ON THE ORIGIN OF NEUTRON STARS IN GLOBULAR CLUSTERS

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ABSTRACT. The formation of neutron stars in globular clusters is discussed in light of a number of recent results and, in particular, studies of the origin and evolution of the high luminosity x-ray binaries found in globular clusters. We argue that the neutron stars most probably arise from the accretion-induced collapse of white dwarfs in compact binary systems, themselves detectable as low luminosity cluster x-ray sources. The white dwarfs which can collapse are probably the remnants of relatively more massive stars than those presently found in globulars. This can account for the predominant occurrence of the high luminosity cluster sources in clusters of relatively high metallicity, since those clusters have recently been found to probably have flatter mass functions of their component stars.

1. INTRODUCTION

The existence of neutron stars (neutron star is hereafter abbreviated NS; plural is NSs) in globular clusters has long been suspected on the basis of the existence of luminous x-ray sources in globulars (e.g., Clark 1975) as well as the central surface brightness peaks in clusters such as M15 (e.g., Illingworth and King 1977). With the determination of the approximate mass of the the high luminosity ($L_x \geq 10^{36}$ erg/sec) x-ray sources as approximately 1.5 $\pm$0.5 $M_\odot$ (Grindlay et al. 1984, Grindlay 1985a), it was confirmed that these were indeed NSs accreting from low mass companions in compact binaries, as suspected from the fact that the majority of these sources are x-ray bursters as well as other arguments (cf., Lewin and Joss 1983). The alternative model that the luminous x-ray sources in globulars are massive black holes was ruled out (Grindlay 1981), although it has been claimed that globulars could contain a significant fraction of their "dark" mass in stellar mass black holes of approximately 3 $M_\odot$ (Larson 1984). It has been clear from stellar evolution, as well as recent observational evidence (discussed below), that globular clusters must also contain an appreciable fraction of their total mass in the form of white dwarfs (white dwarf is hereafter abbreviated WD; plural is WDs), and indeed the apparently distinct population of low luminosity (with $L_x \leq 10^{34.5}$ erg/sec) x-ray sources discovered in globular clusters (Hertz and Grindlay 1983) has been interpreted as being largely due to WDs accreting in compact binary systems. We return to this point in section 4.

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In this paper we consider the origin of NSs in globulars. After reviewing the arguments for the required density and number of NSs, we point out the special constraint on their origin imposed by the relatively low escape velocity from the cluster. We then outline the three principal schemes suggested for the production of NSs: as a consequence of the evolution of single, massive stars with or without "normal" supernova production (referred to below as IMF models 1 and 0, respectively), and as a consequence of the evolution of WDs in compact binaries (referred to here, and by Van den Heuvel 1986, as the accretion induced collapse, or AIC, model). In each case we discuss the assumptions and limitations. Specific predictions for on-going observational programs are made, and the indirect consequences of each of the three models are discussed. We conclude from a variety of arguments that the AIC model is preferred, and that the formation of low mass x-ray binaries in the galactic bulge apparently outside of globulars may be related to globulars.

2. STATEMENT OF THE PROBLEM

2.1 Direct Evidence for NSs and Constraints on NS Masses and Numbers

The best evidence for the existence of NSs, as opposed to WDs or stellar mass black holes, in globular clusters is the population of accreting x- ray binaries found in globulars. The properties of these sources as well as the clusters they are found in have been recently reviewed (Grindlay 1985b), and a suggested scheme for the origin and evolution of these compact binaries has been proposed (Grindlay 1986). In brief, some 10 clusters contain x-ray sources with persistent luminosities (usually) above 10^{36} erg/sec and all of these sources but one (the source in M15) are known to be x-ray burst sources. This virtually requires that the compact objects be NSs, given the overall success of the thermonuclear flash models (cf., Joss and Rappaport 1984 for a recent review). As mentioned above, the statistical determination of the mass of these systems from their distribution of radial offsets from their respective cluster centers, assuming isothermal King models for the cluster potentials, also leads to a 90% confidence interval for their mass of 0.8-2.5 $M_\odot$ (Grindlay 1985a), or consistent with them being NS binary systems (Lewin and Joss 1983, Grindlay et al. 1984).

The companion stars in the compact x-ray binaries in globulars are almost certainly of lower mass than the NSs, since the latter are expected (see discussion in sections 3 and 4 below) to have masses near 1.4 $M_\odot$ (or greater) and the former are limited to be less than the present turnoff mass of 0.8 $M_\odot$ in globulars. Therefore the mass transfer on to the NS will widen the orbit, and the mass transfer will cease unless either the donor star expands to keep its Roche lobe filled or angular momentum can be removed from the system to counteract the orbital expansion. In the first case, however, the resulting mass transfer rate and x-ray luminosity will be too high, since precisely this mechanism of evolution of the companion star up the giant branch to maintain mass transfer in a low mass x-ray binary was considered by Webbink, Rappaport, and Savonije (1983) for the more luminous (Verbunt et al. 1984, Grindlay 1985b) galactic bulge x- ray sources outside globular clusters. Therefore, the binary companions in the globular cluster sources are most probably main sequence stars, since the x-ray luminosities (Grindlay 1985b) imply accretion rates which are generally 10^{-10} - 10^{-9} $M_\odot$/yr, and this can be supplied by gravitational radiation and magnetic braking angular momentum losses in a system with a lower mass secondary star overflowing its Roche lobe (Rappaport, Joss and Webbink 1982).

It is perhaps even more reasonable, and more interesting, to invert the arguments given above and conclude that the observed x-ray luminosities of the high luminosity cluster sources as well as the upper limit on the mass of the mass-losing stars in these binaries implies a corresponding lower limit of 0.8 $M_\odot$ for the masses of NSs in globulars. Although the initial analysis for the most likely mass of the high luminosity x-ray sources in globulars suggested (Grindlay et al. 1984) that perhaps the NSs were formed with masses less than the 1.4 $M_\odot$ value found for NSs in the field (cf., Rappaport and Joss 1984), the more complete analysis of Grindlay (1985a) showed this is by no means required since a somewhat broader mass range (90% confidence) is indicated. We note also that the one claim for a NS mass significantly lower than 1.4 $M_\odot$ (for the NS in the 5 hour binary 4U2129+47), possibly as low as 0.6 $M_\odot$ (Horne, Verbunt and Schneider 1986), is subject to possible systematic errors since it was derived in part from the velocity variations in the He II emission line which could be subject to uncertain streaming motions of the gas in the system. A velocity study of this system is currently being attempted by M. Garcia which should avoid this problem, since the x-ray source is currently in an extended low state and no emission lines are visible.

Independent of their mass, the required number of NSs in the cluster core (where the more massive NSs will accumulate in an isothermal cluster) is about 3% by <u>number</u> to produce the observed number of clusters with high luminosity x-ray sources currently detected (Lightman and Grindlay 1982). This estimate is based on the tidal capture model (Fabian, Pringle and Rees 1975; Press and Teukolsky 1977) for the formation of the x-ray binaries, which continues to be the favored mechanism for their production (c.f. Grindlay 1986). Since the NSs are more massive than both the visible cluster stars (i.e., their potential binary companions) by the argument above and the cluster WDs, which are expected to be currently formed at about 0.5 $M_\odot$ (but whose mass spectrum probably also extends to above 1 $M_\odot$--cf., discussion below), their total contribution to the mass in the cluster core is in the range 10%. Adopting a core mass for a typical globular cluster of about 1% of the total cluster mass, the fractional mass in NSs in a typical cluster implied by the presence of the high luminosity x-ray binaries is only about 10^{-3}. Thus, only about 100 NSs are required in the cluster (core). We note that this is a much smaller total number, or mass fraction, in the total cluster than that attributed to dark remnants in clusters such as 47 Tuc, where DaCosta and Freeman (1985) find a dark mass fraction of 35%. The comparison with 47 Tuc is appropriate since the (high luminosity) X-ray globular clusters are predominately concentrated to the galactic center and metal rich. The bulk of dark matter in cluster cores, therefore, is probably in the form of WDs, not NSs (or more massive stellar black holes).

2.2 Retention of NSs in Globulars

The central problem in obtaining this apparently modest total number of NSs is not only to form the NSs but to keep them in the cluster during the formation process. Globular clusters are both robust and fragile structures (cf., discussion following the paper by Grindlay 1985a), since their escape velocities are typically only 10-30 km/sec. Thus any model for their formation must have a "channel" for low velocity production of the NS. For models where the NS results from the supernova of a massive star, the supernova and collapse event must be able to be very symmetric (to limits much less than 0.1%) to avoid escape. For models involving the NS formation in a binary system, the mass lost from the supposed supernova event leading to the creation of the NS must not exceed half the binary mass or else the binary will become unbound and the NS will be given the orbital velocity of its progenitor star. In the case of a progenitor binary system in a globular cluster, where the only binaries that survive are those with orbital velocities greater than the cluster velocity dispersion (i.e so-called "hard binaries"), this means the NS would be ejected from the cluster in the case when the binaries are unbound by mass loss in the supernova event.

2.3 Formation Models to be Considered

Both formation and retention in the cluster are the topics we address in the remainder of this paper. We consider two major scenarios: the IMF model, that the NSs formed directly from the evolution of a prior generation of massive stars, and the AIC model, that they are forming even now from the accretion-induced collapse (AIC) of WDs. IMF models are discussed in section 3, where we review recent work on the measurement of the mass function, and by inference constraints on the initial mass function (IMF), in globular clusters. We consider this in light of the NS formation and retention problems and discuss two possibilities: model IMF- 1, where the NS is produced as a result of a supernova (Type I or, more probably, Type II) explosion vs. model IMF-0, where the NS is produced in a "quiet" collapse (a Type 0 "supernova" event ?) as suggested by Katz (1983). The AIC model is then considered in section 4, where we review the recent evidence for populations and masses of WDs in globulars and the recent theoretical work on the fate of an accreting WD which may lead to either disruption in a Type I supernova or collapse to a NS.

3. IMF MODELS: NS FORMATION FROM SINGLE, MASSIVE STARS

3.1 IMFs in Globular Clusters

The IMF in globular clusters has long been the subject of much interest as it obviously must constrain the conditions in the early history of star formation in the Galaxy. Numerous attempts have been made to derive IMFs, but it is with the advent of new color magnitude data from the much more sensitive and linear CCD detectors that the greatest progress has come and is yet to come. Recently, McClure et al. (1986) have presented results which, if confirmed, are of fundamental importance: the IMF slope in globulars appears to show marked

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variations from cluster to cluster (in their sample of seven) and appears to be strongly correlated with the metallicity of the cluster. The derived power law index, x, for the usual mass function formula,

$$\frac{dN}{dm} = \phi(m) \propto m^{-(1+x)} ,$$

where m is the stellar mass and N(m) is the number of stars with mass m, ranges from -0.5 for the most metal rich cluster in the sample (47 Tuc) to 2.5 for the most metal poor cluster (M15). [Recall that the Salpeter mass function index is 1.35, though even this value is uncertain and may be as flat as 0.85 in the solar neighborhood.] The uncertainties in these derived indices are estimated as ±0.5, but in fact the results are subject to a variety of systematic effects which must be considered (and are now being considered in a series of follow-up papers).

First, the measurements used by McClure et al. are of present day luminosity functions and have been converted to mass functions using theoretical isochrones of VandenBerg and Bell (1985). In addition to the dependence on these models, a cluster age (~15 Gyr) and helium abundance must be assumed. Second, and more important, the measurements were conducted at a variety of radial offsets from the cluster centers so that the effects of mass segregation, if the clusters are indeed relaxed, must be considered. Pryor, Smith and McClure (1986) have done this and show that the derived mass function indices are indeed affected somewhat but that an apparently strong correlation with metallicity still remains. Finally, the effects of both the dynamical and chemical enrichment in the clusters themselves (those with more massive stars being expected to have more self-enrichment) must be considered, as has been done by Smith and McClure (1986). They show that the variation in x, while large, may require that the most metal rich clusters with the flattest indices have sharply defined upper mass limits.

It should be noted that these new results must be checked by other groups since they are both consistent and inconsistent with previous results, or inferences, for (in some cases) even the same cluster. For example, the authors cited above point out that the trend of x with metallicity is as expected given the dynamical evidence reported by DaCosta and Freeman (1985) for a fraction of mass in dark remnants, primarily WDs, of 35% in 47 Tuc. Yet DaCosta (1982) found a much steeper mass function for 47 Tuc, though his (photographic) results were probably more contaminated by the non-constant background of stars from the SMC.

We point out that if the results for the IMF and its metallicity dependence are confirmed in future studies, a major puzzle concerning the distribution in the Galaxy of luminous x-ray sources in globular clusters (and perhaps also the galactic bulge) may be elucidated. That is, the strong correlation of the high luminosity sources with galactocentric distance (Lightman and Grindlay 1982), coupled with the strong correlation of metallicity with R, suggests that the primary correlation for the presence of a high luminosity x-ray binary (i.e., a significant NS population) is the cluster metallicity. If so, this can now be understood, since these clusters have flatter IMFs and thus had larger populations of more massive stars from which the NSs were produced. Unfortunately, this does not tell us how the NSs were produced, since the same population of more massive stars will produce both more massive WDs, which might undergo AIC (see section 4) as well as more higher mass stars, which might produce NSs through either the IMF-1 or IMF-0 models. We turn to these next.

3.2 Model IMF-1

In this model we assume that the NSs are formed as remnants in the supernova events which presumably end the evolution of the most massive stars formed in the cluster IMF. The lower limit for formation of a NS in an isolated supernova is probably in the range 8 - 12 $M_\odot$, so this scenario depends on the number of stars initially in the cluster in this mass range and above. Since stars in this mass range have lifetimes only of at most about 3 x 10^7 years, all the NSs are formed while the cluster is still very young. As Smith and McClure (1986) also point out, the gas liberated by this much supernova activity in metal rich globulars in a time comparable with (or shorter than) the cluster dynamical timescales would have both important chemical and dynamical effects on the subsequent evolution of the cluster. That is, a large mass loss in stellar winds (pre-supernova) and supernova ejecta would tend to expand the cluster and also modify the chemical enrichment of the remaining stars. Since the metal rich globulars in the galactic bulge are also typically more centrally condensed, and those containing the high luminosity x-ray sources certainly are (Lightman and Grindlay 1982), this does not seem to have occurred. Thus we agree with Smith and McClure that the high metallicity clusters with apparently flat IMFs must have sharp cutoffs or steepenings of their IMFs above some critical mass. If this critical mass is as low as only 2 $M_\odot$ as they suggest for 47 Tuc, then the flat IMFs will not produce an overabundance of NS remnants (indeed none would be produced for such a low critical mass), but rather would produce more WD remnants.

Whatever the number of initial cluster stars sufficiently massive to form NS remnants in isolation, only a fraction of those formed will be retained in the cluster if the formation process is at all similar to that apparently operative for Pop I stars today. That is, from the observed distribution of radio pulsar velocities (see, e.g., the paper by Cordes in these proceedings), it appears that most pulsars are given a large kick of some 100-200 km/sec at their birth. This, of course, would eject them from the globular cluster. The published velocities of Anderson and Lyne (1983) indicate that at most about 10% of the neutron stars so produced would have velocities $\leq$30 km/sec and so would be retained in the cluster. Thus instead of the $\sim$100 NSs now present in a "typical" cluster, more than 1000 would have to have been produced. This would seem to further complicate the problems of cluster enrichment and expansion mentioned above.

Finally, NS formation in the IMF-1 model would lead to NS ages as old as the cluster itself, or some 15 Gyr. However, if the magnetospheric models are accepted for the quasi-periodic oscillations (QPOs) now known to be present from at least two of the high luminosity x-ray binaries in globulars (the "Rapid Burster" source in the cluster

Liller 1 and the source in NGC 6624), then the magnetic fields on their NSs are probably in excess of the now-presumed base magnetic field of $\sim 10^9$ gauss (Taam and Van den Heuvel 1986). This, together with the strong evidence that magnetic fields on NSs decay down to a base value with a time constant of $\sim 10^7$ years (see paper by Taylor in these proceedings), suggests these NSs are relatively young. In this case, they cannot have been formed by the IMF-1 model, and either a combination of processes or primarily other ones must be operative for NS formation.

3.3 Model IMF-0

This model, though not so named, was proposed by Katz (1983) to circumvent the NS escape problem as well as to account for the possibly discrepant age of a NS in an apparently old supernova remnant. It presupposes a mechanism for the formation of NS in a "quiet collapse" event. As such, it would not be subject to the difficulties of mass loss associated with the IMF-1 model. However there is as yet no compelling observational or theoretical reason to believe that such events occur in nature. This formation mechanism, if it also relied on massive stars with short lifetimes, would also be subject to the magnetic field problem mentioned above. It remains an interesting possibility in search of a unique application.

4. AIC MODEL: NEUTRON STAR FORMATION FROM WHITE DWARFS IN BINARIES

We therefore turn to the AIC model for the formation of NSs in globulars. Arguments in favor of this model have been given by Grindlay (1986), Van den Heuvel (1986) and Taam and Van den Heuvel (1986). Here we review these and relate them to the new IMF results mentioned above.

4.1 Evidence for WDs in Globulars

By analogy with the evidence for NSs in globulars, the most direct evidence for WDs are both observations which directly suggest the presence of WDs in binaries (e.g., the low luminosity x-ray sources in globulars-- Hertz and Grindlay 1983) as well as the studies referred to above which suggest substantial dark matter contributions in cluster cores. Before turning to the arguments for WDs in binaries, which form the basis for the AIC model, we review briefly the arguments for a substantial number of isolated WDs in clusters. Recall that essentially all of the cluster mass originally present in the IMF at stellar masses above the present turnoff mass of $\sim 0.8\ M_\odot$ will have now evolved into post-AGB stars, WDs, NSs and liberated gas. The total fraction of the original cluster mass in this evolved form is obviously dependent on the index x of the IMF as well as the upper mass limit, m_u, in the cluster IMF. As shown by Smith and McClure (1986), the ratio of mass in dark remnants (i.e., the WD and NS masses assumed for a given model of stellar evolution, which relates their masses to their progenitor stellar masses) to the still-visible stellar mass (i.e., the mass in stars below the turnoff mass) is between ~ 0.9 - 0.1 for x in the range 0 -2 and a maximum initial mass $m_u = 2\ M_\odot$. This is consistent with the dark mass fraction of 35% (of the total) estimated

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for 47 Tuc (DaCosta and Freeman 1985) and indeed is what fixes m_u given the observed value of $x \simeq 0$ for this cluster (although Pryor et al. 1986 find that x should be ~0.3 flatter still to account for mass segregation; this would reduce m_u still more). Alternatively, Smith and McClure show that the dark mass fraction in 47 Tuc could be produced by a more complicated mass function (and IMF) such as one with a break (at the present day turnoff mass) from $x = 0$ to $x = 1.83$ and $m_u = 20\ M_\odot$.

In either case, a substantial fraction of the dark mass must be in the form of WDs (which would account for all of the dark mass in the first case). However, only in the broken power law case would there be an appreciable range of WD masses (as well as NSs, fractionally retained, from the IMF models of section 3 above) produced from the range of stellar masses above the turnoff mass. We shall see below that this may be necessary for the production of NSs from the AIC model.

The observations of historical novae and, recently, two dwarf nova systems (spectroscopically) in globular clusters (cf., Shara et al. 1985 for a brief review) provide direct "proof" that WD-binaries exist in globulars. However, as Shara et al. also report, no direct optical detection of cataclysmic variables (CVs) in globulars have yet been made down to absolute magnitudes $M_B \simeq 6$ (in the cluster M3). CVs are expected on the basis of the expected number of WDs that should tidal capture main sequence stars in cluster cores (Hut and Verbunt 1983). Indeed this is what led Hertz and Grindlay (1983) to (independently) propose this process for the explanation of the new class of low luminosity x-ray sources they found in globulars with the Einstein Observatory. The fact that the luminosity distribution of compact x-ray sources in globulars (i.e., not including the additional diffuse x-ray emission from hot cluster gas--cf., Grindlay 1985a) has a significant gap between $\sim 10^{34.5}$ and 10^{36} erg/sec (Hertz and Grindlay 1983, Hertz and Wood 1985) provides strong evidence that the low luminosity sources are by and large a separate class from the high luminosity neutron star systems. The factor of $\sim 10^3$ in maximum x-ray luminosity for the two distributions points to WDs as the compact objects in the low luminosity systems, although undoubtedly some of the low luminosity sources (e.g., the soft x-ray transient in NGC 6440) are NS systems with their mass transfer essentially turned off.

From the observed distribution of x-ray luminosities for the low luminosity sources as well as the upper limits for the entire cluster sample surveyed with both the Einstein and HEAO-1 x-ray satellites, Hertz and Wood (1985) extended the calculations of Hertz and Grindlay (1983) to derive the rate of tidal capture of main sequence stars on WDs and thus the number of x-ray emitting WD binaries in a "typical" cluster. They concluded that the "typical" globular cluster (with central density $\sim 10^4$ pc^{-3}) would contain approximately 10 low luminosity sources for an assumed mass fraction in WDs of 15%, an IMF index $x = 2$, and a fixed WD mass of $0.6\ M_\odot$. This is approximately 100 times the number of high luminosity sources (NS binaries) per cluster (cf., Lightman and Grindlay 1982) and indicates that the ratio of WDs to NSs in the cluster core is at least this ratio. In fact the ratio must be even larger since the NSs, being more massive than the WDs,

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will be more centrally concentrated in the core and will have a larger gravitational focusing contribution to the tidal capture cross section.

4.2 Requirements for AIC

Clearly the first requirement for the AIC model is met: a globular cluster (core) contains a substantial fraction of its mass in WDs and a relatively large number of these are probably in (tidal capture) binary systems. The next major requirement is for the WD to be able to accrete enough mass to exceed the Chandrasekhar limit without losing the mass in (a series of) nova explosions. Finally, the WD must be able to collapse without being disrupted in a supernova Type I explosion. Recent work by a number of investigators suggests that each of these conditions can be met in different regions of the two-dimensional space of accretion rate vs. "seed" WD mass.

A particularly interesting summary of the possible NS formation regimes in the M_{WD} vs. accretion rate plane is given by Nomoto 1986. A O-Ne-Mg WD can collapse to a NS if its mass is $\geq 1.05\ M_\odot$ and it accretes at a rate $\geq 10^{-7.3}\ M_\odot$/yr or at a rate of only $\leq 10^{-9.2}\ M_\odot$/yr if its mass is above about 1.12 $M_\odot$. Thus these relatively massive WDs, which would arise from the ~8 $M_\odot$ stars of the cluster IMF or might arise from the mergers of less massive WDs (see discussion below) are very likely progenitor systems for the AIC production of NSs. The more numerous C-O WDs, with masses in the approximate range 0.8-1.15 $M_\odot$, will collapse to form O-NeMg WDs and then NSs if their accretion rate is maintained above about 0.2 of the Eddington value (~$10^{-5}\ M_\odot$/yr). These results are reviewed by Nomoto but have been obtained previously. However two new accretion rate vs WD mass regimes for C-O WD collapse are also reported: for C-O WD masses $\geq 1.2\ M_\odot$ and accretion rates $\geq 10^{-7.4}\ M_\odot$/yr and for $\geq 1.13\ M_\odot$ and accretion rates $\leq 10^{-9}\ M_\odot$/yr. At intermediate accretion rates in this same mass range Nomoto finds the possibility of "dim" supernovae (Type Is); these should not be confused with the IMF-0 "quiet collapse" model discussed in section 3 since accretion from a binary companion is required.

The low accretion rate regime for collapse of C-O WDs is particularly relevant to the globular case considered here, since the accretion rates needed ($\leq 10^{-9}\ M_\odot$/yr) are just those expected for WDs which tidally capture main sequence companions. These are in fact the typical accretion rates indicated for the low luminosity cluster x-ray sources. Thus AIC and not disruption in a supernova appears possible for a range of WD masses and accretion rates provided the WD masses are initially above about 1 $M_\odot$. These C-O WDs will arise "naturally" from the evolution of single cluster stars with masses above about 4 $M_\odot$ so that the AIC production process will be enhanced in accordance with the IMF numbers of stars in this mass range. This, in turn, would suggest that the metal rich clusters, provided they do indeed have flatter IMFs (or at least flatter IMFs up to a cutoff mass, as discussed above for 47 Tuc) will indeed produce more NSs. Thus the significant tendency for the high luminosity cluster x-ray sources to be in clusters relatively near the galactic center, and thus (statistically at least) more metal rich, could be understood.

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The presence of NSs in all clusters, and particularly metal poor clusters such as M15, could also be understood if there were a "natural" way to enhance the numbers of C-O (and, ultimately, O-Ne-Mg) WDs in these clusters. A mechanism may be provided by the merger process considered by Nomoto and Sugimoto (1977) for (field) WD binaries, which themselves presumably arise from the evolution of a giant binary pair. In a high central density globular cluster, many such binaries will be formed by tidal capture between various pairings of main sequence, giants and WD stars. All of these will eventually lead to WD-WD binaries, where the typical component WD members will be $\sim 0.6\ M_\odot$ He WDs (now being formed in the clusters). The merger of these will be a C-O WD. Thus these more massive WDs can be "grown" in the dense cores of globulars, and a correlation of NS production rate and central density of the cluster is expected.

5. RELATION TO NS ORIGIN IN FIELD LMXRBS

The AIC process seems very likely to occur and to be self-sustaining in globular clusters where the stellar densities are very high and binary evolution is important. The low mass x-ray binaries (LMXRBs) in the field, however, are more difficult to understand. Certainly the bursters in the field, which are now increasingly identified with systems with orbital periods of ~3-5 hours and main sequence companions, are not readily understood by either the IMF or AIC models discussed in sections 3 and 4 above: the IMF models would be expected to disrupt the (pre- existing) binary as the more massive star explodes, while the AIC model doesn't naturally lead to a C-O or O-Ne-Mg WD in the (pre-existing) binary system for the same reason (disruption). Thus the considerations for the formation of the NSs in these field LMXRBs, as well as the evidence for binary evolution and hierarchical triple systems, continue to support the suggestions (Grindlay 1985a,b, and 1986) that these compact binaries were born in globular clusters (by the tidal capture and NS evolution processes discussed above) and either ejected or, more likely, liberated from globulars undergoing disruption in the galactic bulge.

6. CONCLUSIONS

At first sight, NSs were (are) not expected in globular clusters, as witnessed by the general surprise and interest in the discovery of the luminous x-ray sources and bursters in globulars in the mid-1970s. The existence of NSs in globulars is now certain beyond a doubt but their origin and implications for both stellar and binary evolution in globulars remains a challenge. We have reviewed a variety of recent results and contributed arguments which suggest that AIC is the dominant mode of formation of NSs in dense globular cluster cores. The arguments will be tested by continuing searches for the optical counterparts of both the high and, especially, the low luminosity x-ray sources. Optical identifications of the low luminosity systems are especially critical to confirm that they are indeed the CVs expected (cf., discussion of on-going searches and preliminary results in Grindlay 1986). NS production should be maximum in clusters which are both metal rich and of the highest central densities n_c. Although the distribution of clusters in the [m/H] vs. n_c plane will be studied in a forthcoming paper, it is interesting that the clusters containing high luminosity x-ray sources are generally both metal rich and with high central densities, whereas clusters with comparably high central densities but lower metals (e.g., NGC 5824) generally do not contain high luminosity sources. The clusters with the largest values of n_c and [m/H] should also then be the best prospects for finding the probable evolutionary end-products of NS-binaries in globulars: binary radio pulsars with spin periods of a few milliseconds and orbital periods of ~10 days (though some will have been scattered out of their parent binaries by interactions with both single stars and other binaries in the cluster core). In this regard the steep spectrum radio source in the core of the globular cluster M28=NGC 6626 (Hamilton, Helfand, and Becker 1985) is particularly intriguing and searches for millisecond pulsars in more metal rich globulars should be continued.

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DISCUSSION

R. Dewey: Are the white dwarfs in the giant-driven sources likely to be of the right composition to collapse rather than completely disrupt?

J. Grindlay: That is an excellent question. If massive white dwarfs (O - Ne - Mg) are produced from an early generation of massive stars in globulars, then they should not disrupt. If the more numerous CO white dwarfs have cooled to have a gradient in their composition (with oxygen settling to their core), as suggested by Canal et al., they they should not disrupt.

S. Woosley: If the neutron star in your binaries comes from white dwarf collapse the mass should not be much less (or much greater for that matter) than 1.1 $M_{\odot}$. You start with 1.4 $M_{\odot}$ subtract no more than 0.2 $M_{\odot}$ in the explosion (nucleosynthetic limits will likely reduce this to $<$ 0.1 $M_{\odot}$) and about 0.1 to 0.2 $M_{\odot}$ for the neutron star binding energy.

J. Grindlay: I agree; a mass loss of no more than ~0.2 $M_{\odot}$ is also implied by the requirement to keep the resulting neutron star binary in the globular cluster, where it may subsequently interact with (predominantly) main sequence stars in the cluster core to produce (by exchange collisions) the neutron star - main sequence star binaries predominantly observed.

F. Verbunt: I am pleased to see that you have an indication that neutron stars in globular clusters are less massive than 1.4 $M_{\odot}$. There is one low-mass X-ray binary in which the mass of the neutron star has been estimated, 4U2129+47 (Horne et al. 1986, MNRAS **218**, 63) and the mass of this neutron star is 0.6±0.2 $M_{\odot}$.

J. Grindlay: I mentioned that lower mass neutron stars are possible (i.e, consistent with) but not yet required by the X-ray positions and mass determination. Lower mass neutron stars would be required only to the extent that the accreted mass is a significant fraction of the current total mass, and to the extent required by improved models of the cluster potential to be derived from our optical studies of cluster cores. As for the evidence for a reduced mass in the reference you cite, this is subject to the highly uncertain kinematics of the orbit when derived from emission, rather than absorption lines (i.e., the effects of gas streams on the derived mass are very uncertain).

S. Kulkarni: In response to the previous question asked by Verbunt to Grindlay, is it not true that we expect the neutron stars to be <u>more</u> massive than 1.4 $M_\odot$ since neutron stars in globular clusters always end up with a companion and may have had more than one episode of extended accretion phase?

J. Grindlay: The neutron stars are probably formed in globular clusters with masses of ~ 1.1 - 1.2 $M_\odot$ if they are formed from white dwarf collpase. If they accrete for ~10^9 yrs, they may indeed gain an additional several tenths of a solar mass.

S. Kulkarni: Dissipation of a globular cluster is a very inefficient way to create an LMXB. The formation rate of galactic LMXBs is ~10^{-6} - 10^{-7} yr^{-1}. In your scenario we would need a very large number of galactic clusters in the past. Could you please comment on this point?

J. Grindlay: The formation rate of ~ 10^{-7} - 10^{-8}/yr is that for the brightest luminosity systems, with mass transfer supplied by a giant. The globular cluster disruption scenario, on the other hand, attempts to account for the lower luminosity LMXBs in which mass transfer is supplied by a main sequence star (typically a K or M dwarf). The lifetime of these systems is much longer (~10×10^9 yrs) so that the required rate and number of disrupted globulars is reasonable as I have shown in several papers.