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DETERMINATION OF THE MASS OF GLOBULAR CLUSTER X-RAY SOURCES

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ABSTRACT

The precise (~ 1″) positions of the luminous X-ray sources in eight globular clusters have been measured with the *Einstein X-Ray Observatory*. When combined with similarly precise measurements of the dynamical centers and core radii of the globular clusters, the distribution of the X-ray source mass is determined to be in the range 0.9–1.9 $M_{\odot}$ (90% confidence interval). The X-ray source positions and the detailed optical studies indicate that (1) the sources are probably all of similar mass (~ 1.5 $M_{\odot}$), (2) the gravitational potentials in these high–central density clusters are relatively smooth and isothermal, and (3) the X-ray sources are compact binaries and are probably formed by tidal capture.

Subject headings: clusters: globular — stars: binaries — X-rays: bursts — X-rays: sources

I. INTRODUCTION

The high-luminosity ($\geq 10^{36}$ ergs s^{-1}) X-ray sources apparently located in globular clusters have long been of special interest both for X-ray astronomy and for their implications for dynamical processes in globular cluster cores. The general properties of globular cluster X-ray sources and some of their implications have been discussed in several reviews (e.g., Grindlay 1977, 1983; Lewin and Clark 1980). Of particular interest has been whether these sources are massive (~ 10^3 $M_{\odot}$) black holes (Bahcall and Ostriker 1975; Silk and Arons 1975), intermediate-mass (~ 10–100 $M_{\odot}$) black holes (Grindlay 1978), or low-mass binary systems (Clark 1975; Katz 1975). Strong evidence for the low-mass binary picture has been developed from the study of X-ray bursters and the bright galactic bulge X-ray sources not in globular clusters but with X-ray properties essentially indistinguishable from the bright globular cluster sources (see Lewin and Joss 1983 for a recent review and references).

In this *Letter*, the mass of the typical X-ray source in a globular cluster is measured statistically from the precise (~ 1″) X-ray versus cluster center positions and found to confirm the low-mass binary picture. The mass of an X-ray source in a fully relaxed globular cluster may be derived from the radial offset between the X-ray source and the cluster center (Bahcall and Wolf 1976; Bahcall and Lightman 1976). Previous estimates of the globular cluster X-ray source masses using roughly 20″–30″ X-ray positions from *SAS 3* have suggested only that the sources are more massive than typical cluster stars (Jernigan and Clark 1979). Although preliminary results of the *Einstein* data analysis (Grindlay 1981; Grindlay 1983) have ruled out supermassive and intermediate-mass black holes, the final analysis reported here rules out even roughly 3 $M_{\odot}$ objects at the $\geq$ 99% confidence level, provided the cluster cores are isothermal. The data are now sufficiently precise to test this key assumption of isothermality.

II. OBSERVATIONAL PROGRAM

An estimate of the mass M_x for an X-ray source (or any other "labeled" object) in a globular cluster may be derived from its projected radial offset, R_x, from the cluster center, since $\langle R_x \rangle \approx 0.7 r_c\, q^{-1/2}$ (for $q \gg 1$), where $q = M_x/m$ is the ratio of the X-ray source (total system) mass to the mean stellar mass, m, in the cluster core and r_c is the cluster core radius (Bahcall and Wolf 1976; Bahcall and Lightman 1976). As shown by Lightman, Hertz, and Grindlay (1980) (hereafter LHG), the actual distribution of R_x values for a number of clusters allows a statistical determination of not only a consistent estimate for q, but also the absolute likelihood that the data are consistent with a given model for the cluster potential (e.g., an isothermal sphere) and a given distribution of q (e.g., a single value).

As also shown by LHG, the ability to infer a reasonable given value of q requires the total measurement error σ_t (due to errors in the X-ray position, cluster center and core radius) be less than $r_c(3q - 1)^{-1/2}$. Thus, given a typical value of $r_c \leq 10''$ for the core radius of X-ray globular clusters (Grindlay 1977), σ_t must be $\leq 3''$ to be sensitive to a value $q = 4$. Therefore, the X-ray positions, cluster centers, and core radii must each be measured with absolute precisions approximately 1″. This requirement for arc second position accuracy for the globular cluster sources necessitated use of the High Resolution Imager (HRI) on the *Einstein Observatory* (Giacconi *et al.* 1979). This requirement was also central to our investigation and solution (Grindlay 1981) of the star tracker anomalies (caused by the geomagnetic field) on the *Einstein Observatory*. The final reprocessed HRI data yield X-ray positions determined in a single observation with an accuracy of 1″.5 (1 σ radius) or 3″.2 (90% confidence radius) as determined from the distribution (very nearly Gaussian) of many HRI observations of optically identified X-ray sources.

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The globular cluster sources included in this study were the eight clusters detected in the HRI survey (Hertz and Grindlay 1983) and for which accurate cluster centers and core radii could also be measured (Hertz and Grindlay 1984). Each cluster was observed with the HRI at least four times with pointing positions offset (by $\sim 8'$) for each so that the guide stars were observed in different regions of the star trackers and any remaining systematic errors were randomized. The resulting independently measured positions for each cluster source were all consistent with a two-dimensional Gaussian distribution about a fixed mean for each cluster. The mean X-ray source positions derived and 1 σ uncertainties (on the mean) are given in Table 1. Analysis of the X-ray images for each source showed that each was consistent with a *single* point source; additional sources in the cluster core up to 10–30 times fainter could have been detected in the HRI images, but were not. This provides additional evidence that the gap in the X-ray luminosity function (Hertz and Grindlay 1983) at $10^{34} \lesssim L_x \lesssim 10^{36}$ ergs s^{-1} is real.

The absolute position for the cluster center and the cluster core radius are also given, together with their estimated uncertainties, in Table 1. These values are derived from our detailed analysis (Hertz and Grindlay 1984) of digitized Cerro Tololo Inter-American Observatory (CTIO) 4 m plates obtained (by J.E.G.) for each cluster. Finding charts (from our CTIO 4 m plates) for the eight clusters are shown in Figures 1*a* and 1*b* (Plates L1 and L2) where the cluster centers and core radii are marked together with the X-ray source positions. In Figure 2 all of the X-ray source position offsets are plotted on a common schematic cluster with displacements measured in units of the cluster core radius.

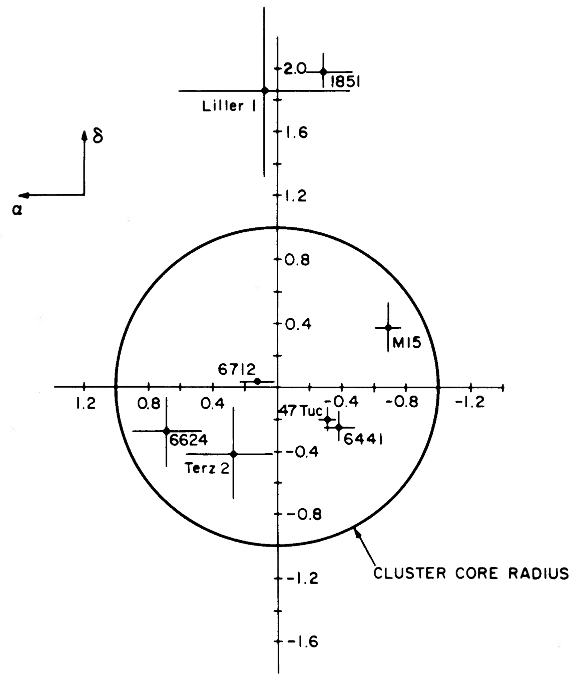

FIG. 2.—Measured radial offsets of X-ray sources from the centers of their respective globular clusters in units of the cluster core radius. All sources except those in 47 Tuc and M15 have been observed to burst.

III. ANALYSIS FOR SOURCE MASS

From the normalized radial offsets, $\Delta \equiv R_x/r_c$, listed in Table 1 and the source positions in Figures 1*a*, 1*b*, and 2, it can be seen that the X-ray sources are distributed "evenly" about the cluster centers (two sources are offset in each of the four quadrants) and that half of the sources are within 0.5 core radii of the cluster centers. In only one cluster (NGC 6712) do the X-ray position and cluster center position overlap at the 1 σ level; a second cluster (Terzan 2) overlaps at the 2 σ level. It is interesting, but not statistically significant, that the cluster NGC 6712 with anomalously low central density and concentration (cf. Grindlay 1977) should have its X-ray source closest to the center. On the other hand, NGC 1851,

TABLE 1

X-RAY SOURCE AND GLOBULAR CLUSTER POSITIONS

Cluster	X-Ray Position	Cluster Center	Core Radius	Offset
NGC 104 (47 Tuc) ...	00 21 51.58 ± 0.4	00 21 53.16 ± 1.3	23.6 ± 1.3	0.36 ± 0.07
	−72 21 34.6 ± 0.8	−72 21 29.9 ± 1.3		
NGC 1851	5 12 27.88 ± 1.0	5 12 28.03 ± 0.7	5.9 ± 0.7	2.00 ± 0.30
	−40 05 59.7 ± 0.4	−40 06 11.4 ± 0.7		
Terzan 2	17 24 20.09 ± 1.6	17 24 19.95 ± 1.0	6.5 ± 1.4	0.50 ± 0.31
	−30 45 39.4 ± 1.6	−30 45 36.7 ± 1.0		
Liller 1	17 30 6.63 ± 1.6	17 30 6.61 ± 1.0	3.5 ± 0.5	1.86 ± 0.60
	−33 21 13.2 ± 1.6	−33 21 19.7 ± 1.0		
NGC 6441	17 46 48.49 ± 0.6	17 46 48.75 ± 0.7	8.2 ± 0.3	0.45 ± 0.11
	−37 02 17.8 ± 0.5	−37 02 15.8 ± 0.7		
NGC 6624	18 20 27.84 ± 0.90	18 20 27.56 ± 0.7	5.2 ± 0.5	0.75 ± 0.23
	−30 23 17.0 ± 0.9	−30 23 15.6 ± 0.7		
NGC 6712	18 50 21.18 ± 0.4	18 50 20.78 ± 5.6	49 ± 5	0.13 ± 0.08
	−8 46 4.4 ± 0.3	−8 46 6.5 ± 0.9		
NGC 7078 (M15) ...	21 27 33.14 ± 0.5	21 27 33.40 ± 0.5	5.5 ± 1	0.79 ± 0.20
	11 56 51.0 ± 0.7	11 56 48.9 ± 0.5		

NOTE.—Positions listed for both the X-ray source and cluster center are (*upper*) R. A. (1950) and (*lower*) decl. (1950); the listed errors are ±1 σ and are in units of *arc seconds* for *both* right ascension and declination. The cluster core radius r_c (and its ±1 σ error) is in arc seconds, and the offset, $\Delta \equiv R_x/r_c$, is the projected radial offset of the X-ray source from the cluster center in units of the cluster core radius.

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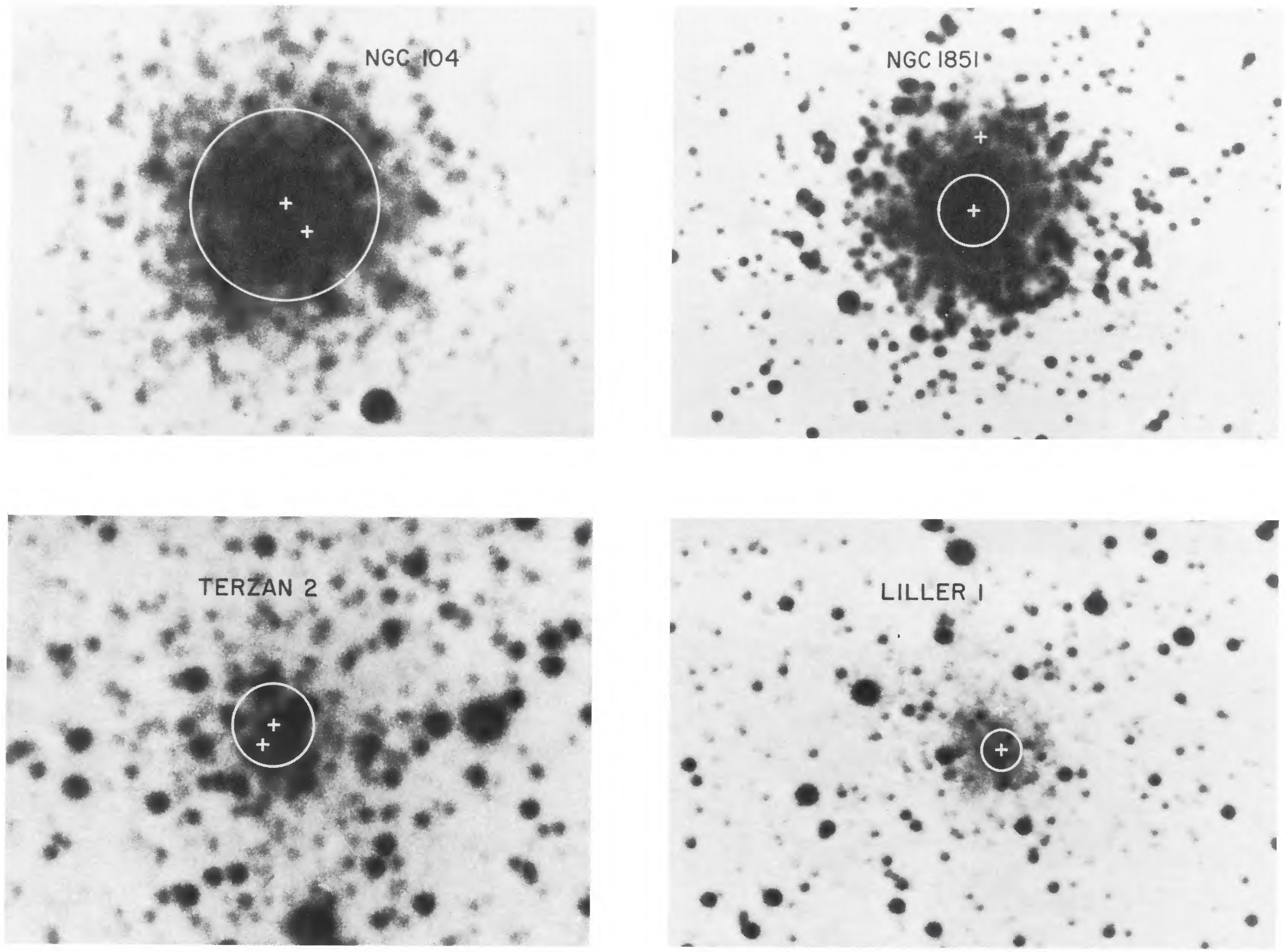

FIG. 1*a*

FIG. 1.—Finding charts (from enlargements of CTIO 4 m *U* plates) for each of the eight globular clusters containing luminous X-ray sources. For each of the finding charts, the X-ray position and cluster center position are plotted with approximate error bars (exact values are shown in Fig. 2), and the cluster core radius is marked as a circle. The cluster centers are consistent with the (usually less accurate) values determined for several of these clusters by Shawl and White (1980). North is up and east is left, and the scale of each chart can be derived from the core radii given in Table 1.

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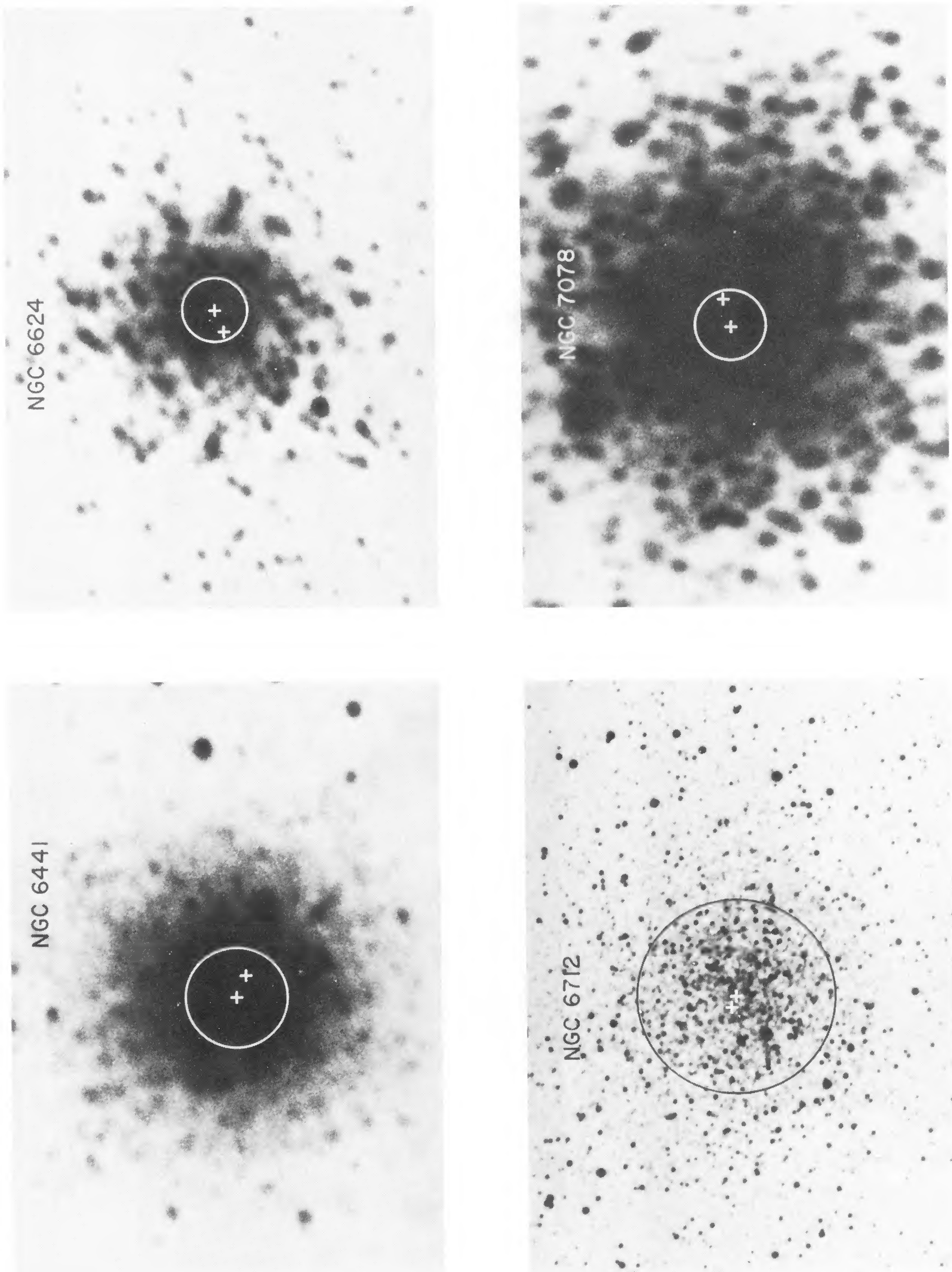

FIG. 1b

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the only globular cluster X-ray burst source not in the galactic bulge, is the only source located (at the $\geq 99\%$ confidence level) outside the cluster core. The rapid burster in Liller 1 is also probably outside the core, but in this case the core radius is relatively more uncertain.

The (weighted) average radial offset is $\langle \Delta \rangle = 0.38$ which would imply a source mass ratio $q \approx 3.4$. However, much more information is contained in the Δ-distribution than in the average, which can be misleading. It is possible to test whether a single value of q describes the data and, if so, the most probable range of values of q allowed. Employing the methods of LHG, but using a numerical integration of the integral equations rather than the analytic large-q approximation discussed by LHG, we obtain the absolute likelihood curve for $L(q)$ shown in Figure 3. $L(q)$ is the probability according to the Kolmogorov-Smirnov (KS) test that a given value of q, subject to measurement errors, could have generated the observed data set. In deriving this result, we have also used the correct two-sided KS test (Massey 1950) rather than the probability formulae (from Birnbaum and Tingey 1951) for the one-sided KS test as discussed by LHG. The corrected probability distribution for the two-sided KS test slightly broadens the $L(q)$ distribution (for a given "true" value of q and fixed measurement errors) over those shown by LHG. Nevertheless, the overall comparison between the actual data (Fig. 3) and the hypothetical models of LHG is very revealing: the sources are extremely well described by a single value of $q = 2.6$ for which $L(q) \approx 0.9$. The $L(q)$ distribution has a width totally consistent with the measurement errors, and it is completely consistent with a single-q and single-core potential.

To explore the range of q allowed for a single-mass model, we employ a relative-likelihood analysis similar to that of Jernigan and Clark (1979) in which q is varied to maximize the probability of observing the data. This test is strictly appropriate only when the validity of the particular model used for the cluster potential and the single q distribution have first been established with a KS test, as in Figure 3. The resulting relative likelihood distribution as a function of q is plotted in logarithmic form in Figure 4. The ordinate is in units of $\Delta\chi^2 = 1$, or in deviations of χ^2 from its minimum value for the one-parameter fit of q to the data. The minimum χ^2 is again found to occur for $q = 2.6$, but it is now possible to read off the allowed range of q for any given confidence level. For $\Delta\chi^2 = 2.7$, or a 90% confidence level in q, the allowed range is $1.8 \leq q \leq 3.8$. Since the typical mass of a cluster star in the core is about 0.5 $M_\odot$, the corresponding range for the total mass of the X-ray source is 0.9–1.9 $M_\odot$.

This conversion to mass is, of course, dependent on the actual mass spectrum of field stars in the cluster. The mass spectrum is uncertain but has been estimated for the cluster M3 by Gunn and Griffin (1979) to be consistent with a power law with an index of roughly 3 (vs. 2.35 for a Salpeter mass function) and cutoffs at about 0.2 $M_\odot$ and about 0.8 $M_\odot$. Integrating such a distribution would give an average field star mass of 0.32 $M_\odot$ and correspondingly lower values for the X-ray source mass. However, this is not warranted since our estimate for q from the measured X-ray positions is itself based on a single-mass King model for the cluster stars. We therefore conclude that the X-ray source mass is approximately 1–2 $M_\odot$, with the allowed range determined on an absolute mass scale to within a factor of about 1.5.

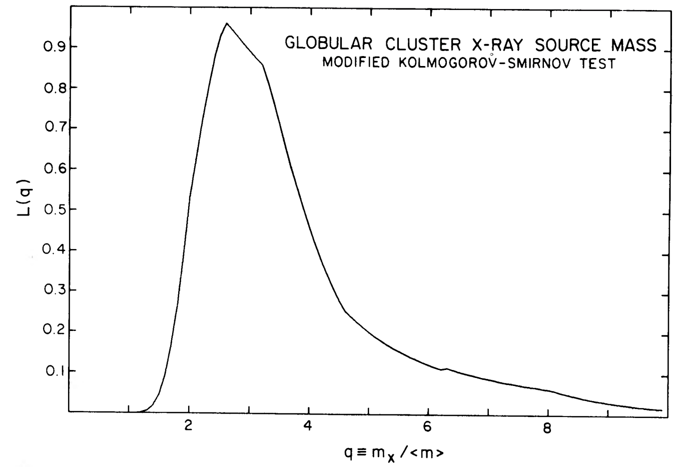

FIG. 3.—Result of Kolmogorov-Smirnov test for absolute likelihood that the observed X-ray source offsets from cluster centers are due to a distribution of sources with the particular value of q (X-ray source mass in units of cluster field star mass) shown. A simple isothermal cluster potential is assumed.

IV. CONCLUSIONS

The globular cluster X-ray sources with luminosity $L_x \gtrsim 10^{36}$ ergs s^{-1} have a most probable mass of 1–2 $M_\odot$. The sources are then almost certainly low-mass binary systems, since our derived mass and the limits on diffuse gas in cluster cores (e.g., Hartwick, Cowley, and Grindlay 1982), as well as the required accretion rate, necessitate either a binary companion or a fossil accretion disk for the gas supply (cf. Lewin and Clark 1980). Our results appear to rule out either single (typical) cluster stars or massive stars as the source of the X-ray emission. Given the direct evidence that several bursters apparently outside globular clusters are indeed in binary systems (e.g., Walter *et al.* 1982; White and Swank 1982; Cominsky and Wood 1983), the globular cluster X-ray sources discussed here, most of which are also bursters, are also very likely to be compact binaries composed of a cluster field star

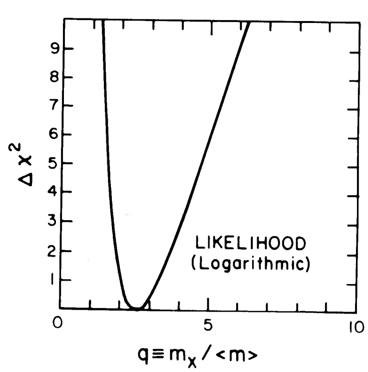

FIG. 4.—Relative likelihood analysis for allowed range of q about the best estimate value of $q = 2.6$. The 90% confidence level ($\Delta\chi^2 = 2.7$) interval for q is approximately 1.8–3.8.

and a compact object. Since the cluster field star has mass $\lesssim 0.8\ M_{\odot}$ and probably only about 0.5 $M_{\odot}$, the compact object mass must be $\lesssim 1.5\ M_{\odot}$. The compact object mass is then almost certainly a neutron star since white dwarfs may be ruled out from the X-ray luminosity function (Hertz and Grindlay 1983).

The implied neutron stars in globular clusters with mass presently $\lesssim 1.5\ M_{\odot}$ were probably formed with lower mass than the roughly 1.4 $M_{\odot}$ value found by Rappaport and Joss (1981) for (primarily) neutron stars in massive X-ray binaries. This is because an additional approximately 1 $M_{\odot}$ may have been transferred to the cluster neutron stars during the probable lifetimes of roughly 10^9 years with mass transfer rates of approximately 10^{-10}–$10^{-9}\ M_{\odot}\ \mathrm{yr}^{-1}$. The lifetime estimate, in turn, is consistent with the observed occurrence rate of luminous X-ray sources in globulars (where only one luminous source per cluster is observed) and the formation rate of the compact binaries by tidal capture in cluster cores containing approximately 1% of their mass in neutron stars (Lightman and Grindlay 1982). Such neutron stars, with a probable mass of roughly 1 $M_{\odot}$, would settle into the central region of the core and may contribute a detectable perturbation to the central potential (see Illingworth and King 1977) and the excess surface brightness peaks at the *center* of M15 and NGC 6624 (Hertz and Grindlay 1984). However, since the X-ray positional offsets appear to be so consistent with a simple King model and not a (significant) double core potential, we conclude that the central "cusps" are dynamical tracers of relatively more light rather than more mass. This could arise from the preferential production of binaries, and hence blue straggler stars (and the NGC 6624 cusp is very blue), in a central low-mass subcore of the cluster in which core collapse is occurring. Binary interactions in such a collapsing subcore could also occasionally eject the binary out of the cluster core, but not (usually) out of the cluster (McMillan 1983), and give rise to the large radial offsets (~ 2 core radii) observed for the X-ray binaries in NGC 1851 and Liller 1.

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