X-RAYING THE DYNAMICS OF GLOBULAR CLUSTERS

Jonathan E. Grindlay
Center for Astrophysics
60 Garden St.
Cambridge, Mass. 02138

ABSTRACT

Recent studies of the x-ray sources in globular clusters have provided important new clues for both the dynamical processes in clusters and the stellar content and evolution of globular clusters. Very deep x-ray images of several globular clusters show evidence for diffuse x-ray emission from hot gas which may be related by a simple shock model to properties of both the cluster, such as its orbit in the Galaxy, and the interstellar medium in the halo of the Galaxy. The x-ray surveys conducted with the Einstein Observatory are reviewed and the results derived for the luminosity function, masses and nature of the compact x-ray sources are discussed. The evidence for the compact binary nature of the sources is now overwhelming, but long-term x-ray variability studies previously reported may suggest that some of the systems are in fact triple systems with distant companions. Possible relationships between the initial mass function, stellar density and cluster evolution are discussed, and our arguments that the ostensibly similar compact x-ray sources in the galactic bulge are remnants of a population of globular clusters disrupted by giant molecular clouds are updated.

1. INTRODUCTION

Globular clusters may be regarded as a laboratory for the study of many of the most interesting current problems in stellar dynamics and evolution. The origin, evolution and internal structure of globular clusters continue to provide challenges for a number of the most currently active areas of astrophysics. It is becoming increasingly clear that these major problems are not isolated but are related in their solutions. For example, the core collapse which must inevitably occur in a globular cluster of high central density will apparently be strongly affected by the stellar content, and particularly the binary content, of the stars in the cluster core (Cohn and Hut 1984, Hut 1985, and other papers in these proceedings). The binary stars, in turn, are formed predominantly by capture processes within the cluster cores but

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survive and evolve predominantly by processes dependent on their initial mass and composition. Thus a complete understanding of globular clusters, or even their internal stellar dynamics, must involve a synergistic study of a number of cluster properties. X-ray observations of globular clusters offer a relatively new and powerful tool for achieving new insights into a number of these problems.

In this paper we review the major investigations of cluster content, internal dynamical structure and long-term cluster evolution which x-ray observations have stimulated. In accordance with the primary topic of this Symposium, most of the studies to be discussed are related to the dynamical structure and properties of globular clusters. We begin with a discussion of the large scale structure and motions of globulars as revealed by the recently discovered diffuse x-ray emission which may arise from their motion through the interstellar medium of the Galaxy. Cluster proper motions and total mass loss rates may be inferred from more sensitive studies of this emission in the future. We then discuss the results of the surveys for point sources in globulars. The derived luminosity function for these sources out to 10 core radii suggest they are compact binaries containing either degenerate dwarf or neutron star remnants and were formed by tidal capture within the cluster cores. The long-term x-ray variability of several of these compact binaries suggests they may have an appreciably probability having a distant third-body companion which modulates the mass-transfer rate in the compact binary during each periastron passage of the third body. We consider the possibility that the very formation and existence of compact binary x-ray sources contributes to the rapid demise of the cluster by first heating the core and causing the cluster to expand when it can then be more easily disrupted by tidal forces and giant molecular clouds in the Galaxy. The so called galactic bulge x-ray sources, with x-ray properties very similar to those for sources in globular clusters, may have both luminosity and spatial distributions consistent with their previously suggested (Grindlay and Hertz 1985, Grindlay 1984) origin in globular clusters now disrupted. Additional tests of this hypothesis are described.

2. CLUSTER WINDS AND ORBITS

The discovery of diffuse x-ray emission from globular clusters by Hartwick, Cowley and Grindlay (1982) was interpreted as being due to hot gas since it appears to be asymmetric with respect to the cluster cores. The gas may arise from cluster giants which lose mass in a wind. Such a wind could be shock-heated to x-ray temperatures by the ram pressure of a diffuse interstellar medium through which the cluster is moving. From the observed surface brightness and approximate temperature of the x-ray emission, we may derive constraints on the interstellar medium density density and cluster mass loss rate for an assumed cluster velocity. Detailed measurements of the emission temperature would eventually allow the cluster velocity and thus orbit to be measured.

We consider the case for the diffuse emission from the globular cluster ω-Cen. The hot gas (or diffuse emission) is detected primarily on the south side of the cluster at about 20 arcmin from the cluster center. Hartwick et al. note that this is where a bow shock might be expected from hot gas flowing out of the cluster and encountering the ISM since the direction of the cluster proper motion (Murray et al. 1965) is also to the south. The apparent angular size of the emission (approximately a shell with angular dimensions 5 x 20 arcmin) and the total diffuse emission luminosity (approximately 5 x 10^{33} erg sec^{-1}) allow the density of the radiating gas to be derived for an assumed temperature (or cluster velocity; see discussion above). Unfortunately, the counting statistics of the detected emission and the energy response of the IPC are such that the x-ray temperature cannot be measured directly. However the emission appears soft as it is detected only in the lowest energy channels of the IPC detector in the Einstein observations. Thus the temperature is probably not greater than 10^7 K, and is in fact only 1.4 x 10^6 K if the emission is due to an adiabatic shock with temperature proportional to the ram-pressure of the moving gas. For an assumed cluster velocity v, the temperature is (Spitzer 1978)

$$T = (\text{const})(\rho/\rho_0)v^2$$

where ρ/ρ_0 is the compression factor in density in the shock. This yields a temperature of 1.4 x 10^6 K for an assumed cluster velocity of 300 km sec^{-1} and a compression factor $(\rho/\rho_0) = 4$ behind the shock. The corresponding density in the shock is 0.016 cm^{-3} or a reasonable 4 x 10^{-3} cm^{-3} in the ambient ISM/galactic halo at the 1.3 kpc height above the galactic plane for ω-Cen. This density is compatible with recent estimates for the density and scale height of gas in the galactic halo as derived from LMC absorption line studies (Savage and deBoer 1979); the globular cluster diffuse x-ray emission would provide a new tool for measuring the density and distribution of this halo material. In deriving the density, we have assumed a optically thin bremsstrahlung emission process and cooling function given by Dalgarno and McCray (1972). This implies a cooling time for the shocked gas which, at 3 x 10^7 years, is much longer than the 1.7 x 10^5 year sonic crossing time across the shocked shell, so that the shock is indeed adiabatic and not isothermal.

The total mass of radiating gas in the shocked shell is about 12 $M_\odot$, which must be re-supplied at a rate $\dot{m}$ = Mgas/Tcool = 4 x 10^{-7} $M_\odot$/yr. Allowing for the approximate solid angle subtended by the radiating shell, this requires some 300 giants in the cluster to be supplying the mass loss at a rate of 3 x 10-9 $M_\odot$/yr per star. This is comparable with the mass loss rates found for extreme giants in clusters in the spectroscopic studies of Cohen (1976) and thus seems reasonable. The implied density of pre-shocked gas in the cluster core is about 0.01 cm-3, or a total gas mass of 0.1 $M_\odot$ if most of the giants are in the cluster core with core radius 4 pc. This mass is well below the typical upper limits for cool gas in cluster cores set by various searches (e.g., Scott and Durisen 1978).

More sensitive x-ray observations of ω-Cen and other relatively large or nearby globular clusters in which the diffuse emission from winds lost by the cluster giants could be detected (e.g., 47 Tuc and M22, as also detected by Hartwick et al.) could be expected to open up new dynamical studies of globular clusters. The tangential velocities and thus cluster velocity vectors could be derived or at least constrained for the first time for a large sample of clusters, and cluster orbits in the Galaxy finally studied. Gas dynamics within the clusters could also be investigated, and questions such as the degree of gas stripping in clusters just exiting from passage through the galactic plane could be studied. These studies should be possible to carry out with the permanent x-ray telescope, AXAF, to be launched in about 1992; preliminary studies may be possible with the German x-ray satellite ROSAT set for launch in 1987.

3. X-RAY LUMINOSITY FUNCTION: WHITE DWARFS VS. NEUTRON STARS IN GLOBULARS

The x-ray survey of some 71 globular clusters in the Galaxy reported by Hertz and Grindlay (1983) (hereafter HG) resulted in the first luminosity function for compact galactic x-ray sources in general and globular clusters in particular. Since the same deep exposures on ω-Cen, 47 Tuc and M22 which showed the diffuse x-ray emission discussed above also showed multiple point sources within several core radii (typically 10) of each cluster center, the globular cluster x-ray luminosity function actually derived is that for the brightest source in each cluster. Compact x-ray sources were detected in 16 clusters: 8 with high luminosity ($\gtrsim 10^{36}$ erg/sec) sources (including 7 clusters previously known and 1 discovered in the IR — Grindlay and Hertz 1981), and 8 with low luminosity ($\lesssim 10^{34.5}$ erg/sec) sources. The most striking result of the distribution of detected luminosities and the 56 upper limits derived in the Einstein survey is the gap in x-ray luminosity between approximately $10^{34.5}$–10^{36} erg/sec. The existence of this gap, as well as the approximate shape of the x-ray luminosity function derived by HG, lead HG to suggest that the low luminosity sources (below the gap) were predominately accreting white dwarf systems (i.e. cataclysmic variables) whereas those above the gap were compact binaries containing neutron stars. Support for the neutron star binary identification of the high luminosity sources comes from a wide variety of arguments although primarily from the study of x-ray bursters (often found in globular clusters) as reviewed by Lewin and Joss (1983) and the direct measurement of the masses of globular cluster x-ray sources (see discussion below) recently reported by Grindlay et al. (1984).

The existence of the gap and the shape of the overall x-ray luminosity function have now been even better constrained by Hertz and Wood (1984) with the addition of a large number of upper limits derived from the all-sky survey carried out with the HEAO-A1 experiment. Some 134 globulars were observed, or nearly double the sample studied with

Einstein, but no new sources were detected despite sensitivities for many clusters below the 10^{34} erg/sec level. Thus the probability that the gap is real is increased to be at greater than the 99% confidence level, and the total number of globulars in the Galaxy that could be expected to have their brightest source with luminosity in the gap is less than 0.5. The luminosity function derived by Hertz and Wood for the brightest source in each globular is shown in Figure 1. In deriving this brightest source luminosity function (BSLF), most of the detected clusters contained only one x-ray source. However, as reported by the Einstein survey of HG, the several clusters observed in very deep exposures contained several sources each although their total luminosity is less than a factor of 2 times that of the brightest single source. Thus the luminosity function shown in Figure 1 is equivalently the luminosity function for the total x-ray luminosity from all compact sources in the globular cluster. The additional contribution from the diffuse emission from hot gas as discussed in the section above, is relatively small: in the extreme example (in cluster mass) ω-Cen it is comparable with the lowest bin in the point source luminosity function.

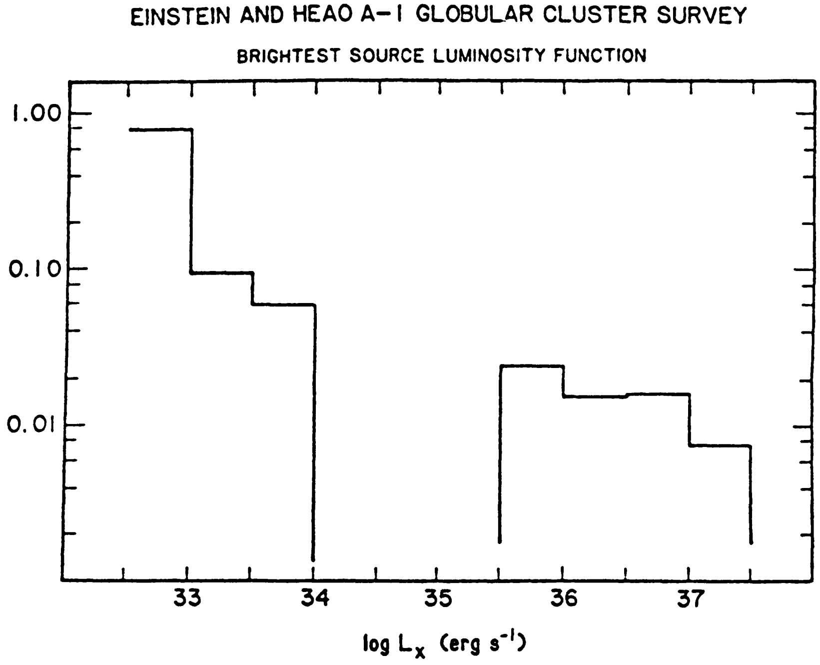

Figure 1 X-ray luminosity function for the brightest sources in globular clusters as derived by Hertz and Wood (1984).

The BSLF may be related to the actual luminosity function of the sources within a given globular cluster provided a model for the formation and nature of the sources is specified. Hertz and Wood (1984) have carried out this exercise for the tidal capture formation mechanism for the low luminosity sources and the simplifying assumptions for the accretion x-ray emission process, the cluster mass spectrum and the white dwarf mass-radius relation. The resulting luminosity function is a power law with index 1.3 and cutoffs at approximately 10^{31} and 10^{34} erg/sec corresponding to the range in accretion rates ($\sim 10^{-11}$–10^{-8} $M_\odot$/yr), white dwarf masses and binary parameters expected from the capture model. The total number of low luminosity x-ray sources in a typical globular cluster is derived by Hertz and Wood to be

$$N_{tot} = 9.2(n_x/8.3x10^3\ pc^{-3})(n_x/1.3x10^3\ pc-3)(V/3.2\ pc^{-3})$$
$$x\ (v_o/5.7\ km\ s^{-1})^{-1.2}\ (t/10^9\ yr)$$

by integrating this luminosity function. The capture formation volume V is approximately the cluster core radius cubed, and the stellar density n_s and velocity dispersion v_o are mean values for galactic globular clusters (Madore 1980). Thus for a fractional density of white dwarf stars in the cluster, or n_x/n_s, of about 15%, the typical cluster parameters given in the expression yield $N_{tot} \simeq 9$ low luminosity x-ray binaries per cluster. These parameters are such that the predicted BSLF agrees with that observed. Note, however, that the total number of capture binaries expected in the cluster core from this analysis is greater than the number of currently emitting x-ray binaries N_{tot} by the ratio of cluster age to x-ray emitting lifetime t (which is approximately 10^9 yrs, cf. Lightman and Grindlay 1982) so that the total number of compact binaries in the cluster is expected to be of order 100.

Most of these binaries will be in the cluster core (or at most a few core radii out) where they will have been "hardened" by successive interactions with stars in the cluster (e.g., Hut 1983). Their typical binding energies will thus be much greater than that of the cluster and thus their orbital periods should be less than a year. In fact, since these binaries are inferred entirely on the basis of their producing the low luminosity x-ray sources, their orbital semi-major axes must be typically less than a few (perhaps 10, at most) stellar radii for them to have been produced by tidal capture. The mass ratios of these binaries will be very nearly unity since the white dwarf masses are expected to cluster tightly around 0.5 $M_\odot$ (Renzini et al 1984) and the typical companion star mass should also be about 0.5 $M_\odot$. Thus their periods will be typically less than about 10 days (assuming binary companions with radii 1 $R_\odot$) and their orbital velocities will be typically greater than 70 km/sec. Allowing for random orbital inclinations, the expected orbital velocities of the companion (i.e. light emitting) star are still in excess of 50 km/sec. These expected orbital velocities are then sufficiently far from the cluster mean velocity that these stars would be rejected as cluster members in many searches.

A search for these expected compact binaries in the cores of clusters with the Hubble Space Telescope, therefore, need "only" be a spectroscopic survey of several hundred stars, each observed once with only moderate resolution (3-5 km/sec would be adequate). We have embarked on a pilot version of such a search in the diffuse globular cluster NGC 6712, which also contains one of the high luminosity x-ray sources within only 0.2 core radius of the cluster center (Grindlay et al 1984). These observations will be carried out with the FLWO 1.5-m and the MMTO MMT telescopes using Echelle spectrographs with reticon detectors for a velocity resolution of about 1 km/sec in this low velocity dispersion cluster. Further motivation for these observations is discussed in Section 7 below where we discuss the possible evolution of globular clusters containing large numbers of compact binaries (i.e. those clusters most likely to have a high luminosity source now detectable).

4. MASSES AND NATURE OF THE HIGH LUMINOSITY SOURCES

We have recently published (Grindlay et al. 1984) the final results of the analysis of the precise positions of the high luminosity globular cluster sources (measured with the Einstein X-ray Observatory) as well as the cluster centers and core radii (measured with optical data from CTIO) and have derived the constraints on the masses of the sources using the methods of Lightman, Hertz and Grindlay (1980). In this analysis, several simplifying assumptions were made about the sources and the gravitational potentials of the clusters they are found in. First, the cluster potentials were assumed to be isothermal spheres described by King (1966) models of single mass stars. Second, the source masses were assumed to be all the same, and the best estimate of that mass was derived from the data and the cluster model. Both of these assumptions were justified by first testing the observed distribution of source offsets against that expected for a model cluster potential containing single-mass sources; a two-sided Kolmogorov Smirnov test indicated the observed distribution would be obtained in more than 90% of the realizations of the model for sources with mass ratio $q = m_x/m = 2.6$ (where m_x is the total mass of the x-ray binary and m is the mean mass of the cluster field star). Thus, given the measurement errors for both the x-ray and optical position measurements, our data were completely consistent with both a single-q, single-core model.

Although we must await future x-ray observatory telescopes such as AXAF with both higher sensitivity and higher angular resolution to improve upon the x-ray data, more constraints may be inferred from the current observations. First, the fact that one of the eight sources used in the analysis is the source in 47 Tuc, which is actually a low-luminosity source ($L_x = 2 \times 10^{34}$ erg/sec) means that the single-q assumption may be invalid if the low luminosity sources are white dwarf binaries with total mass 1 $M_\odot$, as argued by HG and the discussion above. Of course it is also possible, as discussed by HG and also by Verbunt et al. (1984), that the low luminosity sources are actually a mixed sample with mostly white dwarf binaries but also some neutron star binaries in a very low accretion state (i.e. the low states observed in the so-called transient x-ray sources, at least one of which may in fact be the "low luminosity" source in the globular cluster NGC 6440--cf. HG). If we remove 47 Tuc from the KS test analysis for the source mass, the remaining 7 globulars yield an absolute likelihood distribution for L(q) of the definite high luminosity sources that is shown below. This distribution is somewhat broadened and shifted to lower q than that for all 8 sources originally presented. However, the original range in q (with 90% confidence interval 1.8-3.8) derived from the relative likelihood analysis would be only slightly changed to 1.5-4.3 in this modified sample.

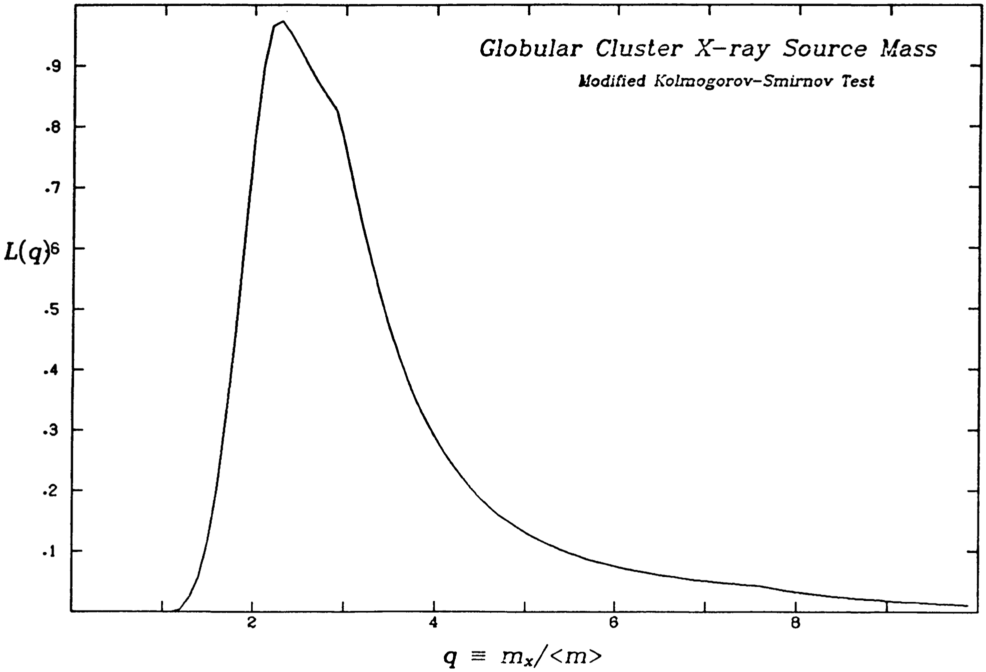

Figure 2. Absolute likelihood distribution for L(q) with 47 Tuc omitted from the sample originally reported by Grindlay et al. (1984).

A second possible modification which could now be made to our original analysis for the mass of the high luminosity sources comes from using the more precise x-ray source positions which can be measured by detecting the radio counterparts of these sources and measuring their positions with the VLA (Grindlay and Seaquist 1984, hereafter GS). In a survey of globular cluster and (the closely related--see discussion below) galactic bulge x-ray sources, all of the high luminosity globular cluster sources except NGC 1851 were observed with the VLA in short (15 min) observations at 6 cm and (for several fields) 20 cm wavelengths.

Only NGC 6624 was detected with a significance of 5 sigma at 20 cm; our upper limit at 6 cm suggests that the source may have a non-thermal spectrum as was also derived for the brighter galactic bulge sources in these same observations. A similar percentage of the galactic bulge x-ray sources not apparently in globular clusters was also detected with significance greater than 5 sigma (and 3 sigma effects, probably consistent with the fluctuations expected from the background in the maps produced, were found within the Einstein HRI error circles [90% confidence radius 3.2 arcsec] for the source in the globular Liller 1 as well as one galactic bulge source). The VLA position for the source in NGC 6624 has an uncertainty of only 0.1 arcsec as opposed to the 0.9 arcsec uncertainty we derived for the mean of a number of separate x-ray observations. The radio and x-ray positions agree but the radio position is closer to the cluster center by 1.8 arcsec. Using this refined source position for the NGC 6624 source but with all the other source positions as used in Grindlay et al. or in Figure 2 above, we derive the L(q) distributions shown below.

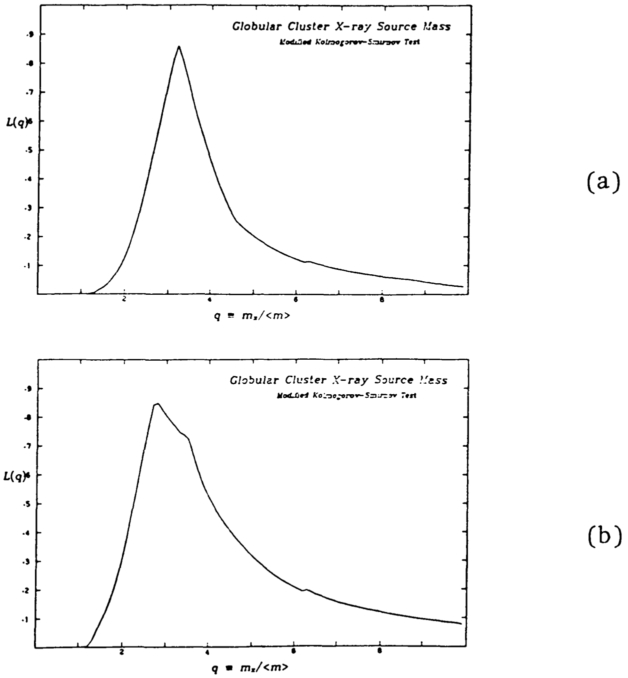

Figure 3. L(q) distributions using the VLA radio position for the source in NGC 6624 and a) the 7 other sources measured with the HRI (i.e., the total sample reported by Grindlay et al. 1984) and b) the 6 other sources known also be high luminosity or neutron star binary sources (i.e. 47 Tuc omitted as in Figure 2).

The more precise position for the source in NGC 6624 moves the peak in the L(q) distribution to slightly larger values of q, as would be expected.

The maximum value for L(q) in any of the three absolute likelihood test results shown here (in Figures 2 and 3) is comparably large (approximately 0.9) and essentially indistinguishable when compared to our original results indicating the single-q (albeit different values) and single-core models are equally well described by the different data sets. Thus either more precise x-ray source position offsets (perhaps from further radio studies) or more high luminosity cluster sources are needed before the single-q, single-core models can be further tested. There is immediate hope for both possibilities: more sensitive VLA observations are planned, and the heavily reddened globular clusters containing high luminosity x-ray burst sources will be studied at both IR and x-ray wavelengths. For example, the IR globular Grindlay 1 which contains the burster MXB1728-34 (Grindlay and Hertz 1981) will be mapped in very deep I-band CCD observations to derive a precise cluster center and core radius, whereas the bursters apparently in the globulars Terzan 1 and Terzan 5 (Makishima et al. 1981) might be located precisely in future ROSAT (and certainly AXAF) observations.

The existing data may nevertheless be used to derive a revised range for the source mass ratio q, or the source mass itself, which includes the uncertainty of whether 47 Tuc is really a high luminosity source and also includes the more accurate radio position for the one cluster source now detected. A maximum likelihood analysis for the 90% confidence interval for the value of q which is consistent with any of the three modified data sets discussed above gives the range 1.5-4.9 for q. That is, for a mean cluster star mass of approximately 0.5 $M_\odot$ (cf. Grindlay et al. 1984), the total mass of the x-ray source in these 7 or 8 high luminosity-source clusters is in the range 0.8-2.5 $M_\odot$ at the 90% confidence level provided (again) that the sources all have the same mass and that the cluster cores are isothermal. This somewhat expanded range of allowed q-values does not weaken our firm conclusion that the high luminosity x-ray sources in globular clusters must be compact binaries containing neutron stars (since the maximum mass allowed still does not require a black hole) but it does weaken somewhat our inference that these neutron stars are born in globulars with masses probably below the 1.4 $M_\odot$ value inferred for neutron stars in the galactic plane. Our previous conclusions (cf. HG and Lightman and Grindlay 1982) for the source formation mechanism also remain valid: namely, that the observed rate of 0.1 high luminosity source per cluster implies each typical cluster contains 1-3 neutron star binaries (each with x-ray emission phase of duration ~10^9 years) formed by tidal capture from a reservoir of about 1% of the cluster mass in neutron stars. However, we now present new evidence (culled from existing data or published results) that some of these compact binaries in cluster cores may in fact have distant companions and thus be members of hierarchical triple systems.

5. GLOBULAR CLUSTER AND GALACTIC BULGE SOURCES: BOUND TRIPLES ?

The compact binary systems containing either white dwarfs or neutron stars that we infer to be in globular cluster cores must themselves have a significant probability of capturing a distant third body companion. This is because these basically double-mass compact binary systems will both be more likely found in the high density cluster core, where capture of a distant companion is enhanced by the increased stellar density, and will have reduced isothermal velocity such that again (for the same reason) capture is more likely. Indeed the recent models of the evolution of cluster cores in which binaries are forming show that these systems often have a third body distant companion (cf. McMillan 1983, and Lightman, this volume). The orbits of these third body companions will be stable if the ratio of the third-body period to the compact binary period is large enough. Period ratios greater than about 100 are stable over a wide range of relative orbital inclinations (cf. Soderhjelm 1982). Thus if the compact x-ray binaries themselves have periods of order 3 hrs-1 day, as is now observed for several x-ray bursters/galactic bulge x-ray source systems, the third-body period expected would be in the 100-day range. Since the third body will itself be most efficiently captured by tidal encounters with passing field stars in the cluster, the surviving systems (with long enough periods for stability) will most likely have cluster giants as the third body. We might then expect third-body periods as long as 1-3 years for capture of cluster giants with radii as large as 0.3 AU at typical capture radii (orbital semi-major axes) of 3 stellar radii.

Such long-term periods may have been detected in 2 or 3 of the 8 high luminosity globular cluster x-ray sources as well as several of the closely related galactic bulge x-ray sources. Perhaps the best case, and the one first made for a possible long-term periodicity in the x-ray emission of a globular cluster x-ray source, is the occurrence of burst activity from the so-called rapid burster in the globular cluster Liller 1. Grindlay and Gursky (1977) pointed out shortly after the discovery of this remarkable source by Lewin et al. (1976) that the times of bursting activity seemed to cluster around the February-March and August-September time periods despite historical observations throughout the year with the Uhuru satellite as far back as 1971. Subsequent observations with the x-ray satellites Ariel 5 and SAS-3 (1975-1979), HEAO-1 (1978-1980) and the Japanese satellites Hakucho and Tenma (1980-1984) have remained consistent with these apparent "windows" for burst activity. The source became burst-active again in August 1983 for the first detected activity since August 1979 despite a number of extended observations with the Japanese experiments (Inoue et al. 1985). The overall record of burst activity is shown in Figure 4, which is from Lewin and Joss (1983) and does not include the 1981-1983 Japanese observations. The occurrence times of burst activity suggest, but do not prove, that the bursts may be triggered with a ~6 month period. Bursts are not always observed during these times, so that the trigger is not totally reliable. We propose that this trigger may be the tidal influence of a third-body companion with a ~6 month orbital period and small eccentricity in its orbit. Burst activity is initiated each periastron passage by a change in the accretion rate in the compact binary induced by the tidal shock of the passing third-body companion. The increased mass transfer rate and burst activity is sustained partially by the x-ray heating effect of the Type II (or rapid) bursts themselves but may not occur if the phase of the compact binary is not optimally aligned (i.e. approximately pointing towards the distant companion) at periastron passage.

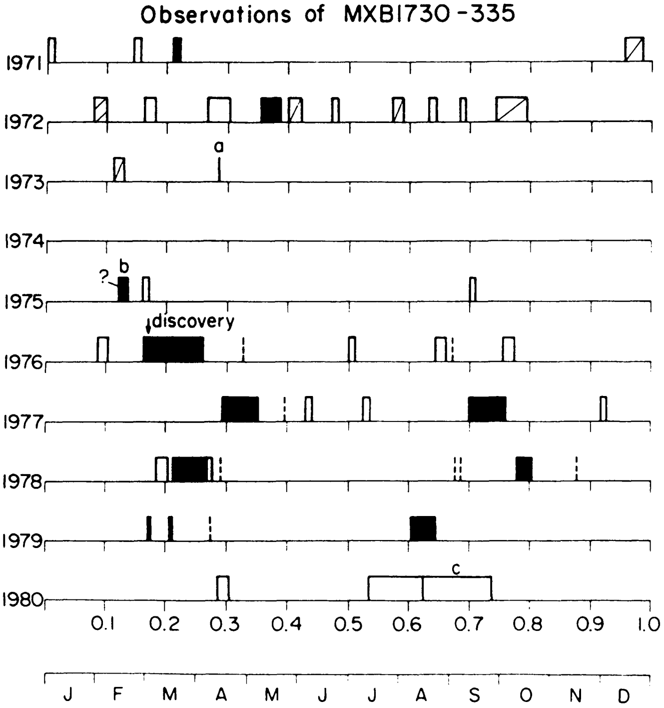

Figure 4. Long-term burst activity record for the burster MXB1730-33 in the globular cluster Liller 1 (from Lewin and Joss 1983). Burst activity periods are denoted by the filled rectangles, quiescent periods with the open rectangles, and ambiguous periods (in which probably only Type I bursts from a nearby burster were detected) are marked with the diagonals in the open rectangles. Short periods (1 day) of observation in which no burst activity was observed are indicated with the vertical dashed lines.

Another high luminosity globular cluster source which has recently been reported (Priedhorsky and Terrell 1983) to have a 176.4±1.3 day period in its overall x-ray intensity is the burster in NGC 6624. Long-term variations of the sources were observed with the 3-12 keV x-ray detector on the Vela 5B satellite over the interval 1969-1976. The apparent periodicity discovered is in the persistent emission, not the burst activity, of the x-ray source. The x-ray flux varies by a factor of 2 over the 176 day cycle, and the light curve shape can be described qualitatively as having a relatively rapid rise and longer decay. This relatively rapid onset and slower decay may suggest modulation of the mass transfer rate by a distant third body followed by x-ray heating effects as mentioned above but with a still larger period ratio or smaller eccentricity so that the variations are more regular and smooth. Alternatively, of course, the 176 day modulation could be simply a binary period in which case the binary is relatively wide separation and the companion (to the neutron star) must be a cluster giant. Such systems have in fact been proposed by Webbink, Rappaport, and Savonije (1983) as possible counterparts for galactic bulge x-ray sources.

The major difficulty with this interpretation for the bursters in globular clusters is that it is in conflict with what is becoming increasingly clear for bursters in the galactic bulge — namely, that their binary periods are in the range ~1-5 hours with perhaps a few in the range ~1-5 days. The most striking case is the galactic bulge burster 4U1915-05 which shows a 50 min period of x-ray dips (Walter et al. 1982, White and Swank 1982) which is almost certainly due to a binary, not spin, period (such dips, with similar periods in the ~1-5 hour range, have now been detected in several other bulge sources). What is remarkable about 4U1916-05, though, is that Priedhorsky and Terrell (1983) also find it to have a long period of 199 days. Thus the ~200 day periods found with the long-term Vela satellite data cannot all be binary periods and we consider it simplest to assume that none of them are. The obvious test is to carefully search sources with possible long term (~100-300 day) periods for short (~1-5 hours) periods; this is being undertaken with EXOSAT observations which can finally search this most interesting period range which was previously very difficult for x-ray satellites in low-earth orbit. Alternatively and in addition, more examples of long-term periods in either known or unknown short period binaries might be sought. Priedhorsky (private communication) has evidence for a 0.93 year period for the high luminosity x-ray source in NGC 6441 and a 0.80 year period for the galactic bulge source/burster GX17+2. We shall return to the implications of this possible GX17+2 period in the next section.

The ~200-400 day periods discussed here could naturally be, therefore, third-body periods for the globular cluster sources. What about the galactic bulge sources apparently not in globular clusters such as 4U1915-05 or GX17+2? The long period (199 days) for 4U1915-05 is such a large multiple of the 50 min binary period that we consider it unlikely this long period is due to precession. This is because the period ratios do not scale from systems with comparable long periods, which may be due to precession (e.g., Her X-1, SS433, Cyg X-1), unless the mass of the companion star is implausibly small (see, however, discussion by Priedhorsky and Terrell 1984). Thus we propose that the galactic bulge sources with long-term periods are also bound triple systems. General arguments that such systems might be relatively common for x-ray binaries were in fact made some time ago by Bahcall et al. (1974) with specific application to Cyg X-1. The question now is, how do such systems arise (if they indeed exist) for apparently isolated galactic bulge sources?

6. GLOBULAR CLUSTER DISRUPTION PICTURE FOR GALACTIC BULGE SOURCES

We have suggested (Grindlay and Hertz 1985, Grindlay 1984) that the so-called galactic bulge or galactic x-ray burst sources (or GXRBs, within ~30° of the galactic center) are compact binaries which formed by tidal capture in globular clusters before the clusters themselves were (rapidly) disrupted by encounters with giant molecular clouds (GMCs) in the galaxy. This was proposed as a hypothesis to explain a variety of facts including the high probability of optically identified bursters being in globular clusters, the basic similarities of bursters in and out of globulars, and the apparently significant coincidence in the spatial positions of 4 bursters in the field and G-K giants, which themselves could not be the binary companion (e.g., one of these 4 sources is 4U1915-05 with its 50 min period). The G-K giants could be either tracers of the remnant core to which the compact x-ray binary is still bound or, more likely (cf. Section 5 above), bound triple companions. Since both 4U1915-05 and GX17+2 now show evidence for long-term periods (see discussion above), this interpretation now seems more likely. The most basic argument for this cluster-disruption origin of GXRBs, however, is that a simple application of the Spitzer (1958) impulse approximation theory of cluster disruption to globular clusters and the relatively recently recognized large scale distribution of GMCs in the Galaxy (e.g., Soloman, Sanders, and Scoville 1979) suggests that GMCs will indeed disrupt globulars.

Several points have emerged since our last discussion (Grindlay 1984) of this hypothesis. First, Van Paradijs and Lewin (1984) have pointed out a numerical error in our (Grindlay and Hertz 1985) probability for the G-K star alignments, which we interpreted as remnant cluster giants gravitationally bound to the GXRBs as triple systems or remnant cluster cores. The chance alignment probability is ~0.03, not ~3 x 10^{-8}, for the assumptions given in our paper and is therefore only marginally significant. However, this probability is that <u>any</u> star of $m_V \lesssim 19$ is within 3 arcsec of the GXRB; the chance probability is still further reduced if all of the stars are G-K giants (rather than more numerous K or M dwarfs) as at least two appear to be (Grindlay 1984). Second, Verbunt et al. (1984) have argued that the luminosity distribution of GXRBs in the Galaxy appears to extend to significantly larger luminosities than does the x-ray luminosity function (HG) for globular cluster sources. However, this difference is complicated by several factors. Most notably, the difference is derived by comparing average burst fluxes, which are assumed to be standard candles, without allowing for possible differences in absorption. Since GXRBs are often more absorbed (by an unknown amount) than the globular cluster bursters (which have known optical extinctions in most cases), associating their burst fluxes with a standard candle luminosity will put them farther away than if absorption were included. Hence, the GXRBs would appear to have larger quiescent luminosity than the globular cluster bursters. Note that this "reddening" effect does not affect the burst fluxes the same as the persistent fluxes (and thus cancel out) since the burst spectra are generally softer, and thus more absorbed, than the persistent emission spectra. Indeed there seems to be more of a (positive) correlation between the L_X and distance estimates derived by Verbunt et al. for the GXRBs than for the globular clusters. Thus the difference in the high luminosity end of the L_X distributions for the two types of sources, which was estimated by Verbunt et al. to have only a 0.03 probability of being the same, may not be significant.

A third development relevant to our globular cluster disruption and GXRB origin hypothesis are the updated CO survey results of Sanders, Scoville, and Solomon (1985). These suggest an even larger number (~6000) of massive ($\gtrsim 10^5$ $M_\odot$) GMCs are present in the inner Galaxy ($R \gtrsim 2$ kpc) than we assumed (in Grindlay 1984). Their results continue to show the GMCs are concentrated in a ring-like feature between 4-8 kpc (for an assumed galactic center distance $R_0 = 10$ kpc). Thus the probabilities for disruptive collisions between globular clusters with orbits near ($i \lesssim 10°$) the galactic plane and semi-major axes which extend out to the GMC ring are even further enhanced. Although it appears that only a few globular cluster-GMC encounters (with impact parameters $\lesssim 150$ pc) are needed to disrupt a typical globular, detailed calculations are still needed. The (open) cluster disruption calculations presented by R. Wielen and by E. Terlevich at this meeting are a good starting point for the globular cluster case.

We conclude that the globular cluster and GXRB sources are fundamentally the same and that GXRBs could have been formed by capture processes in globular clusters now (largely) disrupted. The statistical significance of the GXRB/G-star associations is marginal, however, and very deep optical/IR/radio studies of these fields are needed to confirm physical associations. Such observations were planned (again) for 1984 but were not carried out due to bad weather; they are now planned for 1985. If the physical associations are confirmed, and the G-K giants are isolated but bound to the compact binary GXRB as triple systems, then important clues are available to guide studies of the final evolution and dissolution of globular clusters.

7. CONCLUSIONS: ROLE OF X-RAY BINARIES IN CLUSTER EVOLUTION

We conclude with a few remarks on the possible role of compact x-ray binaries in the evolution of globular clusters. It is clear from the large number of papers at this Symposium that both pre- and post-core collapse evolution of the cluster is strongly affected by its binary content. It therefore seems likely that clusters which were able to form the largest number of capture binaries (by virtue of their initial density distributions) should have evolved most rapidly. If the central cusp features found in two of the eight high luminosity x-ray cluster surface brightness profiles (Hertz and Grindlay 1984) as well as in several non-x-ray clusters (Djorgovski and King 1984) are indicative of post core-collapse in clusters, then these features may be dominated by binaries. The fact that the cusps are seen in clusters not detected as high luminosity x-ray sources does not argue the cusps are not related to the binary production or content of the core since only ~10% of the neutron star binaries are expected to be x-ray active (cf. Section 4). Thus we have initiated a massive observational project to search for cusps in most globulars in the Galaxy; preliminary results are presented by Lugger, Cohn, and Grindlay (these proceedings).

If binaries are driving the post-core collapse evolution of globulars, then it may be that it is precisely those clusters with the largest binary content which have also disrupted most rapidly. If post-core collapse evolution is accompanied by cluster core expansion, as Sugimoto (these proceedings) suggests, then these clusters may be the first to be disrupted by the tidal field of the Galaxy and individual GMCs as discussed above. Thus the disrupted population of globulars would have contained the largest concentration of compact binaries including the (~10%) presently x-ray active ones which we now detect as GXRBs and CVs. Since the number of binaries formed will also be sensitive to the number of massive stars or their remnants in the cluster (as these are most easily captured), there is also probably a connection between the cluster IMF and its subsequent evolution. If the disk globulars were formed initially with more massive stars (than the halo globulars), perhaps that accounts for their higher metallicity and propensity to self-destruct by formation of compact binaries. Clearly these various connections are ripe for considerable future study.

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DISCUSSION

SPITZER: Could you compare your estimate that 1% of cluster stars are neutron stars with theoretical expectations? What fraction of the neutron stars produced would need to be retained in the cluster?

GRINDLAY: The estimated fraction of $\sim$1% neutron stars in the cluster was derived by Lightman and Grindlay (1982, *Ap.J.*, 262, 145) to account for the frequency of the bright X-ray sources in globulars for the 2-body tidal capture-formation mechanism. This estimate is similar to that proposed on other grounds -- e.g., by Illingworth and King 1977, *Ap.J.Lett.* 218, L109 -- to account for the central cusp in M15. I have not made a detailed comparison of this required neutron star number with the numbers expected for various initial mass functions. However a back of the envelope estimate would suggest that for a Salpeter mass function and neutron star progenitors of $\gtrsim 8M_\odot$, most of them would have to be created in relatively "quiet" collapse (or at least symmetric collapse) so that they are not kicked out of the cluster.

SHAPIRO: One might expect binaries to be ejected from clusters in (at least) two different ways. One way is by tidal disruption of an entire post-collapsed cluster. In this case one might expect to observe both "low" luminosity (e.g. white-dwarf binaries) *and* "high" luminosity (e.g. neutron star binaries) for galactic bulge sources which you claim may originate from clusters. Alternatively, one might get binaries ejected from the cluster core directly, during the supernova formation of the neutron star or by small-N large-angle scattering effects. In this case one expects to observe "high" luminosity sources only. Which mode is suggested by the X-ray luminosity function of the Galactic bulge sources?

GRINDLAY: Unfortunately, the luminosity function for the other compact X-ray binaries in the galactic bulge is very poorly determined (if at all) since the distance to these sources, not apparently in globular clusters, is in general not possible to derive. However, it can be stated that the luminosity function for both the "dim" and "bright" X-ray sources in globulars is not inconsistent with the available constraints for the corresponding sources in the bulge. The Einstein Galactic Plane Survey (Hertz and Grindlay 1984, *Ap.J.* 278, 137) demonstrated this consistency.

APPLEGATE: What fraction of the high liminosity X-ray sources in globular clusters burst? What fraction pulse?

GRINDLAY: Essentially, *all* of the high luminosity cluster sources burst (only the source in M15 has not been observed to burst), whereas *none* of the cluster sources have been observed to pulse despite very intensive searches (see, e.g., Leahey *et al.* 1983, *Ap.J.* 266, 160)

KING: You have more than once referred to globular clusters as "fragile." I don't believe that they are. A high-concentration globular cluster is one of the most durable things that you can find in the Galaxy. Before speculating about products of disrupted clusters, one should have a quantitatively effective mechanism for disrupting them.

GRINDLAY: I couldn't agree more that a detailed theoretical treatment of cluster disruption is needed, as I urged in my talk. My point about the "fragility" of clusters here is this discussion was actually with reference to their relatively low binding energies (escape velocities) which would seem to require a "quiet" formation mechanism for the neutron stars we know must be present in cluster cores. As for cluster disruption by GMCs, as I have discussed in a recent paper it appears that a simple application of Spitzer's (1958) theory shows that a typical globular will be disrupted by GMCs in the $\sim$4-6 kpc ring within several cluster orbits if the cluster orbit is near the disk. However, once again, the detailed appearance and time scale(s) for a cluster in the process of disruption is a topic ripe for theoretical treatment so that comparisons with some of the observations I discussed may be made.

OSTRIKER: Perhaps extra destruction of globular clusters could occur if our galaxy had a bar. Then orbits would be box-like and clusters would occasionally come very close to the center and suffer extreme tidal forces.

BAHCALL, N.A.: 1) If the galactic X-ray burst sources are due to disrupted globular clusters, they should have a similar luminosity function to that observed for the cluster sources. Do they? 2) How significant is the gap in the liminosity function of the globular cluster sources?

GRINDLAY: 1) Unfortunately, as I remarked in response to Shapiro's question, the luminosity function for the galactic bulge sources (i.e. bursters apparently outside of globulars) is essentially unknown due to their very uncertain distances. To the extent bulge source luminosity estimates are available, however, they are consistent with the luminosity function derived for the cluster sources although the bulge sources *may* extend to somewhat higher luminosities than the globular sources, as recently discussed Verbunt *et al.*(1984, preprint). 2) The gap is now extremely significant as a result of the added upper limits from the HEAD-1 survey as recently reported by Hertz and Wood (1984, preprint). With these additional upper limites, $\leq$0.5 globular clusters in the Galaxy (at the 90% confidence level) are expected to have their brightest sources in the gap.

DJORGOVSKI: A comment on NGC 6712: Our surface photometry shows no indication of post-core-collapse morphology.

GRINDLAY: I agree NGC 6712 does not show an obvious central cusp (as a result of the photometry Hertz and I have done). However, for a cluster sufficiently past the post-collapse phase, any central cusp may have long since expanded (by binary heating) provided clusters do not oscillate.