferred from the equatorial velocity, the only necessary change in equations (1) and (2) is to replace k^2 by k^2f. The star thus behaves like one with a smaller polytropic index. For values of f of about 2 or less this would merely compensate for the change of k^2 due to rotational distortion. Thus for such cases Figures 1 and 2 would be realistic.

Extreme amounts of non-uniform rotation ($f > 3$) lead to fission, at least for a polytropic index of 1.5 (Stoeckly 1964). Stars that develop values of f between these values could shed enough mass to become white dwarfs. The white dwarfs would have typical equatorial velocities of 3000 km/sec, and mean values of $v \sin i$ of about 2000 km/sec. Line half-widths due to such rotation would be about 30 Å. Published spectra of white dwarfs appear to show features far sharper than this (Greenstein 1958), again suggesting that rotational mass loss is not a major mechanism in the formation of white dwarfs.

IV. THE TIME SCALE FOR MASS LOSS

Although supernovae probably do not lead to the formation of white dwarfs, it is possible that mass loss could occur almost as suddenly but less spectacularly. We have attempted to set an upper limit on the rate at which mass is lost by considering the stability of binary stars with a white-dwarf component.

If a binary loses mass instantaneously, it will disrupt if inequality (3) is fulfilled (Huang 1963):

$$\frac{\text{Final mass of binary}}{\text{Initial mass of binary}} \le 1 - \frac{r}{2a}, \tag{3}$$

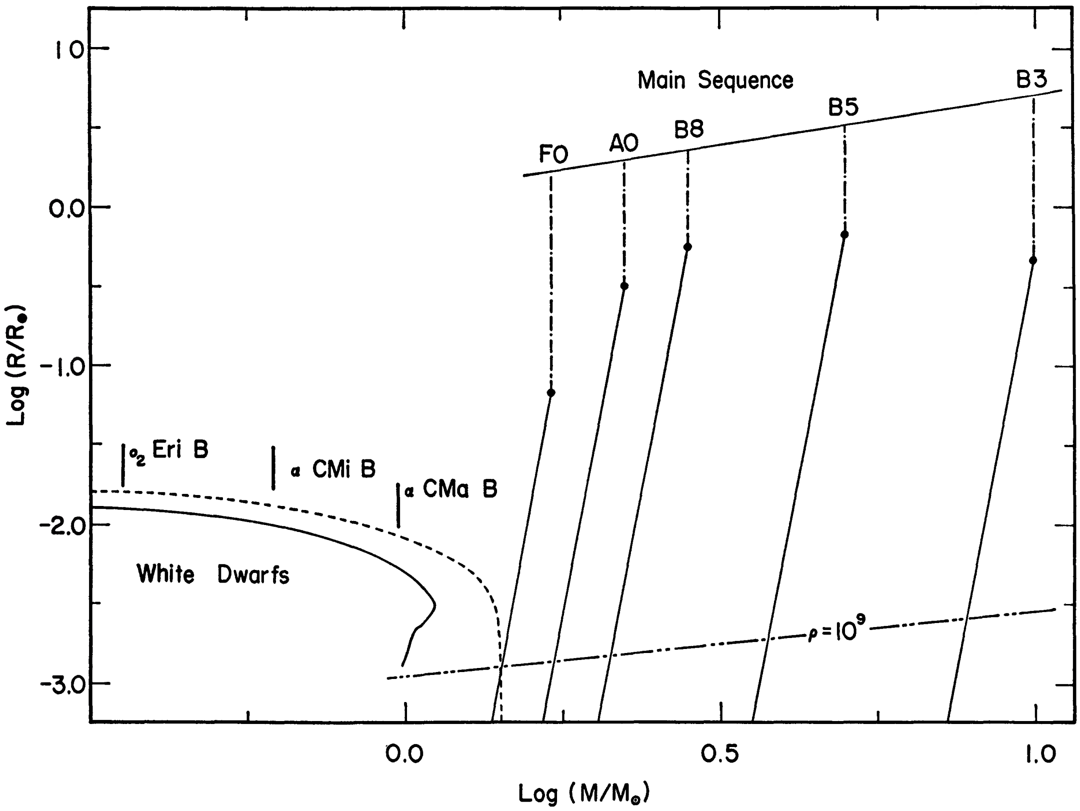

FIG 2 —This figure is identical to Fig 1 except that the value of k^2 during final contraction is assumed to be 0 076.

where a is the semimajor axis of the orbit, and r is the radial separation at which mass loss occurs. For a circular orbit, this means that the binary must lose at least half of its mass for it to separate. Though mass loss is not actually instantaneous, nevertheless events on a time scale shorter than one-quarter of an orbital period may be considered "instantaneous."

In Table 3 we list the seven known white-dwarf binaries within 20 pc (Gliese 1957) and seven other systems observed by Luyten (1952) for which proper motions but not parallaxes are available. We have tabulated periods for the last eleven of these systems by assuming that the sum of the masses is 1 $M_\odot$ and that the projected separation of the stars is equal to the semimajor axis of their orbits. Distances for the last seven of these systems are inferred from the colors and spectra of the companions. New data, kindly made available by Dr. J. Greenstein after submission of this article has been incorpo-

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rated. We have estimated masses for the companions by referring to the mass-luminosity–spectral-type relationship for nearby stars (Strand, Harris, and Worley 1963). If the average white dwarf had an initial mass of 1.5 $M_\odot$ or greater, and has a present mass of 0.5 $M_\odot$, then the pairs in which the mass of the companion is less than 0.5 $M_\odot$ will have more than halved their mass. The continued existence of these systems for many revolutions, vouched for by the white dwarf having cooled, is an indication that the mass loss has not been sudden. Objects like Nos. 5, 9, 10, and 14 of Table 3 suggest that some white dwarfs have lost mass on a time scale greater than 10^4 years.

There is no observational indication that binaries which develop a white-dwarf component are frequently disrupted. A high proportion of white dwarfs near the Sun are known to be members of binary systems. However, the argument that disruption should occur is weakened when allowance is made for eccentric orbits and mass loss probably occurring near apastron. Thus this argument becomes at present inconclusive but possibly still correct.

TABLE 3

WHITE-DWARF BINARIES

No *	STAR	π	COMPANION			PERIOD	WHITE-DWARF MASS
			M_v	Type	Mass		
1	α CMa	0 375	1 4	A1 V	2 37	50	0 98
2	α CMi	287	2 6	F5 IV–V	1 74	40	65
3	o^2 Eri	201	12 5	M4	0 18	252	0 43
4	L745–46	164	18 7	M	0 02	10^3	
5	W485	062	13 9	M6	0 07	7×10^5	
6	−37°6571	069	5 5	G6 V	1 0	3×10^3	
7	LDS678	118	12 5	dM5	0 10	3×10^3	
8	LDS235	011	6 8	dK3	0 60	10^5	
9	L1405–40	023	12 4	dM2e	0 10	6×10^4	
10	LDS455	019	10 2	K-M:	0 20	2×10^4	
11	W672	038	11 9	sdM6	0 15	5×10^3	
12	LDS683	011	8 8	sdM1	0 35	10^5	
13	LDS749	029	7 2	sdK4	0 50	2×10^5	
14	L1512–34	0 080	11 2	dM5	0 20	10^5	

* Data for Nos 1–7 from Gliese (1957) Periods are inferred for Nos. 4–14 Parallaxes for Nos. 1–7 are trigonometric Data for Nos 8–14 are from Luyten (1952) and Eggen and Greenstein (1965) Parallaxes are inferred from the colors of the companion Masses for Nos. 4–14 are inferred from the luminosity of the star, using the empirical mass-luminosity relation of Strand, Harris, and Worley (1963).

V. THE ENERGY REQUIREMENT FOR MASS LOSS

In order to eject mass, enough energy must be supplied to overcome the gravitational potential of the star. Assuming a reasonable efficiency, energy from gravitational contraction of the star will not be sufficient and nuclear fuel burning must supply the energy. Hydrogen burning liberates 6×10^{18} ergs/gm; helium burning, 6×10^{17} ergs/gm, and carbon burning, 4×10^{17} ergs/gm. Further burning will be unimportant because of neutrino losses. The red giants α Herculis and α Orionis are at present wasting their nuclear fuel by radiating 10^{18} ergs during the time in which they eject 1 gm of matter (Weymann 1963). At such rates stars are likely to find that they have insufficient fuel in the core to eject enough mass to become white dwarfs. However, efficiencies may be higher in other evolutionary phases such as those in which a star pulsates. Very massive stars will have insufficient fuel in the core to become white dwarfs.

One can ask: Why does a star stop shedding mass? It is remarkable that typical white-dwarf masses are well below the limiting mass. Greenstein (1958) has used the Chandrasekhar mass-radius relationship to estimate that observed white dwarfs have mean masses of 0.56 $M_\odot$. We notice that stars less massive than 0.7 $M_\odot$ cannot burn carbon, and stars less massive than 0.3 $M_\odot$ cannot burn helium (Cox and Salpeter 1964). These values are close to the typical masses of white dwarfs. If a white dwarf burning the appropriate fuel attains these masses, it will be unable to liberate more nuclear energy or lose more mass.

It seems probable that the more massive the initial star, the more fuel must be burned in the white dwarf to shed the extra mass. Thus the more massive stars should give rise to the more massive white dwarfs. The three measured masses of white dwarfs are probably consistent with this suggestion.

The new data of Eggen and Greenstein shows that the factors determining the masses of white dwarfs must be more complex than our simple arguments. The new data has two very significant points: (1) white dwarfs divide into two groups with radii corresponding to masses of 0.3–0.4 $M_\odot$ and 0.70 to the Chandrasekhar limiting mass; (2) no obvious correlation is found between space motion and white-dwarf masses. The Hyades are producing white dwarfs predominantly in the low mass range, while high-velocity stars are at present producing white dwarfs in both mass ranges.

We notice that, for point (1), the minimum masses of the two sequences of white dwarfs are apparently the minimum masses for helium and carbon burning. However, for the same physical reasons the minimum white-dwarf masses are also closely the masses that the core of a star must have to flash-ignite helium or carbon. Thus, without detailed discussion of mass loss processes, it is not possible to determine whether the major mass loss occurs during steady burning or as part of the consequences of a flash. It may even differ for different stars. Nevertheless the energy-requirement argument shows why a white dwarf ceases significant mass shedding after it attains these masses.

Point (2) clearly shows that our suggestion that there might be a one-to-one relationship between the mass of a white dwarf and its predecessor is inadequate. There must be at least one further factor, which we suggest is initial chemical composition. The abundance of He and heavy elements in a star greatly affect the details of a flash, of pulsation, and also of the maximum radius and minimum effective temperature in the red-giant phase. All of these are likely to affect the details of mass loss.

Finally, we note that, if mass loss is indeed stopped by fuel burning ceasing, the mean atomic weight of white-dwarf matter will be related to its radius, and the cooling times of the larger, lower-mass white dwarfs will be lengthened with respect to the smaller, heavier white dwarfs.

VI. CONCLUSIONS

It has been shown that some white dwarfs arise from stars initially more massive than 2.5 $M_\odot$ and possibly more massive than 7 $M_\odot$. Stars do not lose their excess mass by becoming rotationally unstable since stars would attain white-dwarf masses with radii far smaller than those observed if solid-body rotation persists throughout evolution.

We have attempted to estimate the rate at which stars lose mass by considering binaries with a white-dwarf component. We have found no observable effects that might be caused by rapid mass loss. From this, we conclude that some stars have probably shed mass over a time scale greater than 10^4 years. However, the result is not conclusive because it depends upon assumptions about the eccentricities of the orbits of these very wide binaries.

The ejection of mass by a star demands considerable expenditure of energy. Massive stars may have insufficient sources of nuclear fuel to attain white-dwarf masses. There will be a critical mass substantially greater than the white-dwarf limiting mass above which stars become supernovae and below which they become white dwarfs. It is pointed out that the masses of white dwarfs are similar to the minimum masses that can liberate energy by helium and carbon burning. A star attaining these masses will be unable to liberate more energy and lose more mass.

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