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Hydrodynamic Stellar Interactions in Dense Star Clusters[1]

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ABSTRACT. Highly detailed *HST* observations of globular-cluster cores and galactic nuclei motivate new theoretical studies of the violent dynamical processes which govern the evolution of these very dense stellar systems. These processes include close stellar encounters and direct physical collisions between stars. Such hydrodynamic stellar interactions are thought to explain the large populations of blue stragglers, millisecond pulsars, X-ray binaries, and other peculiar sources observed in globular clusters. Three-dimensional hydrodynamics techniques now make it possible to perform realistic numerical simulations of these interactions. The results, when combined with those of *N*-body simulations of stellar dynamics, should provide for the first time a realistic description of dense star clusters. Here I review briefly current theoretical work on hydrodynamic stellar interactions, emphasizing its relevance to recent observations.

1. INTRODUCTION

Close dissipative encounters and direct physical collisions between stars should be commonplace in dense star clusters. Indeed, the typical time between close encounters (with pericenter separation less than a few stellar radii) for a star of radius R in a cluster with density ρ and velocity dispersion σ is given by

$$\tau_{\rm coll} \sim 10^{11}\ {\rm yr}\left(\frac{\rho}{10^{6}\ M_{\odot}\ {\rm pc}^{-3}}\right)^{-1}\left(\frac{\sigma}{10^{2}\ {\rm km}\ s^{-1}}\right)\left(\frac{R}{1R_{\odot}}\right)^{-1}$$

(see, e.g., Binney and Tremaine 1987). The dissipation of kinetic energy in close stellar encounters can have a direct influence on the dynamical evolution of a cluster, since it encourages secular core collapse.

There is now direct observational evidence for the existence of star clusters with densities $\rho \sim 10^{6}$–$10^{9}\ M_{\odot}\ {\rm pc}^{-3}$ in the nuclei of nearby galaxies. For example, recent *HST* Planetary Camera images of M32 have revealed a dense, unresolved nucleus with density $\rho > 4\times 10^{6}\ M_{\odot}\ {\rm pc}^{-3}$ and velocity dispersion $> 60\ {\rm km\ s}^{-1}$ (Lauer et al. 1993). Similar observations of M87 indicate that the mass within the central few parsecs is $> 10^{9}\ M_{\odot}$, with a velocity dispersion $> 400\ {\rm km\ s}^{-1}$ (Lauer et al. 1992). In addition, theoretical modeling of these observations argues strongly for the presence of a massive black hole at the center of the stellar cluster (see Kormendy 1992 for a review). Theorists have suggested in fact that most galaxies probably contain a massive black hole at their center (see Rees 1990, and references therein). One possible mechanism for the formation of this central black hole involves multiple stellar collisions and mergers (Quinlan and Shapiro 1990).

In the cores of globular clusters, although the density ($\rho \lesssim 10^{6}\ M_{\odot}\ {\rm pc}^{-1}$) and velocity dispersion ($\sim 10\ {\rm km\ s}^{-1}$) are typically much smaller than in galactic nuclei, close stellar encounters may also be dynamically important (see, e.g., Spitzer 1987). In addition, they are expected to produce a variety of interesting observable objects at rates far exceeding those in the rest of the Galaxy. In particular, low-mass X-ray binaries (LMXBs) and millisecond pulsars are thought to result from close encounters between a main-sequence or red-giant star and a neutron star (Davies et al. 1992; Di Stefano and Rappaport 1992; Rasio and Shapiro 1991). Collisions between two main-sequence stars could be responsible for the formation of blue stragglers (Hills and Day 1976; Leonard 1989), which are now being discovered in large numbers in the cores of dense clusters (Paresce et al. 1991, 1993; Guhathakurta et al. 1992). Collision rates in globular clusters can be increased considerably by the presence of even a small population of primordial binaries, for which there is now clear observational evidence (see Hut et al. 1993 for a recent review).

Two basic types of close stellar encounters can be distinguished. In *tidal encounters* (Sec. 2), energy is dissipated through distant tidal interactions, but the stars do not physically collide. In a true *stellar collision* (Sec. 3), the stars come into physical contact and energy is dissipated primarily through shock heating.

2. TIDAL ENCOUNTERS

A sufficiently close encounter between two stars can result in the formation of a bound system. This occurs when the energy of internal fluid motions induced by the time-dependent tidal forces during the encounter exceeds the initial orbital energy of the two stars (Fabian et al. 1975). This process of *tidal capture* can occur only in globular clusters, where the stellar velocity dispersion is very small compared to the typical escape speed from the surface of a star, and, as a result, the entire orbital energy in a close encounter can be dissipated without necessarily disrupting the stars. Tidal capture has been well studied in the *linear regime*, where semianalytic perturbation techniques can be used (Press and Teukolsky 1977; see also Lee and Ostriker 1986; McMillan et al. 1987). For typical globular-

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cluster parameters, capture requires that $r_p/R \lesssim 2.5$–4, where r_p is the pericenter separation and R is the stellar radius.

The formation of tidal-capture binaries can be very important for the dynamical evolution of globular clusters. Inelastic scattering between these binaries and passing stars will tend to increase the binding energy of the binary, providing an effective heat source for the cluster. Numerical solutions of the Fokker–Planck equation taking this effect into account show that the heating can be strong enough to halt and reverse core collapse (Statler et al. 1987). The recent *HST* observations by Lauer et al. (1991) of a resolved core in the globular cluster M15 (the classic candidate for a core-collapsed cluster) support this idea.

Tidal capture of a main-sequence star by a neutron star has long been considered the most likely formation process for bright X-ray sources (LMXBs) and millisecond pulsars in globular clusters (see, e.g., Verbunt 1990). Most theoretical calculations of this process based on the semianalytic perturbation method of Press and Teukolsky (1977) have concentrated on the dissipation of orbital energy during the first pericenter passage. The subsequent evolution of the binary over a large number of orbits is, however, just as important since it determines the final, observable equilibrium state of the system.

The problem was first examined by Ray et al. (1987) from the point of view of global *energetics*. They calculated the total amount of tidal energy deposited during the first and later pericenter passages. They realized that the viscous dissipation of this total energy on a $\sim 10^4$-yr time scale corresponds to a luminosity $\sim 10^3$ times the normal luminosity of a main-sequence star, and concluded that the resulting expansion of the star is likely to lead to its complete disruption. More recently, Kochanek (1992) has examined the problem of the long-term *dynamical* evolution of tidal capture binaries, making the assumption that viscosity remains always negligible. His conclusion is that a large majority of tidal captures will eventually lead to stellar disruption or extensive mass losses. In particular, he finds that a main-sequence star of mass $\lesssim 0.7\ M_\odot$ is always destroyed after tidal capture by a $1.4\ M_\odot$ neutron star. For a $0.8\ M_\odot$ main-sequence star (corresponding to the typical turn-off mass in a globular cluster) the probability of destruction is about 95%.

Main-sequence stars may be able to survive tidal capture by a low-mass *white dwarf*. This is thought to lead to the formation of cataclysmic variables, for which the large globular-cluster population of low-luminosity X-ray sources has been invoked as evidence (Hertz and Grindlay 1983). Indeed, a cataclysmic variable has been recently identified with the *HST* FOC as the optical counterpart of a low-luminosity X-ray source in the core of 47 Tucanae (Paresce et al. 1992). However, Bailyn et al. (1990) have pointed out that the formation of *stable* binaries with white dwarf masses $\lesssim 1\ M_\odot$ will in fact be highly suppressed. This is because mass segregation tends to concentrate the heavier white dwarfs in the core and because mass transfer instabilities will lead to the tidal disruption of main-sequence stars more massive than about 0.8 times the mass of the white dwarf.

For capture of *red-giant* stars by compact objects, Rasio and Shapiro (1991) have shown that the stellar envelope is always disrupted during encounters with pericenter separation small enough to capture another $\sim 1\ M_\odot$ star (see also Davies et al. 1991). This is in agreement with the prediction of Bailyn (1988), based on a simple dimensional argument.

Thus it appears that in very few cases, if any, can a star survive the process of tidal capture in a globular cluster. The most likely end-result of a tidal capture appears to be the complete disruption of the (noncompact) stars involved.

An alternative to tidal capture binaries is provided by *primordial binaries*, for which there is now direct observational evidence (see Hut et al. 1992). Mass segregation will tend to concentrate these binaries in the cluster core. By assuming that the reexpansion of the cluster after core collapse is entirely due to the heat generated by primordial binaries, Goodman and Hut (1989) predicted a relatively large core of radius $r_c \approx 0.1$ pc. This is in remarkable agreement with the value $r_c = 0.13$ pc determined by Lauer et al. (1991) from their recent *HST* PC image of the core of M15.

How long a primordial binary can survive in the core, however, is not clear. Because of their large orbital separations primordial binaries present a large cross section to penetration by other stars or other binaries. Of particular importance are resonant interactions, in which all stars involved form a long-lived intermediate system in which a close encounter between any two stars is likely. Other interactions can lead to the disruption of the binary or to an exchange reaction. Direct observational evidence for binary disruption is provided by the recent discovery by Meylan et al. (1991) of two high-velocity stars that appear to have been ejected recently from the core of the globular cluster 47 Tuc. In addition, Phinney and Sigurdsson (1991) have shown that the position of the binary pulsar PSR 2127+11C well outside the core of M15 is naturally explained as resulting from an exchange reaction between a neutron star and a binary which took place $< 10^8$ yr ago in the cluster core. Models of the post-core-collapse evolution of clusters (Murphy et al. 1990) indicate that the density of compact stellar remnants in the core of M15 may be as high as $10^7\ \mathrm{pc}^{-3}$, making interactions with primordial binaries highly probable.

Compact binaries that are not disrupted by interactions with other binaries or single stars can still lead to mergers because of orbital decay. Repeated distant encounters with passing stars, magnetic breaking, and the radiation of gravitational waves all contribute to the secular loss of angular momentum from the binary (Hut and Paczyński 1984; Krolik et al. 1984; Rappaport et al. 1983). However, the final merging of the two stars into a single object could still occur on a hydrodynamic time scale (rather than continuing on the secular orbital decay time scale) because of instabilities that can develop in a close binary system once the orbital separation becomes comparable to the stellar radii. These instabilities can be true dynamical instabilities

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associated with the hydrostatic equilibrium configuration of a close binary (Rasio and Shapiro 1992; Lai et al. 1993a), or they can be triggered by mass transfer (Hut and Paczyński 1984).

3. STELLAR COLLISIONS

If disruptions and merging of stars are so common in dense stellar systems, what do the products of these events look like? Numerical hydrodynamics simulations (Benz and Hills 1992; Davies et al. 1992; Lai et al. 1993b; Rasio and Shapiro 1991; Ruffert and Müller 1990) can only answer this question partially, since the observable properties of an encounter product also depend on thermal relaxation and transport processes which take place on a time scale much longer than the hydrodynamic time scale.

Close encounters involving only main-sequence stars (single or in binaries) result, on a hydrodynamic time scale, in the formation of a rapidly rotating, well-mixed merged object, with a small amount of mass loss (a few percent at most for nearly parabolic velocities). Recent *HST* observations of the high-density cores of the globular clusters 47 Tuc and M15 have revealed the presence of large numbers of blue stragglers (Guhathakurta et al. 1993; Paresce et al. 1991, 1993). These hot, luminous objects appear in the color–magnitude diagram as an extension of the main sequence above the turn-off point. It has long been suspected that they could be the result of main-sequence star collisions (Hills and Day 1976). The very high stellar densities in the cores of M15 and 47 Tuc (one of the densest globular clusters known) tend to support this view. Leonard (1989; see also Leonard and Fahlman 1991) has shown that even in less dense clusters, the observed numbers of blue stragglers are consistent with a collisional origin provided that $\sim 10\%$ of the stars be in primordial binaries. As mentioned before, this can increase considerably the stellar collision rate in the cluster. Alternatively, blue stragglers could also be formed by the merging of two main-sequence stars in a close binary. Direct evidence that at least *some* blue stragglers are formed in this way is provided by the recent detections by Mateo et al. (1990, 1993) of contact binaries among the blue straggler population in NGC 5466.

Interactions involving compact objects are likely to result in the formation of *massive-disk systems*. In these systems, a compact stellar remnant lies at the center of a massive, rapidly rotating halo of shock-heated gas left over from the disruption of a main-sequence or red-giant star. Massive-disk systems were proposed by Krolik (1984) as the likely result of interactions between a compact binary source and a third star. Recent hydrodynamic calculations have shown that they also form during close encounters between a compact object and a main-sequence or red-giant star (Rasio and Shapiro 1991; see also Davies et al. 1992). However, the evolution of these massive-disk systems on a thermal or viscous time scale remains essentially unknown (see Krolik 1984 for a qualitative discussion). If the central compact object is a white dwarf, the thermal relaxation of the system may produce an object resembling a cataclysmic variable. If the central object is a neutron star, a short-lived, bright X-ray source may result. As the neutron star accretes matter from the disk, it will be spun-up, so that the final outcome is an isolated millisecond pulsar. This formation process for millisecond pulsars does not involve a standard LMXB progenitor phase and could provide a solution to the well-known birthrate problem (Kulkarni et al. 1990; Rasio and Shapiro 1991).

All types of stellar collisions result in some mass loss. Since the gas ejection speed is typically of order the escape speed from the surface of the disrupted star (which is usually much larger than the escape speed from the cluster), most of the gas will escape from the cluster. Mass loss from the cluster decreases its total binding energy. In this sense, stellar collisions contribute indirectly to cluster *heating* and could help drive the reexpansion of the core after collapse. In addition, through asymmetric ejection of gas, the merged object can acquire a recoil velocity which partially compensates for the direct loss of kinetic energy resulting from the collision (Benz and Hills 1992). If some of the gas is retained by the cluster, it may become visible as a source of extended X-ray emission, as seen in 47 Tuc, ω Centauri, and M22 (Hartwick et al. 1982). Indeed, the gas can be shock-heated to a temperature $\sim 10^6$ K by the ram pressure of a diffuse interstellar medium through which the cluster is moving (Grindlay 1985).

Stellar collisions in galactic nuclei are qualitatively different from those occurring in globular clusters. This is because galactic nuclei are younger stellar systems, which contain higher-mass stars, and have velocity dispersions that can approach the escape speed from the surface of a star. In this regime, complete disruption of a star can occur during a close encounter (Lai et al. 1993b). Stellar collisions in nearby galactic nuclei may also have directly observable consequences. High-velocity collisions between red giants and compact objects have been proposed as the most likely mechanism for producing the high-velocity gas clouds observed in the central parts ($r < 1$ pc) of our Galaxy (Lacy et al. 1982; Livne and Tuchman 1988; Rasio and Shapiro 1990). More recently, Hernquist et al. (1991) have proposed that the $\sim 10^{39}$ erg s^{-1} unresolved X-ray source in the nucleus of M33 could be a composite of ~ 10 LMXBs which formed there via processes similar to those occurring in globular clusters. Indeed, the nucleus of M33 is very similar to a typical Galactic globular cluster. The velocity dispersion in the core is only 22 km s^{-1}, and its core radius is probably ~ 0.1 pc. The rather short central relaxation time, $\sim 10^7$ yr, implies that the system probably has undergone core collapse.

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