ROSAT OBSERVATIONS OF GLOBULAR CLUSTERS IN THE GALAXY AND IN M31

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Abstract. X-ray sources in globular clusters fall into two categories: the "bright" sources, with $L_X \sim 10^{36}$–$10^{38}\,\mathrm{erg\,s^{-1}}$, and the "dim" sources, with $L_X \lesssim 10^{34.5}\,\mathrm{erg\,s^{-1}}$. The bright sources are clearly associated with accreting neutron stars in binary systems. The nature of the dim sources, however, remains in doubt. We review recent observations of globular-cluster X-ray sources with the ROSAT satellite. ROSAT detected bright sources in M31 globular clusters and greatly increased the number of dim sources known in galactic globular clusters. We discuss what these new observations have taught us about the distribution and nature of such sources, their spectral properties, and their underlying luminosity function.

1. Introduction

The discovery of X-ray sources in globular clusters was made with the UHURU satellite during the first survey of the X-ray sky (Forman *et al.* (1978) which found six sources associated with globular clusters (Katz 1975). A decade later, it was found with the more sensitive EINSTEIN satellite that cluster X-ray sources fell into two distinct categories: sources

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with X-ray luminosities $L_X \sim 10^{36}$–$10^{38}\,\mathrm{erg\,s^{-1}}$ (the "bright" sources), and sources with $L_X \lesssim 10^{34.5}\,\mathrm{erg\,s^{-1}}$ (the "dim" sources; Hertz & Grindlay 1983; Hertz & Wood 1985). The bright sources all show X-ray bursts, and hence may fairly safely be associated with accreting neutron stars in a binary system.

The nature of the dim sources, on the other hand, is much less clear. Prior to ROSAT, there were eight such sources known in the cores of clusters, none of which had convincing counterparts. Hertz & Grindlay (1983) suggested they were cataclysmic variables; however, Verbunt *et al.* (1984) pointed out that the X-ray luminosities of some dim sources are up to 300 times higher than those of cataclysmic variables in the galactic disk, and argued that these are more likely to be quiescent X-ray transients. Other possible sources for the X-ray emission include the combined luminosity of many RS CVn stars (Belloni *et al.* 1993), millisecond pulsars, or even unrelated fore- or background objects.

The launch of ROSAT promised new developments in our understanding of the dim sources. ROSAT has three modes which are important for the investigation of cluster X-ray sources: *(a)* the ROSAT PSPC All-Sky Survey, which covered the entire sky in 6 months; *(b)* pointed PSPC observations, and *(c)* pointed HRI observations. The Survey gives us a measurement of the X-ray flux for every globular cluster, the PSPC gives a spectral resolution of $\sim$45% at 1 keV , and the HRI gives a spatial resolution of $\sim 5''$. Together with the ability of the Hubble Space Telescope to resolve stars even in the dense cores of globular clusters, real progress is now being made on identifying and studying these sources. In Section 2 we discuss ROSAT observations of bright globular-cluster sources in the Galaxy and in M31; in Section 3 we discuss new ROSAT observations of dim sources, particularly their spectra and multiplicity. In Section 4 we discuss how we can combine these observations to derive the underlying luminosity function of the cluster X-ray sources.

2. Bright Globular-Cluster X-ray Sources

2.1. GLOBULAR CLUSTERS IN THE GALAXY: THE ROSAT ALL-SKY SURVEY

The ROSAT All-Sky Survey is the first complete survey of the X-ray sky since HEAO-1. The Survey took place using the Position-Sensitive Proportional Counter (PSPC) starting in August 1990, and lasted for six months. The positions of 141 globular clusters were searched for emission, and a flux measurement or upper limit obtained for every cluster (Verbunt *et al.* 1994). Since the average integration time per cluster was only $\sim$300 s, the only cluster in which a dim source was seen during the Survey was 47 Tuc.

The bright sources, however, were easily detectable.

Prior to ROSAT, ten bright sources were known in globular clusters. That they were variable was already known; three of the six sources detected in the original UHURU survey sank below the detection limits of satellites observing in the following decade (Bradt & McClintock 1983). The ROSAT detections followed the same pattern: ten bright sources were detected, only eight of which had been seen before. ROSAT failed to detect the sources in NGC 6440 (which was a transient source seen only in December 1971–January 1972: Bradt & McClintock 1983) and Liller 1, not surprisingly since this source, the "rapid burster" (MXB 1730–335) has periods of burst activity, lasting $\sim$2–6 weeks, approximately every six months (see, e.g., Lewin & Joss 1981). ROSAT did, however, detect sources in Terzan 6 and NGC 6652 (Predehl *et al.* 1991). Thus approximately a quarter of the bright sources are variable on time scales of about 15 years, by a factor of $\gtrsim 10^2$–10^3 in luminosity.

The spectra of the detected sources are shown in Fig. 1.

2.2. A SUPERSOFT SOURCE IN M3: A NEW KIND OF OBJECT?

Another new source was detected in the All-Sky Survey, which represents a new type of source in globular clusters. An extremely soft source, RX 1342.1+2822, was discovered in the globular cluster M3 = NGC 5272 during the Survey, and was also seen in pointed observations using the HRI. The spectrum of the source is extremely soft, with $kT \sim$ 30–80 eV and $L_X \sim 1.3\ 10^{35}\,\mathrm{erg\,s^{-1}}$ (Verbunt *et al.* 1994). Two separate HRI observations showed the source to vary by a factor of at least 40 in six months (Hertz *et al.* 1993). This cluster contained a dim source in the EINSTEIN survey, but because EINSTEIN had no spectral information, we cannot say whether this is the same source or not.

If the source is a white dwarf, however, it should be noted that the fitting of a model atmosphere spectrum may give rather different luminosities than the fitting of a black body (see the contribution by A. van Teeseling *et al.* to these proceedings).

The temperatures found by this spectral fitting are very similar to those of the new class of supersoft sources found in the Galaxy, in the Magellanic Clouds and in M31 with ROSAT (Hasinger 1994; P. Kahabka, these proceedings). However, supersoft sources have X-ray luminosities approaching the Eddington luminosity, $L_X \simeq 10^{37}$–$10^{38}\,\mathrm{erg\,s^{-1}}$, while the source in M3 is a factor of 10^2–10^3 fainter. Its relationship to the class of supersoft sources is unclear.

The extremely soft spectrum of RX 1342.1+2822 meant that it was detected only in channels 7–50 of the PSPC (see Fig. 1). Its detection in

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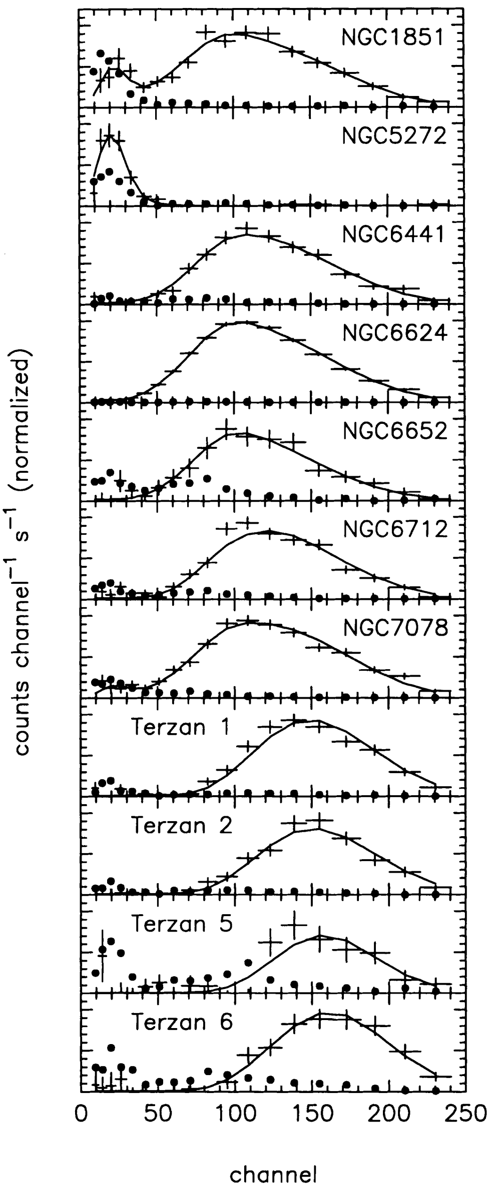

Figure 1. Spectra obtained with the XRT during the ROSAT All Sky Survey for eleven globular-cluster cores. The data have been binned in 19 energy intervals, where channel n corresponds roughly to $n \times 0.01$ keV. The source spectra are shown with crosses indicating horizontally the width of the energy bin and vertically the error, together with a spectral fit. The background spectrum is indicated with •. (From Verbunt *et al.* 1994).

M3 was only possible because of the extremely low reddening towards this cluster ($N_{\rm H} \sim 5.4\ 10^{19}\,{\rm cm}^{-2}$). This raises the question of how many similar sources may be hiding in other clusters. In only 16 other clusters would a 40 eV blackbody spectrum with bolometric luminosity $10^{35}\,{\rm erg\,s}^{-1}$ source have been detectable in the Survey; we can rule out the presence of such a source in 15 of these (Verbunt *et al.* 1994). Thus the total population of such sources is probably limited. However, several clusters could contain similarly soft sources at a lower luminosity; see Section 3.2.

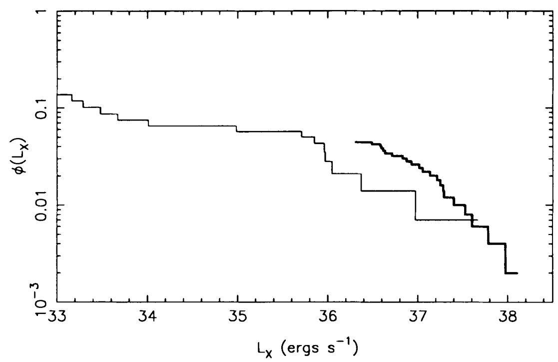

Figure 2. Cumulative luminosity function of globular-cluster X-ray sources in M31 (from Supper *et al.* 1995; thick line), and the Galaxy, (as described in Section 4 and Fig. 6; thin line). The curves represent the Kaplan-Meier estimator of the distribution. Increasing the number of upper limits shifts the curve vertically downwards. (After Supper 1994).

2.3. GLOBULAR CLUSTERS IN M31

ROSAT observed M31 in a 200 ks pointed PSPC observation in July 1991 (Supper 1994; Supper *et al.* 1995) with a sensitivity limit of $\sim 10^{36}$ erg s^{-1}, which, while a factor of ten deeper than that reached by EINSTEIN allows detection of only "bright" cluster sources, above the $10^{34.5}$–10^{36} erg s^{-1} gap. Eighteen sources had positions consistent with the position of a globular cluster (Supper *et al.* 1995).

Previous investigations had found significant differences between the luminosity function of globular-cluster X-ray sources in our Galaxy and in M31, suggesting that the sources in M31 were either more luminous or more numerous per cluster than in our Galaxy (see, e.g., figure 4 of Primini *et al.* 1993). The new ROSAT observations, combined with a new CCD program of detecting M31 globular clusters (Magnier 1994) reveal that at least part of the earlier discrepancy resulted from incompleteness in the catalogues of globular clusters. Fig. 2 shows the luminosity function derived from the M31 globular clusters compared with that of the Galaxy from ROSAT data (see Fig. 6). The Galactic luminosity function is still lower than that of M31.

3. Dim Globular-Cluster X-ray Sources

The study of the dim sources, with $L_X \lesssim 10^{34.5}$ erg s^{-1}, requires the use of pointed ROSAT observations. Only one dim core source was detected in the All-Sky Survey, the source in 47 Tuc, with $L_X = 5\ 10^{33}$ erg s^{-1}. The sky density of EINSTEIN dim sources that are not located in the cores of clusters indicates that they are probably not associated with the clusters (Verbunt *et al.* 1994); this has been confirmed by follow-up optical observations, which have identified several of the non-core sources as foreground dMe stars, quasars etc. (Grindlay 1994).

Pointed ROSAT observations, on the other hand, offer two important

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TABLE 1. Properties of dim X-ray sources in the cores of globular clusters. L_X in the band 0.5–2.5 keV is calculated assuming a blackbody spectrum using the best-fit temperature of the source (shown in column 5), where available, or a 3 keV thermal bremsstrahlung spectrum otherwise. The distance and reddening to the cluster are assumed, from Djorgovski (1993). The bolometric luminosity L_{bol}, assuming a 0.04 keV blackbody spectrum, is shown in column 4 for sources which are compatible with a spectrum this soft (including sources for which we have no spectral information). Luminosities of clusters containing multiple sources are those of individual sources.

Cluster	No. of sources	$\log L_X$ (erg s^{-1})	$\log L_{bol}$[a] (erg s^{-1})	kT_{bb} (keV)	Reference[b]
NGC 104 = 47 Tuc	5	32.6–33.1	-	0.6–1	H94, V94
Pal 2	1	33.9	38.2	-	R94
NGC 1904 = M79	1	33.7	34.0	-	HG83
NGC 5139 = ω Cen	2	32.0	-	0.6 ± 0.2	J94
NGC 5272 = M3	1	-	35.3	0.05	V94
NGC 5824	1	34.6	36.6	-	HG83
NGC 6304	1	33.0	36.0	-	R94
NGC 6341 = M92	1	32.5	32.6	< 0.3	J94
NGC 6397	5	31.2–31.8	33.2–33.8	< 0.1	C93, J94
NGC 6541	1	33.2	35.1	-	HG83
NGC 6626 = M28	1	32.8	36.1	< 0.3	J94
NGC 6656 = M22	1	30.9	-	$\gtrsim 0.3$[c]	J94
NGC 6752	3	31.6–32.1	-	0.35 ± 0.05	G93, J94
NGC 7099 = M30	1	32.7	33.5	< 0.2	J94

[a]For a 0.04 keV spectrum: see caption

[b]References: C93: Cool *et al.* 1993; G93: Grindlay 1993; H94: Hasinger *et al.* 1994; HG83: Hertz & Grindlay 1983; J94: Johnston *et al.* 1994; M94: Margon 1994; R94: Rappaport *et al.* 1994; V94: Verbunt *et al.* 1994.

[c]Spectral colours are not well represented by a blackbody.

elements for understanding the nature of the dim sources (not, unfortunately, both at the same time!): spatial resolution, particularly useful for determining the multiplicity of sources, and spectral resolution, which we can use to determine source temperatures. We now know of at least 25 dim sources in 14 clusters; Table 1 lists the known sources and their properties.

3.1. MULTIPLICITY OF SOURCES

The spatial resolution of ROSAT reveals that many of the sources in the cores of clusters are multiple. Sometimes this multiplicity is visible even in PSPC observations, which have spatial resolution of $\sim 25''$. PSPC observations of ω Cen and NGC 6752 showed the former to be double, with

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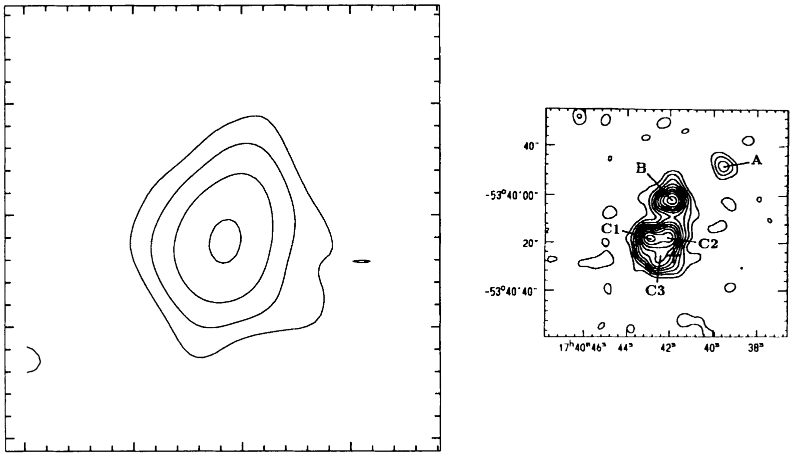

Figure 3. **Comparison between a PSPC and an HRI observation of the globular cluster NGC 6397. Both figures are on the same scale, showing the inner $\sim 3' \times 3'$ and $\sim 1\overset{'}{.}5 \times 1\overset{'}{.}5$ respectively. The former is from Johnston *et al.* 1994, and shows a hint of asymmetry in the contours; the latter is from Cool *et al.* 1993 and clearly shows the source resolved into at least three, probably five separate components.**

the fluxes of the two components approximately equal, while the latter is asymmetrical, suggesting a flux ratio of ~2:1 (Johnston *et al.* 1994).

However, the multiplicity of sources is better seen by far in HRI observations, with a spatial resolution of 5″. Fig. 3 shows a comparison between a PSPC observation and an HRI observation of NGC 6397, showing the enormously superior ability of the latter instrument to resolve sources.

So far, HRI observations of four clusters have revealed the X-ray emitting sources to be multiple: in NGC 6397 the core source is resolved into 3–5 sources (Cool *et al.* 1993); in 47 Tuc five separate sources have been seen in the core, plus four more close to the core (Hasinger *et al.* 1994); in NGC 6752 at least three sources are resolved (Grindlay 1993), and in NGC 6304 the core source appears to be extended (Rappaport *et al.* 1994). The same observations show evidence of significant variability: of four core sources in 47 Tuc seen in 1992, only two were visible in 1993, plus one new one, indicating variability of a factor of 5 or more (Hasinger *et al.* 1994).

3.2. SPECTRAL PROPERTIES

The ROSAT PSPC can give information on the spectra of the dim X-ray sources. The number of photons in each observation is low – typically less than 50 counts per source in an observation of several thousand seconds – but we can use the observed colours to constrain their spectra. The high column density towards globular clusters ($N_{\rm H} \sim 10^{21}\,{\rm cm}^{-2}$)

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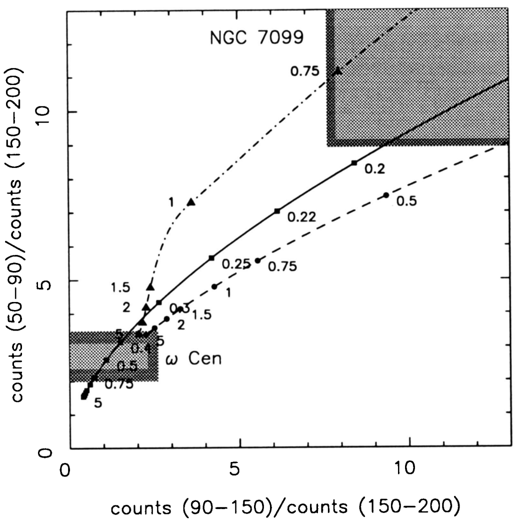

Figure 4. X-ray colour-colour diagram showing predicted colours for various spectral models. An absorption of $N_{\rm H} = 5\ 10^{20}\ {\rm cm}^{-2}$ was used. The observed colours for ω Cen ($N_{\rm H} = 9\ 10^{20}\ {\rm cm}^{-2}$) and NGC 7099 ($N_{\rm H} = 3.6\ 10^{20}\ {\rm cm}^{-2}$) are shown as shaded boxes (1σ error box with light shading, 2σ box with dark; where the box touches the edge of the graph it is a lower/upper limit to the true colour). Also plotted are three theoretical spectral models: blackbody (solid line), thermal bremsstrahlung (dashed line) and optically thin (dot-dashed line). The numbers next to points indicate the temperature in keV. (From Johnston *et al.* 1994).

means there are usually no counts in the lowest energy band. Thus we define three bands: a soft one, channels 50–90 (corresponding roughly to 0.5–0.9 keV), and two hard ones, channels 90–150 (0.9–1.5 keV) and 150–200 (1.5–2.0 keV). Comparison between the observed colours and various model predictions enables us to constrain the models. Fig. 4 shows the comparison between the observed colours and the colours of various spectral models as a function of temperature. It can be seen that the spectrum for NGC 7099 must be soft, with $kT \lesssim 0.2$ keV for a blackbody spectrum, $\lesssim 0.75$ keV for a bremsstrahlung or optically thin spectrum. For ω Cen, however, soft spectra are excluded: the observed colours predict temperatures of $kT = 0.6 \pm 0.2$ keV for a blackbody spectrum, $kT > 5$ keV for the other two spectra.

Performing this comparison for all sources observed shows that the spectra of the dim cluster sources are not all identical. Some, like NGC 7099, are soft, with $kT \lesssim 0.3$ keV. Observations of 47 Tuc show the core sources there to fall into this category (Verbunt *et al.* 1994; Margon 1994). As shown in Table 1, four sources have only upper limits to their temperature. Assuming a blackbody spectrum of 40 eV for these sources yields bolometric luminosities between $4\ 10^{32}\ {\rm erg\,s}^{-1}$ and $10^{36}\ {\rm erg\,s}^{-1}$. Thus several of these sources could be similar to the source in NGC 5272 (Section 2.2). Soft spectra can be excluded for three clusters: ω Cen, M22 and NGC 6752 (Johnston *et al.* 1994). For several sources (e.g., Pal 2), we have no spectral information; if these sources have spectra as soft as 40 eV, their bolometric luminosities could be as high as $2\ 10^{38}\ {\rm erg\,s}^{-1}$.

3.3. OPTICAL COUNTERPARTS OF DIM SOURCES

Having identified multiple sources in several clusters, it is natural to ask whether we can identify their counterparts at other wavelengths. However, here the limited positional accuracy of ROSAT hinders us; for the PSPC positions are accurate to $\sim 10''$, and for the HRI to $\sim 5''$. Since these sources are in the very crowded cores of globular clusters, the X-ray error circle can contain hundreds of stars in (for instance) an HST image. In cases where there is only one truly unusual object in a cluster, the identification can be regarded as fairly definite (e.g., the identification of an extremely bright UV source as 4U 1820–30 in NGC 6624 using HST observations; King *et al.* 1993). In cases where a proposed counterpart is less unusual, however, such as being a blue straggler or emission line object, the identification must remain more tentative (e.g., Paresce *et al.* 1992). Thus, positional coincidence of an unusual object with an X-ray error circle is not enough to prove it is a counterpart, especially when the error circle encompasses the whole core, as is the case for many of the clusters of interest. Since most of the unusual objects in a cluster are to be found in the core – pulsars, X-ray binaries, blue stragglers, etc. – we really require correlated variability or some such unambiguous signature at two wavelengths to prove association.

3.4. THE NATURE OF THE DIM SOURCES

The dim X-ray sources in clusters have luminosities down to a few times $10^{31}\,\mathrm{erg\,s^{-1}}$ in the ROSAT band (Table 1). We can now begin to answer the question: what is the nature of these sources? Their spectral colours indicate we may be dealing with more than one type of source (see Section 3.2). Their luminosities are an important clue. In Fig. 5 we plot the X-ray luminosities of the observed sources, together with the luminosities of some of the proposed counterparts for these objects. The X-ray luminosities of the faintest sources are now compatible with the luminosities of disk cataclysmic variables. The brightest ones are probably not. Nearly all disk cataclysmic variables have $L_\mathrm{X} < 10^{32}\,\mathrm{erg\,s^{-1}}$ (though some, e.g., GK Per, can be much brighter in outburst: Watson *et al.* 1985); thus if the brightest sources, with $L_\mathrm{X} \sim 10^{33.5}$–$10^{34}\,\mathrm{erg\,s^{-1}}$, are cataclysmic variables, there should be *large* numbers visible at other wavelengths, of order ten or more for every X-ray object. This is particularly true because the brightest X-ray source may very well not be the brightest optical or ultraviolet source; Van Teeseling & Verbunt (1994) showed that these quantities are essentially uncorrelated for a sample of disk cataclysmic variables. Any large number of X-ray quiet cataclysmic variables also compounds the optical ID problem in the large X-ray error circles.

The observed luminosities in the range $L_\mathrm{X} \sim 10^{32}$–$10^{33}\,\mathrm{erg\,s^{-1}}$ (Fig. 5)

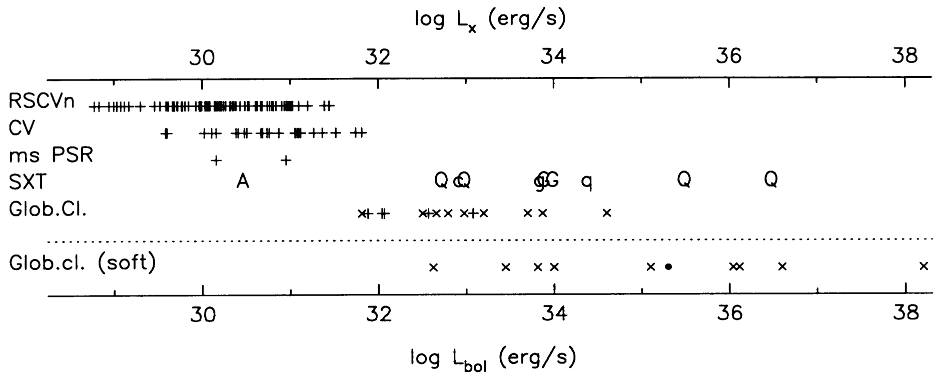

Figure 5. **Comparison of the luminosities of dim globular cluster X-ray sources with some of their proposed counterparts in the disk. In the upper part of the figure the X-ray luminosities L_X in the band 0.5–2.5 keV are plotted for RS CVn systems (from Dempsey *et al.* 1993), cataclysmic variables (from the ROSAT Survey), millisecond pulsars (Kulkarni *et al.* 1992, Fruchter *et al.* 1992), soft X-ray transients (F. Verbunt, these proceedings), and globular-cluster dim sources (Table 1). For the SXTs, different letters indicate indicate different sources, with upper case letters being ROSAT observations: A = A 0620–00, G = GS 2023+338, C = Cen X-4, Q = Aql X-1. For the cluster sources, the sources whose spectra could be extremely soft (Table 1) are indicated with a $\times$. For these sources, the bolometric luminosity assuming a spectrum of 0.04 keV is plotted in the lower part of the figure, with the source in NGC 5272 indicated with a $\bullet$. Note that the luminosities are much higher for a spectrum this soft.**

and the soft colours, $kT \sim 0.3$ keV, which are measured for at least some of the core sources (Table 1), look very much like those of soft X-ray transients. X-radiation from four soft X-ray transients, including two neutron star systems and two black-hole systems, has now been detected in quiescence (F. Verbunt, and H. Inoue, these proceedings).

4. The X-ray Luminosity Function

Combining pointed observations and ROSAT All-Sky Survey observations, both detections and upper limits, we can derive the underlying luminosity function of cluster X-ray cores. The Survey improved the upper limits on the X-ray luminosities of the cluster centers by one or two orders of magnitude for many clusters. ROSAT also discovered more and fainter dim sources, so we can improve the determination of the luminosity function significantly.

The result of a maximum-likelihood determination of the luminosity function, using both the flux measurements of detected sources and flux upper limits (Avni *et al.* 1980) is shown in Fig. 6. The double-peaked nature, with a distinct gap between bright and dim sources first seen by EINSTEIN and HEAO-1, is still visible, but is less significant. This is partly due to the different bandpass used by ROSAT.

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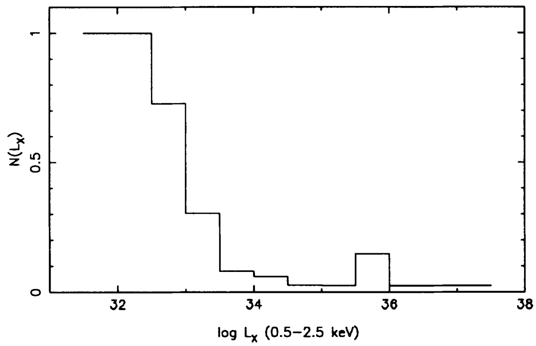

Figure 6. Maximum-likelihood estimate of the luminosity function of X-ray sources in globular clusters, using the method of Avni *et al.* 1980. The observational data used were detections and upper limits from the ROSAT All-Sky Survey as well as EINSTEIN and ROSAT pointed observations. (From Verbunt *et al.* 1994).

The luminosity function at low luminosities, $L_X \lesssim 10^{32.5}\,\mathrm{erg\,s^{-1}}$, is now much better constrained. In particular, the slope of the luminosity function is not rising as steeply at low luminosities as in previous determinations. Hertz & Grindlay (1983) using EINSTEIN data, and Hertz & Wood (1985), using HEAO-1 data combined with EINSTEIN data, had observed the luminosity function to rise steeply below $10^{34.5}\,\mathrm{erg\,s^{-1}}$. Hertz & Wood measured the slope below $10^{34.5}\,\mathrm{erg\,s^{-1}}$ to be -1.4 ± 0.7; we measure -0.67 ± 0.2. This implies that no more than two-thirds of all globular clusters contain X-ray sources with $L_X \gtrsim 10^{32}\,\mathrm{erg\,s^{-1}}$.

5. Conclusions

ROSAT has added greatly to our understanding of the population of X-ray sources in globular clusters, particularly as regards the dim X-ray sources. It has increased greatly the number of such sources known, so that we now know of nearly as many dim X-ray sources in globular clusters as we do millisecond pulsars (Lyne 1992). Several clusters contain multiple sources, some of which are variable. The spectral characteristics show that they cannot all be described by the same spectrum; some sources are very soft, with $kT \lesssim 0.3\,\mathrm{keV}$, while others are much harder. The luminosity function suggests that no more than two-thirds of all globular clusters contain X-ray sources with $L_X \gtrsim 10^{32}\,\mathrm{erg\,s^{-1}}$.

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Discussion

R.-D. Scholz: What is the angular distance of the ROSAT source in M3 from the cluster center?

H. Johnston: It is in the core.

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