Mon. Not. R. astr. Soc. (1975) **172**, *Short Communication*, 15P–18P.

TIDAL CAPTURE FORMATION OF BINARY SYSTEMS AND X-RAY SOURCES IN GLOBULAR CLUSTERS

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(Received 1975 May 16; in original form 1975 May 8)

SUMMARY

We propose that the X-ray sources associated with globular clusters are very close binary systems. These result from the tidal capture of compact objects by ordinary stars in the core of the cluster.

1. INTRODUCTION

Several variable X-ray sources have been found to coincide with globular clusters. In particular, the sources 3U 1820 − 30, 3U 1736 − 37 (Giacconi *et al.* 1974) MX 0513 − 40 and 3U 2131 + 11 (Clark, Markert & Li 1975) are very close to the clusters NGC 6624, 6441, 1851 and 7078 respectively. The error boxes are of comparable size to the clusters (less than a few arc minutes across). Katz (1975) has noted that this implies an X-ray luminosity-to-mass ratio about 100 times greater than that for the Galaxy as a whole. In this paper we estimate the probability of forming very close binaries via tidally dissipative *two body* encounters in the dense cores of globular clusters, and show that, if clusters contain large numbers of compact stellar mass remnants (neutron stars or black holes), the present X-ray data can be understood.

2. BINARY FORMATION

Consider a close encounter during which a compact object of mass M approaches within x stellar radii of an ordinary star of mass M_* and radius R_*. During the encounter, a tidal impulse is given to the star and this excites non-radial oscillations. The energy required to excite these oscillations must come from the orbital energy of the two stars, and, if enough energy is absorbed in exciting the oscillations, the two stars remain bound after the encounter. Note that this process does not depend on the details of the subsequent dissipation processes within the star. The relative velocity $V_m \approx (2G(M+M_*)/xR_*)^{1/2}$ is typically several hundred km s^{-1} at periastron passages with $x \lesssim 10$; whereas the velocity dispersion, V_d, in the core of a globular cluster is only ~ 10 km s^{-1}. Thus to form a binary system only $\sim (V_d/V_m)^2$ of the kinetic energy available at closest approach need be converted to oscillational energy. The maximum tidal oblateness that can be induced is $\epsilon \approx Mx^{-3}/M_*$, and the associated energy is $\sim (GM_*^2/R_*)\,\epsilon^2$. The actual amount of oblateness is reduced, however, if the frequency associated with the encounter $\Omega_m = \Omega_*(M+M_*/M_*)^{1/2}\,x^{-3/2}$, where $\Omega_*^2 = GM_*/R_*^3$, differs appreciably from the frequency of the induced oscillations, Ω. We expect the reduction factor f to be approximately of the form $f \sim \Omega/\Omega_m$ for $\Omega \ll \Omega_m$ and $\sim \exp(-\Omega/\Omega_m)$ for $\Omega \gg \Omega_m$. We then find that the encounter results in the formation of a binary system if

$$x \lesssim f^{1/3} \cdot \left\{ \frac{GM_*}{R_* V_d^2} \frac{M(M+M_*)}{M_*^2} \right\}^{1/6}. \tag{1}$$

The first term within the bracket is in the range 10^3–10^4 and the second is of order 1–10^2 (depending on whether the remnants are envisaged as neutron stars or as $\sim 10\, M_\odot$ black holes). The oscillations induced by the tidal interaction are the $l = 2$ modes whose fundamental frequencies are approximately $\Omega/\Omega_* \sim 2$ or 3 (Robe 1968). Thus we may approximate (1) by $x \lesssim 3$, irrespective of the precise details, since the expression in the brackets is raised to a feeble power and since, for $x \lesssim 3$, $\Omega \sim \Omega_m$ and $f \sim 1$.

The cross-section σ yielding an encounter closer than a given value of x is

$$\sigma \simeq 2\pi \frac{GxR_*}{V_d^2} (M+M_*). \tag{2}$$

Taking the typical stellar mass in a globular cluster as $\sim 0.5\, M_\odot$ and taking $R_* \simeq 5 \times 10^{10}$ cm we obtain

$$\sigma \approx 4.2 \times 10^{25}\, x \left(\frac{M}{M_\odot} + 0.5 \right) \left(\frac{V_d}{10 \text{ km s}^{-1}} \right)^{-2} \text{cm}^2.$$

The globular clusters with the highest degree of central concentration have cores of radii ~ 0.5 pc and densities $\sim 10^4$ stars pc^{-3} (Peterson & King 1975). The core relaxation times for such systems are $\lesssim 10^9$ yr. If there are N compact remnants in the core then close encounters involving these remnants occur at a rate

$$\sim 1.6 \times 10^{-20}\, xN \left(\frac{M}{M_\odot} + 0.5 \right) \left(\frac{V_d}{10 \text{ km s}^{-1}} \right)^{-1} \text{s}^{-1}.$$

N may be as high as $\sim 10^4 (M/M_\odot)^{-1}$, especially in view of the fact that relaxation processes cause the remnants to become concentrated towards the cluster centre.

We therefore expect $\lesssim 14(NM/10^4\, M_\odot)$ captures involving compact objects to occur during the core relaxation time of $\lesssim 10^9$ yr.*

A compact object captured by this process has initially a highly eccentric orbit with major axis $\sim 10^{14}$ cm. Tidal effects during each subsequent periastron passage tend to circularize the orbit, and within $(V_m/V_d)^2 \sim 10^3$ orbital periods a very close binary system is set up, whose X-ray properties are discussed below.

We draw attention to the following:

(i) This capture process can *only* form *very close* binaries. In fact the systems are so close that the final stages of circularization of the orbit occur rapidly through highly non-linear tidal processes, and continuous mass transfer can commence as soon as the orbit is sufficiently circular.

(ii) Pairs of *ordinary* stars can form close binary systems by this process. Indeed they are likely to be more common than binaries containing a compact object since (a) ordinary stars probably outnumber compact objects, and (b) tidal oscillations can be set up in both components. The resulting binaries are formed in the core of the cluster and are therefore almost impossible to detect.

* An equivalent way of appreciating this result is by realizing that the fraction of compact objects captured during one relaxation time is $\sim (V_d/V_m)^2$.

(iii) The above estimates show that the chance of a genuine collision between a compact object and an ordinary star is by no means negligible (probability $\sim\frac{1}{3}$ that of the binary capture process). When this occurs, the star may form a massive disc enveloping the compact object; or may, if the latter is a black hole, be completely swallowed. These phenomena are unlikely to generate X-rays so efficiently because of the high density and the likely opacity of the surrounding medium, but could be detectable as emission line objects.

(iv) Collisions between pairs of ordinary stars might be relevant to the 'blue straggler' phenomenon.

3. X-RAY EMISSION

The expected X-ray lifetime for a binary system containing a compact object and a typical evolving globular cluster star is much longer than that of the galactic X-ray binaries identified so far. In an X-ray binary the mass transfer rate on to the compact object must lie in the range 10^{-8}–$10^{-10}\,M_{\odot}\,\mathrm{yr}^{-1}$: if the rate exceeds that required to supply the 'Eddington luminosity', the surplus material obscures the X-ray source; and if the rate is below $10^{-10}\,M_{\odot}\,\mathrm{yr}^{-1}$, the X-ray luminosity would be too low.

For low mass stars such as those in globular clusters Roche lobe overflow is the only way of achieving the appropriate mass transfer rate on to the compact object (van den Heuvel 1975). The identified binary X-ray sources all contain compact objects *less* massive than their companions, implying a runaway mass transfer rate because the separation diminishes as the masses become more equal. (For example, the binary system Her X-1/HZ Her which has a mass ratio of $\sim 0{\cdot}5$ can be expected to have a mass transfer rate in the range 10^{-8}–$10^{-10}\,M_{\odot}\,\mathrm{yr}^{-1}$ for less than $\sim 3\times 10^{5}$ yr (Webbink 1975, private communication).) For X-ray binaries in globular clusters, however, we expect the compact object to be *more* massive than its evolving companion. Thus the rate of mass transfer is stable and, after the initial burst, continues for a *nuclear* time scale $\tau_{\mathrm{N}} \sim 10^{10}$ yr at a rate $\sim M_{\odot}/\tau_{\mathrm{N}}$.

4. DISCUSSION

Tidally dissipative two-body encounters can preferentially produce binary X-ray sources in globular clusters. A three-body process for binary formation has been discussed by Clark (1975) but this is necessarily less efficient than a two-body process and cannot produce the required *close* binary systems (see also the discussion in Bahcall & Ostriker (1975)). Sutantyo (1975) has discussed the formation of binary X-ray sources through *collisional* encounters between neutron stars and giants. These will be much less frequent ($\sim 0{\cdot}003$) than those formed by the mechanism we consider, despite the larger cross-section, owing to the relative scarcity of giants and the shorter lifetime of the resulting X-ray sources.

An alternative possibility, discussed by Bahcall & Ostriker (1975) and Frank (1975), is that the X-rays are produced by stellar collisions with a hypothetical massive black hole in the centre of the cluster. Such a model would not be tenable if the X-ray flux were found to show *either* periodic *or* very short time scale (millisecond) variations, or if the X-ray source is not exactly coincident with the centre of the cluster. If binary systems are involved in producing the X-ray flux, the probability that at least one of the known cluster sources displays eclipses is $\sim 0{\cdot}4$, with a typical period ~ 5 hr.

ACKNOWLEDGMENTS

We thank Drs S. Aarseth, J. Frank, D. Gough, D. Heggie and R. Webbink for valuable discussions.

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