Y CYGNI ?

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ABSTRACT. It is often assumed that a binary begins to interact when one of its components makes contact with its Roche lobe, thus "switching on" a new evolutionary process. The example of Y Cygni is used to illustrate the view that the whole lifetime of a binary helps to determine whether or not its components will interact. Of particular importance is the interval between the formation of a binary and the arrival of its components on the main sequence, during which probably all binaries are interacting. Barring accidents, the properties of the components when they reach the main sequence will define the whole subsequent history of the system, including whether or not there will be subsequent phases of interaction triggered by contact with the Roche lobe. Like any other mechanical system a binary will tend towards the state of lowest energy consistent with the constraints on it. This it can do by losing mass, equalizing the component masses, or reducing its separation. We therefore expect systems to tend to small masses to mass-ratios of unity, or to coalesce into single stars. In any given system, probably all three tendencies exist, but one dominates. For example, W Ursae Majoris systems may be fusing into single stars. The rotation, chemical composition, and magnetic fields of the component stars may modify the evolution of a binary and be responsible for the variety of interacting systems that we observe. Most interacting pairs are losing mass to the interstellar medium, so a complete study of binary evolution must consider not only the dynamical, but also the chemical, effects of binary systems on the evolution of the Galaxy.

1. Introducing Y Cygni

The system of Y Cygni is not interacting in the sense that that term is being used in this symposium. It is a well-behaved system with relatively well-determined absolute dimensions (Popper 1980). The light-curve displays two fairly deep and equal partial eclipses (Magalashvili and Kumsishvili 1959) and has long been observed well enough for apsidal motion (both Newtonian and relativistic) to be detected. Even the velocity-curve is reasonably well defined (Vitrichenko 1971), considering the difficulties that often attend the measurement of early-type spectra (Y Cygni is either O9 or B0). We have learned that the system contains two stars nearly equal in mass (about 17m⊙), radius (about 6R⊙), and (bolometric) luminosity (about 30,000 L⊙). The orbital period is very close to three days, so the centres of the two stars are less than one-fifth of an astronomical unit apart - yet there are no signs of interaction other than the mutual gravitation and its associated tidal forces. I find this remarkable, as I also find the near identity of the two components and even the very existence of a system containing two O-type stars.

To be sure, each component of Y Cygni has only about half the radius of the respective Roche lobe: many will consider that sufficient explanation of the absence of interaction. I have tried

Y. Kondo et al. (eds.), Evolutionary Processes in Interacting Binary Stars, 235–243.

to emphasize, however, what two very hot luminous objects we have so close to each other. Can we be sure they do not affect each other's evolution? I have often quoted Eddington (1926) writing about the reflection effect: "we shall not appreciably alter the internal state of a star by lightly patting its surface." But we know two things Eddington did not know: stars, especially O-type stars (Conti 1978), have winds, and small perturbations may have a large effect in a complex system ("chaos theory"). Recent estimates (de Jager, Niewenhuijzen and van der Hucht 1988, Howarth and Prinja 1989) suggest that O-type stars lose between $10^{-8}m_\odot$ and $10^{-5}m_\odot$ annually, through their winds. Stars like those in Y Cygni would be expected to be near the lower end of that range -- at least if they were single. Thus "lightly patting" the surface begins to look more like a heavy shower of hail! The two winds in Y Cygni *must* interact, and there have been both theoretical and observational studies of the effects of colliding stellar winds (Heap 1981, Girard and Willson 1987, Shore and Brown 1988, Chlebowski 1989, Gies and Wiggs 1991). Enough matter accumulates in the emission region to affect the spectrum, and enhanced X-ray emission observed in some O-type binaries may originate in the same region. Koch (private oral communication at the symposium) tells me that there is indeed evidence that the winds in Y Cygni are strongly directional. There are no obvious effects on either star, but the interacting winds may be just the kind of small perturbation (in the sense of chaos theory) that will eventually have far-reaching effects on the development of a complex mechanical system such as a close binary. I think we do not yet know how a system like Y Cygni will be affected by the collision of its two winds: perhaps it is interacting more closely than we think.

My second puzzle, the near identity of the two stars, also has, at first sight, an obvious answer. Evolution of O-type stars is rapid, and two such stars of different masses will evolve at such different rates that a binary system that begins with them as components will soon look like something else. Hutchings (1979) points out that, in such a binary, the more-massive component could become a neutron star while the less-massive one is still on the main-sequence. The system of VV Cephei illustrates how tight is the constraint. The observations (admittedly, not the most precise) do not make clear which component is the more massive (Wright 1977). Each is close to $20m_\odot$ and, on the main-sequence, would have been an O8 star: one is now a B-type star and the other an M-type supergiant (Wright's figures actually make the more evolved star the less massive, but they do not rule out the possibility that the mass-ratio is the other way about). If we are to observe any binaries at all containing two O-type stars, the components must be nearly equal in mass. That brings us to the third puzzle: should there be such binaries ?

We have, I believe, been so pleased to find a system like Y Cygni, from which we can derive masses and dimensions for O-type stars, that we have not stopped to ask if this is just good luck. For an O-type system, Y Cygni is relatively nearby: is it just a fluke that it is close enough to be observed? All O-type stars are short-lived: to quote Hutchings (1979) again, there have been 10^4 generations of them in the lifetime of the Galaxy. They are also rare, yet Y Cygni is composed of two of them in a volume much smaller than that of the solar system. Moreover, Popper's (1980) list contains at least one other similar system. Stars on that list must be bright enough to be observable with at least moderate spectroscopic dispersion. If we know at least two systems near enough to qualify, then they appear not to be flukes: a significant proportion of O-type stars must be in such systems. The question of how they came to be is not trivial.

2. Binary Formation and Star Formation

Until quite recently, theories of the origin of binaries were little more than hand-waving. Possible origins were thought to be: capture of one star by another, independent condensation round nearby nuclei, or fission of a rapidly rotating star. It has long been known that the first cannot account for the observed frequency of binary systems in regions where the stellar density is comparable to that found in the solar neighbourhood (Ambartsumian 1937). In star clusters, however, where most stars are born and the stellar density is high capture, shortly after birth may create or modify many binary systems. Abt, Gomez and Levy (1990) believe that the distribution of secondary masses in B-type systems provides some support for this view. Condensation around separate nuclei has been severely criticized by Boss (1987), although the difference between such condensation and capture within a natal cluster seems largely semantic. The formation of one massive star, however, probably inhibits that of another one nearby (Thompson 1985). In that case the components of Y Cygni could not have formed as close together as we now find them: independent condensation alone could not explain this system, even if there were no other difficulties for the theory. Fission, as a credible theory, goes in and out of fashion. As different assumptions have been made about how fission works, different conclusions have been drawn about the end-result. Most modern work suggests that matter thrown off the parent star will not form another star at all. Durisen and Mathieu (in Koch 1991) dismiss fission as a useful theory, but Lebowitz (1989) emphasized that *all* treatments of it are based on assumptions. He argues that the failure to reproduce real binaries by modelling invalidates particular assumptions, but not necessarily the concept of fission. I find his arguments convincing enough to suspend judgement, but undoubtedly the present majority view is that Y Cygni could not have been produced by fission.

The most favoured theory now, developed especially by Bodenheimer (1981 and this conference) and Boss (1987) is fragmentation of an interstellar cloud in such a way that many stars form in binary and multiple systems. Again, the distinction between this idea and independent condensation does seem to me largely semantic, but fragmentation has been worked out in more detail and fits in with what we are now learning about star-formation in general. I shall mean by fragmentation all processes that help to produce binaries *except* fission (which remains superficially attractive as an explanation of some close pairs, despite current difficulties). A similar rather simplified classification of theories of origin was made by Budding and Gallot (1990).

Observations in the infrared, among other factors, have led to a rapid increase, over the last five to ten years, in what we know about star formation (Lada 1985). The collapse of a star ("fragmentation") from a giant molecular cloud is a turbulent and wasteful process. Even a massive star, it seems, contains only a small amount of the matter involved: the rest is returned to the cloud unheated, still in molecular form, and at very high speeds. As low-mass stars emerge from the cloud, they eject bi-polar jets of enormous energy (10^{43} to 10^{47} ergs). Massive stars also eject matter, perhaps in different patterns (Thompson 1985). This phase is short-lived, perhaps about 10^5 years, but two stars forming nearby must affect each other. If they are destined to become a binary system, they are already interacting. After this violent stage, a protostar is surrounded by a collapsing disk of the kind from which we believe that the Sun and planets emerged. The disk is short-lived too, but since we know that the protosolar disk extended to at least 40 A.U., many binaries must continue to interact in this stage. Boss estimates that fragmentation takes place on a scale of 0.1 parsec (10^4 A.U.), about the separation of the widest known binaries, but protostellar disks are not immediately completely differentiated from the surrounding cloud and stars close enough to form even a wide visual binary will be subject to strong fluctuations in separation, and orbital period, in an interval comparable to the initial orbital period (10^5 years - see Boss 1984). The period may even be decreased permanently by several orders of magnitude (Boss 1984, Alexander 1987) so close binaries may be produced from wide binaries. Observational evidence of interaction in these early stages may be provided by the short-period circular orbit of V826 Tauri (Reipurth *et al.* 1990).

To make a system like Y Cygni in this way, however, we would have to postulate two massive O-type stars forming at a distance from each other of about one-tenth of that between the Sun and α Centauri. It is not clear that this is possible, and we may still have to appeal to capture within a natal cluster. Several investigations have suggested that, as single stars escape from a cluster, the remaining binaries become more and more tightly bound. Aarseth and Hills (1972) showed by numerical integration, that the binaries themselves would exchange partners in encounters, and the two most massive stars in any encounter would tend to stay together. The probable end-result is an isolated close binary containing the two most massive stars from the cluster that has now dissipated. Since Y Cygni is such an isolated system, one is tempted to suppose that it formed in this way - but for Aarseth and Hills a "close" binary has an orbital major axis of the order of 100 A.U., and the entire process would take a significant fraction the main-sequence lifetime of O-type stars. Moreover, the process gives no convincing explanation of the nearly identical properties of the components of Y Cygni, and of many less-massive systems. Perhaps we should require that any theory of binary origin can predict the formation of a system like Y Cygni as not merely possible, but also probable. Pringle (1989) has reminded us that we still have much work to do before we fully understand the formation of binary systems.

3. Consideration of Energy

A mechanical system tends towards the state of lowest energy consistent with the constraints on it. Shu and Lubow (1981) showed that the circularization of orbits and the synchronization of the components' rotation with orbital revolution are consequences of this tendency. Neglecting rotation, however, the total energy of a two-body orbit is given by the well-known expression

$$\frac{-\,Gm_1\,m_2,}{a}$$

where all symbols have their conventional meanings. It is easy to see that the closer the two stars (smaller a), or the more nearly equal m_1 and m_2, the less the energy. If either or both stars lose mass, energy will be taken from the system, so a must also change. In any given system, interaction involving loss of energy is likely to result in changes in a, $m_1 + m_2$, and m_1/m_2. The first two will tend to decrease whenever possible, and third will tend to unity. We note that although $m_1/m_2 = 1$ makes the energy a minimum, for any given values of a and $m_1 + m_2$, it makes the orbital angular momentum a maximum. Since rotation of the component stars can absorb only very little of the orbital angular momentum, we can deduce that adjustment of all three quantities is likely to take place simultaneously: conservative mass transfer is all but impossible.

During much of the lifetime of a system, probably all the time its components are on the main sequence, the internal cohesion of each star constrains the rate at which energy can be lost. Stellar winds will take only small amounts of mass and energy with them and cause correspondingly small changes in the orbital separation. Tidal and magnetic (Huang 1966) dissipation of energy may have greater effects on the evolution at this stage. In a few systems, gravitational radiation may be important, but I shall ignore it here. The evolution of the component stars themselves will eventually make one or other of them unstable, but the processes just mentioned also play a role in determining when the system will be able to adjust its energy by large-scale transfer or loss of mass. One such time is certainly when one of the components makes contact with its Roche lobe. In the last two decades, we have studied this kind of interaction the most, and have almost come to think of the Roche lobe as a switch that turns interaction on and off, as contact is made or broken. In early computations, such an assumption was sometimes made explicitly (Plavec, Křiž and Horn 1969) and was probably as necessary - and as artificial - as that of conservative mass-transfer. The latter assumption has claimed our attention and is now no longer believed, while the idea that Roche-lobe contact is necessary, lying as it does in the back of our minds, still tends to be accepted implicitly. We have seen that the pre-main-sequence phase is one in which probably all binaries interact: barring "accidents" - such as encounters with another star or more probably, transits through molecular clouds - the entire future history of a binary is probably determined at the time that its components reach the main sequence. In some systems, for example, one component may become a supernova before either star fills its Roche lobe. The system will then be "interacting." There may be other causes of instability of one or the other component, that we have not yet recognized. On these occasions total mass and separation may change radically: so I suggest, may the mass-ratio, which will tend towards unity.

It will be objected that in Algol systems we see (as most of us believe) the opposite: mass is transferred from the less-massive to the more-massive component: water being pumped uphill, as it were. Perhaps the better analogy is that water cascading down the side of a steep valley will have enough momentum to carry it up the other side: systems will overshoot the mark. Moreover, because of the simultaneous adjustment of total mass, separation, and mass-ratio, few systems will take a direct route to mass-equalization and some will not go that way at all. We are unlikely to see large-scale mass-transfer from the Sun to Jupiter, but I suggest that a mass-ratio different from unity is one potential factor for instability in a binary system.

We need not, however, be surprised if sometimes we find circumstellar matter in a system in which neither component fills its Roche lobe - there may be some other reason for its instability. Such a system may be RZ Ophiuchi, discussed in some detail three years ago. (Smak, as reported by Batten 1989) and still being observed (Zola 1990). Smak objected to the model at present favoured by many investigators (Knee *et al.* 1986) on a number of grounds, one of which was that neither star fills its Roche lobe. This system is difficult to observe, and none of us should be dogmatic about any model, but I do not see this objection as fatal. It appears so only because we make the implicit assumption that Roche-lobe contact is a necessary condition for instability. The circumstellar matter may contain dust (Olson 1989): could we be failing to recognize a pre-main-sequence system? Probably not, because the disk is around the smaller, hotter and more massive star, closer to the main sequence, but I doubt if we know the dimensions well enough yet to rule out the idea completely.

4. The Distribution of Mass-Ratios

Many authors (Scarfe 1986, Halbwachs 1987, Budding & Gallot 1990, and Trimble 1990) have tried to deduce the distribution of binary mass-ratios, a function notoriously subject to selection effects. We have tended to assume that if we could allow correctly for selection, the observed distribution would tell us something about the primeval distribution and the origin of binaries. The primeval protostellar distribution is probably forever hidden from us, although the distribution for systems just arriving on the main sequence may one day be known. The observed distribution, freed from selection effects, may instead be a pointer to the ultimate distribution and to the destiny of binaries. If there is a tendency for masses to equalize, there should be an accumulation of mass-ratios near unity. This is, of course, observed in the raw data, but we all know that selection contributes heavily to this. Trimble, in several studies, championed the reality of this peak, but Scarfe questioned her allowances for selection, and neither Halbwachs nor Budding and Gallot find a peak near unity, but a tendency for there to be more mass-ratios at values more distant from unity. In her latest study, Trimble (1990) still finds a peak at unity, but concedes that its height is very sensitive to the allowances made for relative selection effects between one-spectrum and two-spectrum binaries. I am not sure that we yet fully understand these selection effects, but there is not strong evidence that mass-ratios near unity are favoured in the true distribution. Latham (1991), however, has found evidence that binaries in the halo population have a mean mass-ratio of 0.8, compared with a mean of 0.2 for binaries in the younger disk population.

Some of the most evolved binaries are cataclysmic variables: Do their mass-ratios tend to unity? Ritter's (1990) catalogue gives mass-ratios for 57 such systems and the mean value is 2.72 ± 0.36. Some of these are very uncertain (those most different from unity often being the most uncertain) and many of the individual stars are of such low mass that a small *difference* between the two members of a system may correspond to a large *ratio*. Moreover, we do not know the mass-ratios of the progenitor systems: the presently observed ratio may be closer to unity than the original value, and the system may have overshot the mark. If Sirius B, for example, was formed in a supernova explosion, the mass-ratio could have been between 3 and 4 in the opposite sense from the present-day value of about 2.3 (Sirius A the more massive). Sirius is *not* in Ritter's catalogue. Neither cataclysmic variables nor the distribution of mass-ratios give strong support for a tendency amongst binary systems to equalize the component masses, but they do not rule it our as one of the forces driving evolution whenever the components become unstable.

5. A Programme for Study

Probably all binaries interact in the violent protostellar stage, and perhaps even for as long as at least one component is embedded in a disk. The companion will tend to dissipate the disk (Walter *et al.* 1988) and *that* is a kind of interaction that may even effect the subsequent evolution of the prematurely denuded star. In other words the stars may be, at least for a time, in the same disk. Yet others will go through a series of collisional interactions like those described by Aarseth and Hills. Most binaries, however, will spend their main-sequence lives in a form determined by their properties when the components have reached, or nearly reached, the main sequence itself. Barring accidental encounters, it should be possible to predict (as suggested above) the entire subsequent development of the system from its properties at this stage. The task of explaining the complex variety of interacting systems we have been discussing is that of identifying the relevant properties and evaluating their effects.

The most obviously important property, at least from the point of view of Roche-lobe interaction, is separation. If the components of a binary are still widely separated on reaching the main sequence (visual binaries), neither is likely to activate the Roch-lobe "switch." Nevertheless, some wide pairs do interact: VV Cephei (mean separation of about 25 A.U.) is interacting now;

Sirius (mean separation about 20 A.U.) probably once did - but not by simple Roche-lobe overflow. This suggests that, for given separations, a higher total mass makes interaction more probable. Two solar-type stars separated by 20 A.U. or more are unlikely ever to interact. If my argument in section 3 is correct, a third important property is mass-ratio. If this deviates markedly from unity (provided both bodies are of stellar mass), the system will again be more likely to interact. Naturally, these three properties must be considered together.

I doubt if the complex variety of interacting systems that we observe can be explained by combinations of just the three properties of the last paragraph. Other factors will affect both the evolution of the components and the development of the system. Among them, luminosity and tidal effects are obvious, but they are determined by the properties already considered. Chemical composition and the rotation rates of the two stars may be important, and magnetic fields, when present, are probably very significant. The last-named may account for the chromospheric activity of the RS Canum Venaticorum systems, which are interacting although their mass-ratios are close to unity. We have barely explored the effects of a third body in a system. Many writers have pointed out that both Algol systems and W Ursae Majoris systems often have distant companions, although apparently not all members of either group do. Our task for the future is to investigate the effects of all these factors (and maybe others I have overlooked), remembering again the lesson of chaos theory: small perturbations can sometimes trigger large changes.

6. The W Ursae Majoris Systems

Shapley (1948) suggested that W Ursae Majoris stars might be more numerous than any other kind of eclipsing binary (see also Kraft 1967). Shapley's argument was that these systems figured largely in our catalogues, although they are not intrinsically very bright. We must, therefore, be culling them from a much smaller volume of space than we do more luminous types of eclipsing binary. While the short periods and frequent eclipses of W Ursae Majoris systems may attract attention to them, somewhat offsetting selection against them on account of their low luminosity, there is little doubt that they are abundant in the Galaxy. Since they are numerous, they must be, in some sense, stable - yet their mass-ratios tend to differ appreciably from unity. I suggest that these systems are reducing energy by reducing their separations rather than by adjusting either their total masses or mass-ratios: they are fusing into single stars. The idea is not new, although sometimes W Ursae Majoris systems have been considered to be the products of fission (Roxburgh 1965). Struve (1950) considered fusion, but rejected it. Huang (1966) revived it in the context of magnetic braking, the importance of which to the formation of W Ursae Majoris systems has been emphasized by Mochnacki (1981) and Vilhu (1981). The former also showed that modern data do not fit Roxburgh's theory. Tutukov and Yungelson (1987) have developed the idea of fusion and agree with Walter and Basri (1982) in identifying FL Comae Berenices as a fused star. If it occurs, fusion is slow, since not many W Ursae Majoris systems have secularly decreasing periods, but we should continue to explore the possibility.

7. Interacting Binaries and the Galaxy

Although I hesitate to use a word that has been overused and abused in other contexts, this paper might be described as a plea for a "holistic" view of the evolution of interacting binaries. As I began by considering the formation of binaries from the interstellar medium, so I conclude by considering the return of at least some of that matter to the same medium. Much is returned, unaltered, as we have seen, at the protostellar stage. Algol-type systems (e.g. U Cephei, Kondo *et al.* 1980) return matter to the medium and there is at least some evidence (Plavec 1983) that this has undergone nuclear processing. One of the first images from the Hubble Space Telescope was of a symbiotic binary, R Aquarii, returning matter to its environment. I have already discussed (Batten 1989) the potential importance, to the chemical evolution of the Galaxy, of the return of processed stellar matter to the interstellar medium from Algol systems. If all interacting binaries are returning matter, the topic becomes even more important. Binaries may be cosmic polluters, but apart from the special case of supernovae in binary systems, their impact on the Galaxy has not been much studied. Most investigators now, I believe, recognize the importance of binaries for the dynamic evolution of the Galaxy: their importance for the chemical evolution may be comparable. We should study our interacting binaries from the cradle to the grave. Doing so, would integrate binary-star astronomy more closely with studies of our own and other galaxies, and might provide vital clues to our understanding of *them.* If our own Galaxy is typical, binaries are major constituent of the universe and are bound to affect its development.

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