WHITE DWARFS IN CLOSE BINARY SYSTEMS

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1. The Evolution to White-Dwarf Stage

While it has not yet been possible to give a detailed step-by-step treatment of the evolution of a single star from the main sequence to the white-dwarf stage, such a treatment is available for close binary systems. It has been shown that by calculating the evolution including mass exchange in a system of main-sequence stars of small mass and relatively large separation, one can follow the system to its final stage of a white dwarf and a more massive main-sequence star. This type of evolution arises when the original primary has exhausted its central hydrogen content when mass exchange starts, and the mass of its helium core is small enough so that electron degeneracy prevents the ignition of helium.

The evolution of such a system has been calculated by Kippenhahn *et al.* (1967). The results of these calculations illustrate those processes occurring in a star undergoing mass loss. The system considered consisted initially of a pair of main-sequence stars of 1 $M_\odot$ and 2 $M_\odot$ separated by 6·6 $R_\odot$. The 2 $M_\odot$ star first exhausted its central hydrogen content and then filled its critical Roche volume in $5{\cdot}7 \times 10^8$ years, during the phase of core contraction and envelope expansion. By that time, the star had moved in the H-R diagram (Figure 1) from the main sequence (point A) to point D, at which time a rapid mass loss starts, the time-scale of which is the thermal time-scale of the outer layers. This very rapid change is necessary for the star to keep its radius down to the now steeply decreasing critical radius R_{cr}. Later on, the mass loss becomes gradually slower, especially when (between E and F) R_{cr} again increases. Now the interior is able to adjust thermally. The interior of the star contracts and, consequently, the envelope expands further mass shifting outside the critical volume. At points E, F, G and K, the star's mass is 1·55, 0·96, 0·28 and 0·26 $M_\odot$ respectively. The entire phase of mass exchange lasts for $1{\cdot}1 \times 10^8$ years (points D–K in Figure 1). During the last phases of mass loss, the star becomes a red giant, although a most peculiar one: Its helium core contains 96% of the star's mass and is sufficiently condensed to exhibit the typical properties of a white dwarf. The hydrogen-rich envelope which contains 4% of the star's mass and 99·7% of its volume is very extended. Now, as this envelope contracts and in $1{\cdot}2 \times 10^7$ years the star moves over to the left of the main sequence (to point N), the system again becomes detached. During this period,

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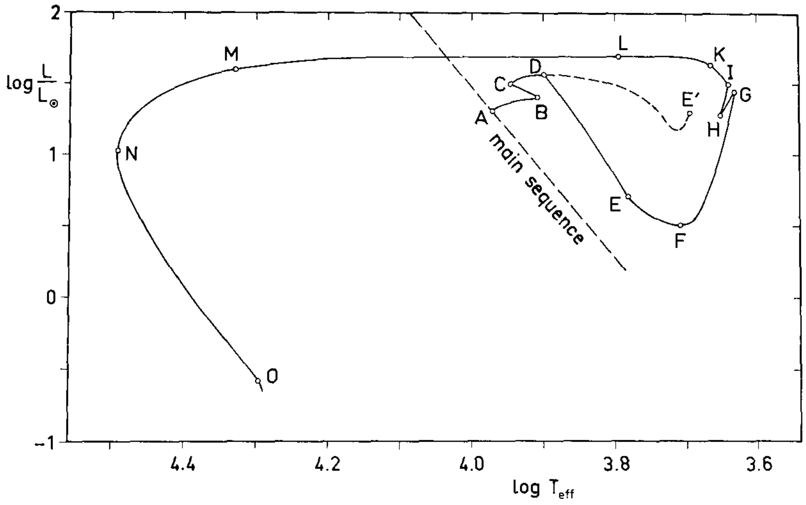

FIG. 1. *H-R diagram showing the evolutionary track of the original primary in a system of 2 $M_\odot$ and 1 $M_\odot$, as described in the text and as calculated by Kippenhahn et al. (1967). The star starts with 2 $M_\odot$ on the main sequence (point A); at point C central hydrogen is exhausted and mass transfer to the companion starts at point D. (Without mass loss, the track would have followed the dashed line.) Mass loss ceases at point K, and at point O the star has become a white dwarf.*

the shell source has burned outwards up to $M_r/M \approx 0{\cdot}99$, and has supplied most of the luminosity. Finally its energy production decreases and the star moves in the H–R diagram downwards into the white-dwarf region (3×10^6 years to point O). During this entire evolutionary process the companion has not had enough time to evolve appreciably away from the main sequence. So we finally are led to a detached system containing a white dwarf and a main-sequence star, their distance having been increased by the mass transfer to about 50 $R_\odot$.

It is important to note that the final phases of mass loss last for a relatively long time (about 10^8 years) so that there is a reasonable chance for such systems to be observed. In this phase, the system is semi-detached since the mass loss is still going on, and the calculations show the now secondary component to be enormously over-luminous (about $\Delta M_{\rm bol} = 9$ magnitudes above the main sequence M–L relation). This may suggest that many of the observed systems of low mass are in a similar phase of evolution, since it is characteristic for them to have a secondary of unusually high over-luminosity.

The evolution of the interior of the star during mass exchange can be seen from the changes of T and ρ at the centre (Figure 2). At the onset of rapid mass loss at point D, the central core cannot follow thermally since its time-scale is much longer than that of the outer layers. Thus, the interior has to change adiabatically implying here that $T_c \sim \rho_c^{2/3}$. This gives the steep increase of the curve in Figure 2 after point D (parallel to $\psi = $const.). Later on, when $R_{\rm cr}$ increases and the mass loss becomes slower, the

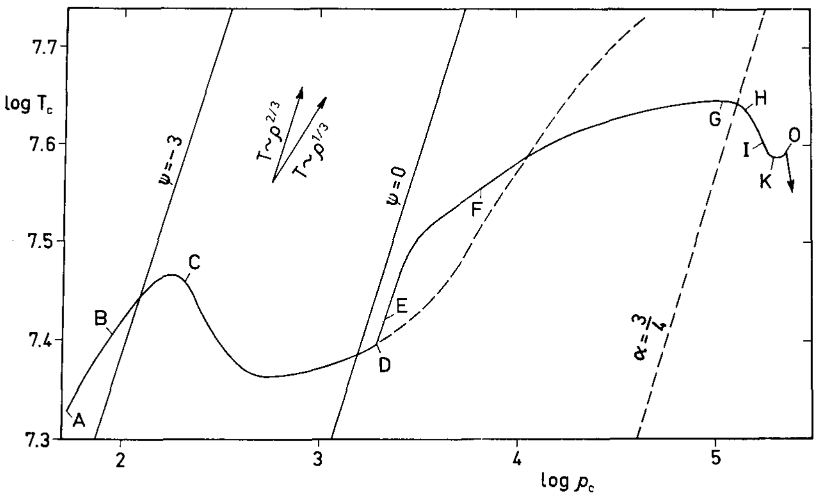

FIG. 2. *The values of temperature T and density ρ at the centre of the star, the evolutionary track of which is given in Figure* 1. *The letters along the curve correspond to those along the evolutionary track. (The dashed curve after point D gives the values of T_c and ρ_c as they would have been without mass loss.) Two lines of constant degeneracy parameter ψ are indicated. (Figure taken from Kippenhahn et al.,* 1967.*)*

centre can adjust; stars of lower mass have larger ρ_c and the curve goes to the right in this diagram. If the core would not further contract, or if the outer layers would not expand with further central contraction, then the mass loss would stop after the first very rapid phase. But the 'mirror effect' (where contraction of the core is coupled to expansion of the outer layers) is still operative, and further mass from the envelope is shifted outside the critical volume.

With increasing ρ_c, the centre becomes gradually degenerate. Due to this, ignition of helium is prevented, since T_c no longer increases with ρ_c. For a homologically contracting core, one can easily show that

$$\frac{\mathrm{d}\ln T_c}{\mathrm{d}\ln \rho_c} = \frac{4\alpha - 3}{3\delta},$$

where the matter obeys an equation of state expressed in the general differential form

$$\mathrm{d}\ln \rho = \alpha \times \mathrm{d}\ln P - \delta \times \mathrm{d}\ln T .$$

With increasing non-relativistic degeneracy of the electron gas, $\alpha \to 3/5$ and $\delta \to 0$, and for $\alpha \leqslant 3/4$ (δ still >0) we have $\mathrm{d}\ln T_c/\mathrm{d}\ln \rho_c \leqslant 0$, i.e. T_c goes down with further contraction (compare Figure 2, where the line for $\alpha = 3/4$ is indicated).

The mass loss ceases when with negligible residual mass in the envelope, the 'mirror effect' no longer holds, i.e. when all parts of the star contract simultaneously.

To predict when this will happen in a particular star is difficult without specific numerical calculations. Therefore, one cannot say whether or not all possible initial systems of such small mass will evolve in the same manner. A rough estimate shows that all primaries with initially somewhat less than 3 $M_\odot$ *can* become white dwarfs in this way; their helium cores as left after the central hydrogen burning phase are too small to ever achieve the helium-burning temperature.

Numerical calculations for this type of evolution were comparatively easy; the physical processes involved here (mass loss, nuclear burning) are very simple as compared to those which must occur in a highly evolved single star. This simplicity is the only reason why the entire evolutionary sequence of a binary component could be calculated, whereas no such calculations are available for single stars.

If stars behave similarly under a mass loss starting in later phases of evolution, then it is likely that more massive white dwarfs can also be obtained in a very similar evolution. If we assume that the mass loss of the original primary starts *after* central helium burning and again the whole envelope is stripped off, then for stars starting with up to about 5 $M_\odot$, the remaining carbon-oxygen core is not massive enough to achieve carbon burning. D. Lauterborn has started calculations for such a case. He begins with an initial system of 5 $M_\odot$ and 2 $M_\odot$, separated by 300 $R_\odot$. This separation is large enough for the primary to fill its critical volume only after exhaustion of helium in the central core. After the mass exchange, about 1 $M_\odot$ was left of the original primary, which means that again the whole hydrogen envelope was stripped off. His most recent calculations indicate that the remnant starts to move in the H–R diagram from the red giant region to the left, the separation of the components after mass exchange having increased to about 700 $R_\odot$ (Lauterborn, to be published).

2. On the Further Evolution of White Dwarfs

Although at the first glance one might suspect that the further evolution of a white dwarf would be rather boring, such a conclusion would not take into account the complications which can arise from two effects: the influence of the companion, and the fact that the white dwarf is not the idealized configuration (homogeneous, completely degenerate) which one likes to imagine. In fact, different and peculiar phenomena may occur in rather short time-scales. This has been shown in several recent calculations.

Numerical calculations were carried out (Kippenhahn, Thomas, Weigert, to be published) on the further evolution of the white dwarf of 0·26 $M_\odot$ which originated from the 2 $M_\odot + 1$ $M_\odot$ system described earlier. Near its surface, this white dwarf still possessed a hydrogen-burning shell source since a small hydrogen-rich envelope was left after the mass loss. This shell source, which had decreased very much in its energy production, becomes thermally unstable, the instability being caused by the fact that the shell source has sharply decreased its radial extension. Two thermal pulses resulted, the time interval between them being about 600 years. In each of the pulses, the luminosity and the radius of the star greatly increased so that the envelope again filled the critical volume. However, in both pulses the resulting mass loss was negligibly small. Only after these pulses were finished, did the star settle down again into the white-dwarf region.

Many such white-dwarf models were tested for pulsational instability by D. Lauterborn. The model's eigenperiod was around 1 min, and a very small excitation was found when the model evolved through the extrapolated Cepheid strip. This excitation is too small to expect an appreciable amplitude to be built up in a reasonable time interval. But, of course, it may be that greater excitation occurs when this model is in the midst of a thermal pulse. A pulsation excited under these circumstances may be visible for a long time.

All these phenomena may also be present in a single white dwarf as long as it has a small superficial hydrogen layer. For a white dwarf in a close binary system, additional disturbances must arise as the (now more massive) companion evolves and expands over its critical Roche lobe. Then hydrogen-rich matter is returned to the white dwarf. The resulting rate of mass increase can be rather high (at least much higher than for any reasonable accretion of interstellar matter on a single white dwarf). Numerical calculations were carried out by Giannone and Weigert (1967). A mass increase was assumed with a rate of 10^{-9} $M_{\odot}$/year on a white dwarf of 0·5 $M_{\odot}$, consisting originally of helium. The hydrogen heated up to ignition, and the new shell source turned out to be thermally unstable in all cases which were treated. Depending on the initial model, the instability was due either to degeneracy or to the very small radial extension of the shell source. Thermal runaways resulted increasing the temperature in the shell source to such an extent that even helium may be ignited in the succeeding phase (which is not yet calculated). Violent effects may be expected to occur, but the results are difficult to predict. Only a small fraction of the produced energy penetrated to the surface, most of it was absorbed by expansion of the outer layers. In the evolution calculated so far, the main observable effect at the surface should come from the large amount of kinetic energy of the infalling gases. This has to be dissipated and finally radiated away, and very hot and peculiar photospheric and chromospheric layers may result. An appreciable amount of X-ray radiation, e.g., can be expected to originate from such a star.

Many varieties of rapid changes, caused by quite different effects, are thus theoretically possible for close binaries containing a white dwarf, as shown even by these few calculations. One might feel tempted to relate one or the other of them to some observed activity in such systems (novae, pulsation), but it is as yet much too early for such speculations.

References

Giannone, P., Weigert, A. (1967) *Z. Astrophys.*, **67**, 41.
Kippenhahn, R., Kohl, K., Weigert, A. (1967) *Z. Astrophys.*, **66**, 58.

DISCUSSION

Conti: Do you anticipate any difference in evolution for a *smaller* primary mass in your case *C* calculation?

Weigert: We estimated very roughly a limiting initial mass of 2·8 $M_\odot$ for a star to follow the evolution to white-dwarf stage. All stars of smaller mass have too small helium cores to ignite helium. For case *C* the corresponding limiting initial mass would be about 5 $M_\odot$. In stars up to that mass the C–O core is too small to achieve C + C burning.

Conti: I understand, then, the 5 $M_\odot$ upper limit for case *C* is analogous to the 3 $M_\odot$ upper limit for case *B*. Is the evolution of the primary directly to the white dwarf the same in both cases?

Weigert: It seems to be very similar, as far as one can tell up to now from the calculations by D. Lauterborn.

Mestel: Can you apply your calculation to the Sirius A and Sirius B system?

Weigert: The Sirius system cannot be explained directly by our calculations, since the separations of the calculated systems are too small. But also in the Sirius system some mass exchange must have occurred, maybe, together with mass loss of the whole system.

Tayler: In the example with initial masses 2 $M_\odot$ and 1 $M_\odot$ the masses after the first mass exchange are 0·26 $M_\odot$ and 2·74 $M_\odot$ with a separation of 15 $R_\odot$. This separation is not large, so would you expect a considerable return of mass to the white dwarf when the 2·74 $M_\odot$ becomes a red giant? In general, for favourable masses and separations might there be several exchanges of mass back and forth?

Kippenhahn: The reason why we have not tried to compute several mass losses, one following the other, was, that in most cases you encounter contact systems. We do not know well enough up to now how to deal with such systems.

Leung: I would like to draw attention to one of the important observational approaches to the study of evolution of binaries. From eclipsing binary in clusters we have an estimation of the age and the location in the H–R diagram with respect to main sequence. There are many of these systems. We may be able to follow the evolution of binaries through this approach. It is my wish that observers would observe these systems.

Plavec: It would be very interesting to catch a system at the phase of rapid mass loss. We believe that two binaries of this kind are known, namely β Lyrae and V 367 Cygni.

Roxburgh: I would like to emphasise the desirability of investigating evolution of very close systems into contact systems. Have any of the groups investigated this problem?

Weigert: We always avoided to calculate such systems which have to come to a contact. The reason is that we do not know up to now how to treat the contact case. If a mass loss of the whole systems occurs, we would have to introduce completely unknown parameters (specific orbital angular momentum carried away).