DIAGNOSING STRUCTURE AND EVOLUTION OF CLUSTERS WITH NEUTRON STAR BINARIES

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Abstract. A key problem in using binaries as a tool for diagnosing cluster evolution is that the tool itself is not very well understood. The theory of binary evolution, despite real successes that can be exploited, has serious problems in many areas relevant to cluster evolution. At least as important but often neglected are *connective* problems, which arise when theoretical model binaries need to be related to observed classes of object, which often requires poorly understood parts of their physics which can be quite irrelevant to their bulk properties. I shall discuss these issues in general briefly, and then illustrate them with the specific example of X-ray binaries and millisecond pulsars.

1. Introduction

Since the cluster dynamics meeting in 1984 in Princeton (Goodman and Hut 1985), binary stars have been found to exist in clusters in large enough numbers to influence the evolution of clusters (Pryor 1996), and for binary-single star and binary-binary encounters to compete with encounters between single stars in the formation of many interesting types of object (Davies 1996). Modelling a realistic cluster is beginning to come within the reach of our computing abilities (Aarseth 1996, Makino 1996) right at the time where new observing techniques are greatly expanding our knowledge of real clusters (Guhathakurta 1996, King 1996).

At the same time we face some (still) unresolved issues in both the theory of the evolution of clusters consisting of point masses and in the evolution of binary stars. Therefore, both those of us coming from the

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side of cluster dynamics and those coming from stellar evolution have our own skeletons to contribute to a still large joint cupboard. To arrive at meaningful conclusions about the workings of star clusters we will each have to find ways to isolate from the simulations those effects that are not so sensitive to the assumptions we make about as yet unresolved physics problems. Having thus gained insight into the role of the various physical inputs, we may search for types of observation that will guide us in solving some of the uncertainties in the input physics.

I discuss the binary stellar evolution end of such a programme of research. First a general outline is given of the problems from a stellar evolution point of view (sect. 2). Then I illustrate them with the evolution of X-ray binaries and millisecond pulsars, which have long been the focus of research on stellar evolution in clusters because they are so observationally conspicuous and overabundant in them. Our knowledge of their evolution contains examples of well-understood and reliably tested theory as well as a few fine skeletons (sect. 3). I then illustrate how the interaction between stellar evolution and cluster dynamics may manifest itself in the numbers and properties of observed millisecond pulsars and X-ray binaries (sect. 4).

2. Overview of the problem

We are to construct in our computer an artificial population of stars and evolve it to some time after its creation; then we compare our simulated population with the best available data and repeat the exercise until the real and simulated worlds look sufficiently alike. It sounds simple enough, but there are more pitfalls than nouns in this recipe. The pitfalls can be classified in three categories: theoretical, observational, and *connective*. By the latter I mean the type of problem that arises when a theoretical star or binary, defined by parameters such as masses, radii, temperatures and orbit is to be translated into an observational beast, usually defined by object class, X-ray variability, equivalent width of some emission line, types of outburst, etcetera. The theoretical problems are straightforward in the sense that the problem areas are usually easily identified by the disputes arising between theoreticians. Among the hardest problems in the theory of single and binary stars are those to do with hydrodynamics, such as convection and common-envelope evolution and encounters between stars, and with magnetic fields, stellar winds and angular-momentum loss. Observational problems are obviously related to trying to detect as many phenomena as possible and to characterising the sensitivities of observations well enough to get an accurate assessment of the selection effects involved in the construction of any sample of objects. The connective problems are often the most hazardous ones.

2.1. CONNECTIVE PROBLEMS

It is quite often non-trivial to endow the theoretically created population with the properties that are needed to properly compare them with observed samples. This is often simply because those properties are rather peripheral to the theoretical structure of the object and require expertise that is different from that needed to model the bulk properties of the object. Yet since observations in globular clusters are always done at the cutting edge of observational techniques and at the detection limits of present instrumentation, an accurate estimate of observable parameters of an object is needed. A classic example of this is the transformation from a theoretical Herzsprung-Russell diagram to an observed colour-magnitude diagram of a cluster. Good stellar atmosphere models are needed (and exquisitely calibrated data) in order to do the transformation, but one can perfectly well calculate the evolution of stars with very simple outer boundary conditions that leave the question of the eventual V and $B-V$ of the star unanswered. However, stellar atmospheres can be calculated fairly accurately in many cases, so the problem can be solved.

The situation in compact-object binaries is worse: imagine my computer programme has created a close binary consisting of a white dwarf and a low-mass main-sequence star. It is tempting to call it a cataclysmic variable, but that will not do. To compare with observations, I will need to know whether this is a transient or a persistent source, a classical nova, a dwarf nova, an AM Her system, a novalike variable or what have you. And I need to know what its accretion rate will be, and understand the structure of the accretion disk, whose brightness dominates the total source brightness. Current theory is simply inadequate to make these predictions and the number of cataclysmic variables with well-known parameters is very small, so these matters have not been settled empirically either (Patterson 1984). Hence the debate at this meeting on whether the non-detection of certain types of CV in globular clusters implies a true paucity of main-sequence white dwarf binaries (Shara 1996).

Similar difficulties exist in the X-ray binaries. Two of the twelve bright ones have not been known very long because they are transients, and one may well ask how many more there are. (In the disk population transient sources outnumber persistent ones.) Many of the dimmer ones are transient or highly variable as well (Verbunt 1996). For the millisecond pulsars one encounters the usual pulsar problem that the radio luminosity is hardly predictable from the other parameters of the pulsar such as spin period and magnetic field: no theory exists for it, nor do we have a good empirical relation to use.

3. Formation of X-ray binaries and millisecond pulsars

The evolution of X-ray binaries and millisecond pulsars has been reviewed very well in the recent past (Bhattacharya and Van den Heuvel 1991, Phinney and Kulkarni 1994, Lewin, Van Paradijs, and Van den Heuvel 1995, Wijers, Davies, and Tout 1996). I summarise only the broad picture here and omit references to the original papers. To a create millisecond pulsar in the standard model is a two-step process. The first step is to make a binary with a normal neutron star like any young, high-field radio pulsar in orbit with a low-mass main-sequence star. In the second step, the binary is brought into contact and mass from the Roche-lobe filling star is transferred to the neutron star. This process causes a reduction of the dipole magnetic field of the neutron star to the low values observed for millisecond pulsars in a yet unknown way. It also causes the pulsar to spin much faster, as angular momentum is added to it with the accreted mass. This process of combined spin-up and field decrease is called *recycling*.

The first step can be accomplished in at least two ways. Beginning from a binary star that consists of an O or B star plus a low-mass main-sequence star, we obtain the desired neutron star binary as follows: the massive star evolves off the main sequence and at some point fills its Roche lobe. Since the mass transfer that ensues is to the lighter of the two stars it is dynamically unstable and the low-mass star plunges into the envelope of the massive star. If the binary is too close the two stars will coalesce and if it is too wide there will never be Roche contact. In a narrow intermediate separation range, a close binary can be formed consisting of the low-mass star and the helium core of the B star. If the B star was more massive initially than about $10\,M_\odot$, it will undergo a supernova explosion and leave a neutron star. A substantial fraction of the binaries may be disrupted at this time due to the sudden mass loss from the system and/or a natal velocity kick imparted to the neutron star. The surviving systems are the input for step two. In view of the limited range of initial binary separations allowed and the destructive effect on the binary of the supernova explosion, this formation channel is rare. This is actually as it should be because the fraction of neutron stars that ends up in a low-mass X-ray binary may well be as low as 10^{-5} in the Galactic disk. Another way of accomplishing step one, only applicable in dense stellar systems, is to create a neutron star separately first and let it encounter a binary or single star. Such encounters can result in a binary star of which the neutron star is one of the members (Davies 1996, Mardling 1996).

The proto-low-mass X-ray binary formed in step one may become a Roche-lobe filling system either because the two stars are brought closer together due to angular-momentum loss from the orbit or because the low-mass star expands to become a (sub)giant at the end of core hydrogen burning. Almost inevitably it will start with a substantial orbital eccentricity, but the time for the orbit to circularise is thought to be much shorter than the evolution time of the binary once either star comes close to its Roche lobe, so we can begin the next step with an orbit that has already been circularised. Let the neutron star have a mass M_1 and the companion (or donor) a mass M_2. For small values of $q \equiv M_2/M_1$ the Roche lobe radius is adequately approximated by $R_{\mathrm{L}}/a = (q/(1+q))^{1/3}$, where a is the distance between the stars. If we further assume that no mass is lost from the system during transfer and the donor radius is always close to the Roche lobe radius (a good approximation), we can write the mass transfer rate as

$$\left(\frac{-\dot{M}_2}{M_2}\right)\left(\frac{5}{6}-\frac{M_2}{M_1}\right)=\frac{1}{2}\left(\frac{\dot{R}_2}{R_2}\right)+\left(\frac{-\dot{J}}{J}\right). \tag{1}$$

The signs are chosen such that each term in parentheses is positive in the cases of interest here; J is the orbital angular momentum of the binary. Among others, this requires that M_2 be less than M_1 by a margin that depends on the circumstances, or else mass transfer will be unstable and some form of common-envelope evolution results (as in step one above with the B star and the low-mass star). We can look at the two extreme cases in which the mass transfer is driven either by the first or by the second term on the right-hand side of eq. 1.

3.1. EVOLUTION DRIVEN BY GIANT EXPANSION

If we neglect angular-momentum loss and the donor is expanding because it is evolving off the main sequence, eq. 1 simplifies to

$$\left(\frac{-\dot{M}_2}{M_2}\right)\left(\frac{5}{6}-\frac{M_2}{M_1}\right)=\frac{1}{2}\left(\frac{\dot{R}_2}{R_2}\right). \tag{2}$$

Because the expansion due to nuclear evolution of a red giant is well understood quantitatively and no other degrees of freedom are left, the outcome is fully predictable: the giant will lose mass, spinning up the neutron star and reducing its field, until its envelope is exhausted and only a white dwarf core is left. The evolution is said to be *conservative*, as no mass or angular momentum leaves the system. Since the system must not come into contact until the (sub)giant phase, the orbital period at the time of first Roche contact must exceed about 10 hours in this approximation. Since orbital angular-momentum loss is uncertain (sect. 3.2), it is not clear how to translate that limit into one on the initial binary period. Probably an initial orbital period of a few days is required. And of course the donor star must be massive enough to reach the end of its main-sequence lifetime between its formation and now. In a globular cluster, that means it had to be at least the current turnoff mass, 0.7–0.8 $M_\odot$.

Because the radius of a giant at the time of envelope exhaustion only depends on the mass of the core, and the orbital separation is fixed by this radius and the fact that the giant must fill its Roche lobe, a unique relation is predicted between the orbital period and the mass of the white dwarf for the 15 or so known millisecond pulsars which have white dwarf companions in wide circular orbits. The measured values are indeed consistent with the prediction, as are the small eccentricities of the orbits which are caused by convective density fluctuations in the envelope of the giant (Phinney and Kulkarni 1994). It also appears that the observationally inferred birth rate of X-ray binaries with (sub)giant donors is similar to that of the wide ($P_{\rm orb} \gtrsim 10$ d) millisecond pulsar binaries, which supports a one-to-one evolutionary connection between these two types of binary.

3.2. EVOLUTION DRIVEN BY ANGULAR-MOMENTUM LOSS

If the donor is on the main sequence when the system comes into contact, no radius expansion occurs spontaneously and mass transfer must be due to loss of orbital angular momentum. Then we have

$$\left(\frac{-\dot{M}_2}{M_2}\right)\left(\frac{5}{6}+\frac{n}{2}-\frac{M_2}{M_1}\right)=\left(\frac{-\dot{J}}{J}\right), \tag{3}$$

where n gives the relation between mass and radius of the donor ($R_2 \propto M_2^n$). Contact on the main sequence implies an orbital period less than about 10 hours for $M_2 < 1\,M_\odot$ (as required for stable mass transfer). The only well-understood mechanism for angular-momentum loss is gravitational radiation, but it can only drive mass transfer rates up to about $10^{-10}\,M_\odot\,{\rm yr}^{-1}$, whereas many low-mass X-ray binaries with short orbital periods have accretion rates up to a hundred times greater. Another mechanism for angular-momentum loss has been proposed by Verbunt and Zwaan (1981). It is based on the fact that low-mass stars have magnetic winds, which can carry away large amounts of angular momentum. Since the star is forced to co-rotate with the orbital period of the binary due to tidal friction any loss of angular momentum of the star will be taken out of the orbit eventually, and the orbit shrinks. The resulting mass loss can plausibly be enough to explain the accretion rates in low-mass X-ray binaries, but because the magnetic angular-momentum loss (called *magnetic braking*) depends on the parameters of the star and the orbit in rather uncertain ways, the theory makes no quantitative predictions that lend themselves to strong observational testing. The mass accretion seen in these X-ray binaries almost certainly leads to recycling of the pulsar, but although it is reasonably plausible that short-period binary (perhaps even single) millisecond pulsars can be the end product, the case for this has by no means been argued convincingly.

3.3. SPIN-UP OF THE MILLISECOND PULSAR

The accreted matter usually has more specific angular momentum than the neutron star, which will therefore be spun up. At some point, the torques exerted by the accreted matter and by parts of the magnetic field of the neutron star coupled to the accretion disk will balance, and the neutron star comes to its *equilibrium spin period* $P_{\rm eq} = P_0 B_9^{6/7}$, where B_9 is the dipole field of the pulsar in units of 10^9 G and P_0 is a constant that depends on the neutron stars properties and the accretion rate. For the maximum accretion rate, the Eddington rate, $P_0 \simeq 2\,{\rm ms}$. We see immediately that the speed to which a pulsar can be spun up is limited by its magnetic field. Since the evolution of the latter cannot be predicted yet, neither can the final spin period. However, for each known pulsar with a measured field, we can calculate what its shortest possible spin period is likely to have been. This limit is known as the spin-up line. (It is clear from the known pulsars that they are not all spun up to the fastest possible spin.) The amount of material needed to spin up a pulsar to a given period also depends on the magnetic field, because the specific angular momentum of the accreted matter is set at the magnetospheric radius. For low-field pulsars, it will take 0.03–0.1 $M_\odot$ of material to spin it up to the spin-up line. One of the problems with the X-ray binary scenario for forming millisecond pulsars is the fact that the accretion should stop fairly suddenly because otherwise the pulsar will start spinning more slowly again to adjust its spin to a lower accretion rate. Especially with the angular-momentum loss driven evolution this requires extra ingredients to the scenario.

4. Some effects of encounters

The most obvious influence of the high stellar density in globular clusters is that stellar encounters add a new formation channel for X-ray binaries. They are in fact the archetypical encounter products, since it is the realisation of their overabundance in globular clusters 20 years ago (Gursky 1973, Katz 1975) and the tidal capture that was suggested as its explanation (Fabian, Pringle, and Rees 1975) that started this field of research. The problem with comparing numbers is that except in such a glaring case selection effects and problems in identifying observationally defined object types with corresponding model systems may prevent us from establishing abundance differences with any certainty. A case in point is the debate over whether there is a paucity of cataclysmic variables in globular clusters or not (Shara 1996). It may therefore be more profitable to look at the observed systems alone and see whether they are different from those in the disk in any way, in hopes of finding differences than cannot be attributed easily to selection effects.

4.1. DISK VERSUS GLOBULAR-CLUSTER RECYCLED PULSARS

The spin period distribution and binary fraction of recycled pulsars are noticeably different between the disk and clusters (fig. 1). Let us consider binarity first. Of the disk pulsars 8 out of 27 are single whereas the cluster pulsars have 21 singles in a total of 34, a rather larger fraction. The difference for slow pulsars ($P > 50\,\mathrm{ms}$) is even more striking : the only single disk pulsar could have come from a massive binary system, and the cluster membership of the only binary cluster pulsar (1718–19) is not very secure, although plausible. Hence it may be that among slower recycled pulsars, the disk ones are all binaries and the cluster ones are all single (see also sect. 4.2). The overall period distributions of disk and cluster pulsars do not, however, seem different. One might therefore imagine that on the whole they were formed in similar ways, but that in clusters there are more efficient ways of making them single. Simple disruption of binary stars is difficult because most binary millisecond pulsars in the disk would be hard binaries if put in a dense cluster. They could still lose their pulsar by exchange encounters, but since the pulsar is the most massive object it is more likely to stay in the binary, hence there would have to be more that are left in binaries than ejected ones.

The two globular clusters with many pulsar in them, M15 and 47 Tuc, are also shown separately in fig. 1. These two clusters have a rather different millisecond pulsar period distribution. Especially the absence of long-period pulsars in 47 Tuc is observationally significant: they would have been seen if they existed. One is left to speculate what causes the difference, and whether the post-collapse nature of M15 is responsible for the slow pulsars' presence.

4.2. THE SLOW GLOBULAR-CLUSTER PULSARS

The four slowest globular-cluster pulsars are listed in table 1, and are rather non-typical of globular clusters in that the measured fields are high and their lifetimes above the death line are therefore quite short compared to the age of the clusters. They were first pointed out as a class by Lyne. The next three slowest cluster pulsars are all in M15. One has a negative period derivative, hence its field cannot be measured; the other two have

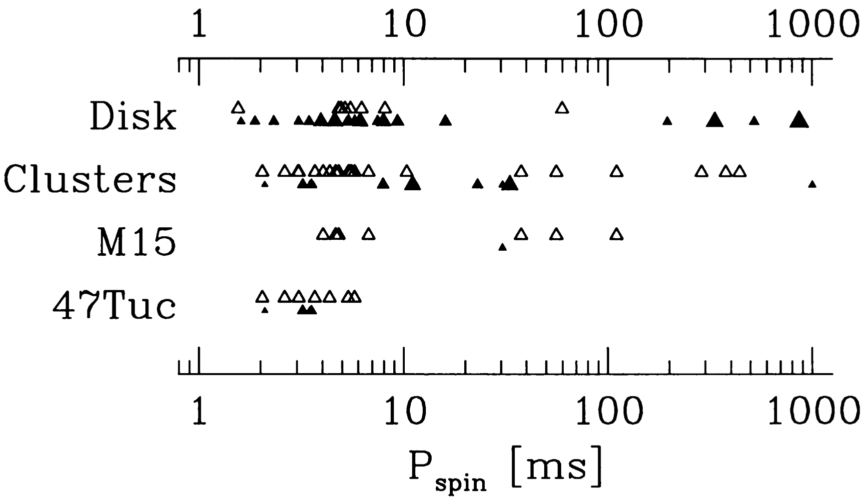

Figure 1. The spin period distribution of recycled pulsars in the disk of the Galaxy, in the total globular-cluster system, and in the two most pulsar-rich clusters, M15 and 47 Tuc. Open symbols are single pulsars, solid ones are binaries and the symbol size increases with orbital period. The disk data are from Lorimer (1994) and the cluster data are from Lyne (1994).

about 10^{10} G fields and ages of about 10^8 yr. Only the cluster membership of 1718–19 is sometimes disputed, the others are secure associations. Their birth rate is reasonably high because of their short ages and because the high luminosities of the four known ones almost certainly mean that there are many more of them that have not been detectable. There must be a fairly efficient production mechanism for them. They are all in clusters which are centrally condensed and have high predicted tidal capture rates. One possibility could be that they are products of failed captures, in which either the initial approach was close enough to disrupt the extended star and leave the pulsar in a thick disk or wide enough that no bound system formed eventually (Mardling 1996) but some material may have been dumped on the pulsar anyway (see also Sigurdsson and Phinney 1995).

5. Discussion and conclusion

Since uncertainties in binary evolution are no less great than in cluster evolution, it is inherently risky to rely on exotic binary stellar evolution products to diagnose the evolution of globular clusters. A careful 'calibration' of binary evolution, to isolate trustworthy results from uncertain ones, is needed. Special attention must be paid to *connective* problems between theory and observation, which are the problems that arise when observable

TABLE 1. Properties of slow globular-cluster pulsars

Name	cluster	P (ms)	τ_c (Myr)	B (10^{12} G)	L (mJy kpc^2)	P_{orb} (hr)
1718–19	6342	1004	10	1.5	400	6.2
1744–24B	Ter 5	443	–	–	200	single
1745–20	6440	289	12	0.4	300	single
1820–30B	6624	379	200	0.11	120	single

properties (often very superficial) are to be derived for theoretical systems.

The properties of millisecond pulsars show clear differences between the disk and clusters, and from cluster to cluster. This begs explanation in terms of processes that are unique to clusters, i.e. stellar encounters. The fact that different types of pulsars appear to come in different typs of clusters will help in telling which are the dominant production mechanisms for each of them.

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