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A field guide to the binary stars

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For most of the history of binary star astronomy, systems have been classified largely on the basis of how they were discovered and qualitative appearance of their spectra and light curves. Our understanding of single and double star evolution has now progessed to the point where most of the classes previously identified, and some new ones, can be arranged into evolutionary sequences, depending primarily on the initial masses and separation of the component stars.

OF the points of light in the sky we call stars, well over half in fact consist of two (or more) luminous bodies in gravitationally bound orbits around each other[1,2]. These are the binary stars. About half of them, in turn, are close binaries—systems in which the stars are too close together to complete their normal evolution without being modified by each others' presence[3].

For single stars, this normal stellar evolution can be crudely divided into several phases: (1) pre-main-sequence contraction from interstellar gas, (2) main sequence core hydrogen burning, ended by (3) exhaustion of hydrogen in the core, which contracts, initiating (4) shell hydrogen burning, during which the star appears as a red giant (or, for massive stars blue or yellow supergiant), followed by (5) core helium ignition and burning as horizontal branch or clump star or yellow-to-red supergiant, (6) shell helium burning as an asymptotic giant or red supergiant, and (7) rapid loss of outer layers (leaving a white dwarf) or rapid additional nuclear reactions ending in a supernova explosion and neutron star formation.

Each of these phases seems also to occur in binary systems and can be modified gently by the gravitational field or stellar wind of a companion or more drastically by gas flow to or from the companion through the inner lagrangian point (L_1 in Fig. 1) between them. This latter is called Roche lobe overflow. A star expands during phases (2), (4), and (6); and Roche lobe overflow beginning during them has historically[3] been called Case A, B, and C of mass transfer respectively.

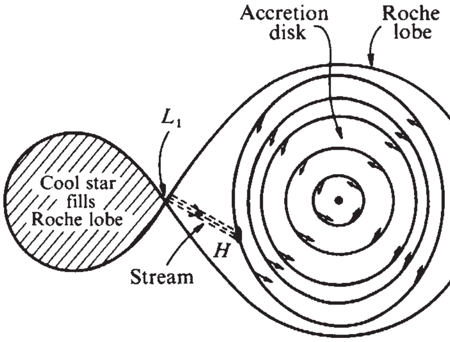

Fig. 1 Generalized, all-purpose close binary in process of mass transfer. Donor and receiver can each be in a variety of evolutionary states. Crucial aspects are the existence (in a coordinate frame that rotates with the system) of an equipotential surface that envelopes both stars, called the Roche lobe, and of the critical point L_1 on that lobe, between the stars, from which material will flow in a stream towards the receiver, carrying considerable angular momentum with it. Thus, at least during rapid transfer, a disk forms, and, especially in the cataclysmic variables, will have a hotspot (H) where the stream hits. Only slightly outside the Roche lobe occurs an equipotential that (again in the rotating frame) is open to the outside world, permitting ready loss of mass and angular momentum from the system as a whole.

A star of mass M evolves on a time scale roughly proportional to M^{-2} (main sequence lifetime $= (M/M_\odot)^{-2}\times 10^{10}$ yr, and so on). Thus, the initially more massive member of a pair, which we shall here and forever after call the primary, is always the first to reach the expansion phases and overflow its Roche lobe, if this is ever to happen at all. Thus we expect evolution of binary systems to occur in the following stages: (1) birth and pre-main-sequence contraction, (2) main sequence hydrogen burning in both stars, usually separate, but sometimes already in contact with their Roche lobes, (3) expansion of the primary, with first stage of mass transfer onto the secondary, and perhaps loss of both mass and angular momentum from the system as a whole, (4) completion of the evolution of the primary, (5) expansion of the secondary, with second stage of mass transfer back to primary and further losses from system, and (6) completion of evolution of the secondary. The sections below divide up the binary systems we have observed and modelled into these six classes, and Table 1 outlines the scheme.

We can also classify binary systems by the kind of observation that reveals the presence of the companion—changes in brightness, as one star eclipses, lights up, or distorts the shape of the

Table 1 Outline of the evolutionary scheme

Phase	What happens	Likely example
1	M_1 and M_2 contract	BM Ori
2	Both stars on main sequence	
	detached	α Cen
	in contact	W UMa
3	M_1 evolves and expands	
	pre-contact	RS Can Ven
	rapid transfer	β Lyrae
	slow transfer	Algol
4	M_1 completes evolution	
	helium stars	KS Per
	binary planetary nebula nuclei	UU Sge
	white dwarf + main sequence	V471 Tauri
5	M_2 evolves and expands	
	pre-contact (M_1 = white dwarf) symbiotic star	Mira
	pre-contact (M_1 = neutron star) massive X-ray binary	Cen X-3
	contact (M_1 = white dwarf) cataclysmic variables	Nova Cygni 1975
	contact (M_1 = neutron star) low-mass X-ray binary	HZ Herc
6	M_2 completes evolution	
	two white dwarfs	AM CVn
	Type I supernova	Tycho's and Kepler's Supernovae
	white dwarf + neutron star	long-period binary pulsar
	neutron star + neutron star	binary pulsar 1913+16

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other (eclipsing binaries), changes in radial velocity caused by orbital motion (spectroscopic binaries), discordant combinations of spectral lines coming from the two stars (spectrum binaries), and motion in the plane of the sky (astrometric binaries, visual binaries, and common proper motion pairs, for one dot of light wiggling, two dots orbiting, and two dots moving together in very wide orbit). This division is clearly less fundamental than the evolutionary one, but it is worth noting that we can know we have a binary system only if one of these effects is detected.

The literature of binary stars is, inevitably, enormous. In an effort to render this feast less indigestible, the present discussion has been largely tied to a secondary literature of review articles, monographs, and conference proceedings (listed as references 1, 3–24 and referred back to by many of the subsequent items). This serves two purposes: first, most of the points made will have been thought about by at least two people besides the present author, and second, the reader pursuing one of the items will generally find it nestled in context among other papers addressing related issues.

Birth and pre-main-sequence contraction (phase 1)

Star formation in general is rather poorly understood[25] and that of binaries doubly so[26], although we have some observational and theoretical evidence that there are two or more mechanisms at work, producing systems with different separations, mass ratios, and so on[26,27]. We catch only a few systems during pre-main-sequence contraction, partly because the phase occupies only about 10^{-3} of the lifetime of a typical star, and partly because it is characterized by the presence of obscuring gas and dust clouds and by activity on the stellar surface that changes the brightness of the stars erratically and messes up their spectral lines so as to make detection of companions difficult.

T Tauri itself, the prototype pre-main-sequence variable, has a faint IR companion[28] with orbit period in excess of 1,000 yr, and a couple other members of the class show visual companions, eclipses, or variable radial velocities[29–31], the statistics of the velocities being consistent with normal binary incidence[29]. Among more massive systems, a few like BM Ori [32], seem to combine a pre-main-sequence secondary with a primary already burning hydrogen. Gaposchkin[30] lists some additional systems probably of this type, as well as systems containing UV Ceti variables, faint, flaring, low-mass stars, generally thought to be newly-arrived on the main sequence. The presence of a companion can, however, enhance flare activity[33], so that these need not all be very young. The BY Draconis variables, binaries with periods of a few days and extensive dark spots on the component stars, probably also have their activity enhanced this way[34].

The preceding remarks apply to Population I stars, those of roughly solar composition and ages $\leq 8,000$ Myr, found in the disk of our Galaxy. We just barely survey the brightest individual Population I stars in other nearby galaxies (Andromeda and the Magellanic Clouds), and these include eclipsing binaries in the same types and numbers as found in our own galaxy[20,35]. The situation for the old, metal-poor stars of the halo (Population II) is quite different. A few isolated halo stars (identified as such by their composition and/or velocity) are spectroscopic binaries[36,37], but within the main concentration of halo stars, the globular clusters, we see no evidence at all for main sequence or giant binaries (although there are several X-ray binaries and, probably, cataclysmic variables, belonging to phase 5 below). This is not easy to explain, except by saying that main sequence systems never formed and the evolved systems must have arisen other than through the course of events just described[38]. Our one other Population II-like sample comes from the Draco dwarf spheroidal galaxy, which apparently has no eclipsing binaries among its brightest stars[20,35]. This situation is not only puzzling but annoying, as models for the dynamical evolution of globular clusters typically make considerable use of energy transfer between binary orbits and the total cluster potential[39].

The main sequence (phase 2)

Stars spend 90% of their nuclear-burning lives on the main sequence. Catalogues of binary systems are rather less dominated than one might have guessed by systems containing two main sequence stars only becuase other, later phases are brighter and more spectacular. But we do see large numbers of main sequence pairs, with separations from nearly as large as half way to the next star[40] to as small as the sum of the stars' own sizes[41].

Well-separated pairs are our only fundamental source of measured stellar masses and one of the most important sources of measured radii[15]. Thus binaries provide the foundation on which we have erected our entire understanding of stellar evolution. The measured masses range from 7% of the mass of our Sun for Ross 614 to a well-determined $32 \pm M_\odot$ for LY Aur [15] and, perhaps, as much as $\geq 50 M_\odot$ for Plaskett's star[20] and V505 Mon [42]. A few astrometric companions may have still smaller masses and are, perhaps, not true hydrogen-burning stars[40]; and some single stars may be even more massive than Plaskett's star[43]. In addition to masses and sizes, we learn something about stars' interior density distributions from the way tidal interactions between binary companions change their mutual orbits. The observed distributions are in reasonable accord with the best model predictions[44].

Within detached systems, many of the things that can happen to single main sequence stars proceed unimpeded. For instance, the classes of mild variables dignified by the names β Cephei stars (or β CMa stars), α CVn stars, δ Scuti stars, and dwarf Cepheids are neither over nor under represented in binaries[32], although some of the binary Delta Scuti variables probably have the precise frequencies of their pulsation modes modified by their companions' tidal influence[45]. The interaction between duplicity and surface chemical abundance peculiarities is more complex: the metallic-line Am stars are essentially always short-period spectroscopic binaries, while the Ap stars (with strong lines of certain rare earths) almost never are[46–48]. The Ap stars, but not the Am's, show strong surface magnetic fields[49]. Both are slow rotators and can be modelled rather well by diffusion processes in their resultingly stable atmospheres[50,51]. We might then blame the differences between the two classes on the effects of interactions among rotation, magnetic field, and companion[48].

This is perhaps the logical point to discuss systems so wide that both stars can complete their evolution without much interaction. Some of these are very informative, for instance the eclipsing class (with VV Ceph and ζ Aur as prototypes), in which the primary has developed an enormously extended, thin red-giant atmosphere, whose structure we can probe as the main-sequence secondary disappears gradually behind it[52]. Popper[15] lists some completely detached red giant pairs; and two of the nearest stars, Sirius and Procyon, have white dwarf companions at such large distances that they must be the products of primaries that completed their evolution essentially unaffected by the secondaries we see now. In the 12 double-white dwarf common proper motion pairs[41] both stars have died undisturbed. From an evolutionary point of view, these are really single stars, and will not concern us further here.

A little less than 0.1% of all stars[53] form in binaries of such small separation that both stars come in contact with their Roche lobes while on the main sequence. These are the W Ursa Majoris stars of spectral types *F*, *G*, and *K*, and their more massive analogues, the SV Cen stars. The latter are much the rarer, a reasonably complete list[54] including not many more than 12 well-studied systems. Contact binary specialists are currently disputing three items: how such systems form; how the component stars exchange mass, energy, and angular momentum to remain in contact; and how they eventually end up. An observed gap in separations between the W UMa's and the closest detached systems suggests that they do not quite form in contact, but get there shortly after birth, perhaps losing angular momentum by magnetic braking[55]. Energy exchange certainly occurs, as most pairs are more similar in luminosity than their mass ratios (as small as 0.08)[56] would permit for two single stars. The massive contact systems studied by Popper (personal communication) share this peculiarity. In SV Cen, the less massive star is actually the more luminous[57]. Two models currently compete, one in which rather unstable transfer takes the systems repeatedly into and out of contact (on time scales too long for us to probe except statistically), and one in which contact is maintained steadily[18]. The former should lead to the stars' eventually coalescing[58], perhaps into a rapidly rotating giant like FK Comae[59], the latter possibly to their evolving into a cataclysmic binary (phase 5, below) configuration[60].

Evolution of the primary and first phase of mass transfer (phase 3)

As the primary begins to evolve and expand, effects attributable to the companion sometimes appear well before contact with the Roche lobe. Heating of the cooler component by the hotter one can drive some mass transfer[61], and winds and other surface activity may be greatly enhanced. There are, for instance, the RS CVn variables, a numerous class of slightly evolved, solar-type stars, still well separated but, nevertheless, marked by conspicuous emission lines, and, quite unexpectedly, radio and X-ray emission of sorts not seen in most single stars of the same spectral types[62]. Most other radio-emitting stars are also binaries, the emission coming from enhanced winds, colliding winds, and the like[63], the chief exception being radio stars such as P Cygni which are known from their spectral line profiles to have strong winds anyway[64]. X-ray stars, on the other hand (apart from the strong emitters discussed below), are typically single objects with extensive coronae[65]. There is some disagreement on how much of the activity to blame on the presence of the companion and how much on rapid rotation and deep convection zones (D. M. Popper, personal communication).

As the primary reaches its Roche lobe, mass transfer begins on a Kelvin–Helmholtz time scale (because the lobe shrinks as the primary mass decreases), until the mass ratio is reversed, after which transfer continues on a nuclear time scale[3].

We catch a few stars, such as ε Aurigae[66] and β Lyrae[67] during the short-lived phase of rapid transfer, and many more, the W Serpentis stars[68] just after the mass ratio is reversed. The brightest stars in other galaxies (the Hubble–Sandage variables) and our local example, η Carinae, are perhaps very massive binaries also experiencing rapid transfer[69]. During the most rapid transfer, the secondary (like that of β Lyrae) is often completely concealed by a disk of accreting material. In fact, the secondaries are likely to have trouble accommodating both the mass[70] and the angular momentum[71,72] as fast as they arrive, and considerable amounts of both can be lost to the system. We know that this happens: several systems show spectral evidence for shells surrounding both stars, gas streams away from them, and the like[73,74]; and the masses and separations of pairs that have completed rapid transfer show that mass and angular momentum cannot generally have been conserved within the systems[75–78].

The most severe losses occur when the expanding primary surrounds both stars in a common envelope[78]. The stars, dragging on the envelope, spiral together and shove it off. Some close pairs among the X-ray binaries, cataclysmic variables, binary nuclei of planetary nebulae, and V471 Tauri stars must be products of such a process. Webbink[79] has attempted to trace some of the intermediate phases and examples of each. The sequence, as the envelope gradually takes over and then leaves, runs: recurrent nova, symbiotic star of the CI Cyg type[80], BQ[ ] star (B type star with spectrum dominated by forbidden emission lines)[81], *F* or *G* emission line supergiant (like ρ Cass), ultra-long period contact binary (such as W Cru), rapidly rotating bright giant with double core (such as FK Comae, although it and its relatives have alternatively been explained as the product of merged W UMa systems[59]), star with strong emission and absorption lines showing rapid mass loss (such as P Cygni), and planetary nebula with double nucleus (such as NGC6164/65 and HD148937). Webbink does not mean to imply that all members of these observed classes are to be explained in this way; many recurrent novae and symbiotic stars, for instance, clearly belong in phase 5.

As mass transfer and loss slow down to the nuclear time scale, we reach the Algol binaries, in which the by now lower mass primary continues to drizzle material onto the more massive secondary sufficiently slowly that there is no conspicuous accretion disk[82]. The class includes Algol itself and many other well-studied stars, and explaining the seeming paradox of the lower mass but more highly evolved primary was one of the early triumphs of binary star theory[3]. Two puzzles remained. One, that of the R CMa and undersized subgiant stars (in which the primary either had remarkably low mass or seemed to have pulled away from its Roche lobe while maintaining an extended envelope), has now largely been eliminated by more accurate observations of the systems concerned[83]. The other is still with us. Naftilan[84] among others found spectroscopic evidence that the evolved star had a lower surface abundance of heavy elements than its companion in many Algols. The implication is that the elements other than hydrogen and helium are concentrated towards stellar surfaces, and stripping has revealed the low-metal zone[85]. This, if true, has enormous implications for models of chemical evolution of the Galaxy, for the solar neutrino problem, and so on[87]. Recent work has not much clarified the situation: giant components have been reported with metal abundances that are lower than[87], the same as[88], and higher than[89] those of the unevolved stars. I hope this is all noise, not signal.

At least some of the Be and shell stars (prototype γ Cas) belong here[5,21]. These show both rapid rotation and emission lines indicative of hot gas around them. A large fraction are undoubtedly in binary systems, and their shells attributable to material being accreted from a more highly evolved companion[90]. The Be stars with X-ray emitting companions, such as X Per, must, on the other hand, be losing material to the neutron stars[91] and belong in phase 5.

Demise of the primary (phase 4)

As the primary continues its evolution, helium ignition or loss of the entire hydrogen-rich envelope will reduce its size until it pulls away from its Roche lobe and mass transfer ceases (possibly to be briefly renewed during shell helium burning). The system becomes much less conspicuous, eventually simply appearing as a fairly normal main sequence star, whose white dwarf or neutron star companion may or may not be detectable. A sufficiently asymmetric supernova explosion of a massive primary can unbind its system, sending both neutron star and OB secondary off at high speed, the former as a pulsar, the latter as a classical OB runaway star[92]. But explosions that yield recoil without disruption must also occur, since about half of known OB runaways have low-mass companions still attached[93]. About half of these companions should be white dwarfs or neutron stars, and half small main sequence stars[94], runaway velocities in the latter case being attributable to ejection from a cluster.

Systems that have reached this stage may reveal their wild past in several ways. First, the secondary will be more massive than a single star of the same age could be. The puzzling blue stragglers, members of galactic and globular clusters and dwarf spheroidal galaxies that are too massive (too blue and bright) to have spent the whole age of their parent star systems in their present state may be mass transfer products[95,96], although mixing between core and envelope in a single star can produce the same effect[97].

Second, either star or both can show composition anomalies as a result of the primary having been stripped down to where hydrogen or helium burning have gone on. Highly evolved, but pre-white-dwarf, primaries can appear as helium stars (meaning, at least, He/H > 1) like υ Sgr and KS Per[98,99], some of these also showing excess nitrogen from CNO cycle hydrogen burning[100], or as Wolf–Rayet binaries[24], in which a compact, but very bright core with lots of He and N or C but no discernible hydrogen orbits a fairly normal OB main sequence star[101,102]. Evolution and stripping of the secondary can eventually produce a second Wolf–Rayet binary stage with white dwarf companion, comprising 20–50% of the observed systems[103–106]. These really belong in phase 6. And there are also single Wolf–Rayet stars, stripped down to the same levels by violent winds[107], but a binary companion clearly helps[3]. The barium stars may belong in here too. Barium is made by slow addition of neutrons to iron in parts of stars where hydrogen and helium burning can interact. Thus an excess of it means that a star's surface has been adulterated by its own or a companion's core nuclear burning products. Self-induced barium excesses appear among (typically single) carbon rich stars[108]. But the classical giant (normal carbon) barium stars are apparently all binaries, with rather low mass secondaries[109]. The obvious interpretation, that the pollution came from the companion, which is now a white dwarf, is not entirely supported by observations, and these systems are still rather a mystery[110].

Third, we may still see portions of an envelope shed by the primary or by common envelope processes, as in the planetary nebula with eclipsing, spectroscopic, or visual binary nuclei like UU Sge, FG Sge, NGC 246, 1514, and 6543 (refs 111–113), and in the class of binary protoplanetary nebulae (prototypes HM Sge and V1016 Cyg), which may or may not really be either binaries or planetary nebula precursors[114–115]. The supernova remnant G109.1 − 1.0, whose central object is an X-ray binary, is another example of a recent demise (to neutron star rather than white dwarf) with remaining gas[116].

Finally, the system may just sit there and stare at you like the V471 Tauri stars, a handful of systems known to have white dwarf primaries, low mass, main-sequence secondaries, and separations small enough that they must be common envelope products[78,117,163]. An extreme example, AA Dor, has a total remaining mass of less than 0.3 $M_\odot$ (ref. 118) and must have lost mass and angular momentum with astounding efficiency, perhaps by magnetic braking and winds as well as a common envelope (P. P. Eggleton, personal communication). None of these has the secondary main sequence mass significantly larger than the white dwarf, as would result from conservative mass transfer in a system with initially almost equal components.

Evolution of the secondary (phase 5)

In due course, the secondary in turn departs the main sequence, resulting in mass transfer back to the primary. Occasionally this may happen before the primary has completed its evolution, resulting in a pair of helium stars, which can either end up as a close white dwarf pair (like others in phase 6) or, with large enough initial masses, give rise to a nuclear-detonation Type I supernova[119].

Normally, the primary is compact before back transfer beings, just because of the steep dependence of stellar lifetime on mass[120]. It thus has a deep gravitational potential well, and the secondary can contribute enough accretion just from its wind to produce conspicuous effects before it ever reaches its Roche lobe. Systems such as Mira (pulsating red giant + white dwarf in a wide orbit) are of this type, as are some of the symbiotic stars (such as V1329 Oph)[122]. This class of erratic variables[23] is defined by the simultaneous presence of spectral features coming from regions with two very different temperatures. Some may be single stars with extended coronae, but most (and all 'real' symbiotics, in current usage) are binaries with significant accretion, normally onto a white dwarf, from wind or Roche lobe overflow. Drilling and Schonberner[122] suggest that the helium-rich binaries KS Per and υ Sgr also involve slow transfer back onto a compact primary. Finally, where a massive O or B secondary's wind impinges on a neutron star, we see a binary X-ray source.

Once the secondary reaches its Roche lobe, transfer speeds up. For a massive secondary and neutron star primary, it becomes so rapid that ambient gas is optically thick to X rays, and the source turns off. For a lower-mass secondary, on the other hand, transfer now for the first time becomes sufficient to produce observable X rays, so that we see two separate, high and low mass, classes of X-ray binaries. These must have been produced, respectively, by first-stage transfer that lost very little and much mass from the system as a whole[123,124]. The mass gap in between represents stars where the wind transfer rate is too small and the Roche lobe overflow rate too large to make detectable X rays. The neutron stars in most of these systems have rotation periods of seconds to minutes (minimum 0.069 for A0538 − 66)[125], surprisingly slow given that accretion is adding angular momentum and the radiation mechanism not draining it away as in true pulsars. Spin-down periods must alternate with accretion episodes in some way[126] or we could not catch as many systems as we do rotating slowly and spinning up[127]. Interesting special cases of the X-ray binary phase include 4U1626 − 67 (ref. 128), whose donor secondary is apparently a white dwarf; SS433 (ref. 129), in which some of the energy goes into expelling two oppositely directed gas jets at about $0.26c$; and Cyg X-1, whose primary is almost certainly a black hole[10]. Continuing accretion onto a neutron star in a close binary is an obvious and straightforward way to form a black hole, but the Cyg X-1 primary is too massive to have grown by this mechanism during the lifetime of the OB secondary, and must have resulted directly from the collapse of a star unable to eject all its envelope in a supernova ($M \gtrsim 15 M_\odot$ according to Hillebrandt[130]).

Finally, Roche lobe overflow onto a white dwarf primary results in an enormous range of phenomena collectively dignified by the name cataclysmic binaries[131]. The main subtypes are the classical novae, the dwarf novae (or SS Cygni stars, subtypes named for Z Cam, with luminosity plateau on the declining branch of the light curve, and U Gem without it), the nova-like variables (UX UMa stars), the polars (or AM Herc stars), the recurrent novae, and the symbiotic (or Z And) stars. Many of them are X-ray sources[132], though never so bright or hard as the accreting neutron stars. The division among types is not absolutely rigid, the known recurrent novae T CrB and RS Oph looking, in between outbursts, like symbiotic stars[133].

Table 2 summarizes observed properties of the several types and what we think we know about the nature of the component stars and the mode of mass transfer. The basic energy source is gravitational (accretion) for the outbursts of the dwarf novae[134] and nuclear (degenerate ignition of hydrogen) for the novae and recurrent novae[135]. This, plus the size of the donor star, the rate of mass transfer, and intensity of magnetic field of white dwarf seem to divide up the various types (refs 136–142, and B. Paczyński, personal communication). We do not identify all possible combinations, including the lowest possible transfer rates (presumably because nothing interesting happens), and the highest ones, at which the hydrogen burns steadily and the systems presumably are indistinguishable from hydrogen-shell-burning giants. These high transfer rates may conceal the systems in which the white dwarf is still the less massive star. These should otherwise be fairly numerous (B. Paczyński, personal communication). Considerable work remains to be done in sorting out the physics of the several classes, aberrant members, and, especially, the precise progenitors, evolutionary history, and cause of mass transfer for each[4,6,8,14,16,23,143].

Several kinds of mass ejection occur in cataclysmic variables: 'true' novae and recurrent novae blow off the partially-burned hydrogen of each explosion in a detectable, expanding remnant[144]. The jets ejected by R Aqr[145], the nucleus of planetary nebula A30[146] and some of the Herbig–Haro objects[147] may or may not have anything to do with this phase. They are all rather similar looking, but the first is almost certainly a binary, and the last almost certainly not.

Table 2 The cataclysmic variables classified in the conventional way

Type	M_v (quiescent)	Outburst amplitude (mag)	Recurrence time	Nature of instability	Stars	Mass transfer
Novae	+5	9–14	$10^{4\text{-}5}$ yr	Degenerate ignition of hydrogen	Main sequence + white dwarf	Lobe overflow $\sim 10^{-9}\ M_\odot\ \mathrm{yr}^{-1}$
Dwarf novae	+10	2–6	10 days–30 yr	Change in $\dot{M}$ and/or disk structure	Main sequence + white dwarf	Lobe overflow $\sim 10^{-10}\ M_\odot\ \mathrm{yr}^{-1}$
Nova-like	+5–10	Irregular	—	Change in $\dot{M}$ and/or disk structure	Main sequence + white dwarf	Lobe overflow $\sim 10^{-9\text{-}10}\ M_\odot\ \mathrm{yr}^{-1}$
Polar	+5–10	Irregular	—	Change in $\dot{M}$ and/or accretion pattern	Main sequence + white dwarf strong B	Lobe overflow $\sim 10^{-9\text{-}10}\ M_\odot\ \mathrm{yr}^{-1}$
Recurrent novae	+2	7–9	10–100 yr	Degenerate ignition of hydrogen	Red giant + white dwarf	Lobe overflow $\sim 10^{-6}\ M_\odot\ \mathrm{yr}^{-1}$
Symbiotic stars	+4–0	Irregular	—	Changes in pattern of quasi-spherical accretion	Red giant + white dwarf	Wind $\sim 10^{-7}\ M_\odot\ \mathrm{yr}^{-1}$

Cataclysmic variables and X-ray binaries, unlike previous stages, are well represented among Population II stars in globular clusters. The strong cluster X-ray sources appear to be standard accreting neutron stars[19], and their number (about eight at last count[148]) constitutes far more than the clusters' fair share of the galactic supply[149]. Optically-identified cataclysmic variables are perhaps similarly overabundant[38] and still more cataclysmic variables are the likeliest explanation of a new class of weak ($L = 10^{32-34}$ erg s^{-1}) cluster X-ray source which currently has about 12 members[148,150].

As during the first transfer phase, donors may now envelop their companions, resulting in extensive mass and angular momentum loss from the system. Some of the closest 'dead' pairs described below require something of the sort within their history[151,152].

For the cataclysmic variables especially, the death process can be gradual and fairly prolonged, resulting in pairs such as HZ 22[153,154], where a hot subdwarf (pre-white dwarf in effect) orbits a cooler degenerate star with very little interaction, and AM CVn[137] whose components are both low mass degenerates but, owing to their very close spacing (orbital period 18 min), interact vigorously enough to put the system on many lists of nova-like variables.

A spectacular termination is also possible: prolonged accretion of burned hydrogen can drive the white dwarf to one of several kinds of violent burning of its entire helium, carbon, and oxygen supply. This is our current 'best-buy' model for (many or possibly all, though progenitors are rather rare[155]) Type I supernovae, the sort occurring among relatively old stars[156].

Death of the secondary (phase 6)

The secondary has much the same options available to it as the primary–planetary nebula plus white dwarf (UU Sge may be such a second-time-around planetary nebula with binary nucleus[79]), neutron star, or black hole. The first of these leads typically to a pair of white dwarfs, with separation depending on the amount of angular momentum lost in previous stages. These are inevitably inconspicuous, but we see a few pairs, both close (AM CVn) and wide (for example, G107 − 69/70)[157]. Many others may be hiding among seemingly-single white dwarfs and could be identified by careful searches for colour anomalies and variable radial velocities. Loss of angular momentum by gravitational radiation and, perhaps, winds, inevitably produces coalescence of such a system, though not necessarily within the age of the Universe. The result is likely to look like a Type I supernova (B. Paczynski, personal communication).

Less often, the secondary white dwarf may find itself orbiting a primary neutron star. The two longer-period binary pulsars may be like this[158,159]. We know the neutron stars must have formed first, because their combination of rapid rotation and weak magnetic field requires them to have been spun up by accretion from a companion[160]. The one visible star within the error box of the 24-h orbit period example is, however, fainter than this hypothesis predicts. Loss of sufficient material from the secondary in a planetary nebula could, in principle, release the newly-spun-up neutron star. Arons[161] proposes this origin for the new 1.56-ms pulsar[162].

Transition of the secondary to a neutron star may lead to a Type II supernova, with sufficient ejection to unbind the (now less massive) primary, yielding an old and a young runaway neutron star, with suitable velocities to explain the pulsar speeds we see. The system may also remain bound if the secondary has already lost most of its hydrogen and helium layers in a common envelope phase. The supernova event could then be quite faint (and/or look like a Type I, owing to the lack of hydrogen), and the product resemble the best-known binary pulsar, 1913+16, whose companion is probably another neutron star[158,159]. Which is the older is puzzling, since spin-up of the one we see apparently required accretion from the companion[160], which we then might also expect to see as a pulsar.

Finally, if the secondary collapses to a black hole, we do not expect to see anything at all from the black hole + black hole or black hole + neutron star pair, short of a final burst of gravitational radiation as they spiral together, or a compressed-dentifrice tube squirt of heavy elements from the disappearing neutron star.

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ARTICLES

Pb–Sr isotope variation in Indian Ocean basalts and mixing phenomena

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Pb and Sr isotopic compositions from the Indian Ocean (active ridges, old ocean floor and aseismic ridge samples) confirm the characteristic nature of the mantle record in this region. The results emphasize the importance of mixing processes between the lower mantle (oceanic-island basalt source), and the upper mantle (ridge-basalt source). The isotopic characteristics of the Indian Ocean islands seem to be in agreement with the hypothesis of the reinjection of sediments into the mantle.

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