4. BINARY SYSTEMS AS X-RAY SOURCES: A REVIEW*

ROBERT P. KRAFT
Lick Observatory, Board of Studies in Astronomy and Astrophysics,
University of California, Santa Cruz, Calif., U.S.A.

Abstract. The observational properties of Sco X-1, Cyg X-2, and Cen X-3 are reviewed in connection with the hypothesis that X-ray power is derived from gravitational energy released when matter is accreted onto the surface of one component in a mass transfer binary star. Evolutionary mechanisms for producing suitable types of binaries are considered. The following boundary conditions on possible evolutionary models are also treated briefly: (1) a quite significant fraction of hard X-ray sources are associated with the nuclear bulge of the galaxy; (2) mass-transfer binaries such as U Gem stars are not hard X-ray sources; (3) counts of binary stars lead to a considerably larger number of X-ray source candidates than are actually observed.

1. Introduction

As a result of the first optical studies of compact X-ray sources, speculation arose that X-ray power might be derived from gravitational energy released when matter was accreted onto the surface of one component in a mass-transfer binary star. The hypothesis was generated by the observation that the optical spectrum of Sco X-1 (Sandage *et al.*, 1966) is similar to that of an old nova or U Geminorum star; it is well known (cf. Kraft, 1962, 1964) that such objects are close binaries in which one component overflows its lobe of the inner zero-velocity surface and transfers mass to its collapsed, probably white dwarf, companion. If the energy of infall of atoms onto a star of radius R and mass $\mathfrak{m}$ is converted into heating the gas, the temperature will be of order

$$T \sim 10^7\,(\mathrm{K})\,\frac{\mathfrak{m}/\mathfrak{m}_\odot}{R/R_\odot}, \tag{1}$$

so that for objects with $\mathfrak{m}/R$ values in the range 1 to 10 or more (in solar units) *i.e.*, for degenerate objects like white dwarfs, thermal bremsstrahlung with $T > 10^7$ K could conceivably be emitted (Chodil *et al* 1965; Grader *et al.*, 1966; Peterson and Jacobson, 1966). This idea was given early treatment by Cameron and Mock (1967), Shklovskii (1967) and Prendergast and Burbidge (1968); the last named carried out the most extensive calculations.

In the Prendergast-Burbidge model, matter flows through the inner Lagrangian point into a disk surrounding a white dwarf; owing to radial viscous dissipation, the disk spreads out. The outer part speeds up and moves out while the inner part slows down and moves inward. Detailed hydrodynamical and radiative transfer

---

* Contributions from the Lick Observatory, No. 368. This paper was prepared for, but not given at the symposium. In the author's absence, Dr E. van den Heuvel kindly consented to present his own review of similar material.

Bradt and Giacconi (eds.), X- and Gamma-Ray Astronomy, 36–50. All Rights Reserved.

equations are set up with prescribed initial values of tangential velocity, density and temperature, along with mass-flux and angular momentum as parameters. The calculations show that X-rays can be emitted from the inner part of the disk and must be transferred through the outer cooler part which emits the optical radiation. X-ray luminosities of the order of 10^{35-36} erg s^{-1} were achieved for accretion onto white dwarfs with a mass transfer rate of 2×10^{19} gm s^{-1} ($3 \times 10^{-6}\ \mathfrak{m}_{\odot}$ yr^{-1}). This transfer rate is one to three orders of magnitude larger than rates measured or inferred for U Gem systems (cf. Crawford and Kraft, 1956; Krzeminski and Smak, 1971), an interesting point to be dealt with later.

The reasonable success of this model spurred an interest in the detection of binary motion both in Sco X-1 and in the less-certainly identified Cyg X-2. Extensive photometric and spectroscopic observations of the former (Westphal *et al.*, 1968; Hiltner *et al.*, 1970) showed, however, no certain evidence either of eclipses or of binary motion; erratic changes of brightness of a magnitude or more and of radial velocity by several hundred km s^{-1} were found but contained no evidence of periodicity. Erratic fluctuations in brightness were detected (Kristian *et al.*, 1967) also in Cyg X-2 along with changes in radial velocity of several hundred km s^{-1} (Burbidge *et al.*, 1967; Kraft and Demoulin, 1967; Kraft and Miller, 1969), but again no certain evidence of binary motion could be demonstrated. The main evidence for the duplicity of Cyg X-2 remained its composite spectrum: a late F or G-type star is accompanied by the emission lines of He II (later λ4650 C III–N III [Bopp and Vanden Bout, 1972]), rather like the spectrum of binary system Nova Per (1901). These results thus led to an epoch in which the mass transfer binary model for galactic compact X-ray sources was decidedly moot, although Wilson (1970) was able to give a binary picture for Cyg X-2 that explained all the observations at least qualitatively. This state of affairs continued until the remarkable properties of the X-ray source Cen X-3 were discovered by UHURU (Giacconi *et al.*, 1971; Schreier, *et al.*, 1972).

Cen X-3 contains an X-ray pulsar with period 4.8 s which is eclipsed every 2.087 days by an unseen (i.e., X-ray dark) companion. The eclipse lasts for a time D equal to 23 % of the period, and the reduced X-ray flux seen during the eclipse is presumed to arise as a result of scattering in a circumstellar cloud. The orbital velocity of the pulsar was derived from its smooth oscillatory period change, (Schreier *et al.*, 1972), and the spectroscopic mass function was found to be

$$\frac{\mathfrak{m}_2^3 \sin^3 i}{(\mathfrak{m}_1 + \mathfrak{m}_2)^2} = 15\ \mathfrak{m}_{\odot}, \tag{2}$$

where $\mathfrak{m}_1$ and $\mathfrak{m}_2$ are the masses of the pulsar and of the unseen companion, respectively, and i is the inclination of the orbit (angle between the line of sight and the imaginary plane of the sky).*

Application of the mass-transfer model enables one to place limits on the masses

---

* In this paper, the quantity $\mathfrak{m}_1$ will always refer to the more massive component when the stars were on the main sequence.

of the objects. This comes about because the unseen component must fill its lobe of the inner zero-velocity surface if it is to be a source of matter for accretion by the pulsar. The radius R of the unseen component, defined in the usual way as the cube root of the product of the three lobe dimensions, is then given in units of the separation *a* as a function of the mass ratio $\mathfrak{m}_2\mathfrak{m}_1$ (cf., e.g., Kopal, 1959; Paczynski, 1971a). At the same time, if we assume that the radius of the pulsar is small compared with the companion, (which seems justified by the large amplitude of the pulsar variation), we have that R/a is a simple trigonometric function of D, the eclipse duration, and i. Thus for any assumed value of i, the mass ratio can be obtained, which, when combined with the mass function, leads to masses for the two components. Treatment of this problem by van den Heuvel and Heise (1972) leads to upper mass limits $\mathfrak{m}_1 = 0.70\ \mathfrak{m}_\odot$ (the pulsar) and $\mathfrak{m}_2 = 17\ \mathfrak{m}_\odot$ (unseen companion) when $i = 90°$. As i decreases, the upper limit decreases, and the value of the mass ratio is quite sensitive to the duration D. It is also sensitive in the same way to the treatment of the geometry, since it is not quite correct to assume that the occulting disk has an eclipse dimension equal to the radius of the star as defined above. A more nearly accurate discussion of this point was made by Wilson (1972), who concluded that the upper limit to the mass of the pulsar must be near $0.23\ \mathfrak{m}_\odot$, rather than the $0.70\ \mathfrak{m}_\odot$ derived by van den Heuvel and Heise.

These considerations make it clear that optical identification for Cen X-3 is urgently required to assist in establishing the correct physical parameters for the system. Information on optical candidates changes almost daily, but at the time of writing, the candidate put forward by Kristian *et al.* (1972), viz., LR Cen, seems somewhat doubtful. According to Hiltner (1972), the period of this optical eclipsing binary is 2.095 ± 0.001 days, as determined in 1972 from photoelectric observations, a value too far from the X-ray figure of 2.08712 ± 0.00004 days. This confirms the earlier conclusion by Elliot and Liller (1972) based on photographic photometry. It is fortunate if this is the case: the phasing of the optical observations of LR Cen and the X-ray data indicate that the X-ray source is in front of the dark companion at principal X-ray eclipse of Cen X-3, a result requiring an extraordinarily complex (impossible?) model for the system. It remains to be seen if the 11th magnitude emission line star, WRA 795, suggested by Margon (1972) as a candidate, is in fact the same as Cen X-3.

Quite aside from the question of the correct physical parameters for Cen X-3, the binary star model for compact X-ray sources must now be taken seriously, and the question raised: how do systems come into existence in which a 'biologically old' collapsed star is accompanied by a presumably 'biologically young' and massive object which overflows its lobe of the zero-velocity surface? A considerable amount of work has been done in recent years, principally by Kippenhahn and his associates, on these questions, and it is the relevant parts of these papers that I now wish to treat briefly. A more extensive review of the evolution of mass-exchange binary systems has been given in an excellent article by Paczynski (1971a) to which the reader is referred for details.

2. Evolution of Mass-Exchange Binaries: Some Examples

As is well known, stars undergoing evolutionary processes in the deep interior can experience drastic changes in radius, by factors of 10 or 100 or more. If such a star is a member of a binary system in which the initial separation is several stellar radii, it will encounter its lobe of the inner zero velocity surface, and its subsequent evolution will be characterized by loss of mass through the inner Lagrangian point L_1. This, however, is not the only mechanism by which mass loss through L_1 can be generated. It is possible for close binaries to radiate enough energy in the form of gravitational waves (Kraft *et al.*, 1962; Kraft, 1966; Faulkner, 1971) that the period is significantly reduced in a time shorter than the nuclear lifetime. In this case, the lobe around the larger star will shrink, eventually cutting down into the star itself. This mechanism for driving mass loss through L_1 has been considered by Faulkner (1971) in connection with the U Gem stars. We return to this point later, but now consider only those binaries undergoing mass transfer as a result of some kind of exhaustion of nuclear fuel.

To fix ideas, consider the evolution of a single star with $\mathfrak{m} = 5\, \mathfrak{m}_\odot$. In Figure 1, we reproduce Iben's (1967) well-known HR diagram, i.e., plot of the evolutionary path in a temperature-luminosity array. Of major interest here are the events associated with points 4 and 7. After an initial period of core hydrogen burning, a thick hydrogen-burning shell is established at point 4, and the star rapidly moves to the

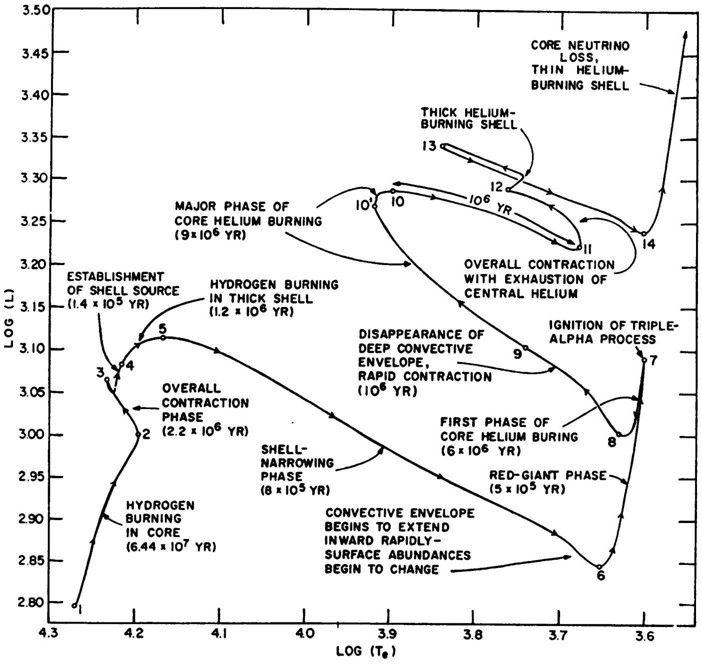

Fig. 1. Evolution in the HR diagram of a star of mass 5 $\mathfrak{m}_\odot$ (after Iben, 1967).

right increasing its radius as the exhausted core continues to contract. At point 7, the radius begins to decrease in response to the onset of core He-burning, even though after point 7, the energy production of the hydrogen burning shell exceeds that of the He-burning core. Very crudely we can say that core contraction is accompanied by an increase in the radius, part of the increased energy generation being taken up in the gravitational potential energy of the star. On the other hand, ignition of nuclear fuel in the center with corresponding expansion of the core burning region seems to be accompanied by a contraction of the stellar envelope.

That these ideas are likely to be relevant in connection with real binary stars is demonstrated in Figure 2, which is taken from the work of Paczynski (1971a). Consider a binary with primary mass $\mathfrak{m}_1 = 5\,\mathfrak{m}_\odot$ and with mass ratio $\mathfrak{m}_1/\mathfrak{m}_2 = 2/1$. From Kepler's third law, we have $a^3/P^2 = \mathfrak{m}_1 + \mathfrak{m}_2$ in appropriate units, a known number. If r is the mean radius of the lobe corresponding to the primary, then r/a is a known function $F\,(\mathfrak{m}_2/\mathfrak{m}_1)$. From Iben's evolutionary track, the radius R of the primary star is obtained at every point on the track, for example at the critical points 1, 4, and 7. If we set $R = r$ at these critical points, then the separation a is found from F, and critical limiting periods indicated in Figure 2, are found from Kepler's third law. If, for example, the actual period of the real binary is less than 1.5 days (corresponding to point 4 of the track), then the primary in the system will

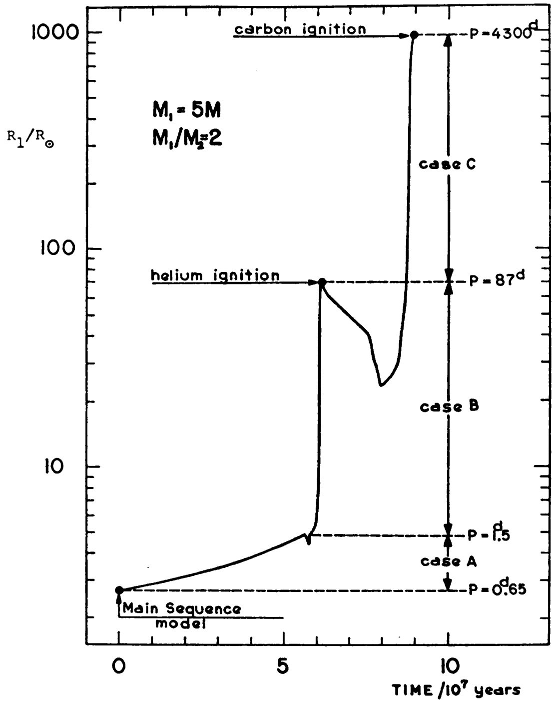

Fig. 2. Case A, Case B, Case C evolution for a binary system with $\mathfrak{m}_1 = 5\,\mathfrak{m}_\odot$ and $\mathfrak{m}_2 = 2.5\,\mathfrak{m}_\odot$ (after Paczynski, 1971a, Figure 1).

encounter its zero-velocity surface before hydrogen exhaustion in the core. Following Kippenhahn and Weigert (1967), this is known as 'Case A' binary evolution. If the period of the binary, on the other hand, is more than 1.5 days but less than 87 days, the surface will be encountered during the stage of shell hydrogen burning ('Case B'), and so forth. These periods are quite characteristic of spectroscopic binaries; indeed, about 40% of all binaries have periods less than 100 days (Kuiper, 1935). This estimate of frequency would not be greatly changed in dealing with evolving stars of mass less than 5 $\mathfrak{m}_\odot$, or in dealing with mass ratios different from 2/1. Thus we may expect mass transfer to be a quite common experience in the evolution of spectroscopic binaries.

We now consider examples of mass transfer binaries in which, after mass loss through L_1, the primary evolves into a degenerate configuration on a time-scale short compared to its main sequence lifetime. Calculations have been carried out by many investigators during the past five years, among them Kippenhahn, Weigert, Giannone, Refsdal, Lauterborn, Barburo, Ziolkowski, Kriz, and Paczynski (see Paczynski [1971a] for a comprehensive list of references). All calculations assume the conservation of total mass and total orbital angular momentum. We chose two representative examples here, one in which the primary is a massive main sequence star ($\mathfrak{m} \gtrsim 3\ \mathfrak{m}_\odot$) of the kind that would now be evolving off the main sequence in the Pleiades or α Per clusters, and one in which the primary is of low mass ($\mathfrak{m} \lesssim 3\ \mathfrak{m}_\odot$), similar to F-type stars near the turnoff of the old galactic cluster NGC 752. According to Paczynski (1971a), a qualitative difference in evolution occurs depending on whether the mass of the primary is greater than, or less than about $3\mathfrak{m}_\odot$. For Case A evolution, an originally massive primary will still be burning hydrogen slowly in the core even after the secondary has begun its expansion, having already acquired the mass ejected by the primary. In this case, the primary and secondary simply exchange roles. In Case B evolution, however, the primary evolves into an object of small radius, regardless of its initial mass. In addition, for primaries of small mass, the same ultimate state is reached independent of whether the evolution proceeds as in Case A or Case B. We therefore choose our examples entirely from Case B.

EXAMPLE 1

$\mathfrak{m}_1 = 9.0\ \mathfrak{m}_\odot$, $\mathfrak{m}_2 = 3.1\ \mathfrak{m}_\odot$, $P = 4.85$ days (Kippenhahn and Weigert, 1967). The critical surface is reached *after* hydrogen exhaustion in the core, and the mass-loss proceeds on the Kelvin time-scale of only 4×10^4 y, about 10^{-2} of the main sequence life-time. At the end of the stage of rapid mass transfer, the primary has a mass of 2.0 $\mathfrak{m}_\odot$, and has transferred most of its mass to the secondary, which moves up the main sequence to a position corresponding to a star undergoing core hydrogen burning at 10.1 $\mathfrak{m}_\odot$. The old primary fills its lobe of the zero-velocity surface burning hydrogen in a shell source. However, before the old secondary is able to exhaust a sufficient supply of hydrogen to move off the main sequence, the primary ignites He in the core, contracts away from the surface, and becomes a star near the He-burning main sequence. This sequence of events is depicted in the HR diagram in Figure 3. With angular momentum conserved, the period is somewhat lengthened, viz., 12.7 days. According to Kippenhahn and Weigert (1967), the first stage of rapid mass transfer can be identified with objects like β Lyr, and the final state is similar to numerous Wolf-Rayet binaries. We note that the two final objects have about the same luminosity even though the masses are very different: this is because the more massive component burns hydrogen while the less massive burns helium. The nuclear lifetime of the less massive component will therefore be significantly shorter than its companion.

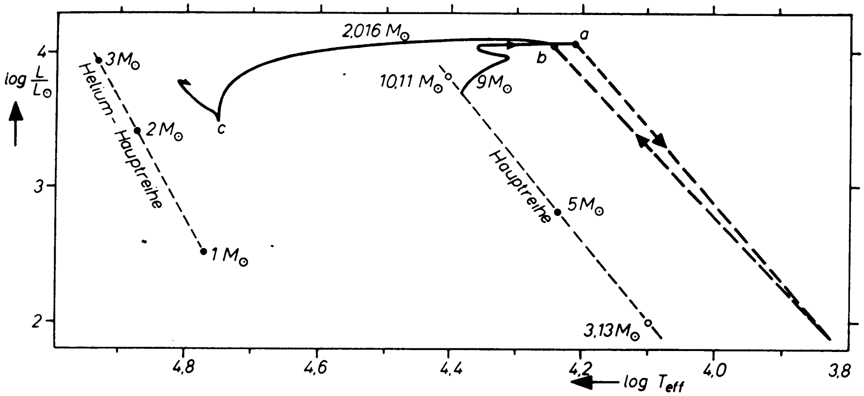

Fig. 3. Evolution in the HR diagram of a system with $\mathfrak{m}_1 = 9.0\ \mathfrak{m}_\odot$, $\mathfrak{m}_2 = 3.1\mathfrak{m}_\odot$, and $P = 4.85$ days (after Kippenhahn and Weigert, 1967, Figure 4).

How the more highly evolved star reaches its final state of exhaustion, and therefore degeneracy, has not been calculated in detail, and several branching scenarios are possible, depending on the mass of the original primary. In the system considered here, the helium burner has a mass of $2.0\ \mathfrak{m}_\odot$. According to Paczynski (1971b), helium stars with masses between 1.0 and about $3\ \mathfrak{m}_\odot$ evolve into the red giant region for a second time. The helium star in our system may therefore transfer additional matter to its main sequence companion and settle down eventually as a helium or carbon white dwarf. If its final mass were (say) $1.0\ \mathfrak{m}_\odot$, the final period would be 77 days. Subsequent evolution would find the 11 solar mass new primary eventually evolving to fill its critical zero-velocity surface, and matter would be expected to accrete onto its white-dwarf companion, a picture conceivably identifiable with an X-ray source. It is easy to see, however, that if too much matter is transferred in this penultimate stage so that the mass ratio becomes very large, the period will become quite long and thus establishment of conditions suitable for the generation of an X-ray source may be delayed to Case C or may not take place at all.

If the mass of the original primary had been somewhat smaller, the mass of the resulting helium star would have been too small for 'red-giant'-type evolution to take place. As an example, consider a system with initial masses $\mathfrak{m}_1 = 4.0\ \mathfrak{m}_\odot$, $\mathfrak{m}_2 = 2.7\ \mathfrak{m}_\odot$ and initial period 3.26 days. According to Ziolkowski (1970), in the end the primary becomes a helium star of mass $0.56\ \mathfrak{m}_\odot$, the secondary becomes a hydrogen-burning main sequence star of mass 6.11 $\mathfrak{m}_\odot$, and the orbital period is 100 days. The helium star ultimately becomes a white dwarf without passing through the red-giant stage (Paczynski, 1971b). Subsequent evolution of this object could produce an X-ray source, although again the period is rather uncomfortably long.

A third branching of possibilities supposes the existence of a primary sufficiently massive that its pure helium descendant has mass $\gtrsim 3\ \mathfrak{m}_\odot$ and cannot further lose mass by ejection in the second red giant stage. Such an object will pass rapidly through He and C burning stages, ignite still heavier elements, and will presumably become a supernova, leaving behind a neutron star or black hole. Whether a binary system dissolves or becomes an accelerated system of longer period depends on whether more or less than half the total mass is ejected, respectively (Blaauw, 1961; Boersma, 1961; Gott, 1972). Since in the present case it is the less-massive component that blows up, the system will in every case remain bound.

This possibility was considered in some detail for the case of Cen X-3 by van den Heuvel and Heise (1972). Their semi-empirical calculation is shown schematically in Figure 4. They begin with a close binary in which $\mathfrak{m}_1 = 16\ \mathfrak{m}_\odot$, $\mathfrak{m}_2 = 3\ \mathfrak{m}_\odot$ and the initial period is 3 days. Using the evolutionary tracks of Paczynski, they find that the descendant object has masses 15 $\mathfrak{m}_\odot$, 4$\mathfrak{m}_\odot$, and the period is 1.53 days. The less-massive component is a pure helium burning star, and the more massive object is still on the hydrogen-burning main sequence. The mass transfer occurred on a time scale equal to 1/300th of the original main sequence lifetime. After about 1/4th of this nuclear time, the helium star explodes. Van den Heuvel and Heise assume, as an example, that a mass of 3.5 $\mathfrak{m}_\odot$ is ejected to infinity, leaving behind a neutron star of mass 0.5 $\mathfrak{m}_\odot$. If the ejection occurs in a spherically symmetrical way, the whole system is accelerated by 30 km s^{-1} owing to recoil, and the binary period is increased to 2.17 days (van den Heuvel, 1968). When the 15 $\mathfrak{m}_\odot$ star eventually fills its critical surface owing to core hydrogen exhaustion, matter will flow onto the surface of the neutron star and an X-ray source similar to Cen X-3 could conceivably result.

Van den Heuvel and Heise interpret the X-ray pulsations as if the object were a classical pulsar: the 4.8 s oscillation is presumed due to the rotation of a neutron star with an embedded dipole magnetic field. If the oscillation is driven instead by the pulsations of a degenerate star (Blumenthal *et al.*, 1972), the period is too long to admit of a neutron star (cf. Thorne and Ipser, 1968), and a white dwarf is required. But, as we have seen in the earlier discussion, consideration of angular momentum makes it difficult to reconcile the large mass-ratio inferred for Cen X-3 with the rather short orbital period unless matter is removed in a supernova outburst, a process probably resulting in a neutron star. However, before we are driven to embrace uncritically the neutron star model we should remember that all calculations of mass-transfer in binaries assume conservation of orbital angular momentum and total mass. If, during some stage of mass-transfer, matter is also lost through one of the outer Lagrangian points, the period could be significantly decreased (Kuiper, 1941; Kruszewski, 1966). If matter were thus lost from the system by the original

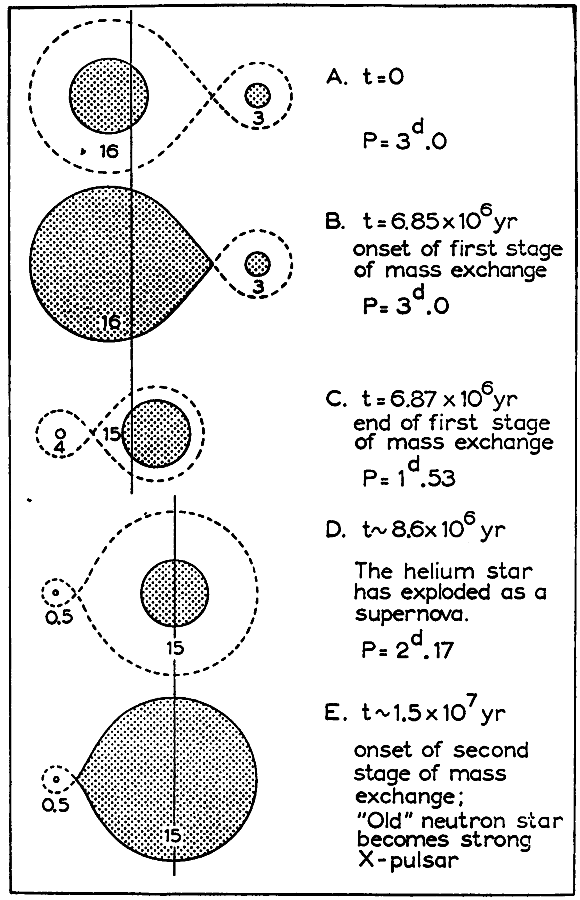

Fig. 4. Possible evolution of a massive binary into an X-ray source like Cen X-3 (after van den Heuvel and Heise, 1972).

secondary, the binary could possibly have a short period in the end, the more evolved component having arrived safely in the white dwarf stage without a supernova explosion. Detailed calculations of this possibility have not, of course, been made.

EXAMPLE 2

$\mathfrak{m}_1=2.0\ \mathfrak{m}_\odot$, $\mathfrak{m}_2=1.0\ \mathfrak{m}_\odot$, $P=1.15$ days (Kippenhahn *et al.*, 1967). In this typical low-mass case, the primary encounters the critical surface after the onset of shell hydrogen burning in 5.7×10^8 yr, and loses all but 0.26 $\mathfrak{m}_\odot$ to the secondary in only 6.9×10^6 yr (see Figures 5 and 6). At this point the original primary fills its critical lobe, forming a semi-detached system of mass-ratio $\frac{10}{1}$ and period 24.1 days which lasts for about 10^7 yr. The so-called 'subgiant components of eclipsing binary systems' are of this kind (Plavec, 1968); a typical object is DN Ori (Smak, 1964), in which $P=12.97$ days, and in which the A2 and giant F5 components have masses of 2.65 and

0.18 $\mathfrak{m}_\odot$, respectively. The subgiant component develops a degenerate core which naturally stops contracting, and never succeeds in igniting helium. In the end we have a main sequence A-type star of mass 2.74 $\mathfrak{m}_\odot$ accompanied by a low mass white dwarf with the same orbital period found above, 24.1 days. The velocities of the stars in their orbits are about 10 and 100 km s^{-1}; only the slower moving component will be seen in the spectrum of the combined light. Considering the errors of radial velocity determinations for A-type stars, we think it likely that many systems of this kind will be missed.

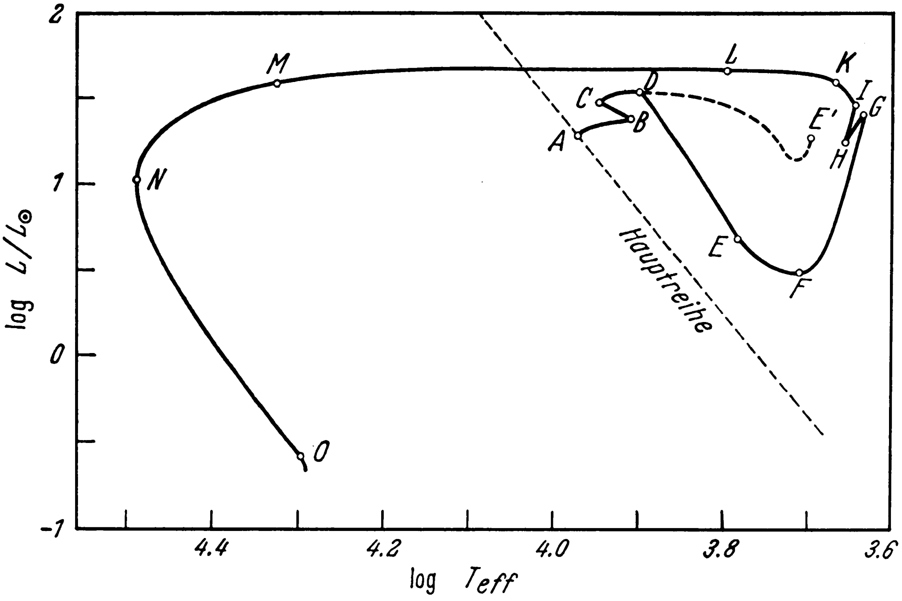

Fig. 5. Evolution in the HR diagram of the primary in a binary with $\mathfrak{m}_1 = 2.0\ \mathfrak{m}_\odot$, $\mathfrak{m}_2 = 1.0\ \mathfrak{m}_\odot$, and $P = 1.15$ days (after Kippenhahn *et al.*, 1967), At point D, Case B evolution begins. At K, the star becomes a 'subgiant', and at O, a white dwarf. The period at K and O is 24.1 days.

The subsequent evolution of the system will lead to a swelling-up of the new primary, spilling of mass through L_1, and capture of this material by the white dwarf, i.e., a possible X-ray source. The accretion heating of the white dwarf may make it visible in the combined optical spectrum. However, if the mass transfer is fast, the radial velocity variations of the degenerate component may well be masked by motions of gas streams within its lobe of the zero-velocity surface, or by streams of matter ejected from the outer Lagrangian points.

3. Some Boundary Conditions on Possible Mass-Transfer Models

In making choices between the various cases considered in the previous Section, three additional observational facts about galactic compact X-ray sources must be kept in mind. First, although many are located in the galactic plane at random longitudes,

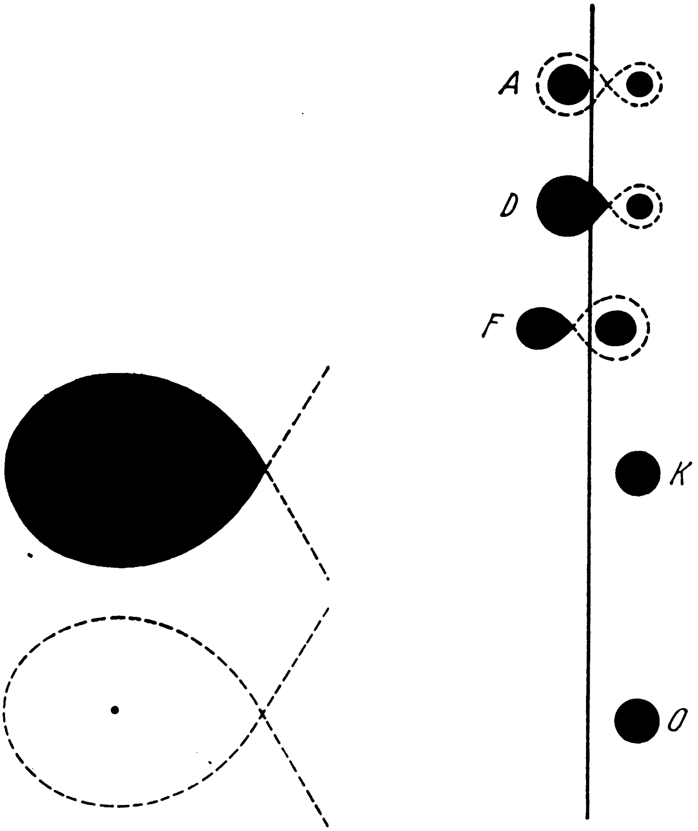

Fig. 6. Scaled dimensions of the binary considered in Figure 5.

a quite significant fraction are associated with the region of the galactic nucleus (Giacconi *et al.*, 1972). Unless these are objects of an entirely unexpected sort, many are presumably mass transfer binaries in the stellar population associated with the galactic nuclear region, viz., an old metal-rich population similar to the stars in galactic clusters like M 67 and NGC 752 (Arp, 1965; Van den Bergh, 1972) or globular clusters like M 71 (Arp and Hartwick, 1971) and NGC 6352 (Hartwick and Hesser, 1972). This means we are dealing with binary systems in which the primaries are of relatively low mass, i.e., in the range 1 to 2 $\mathfrak{m}_\odot$ (cf. also Salpeter, 1972). This suggests that at least some of the X-ray sources are like the system of Example 2. Sco X-1 and Cyg X-2 could fall into this category. Optically, we see only the X-ray source in the former but we see both components in the latter. If the radial velocity variations due to orbital motion are spoiled by gas streams in the case of the X-ray component, our only hope is to detect the velocity variations of the G-type component in Cyg X-2. Unfortunately, this may be nearly impossible if it is very much more massive than its companion, as the above models suggest.

A second type of boundary condition is derived from the fact that U Gem stars and old novae consist of a late-type star that overflows its zero-velocity surface and transfers matter to its degenerate companion. *Why then are not old novae and U Gem stars detected as sources of hard X-rays*? The Prendergast-Burbidge model gives a clue to understanding this anomaly. It will be recalled that the model requires a mass-transfer rate of 2×10^{19} gm s^{-1} to give the required X-ray luminosity. In Figure 7, we plot the rate of mass-loss by hydrogen shell-burning primaries in mass-transfer systems as a function of the mass of the primary. Only models by Kippenhahn and his associates were used for a variety of mass ratios and periods; the result would not be affected by choosing models of other investigators. In a steady state, the ejected matter is, of course, accreted by the secondary. We assume that these rates

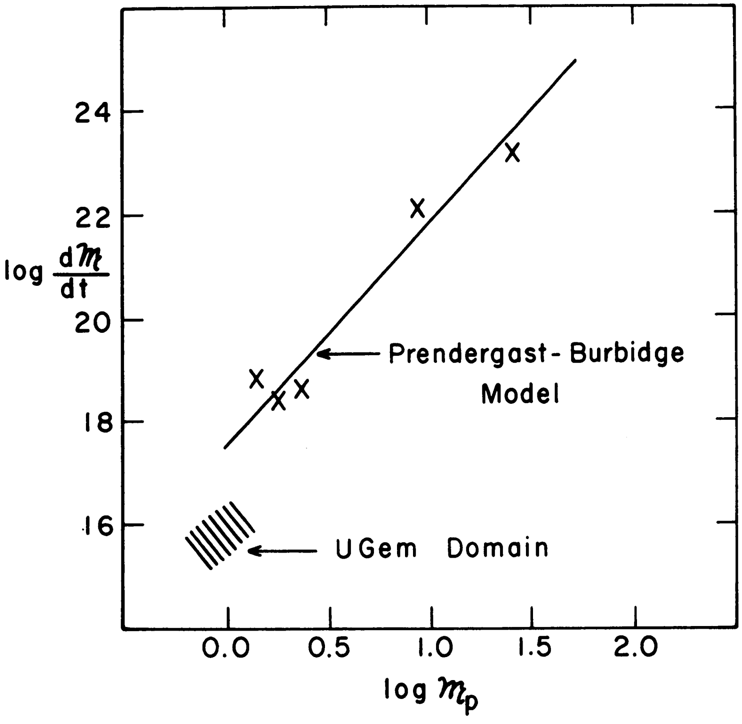

Fig. 7. The mass transfer rate of primaries in Case A or Case B evolution as a function of primary mass.

can be taken to apply to the case when the secondary is a degenerate object since the driving mechanism has a time-scale depending only on the Kelvin time of the primary. We see from the Figure that the rate required by the Prendergast-Burbidge model is comfortably in the range of ejection rates computed for evolving primaries. Thus the required accretion rate can be supplied by stars undergoing evolution to the right in the HR diagram for the first time. This does not seem to us to be accidental.

If the mass transfer rate were reduced by one or two orders of magnitude, the

X-rays would not be produced by the model (Prendergast, private communication). This is because the inner part of the disk does not become sufficiently hot and the outer part is too opaque. But mass-transfer in U Gem stars and many old novae is not driven by hydrogen exhaustion in the primary component, but rather by the emission of gravitational waves (Faulkner, 1971). This is because the masses are too small for significant nuclear burning to have taken place. The corresponding transfer rate is therefore of order 10^{16} gm s^{-1} (Faulkner, 1971), too small to produce X-ray emission. That these objects could be responsible for the discrete sources needed to explain the soft X-ray background (Gorenstein and Tucker, 1972)is unlikely, since their numbers per unit volume of space are too small by a factor of 10^4.

Our third and final boundary condition has to do with the number of X-ray sources expected per unit volume of space if all are derived from mass transfer binaries. Consider for example stars in the low mass group of Section 2. We assume no loss of angular momentum or mass. We start with stars having $P < 3$ days, so that the period of the evolved descendant is short enough to permit eventual mass transfer under Case B. From the luminosity function in the solar vicinity, we find that there are about 2×10^{-5} such binaries per pc^3 (Kuiper, 1935; Anderson and Kraft, 1972) and from the ratio of main sequence to mass-transfer lifetimes, we expect about 10^{-7} X-ray sources per pc^3, or one about every 100 pc. This mean separation is too small by a factor of 5 to 10, but one can easily think of ways to increase it. For example, perhaps the white dwarf becomes unstable under accretion and remains an X-ray source for only a tiny fraction of the Kelvin time of its companion. On the other hand, we could increase the mean distance between X-ray sources by a factor of 2 or 3 by assuming they are derived from binaries originally with B-type (high mass) primaries. At the present state of our knowledge, it seems best to take comfort in the fact that the predicted numbers are at least larger, rather than smaller, than the numbers required by observation.

Acknowledgements

I am indebted to Drs van den Heuvel and R. Wilson, and to members of the staff at American Science and Engineering, expecially Drs Giacconi, Gursky, and Tucker for communicating results in advance of publication.

Appendix

Cyg X-1 has not been discussed here even though it has been identified with the 9th magnitude mass-transfer spectroscopic binary HDE 226868 (Webster and Murdin, 1972; Bolton, 1972). The most certain evidence that this star is, in fact, the X-ray source, stems from the position of the variable radio source given by Hjellming and Wade (1971). If, however, variable radio emission is a normal feature of mass transfer binaries that are not necessarily X-ray emitters (cf. Hjellming *et al.*, 1972), then we may not be justified in assuming that HDE 226868 is identical with Cyg X-1. For this reason, discussion of the properties of HDE 226868 was not included here.

References

Anderson, K. and Kraft, R.: 1972, *Astrophys. J.* **172**, 631.

Arp, H.: 1965, *Astrophys. J.* **141**, 43.

Arp, H. and Hartwick, F.: 1971, *Astrophys. J.* **167**, 499.

Blaauw, A.: 1961, *Bull. Astron. Inst. Netherlands* **15**, 265.

Blumenthal, G., Cavaliere, A., Rose, W., and Tucker, W.: 1972, *Astrophys. J.* **173**, 213.

Boersma, J.: 1961, *Bull. Astron. Inst. Netherlands* **15**, 291.

Bolton, C.: 1972, *Nature* **235**, 271.

Bopp, B. and Vanden Bout, P.: 1972, *Publ. Astron. Soc. Pac.* **84**, 68.

Burbidge, E., Lynds, C., and Stockton, A.: 1967, *Astrophys. J.* **150**, L95.

Cameron, A. and Mock, M.: 1967, *Nature* **215**, 464.

Chodil, G., Jopson, R., Mark, H., Seward, F., Swift, C.: 1965, *Phys. Rev. Letters* **15**, 605.

Crawford, J. and Kraft, R.: 1956, *Astrophys. J.* **123**, 44.

Elliot, J. and Liller, W.: 1972, *IAU Circ.* No. 2395.

Faulkner, J.: 1971, *Astrophys. J.* **170**, L99.

Giacconi, R., Gursky, H., Kellogg, E., Schreier, E., and Tananbaum, H.: 1971, *Astrophys. J.* **167**, L67.

Giacconi, R., Gursky, H., Kellogg, E., Murray, S., Schreier, E., and Tananbaum, H.: 1972, *Astrophys. J.*, (in press).

Gorenstein, P. and Tucker, W.: 1972, *Astrophys. J.*, (in press).

Gott, R.: 1972, *Astrophys. J.* **173**, 227.

Grader, R., Hill, R., Seward, F., and Toor, A.: 1966, *Science* **152**, 1499.

Hartwick, F. and Hesser, J.: 1972, *Bull. Am. Astron. Soc.* **4**, Part 1, p. 241.

Hiltner, W.: 1972, *IAU Circ.*, No. 2398.

Hiltner, W., Mook, D., and Lynds, C.: 1970, *Ann. Rev. Astron. Astrophys.* **8**, 139.

Hjellming, R. and Wade, C.: 1971, *Astrophys. J.* **168**, L21.

Hjellming, R., Wade, C., and Webster, E.: 1972, *Nature* **236**, 43.

Iben, I.: 1967, *Ann. Rev. Astron. Astrophys.* **5**, 571.

Kippenhahn, R. and Weigert, A.: 1967, *Z. Astrophys.* **65**, 251.

Kippenhahn, R., Kohl, K., and Weigert, A.: 1967, *Z. Astrophys.* **66**, 58.

Kopal, Z.: 1959, *Close Binary Systems*, John Wiley and Sons, New York.

Kraft, R.: 1962, *Astrophys. J.* **135**, 408.

Kraft, R.: 1964, *Astrophys. J.* **139**, 457.

Kraft, R.: 1966, *Trans. IAU* **12B**, 519.

Kraft, R. and Demoulin, M.: 1967, *Astrophys. J.* **150**, L183.

Kraft, R. and Miller, *J.* 1969, *Astrophys. J.* **155**, L159.

Kraft, R., Mathews, J., and Greenstein, J.: 1962, *Astrophys. J.* **136**, 312.

Kristian, J., Brucato, R., and Westphal, J.: 1972, (in press).

Kristian, J., Sandage, A., and Westphal, J.: 1967, *Astrophys. J.* **150**, L99.

Kruszewski, A.: 1966, in Z. Kopal (ed.), *Advances in Astron. and Astrophys.* Vol. 4, Academic Press, Inc., New York, p. 233.

Krzeminski, W. and Smak, J.: 1971, *Acta Astron.* **21**, 133.

Kuiper, G.: 1935, *Publ. Astron. Soc. Pac.* **47**, 121.

Kuiper, G.: 1941, *Astrophys. J.* **93**, 133.

Margon, B.: 1972, *IAU Circ.*, No. 2398.

Paczynski, B.: 1971a, *Ann. Rev. Astron. Astrophys.* **9**, 183.

Paczynski, B.: 1971b, *Acta Astron.* **21**, 1.

Peterson, L. and Jacobson, A.: 1966, *Astrophys. J.* **145**, 962.

Plavec, M.: 1968, in Z. Kopal (ed.), *Advances in Astron. and Astrophys.* Vol. 6, Academic Press, Inc. New York, p. 201.

Prendergast, K. and Burbidge, G.: 1968 *Astrophys. J.* **151**, L83.

Salpeter, E.: 1972, 'Remarks before the Princeton Symposium on X-ray Sources', Jan. 15, 1972.

Sandage, A., Osmer, P., Giacconi, R., Gorenstein, P., Gursky, H., Waters, J., Bradt, H., Garmire, G., Sreekantan, B., Oda, M., Osawa, K., and Jugaku, J.: 1966, *Astrophys. J.* **146**, 316.

Schreier, E., Levinson, R., Gursky, H., Kellogg, E., Tananbaum, H., and Giacconi, R.: 1972, *Astrophys. J.* **172**, L79.

Shklovskii, I.: 1967, *Astrophys. J.* **148**, L1.
Smak, J.: 1964, *Publ. Astron. Soc. Pac.* **76**, 210.
Thorne, K. and Ipser, J.: 1968, *Astrophys. J.* **152**, L71.
Van den Bergh, S.: 1972, *Publ. Astron. Soc. Pac.* **84**, 306.
Van den Heuvel, E.: 1968, *Bull. Astron. Inst. Netherlands* **19**, 432.
Van den Heuvel, E. and Heise, J.: 1972, *Nature*, (in press).
Webster, B. and Murdin, P.: 1972, *Nature* **235**, 37.
Westphal, J., Sandage, A., and Kristian, J.: 1968, *Astrophys. J.* **154**, 139.
Wilson, R.: 1970, in L. Gratton (ed.), 'Non-Solar X- and Gamma-Ray Astronomy', *IAU Symp.* **37**, 242.
Wilson, R.: 1972, *Astrophys. J. Letters* **174**, L27.
Ziolkowski, J.: 1970, *Acta Astron.* **20**, 213.