X-ray sources in globular clusters

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**Summary.** We show that the bright \((L_x\approx 10^{36}\text{ erg s}^{-1})\) X-ray sources in globular clusters of our Galaxy are limited to luminosities \(L_x\leq 10^{37.3}\text{ erg s}^{-1}\), whereas the sources in the galactic disc range to \(\sim 10^{38.4}\text{ erg s}^{-1}\). The latter limit also applies to the globular-cluster sources of M31. We investigate two possible explanations for this difference, viz. a dependence of the mass-transfer rate \(\dot{M}\) on the secondary mass in low-mass X-ray binaries, and a dependence of \(\dot{M}\) on metallicity. The first explanation can only hold if \(\dot{M}\) increases by a factor \(\sim 5\) between secondary masses of \(\sim 0.8M_\odot\) and \(\sim 0.9M_\odot\). This steep increase is difficult to reconcile with the observed flatness of the X-ray luminosity distribution. Secondly, the observations of the globular clusters in M31 show that the mass-transfer rate does not depend strongly on the metallicity. Concerning the less luminous X-ray sources \((L_x<10^{34.5}\text{ erg s}^{-1})\) we argue that those with \(10^{33}\text{ erg s}^{-1}<L_x<10^{34.5}\text{ erg s}^{-1}\) are probably too bright to be cataclysmic variables. They may be confined to the cluster cores, and we propose that they are quiescent soft X-ray transients. The existence of a class of moderately bright quiescent soft X-ray transients would also explain that sources in this luminosity interval have been observed in the galactic bulge in the *Einstein* galactic survey.

1 **Introduction**

The X-ray binaries in globular clusters are different from those in the galactic plane in at least one respect: we think we know how they are formed. The number density of stars in globular clusters is so large that close encounters between neutron stars and main-sequence stars frequently lead to the formation of low-mass X-ray binaries, in which the main-sequence star transfers mass to the neutron star (Fabian, Pringle & Rees 1975; Clark 1975). The bulk of the energy liberated by the matter that falls into the deep gravitational potential well of the neutron star is emitted as X-rays. Hence the X-ray luminosity of these sources is a measure of the mass-transfer rate. By combining our knowledge of the binary formation processes with that about the age, mass segregation, initial mass function, etc., of a globular cluster we can study the theoretically expected distribution of

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secondary masses of globular-cluster X-ray sources in some detail. Comparison with the observed distribution of X-ray luminosities may then inform us about the mechanism that drives the evolution of these low-mass X-ray binaries.

Conflicting statements on the globular-cluster X-ray luminosity function have appeared in the literature. On the one hand it has been noted that the globular-cluster X-ray luminosities are significantly below that of the galactic bulge sources (Grindlay 1977, 1981; implicit in Van Speybroeck et al. 1979). On the other hand, it is claimed that the luminosity distributions of these two groups of sources are indistinguishable (Grindlay & Hertz 1984; Hertz & Grindlay 1983a, b).

Therefore, we start this paper with the derivation of the X-ray luminosity distribution of the bright X-ray sources in our Galaxy, both in the galactic plane and in the globular clusters. In Section 3 we discuss the effects of the upper limit to the mass of main-sequence stars in globular clusters, given by the turn-off mass, and of the globular cluster metallicities. We compare the X-ray sources in the galactic globular clusters with those in the galactic plane and in the globular clusters of M31. In Section 4 we consider the nature of the low-luminosity X-ray sources in globular clusters discovered by Hertz & Grindlay (1983a, b).

2 The luminosity distribution of globular cluster X-ray sources

2.1 Our Galaxy

In this section we derive the luminosity distribution of low-mass X-ray binaries, using the following methods for the determination of their distances:

(i) For globular clusters we use published distances based on optical studies of their HR diagrams.

(ii) For a number of sources we can use the observed properties of the companion star.

(iii) For the non-bursting bright galactic bulge sources with $|l| < 20^\circ$, which have not been optically identified, we assume a distance equal to that to the galactic centre (8.5 kpc; Oort 1977). For a reasonable error ($\pm 2.5$ kpc) in these distances the error in $\log L_x$ is $\sim 0.25$.

(iv) We have attempted to estimate distances to sources for which the ‘Sco X-1 type’ optical counterpart is known. As shown by van Paradijs (1981b, 1983) the absolute visual magnitudes $M_V$ of low-mass X-ray binaries cluster around $\sim 1.0$ within a fairly narrow range of $\pm 1.0$ mag (1 s.d.). However, we found that the straightforward application of a standard absolute visual magnitude for these systems leads to systematic errors in the distance estimates: the most luminous sources are apparently located at the largest distances, and also have a systematically larger distance to the galactic plane. We have, therefore, not utilized the results based on this method.

(v) Finally, for X-ray burst sources we use the ‘standard-candle’ idea that the average maximum burst luminosity is the same for all sources (see e.g. Lewin 1982; van Paradijs 1983, for a discussion of this assumption).

Before proceeding to the determination of the distances and X-ray luminosities we will first turn our attention to the value of the ‘standard-candle’ maximum X-ray burst luminosity. This discussion supersedes that given by van Paradijs (1981a).

2.2 Determination of Standard-Candle Value

The value $L_0$ of the average maximum luminosity of X-ray bursts can be determined, if we make the assumption that the X-ray burst sources (not located in globular clusters) are distributed symmetrically around the galactic centre. (This assumption is supported by their sky distribution, see Lewin et al. 1977).
### Table 1. Average maximum burst fluxes for burst sources not located in globular clusters.

<table>
<thead>
<tr>
<th>Source</th>
<th>$F_{\text{max}}$ (erg cm$^{-2}$s$^{-1}$)</th>
<th>N</th>
<th>ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0614+091?</td>
<td>3.5(-8)</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1455-315</td>
<td>1.0(-6)</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>1608-522</td>
<td>1.3(-7)</td>
<td>22</td>
<td>3</td>
</tr>
<tr>
<td>1636-536</td>
<td>3.9(-8)/3.4(-8)</td>
<td>9/43</td>
<td>4,5</td>
</tr>
<tr>
<td>1658-298</td>
<td>9.5(-9)</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>1702-429</td>
<td>4.2(-8)</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>1715-321</td>
<td>3.0(-8)</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>1735-444</td>
<td>1.9(-8)</td>
<td>47</td>
<td>4</td>
</tr>
<tr>
<td>1742-29</td>
<td>2.3(-8)/3.5(-8)</td>
<td>2/10</td>
<td>4,8</td>
</tr>
<tr>
<td>1743-28</td>
<td>1.5(-8)</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>1743-29</td>
<td>5.8(-8)</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>1744-265</td>
<td>5.0(-8)</td>
<td>13</td>
<td>8</td>
</tr>
<tr>
<td>1812-12</td>
<td>7.6(-8)</td>
<td>1</td>
<td>12</td>
</tr>
<tr>
<td>1813-140</td>
<td>1.0(-8)</td>
<td>2</td>
<td>9</td>
</tr>
<tr>
<td>1832-23</td>
<td>8.0(-9)</td>
<td>2</td>
<td>10</td>
</tr>
<tr>
<td>1837+049</td>
<td>1.9(-8)</td>
<td>33</td>
<td>4</td>
</tr>
<tr>
<td>1906+000</td>
<td>1.8(-8)</td>
<td>10</td>
<td>4</td>
</tr>
<tr>
<td>1908+005</td>
<td>1.0(-7)</td>
<td>2</td>
<td>11</td>
</tr>
<tr>
<td>1916-056</td>
<td>1.8(-8)</td>
<td>15</td>
<td>4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Source</th>
<th>$F_{\text{max}}$ (erg cm$^{-2}$s$^{-1}$)</th>
<th>N</th>
<th>distance (kpc)</th>
<th>ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0512-403/NGC 1851</td>
<td>1.2($\pm$0.8)</td>
<td>4</td>
<td>10.8$\pm$2.2</td>
<td>1, 7</td>
</tr>
<tr>
<td>1724-30/Ter 2</td>
<td>5.5($\pm$0.8)</td>
<td>2</td>
<td>10.5$\pm$3.5</td>
<td>2, 3, 8, 9</td>
</tr>
<tr>
<td>1728-337/GrHz 1</td>
<td>7.6($\pm$0.8)</td>
<td>29</td>
<td>8.5$\pm$2.0</td>
<td>1, 10</td>
</tr>
<tr>
<td>1730-335/Lil 1</td>
<td>2.7($\pm$0.8)</td>
<td></td>
<td>8.5$\pm$2.0</td>
<td>4, 11</td>
</tr>
<tr>
<td>1732-30/Ter 1</td>
<td>7.0($\pm$0.8)</td>
<td>2</td>
<td>8.5$\pm$2.0</td>
<td>5, 12</td>
</tr>
<tr>
<td>1745-24/Ter 5</td>
<td>4.0($\pm$0.8)</td>
<td>12</td>
<td>8.5$\pm$2.0</td>
<td>5, 12</td>
</tr>
<tr>
<td>1746-37/NGC 6441</td>
<td>5.0($\pm$0.9)</td>
<td>1</td>
<td>10.0$\pm$2.0</td>
<td>1, 13, 14, 15</td>
</tr>
<tr>
<td>1820-30/NGC 6624</td>
<td>1.1($\pm$0.7)</td>
<td>22</td>
<td>6.6$\pm$1.4</td>
<td>6, 14, 16, 17</td>
</tr>
<tr>
<td>1850-08/NGC 6712</td>
<td>5.2($\pm$0.8)</td>
<td>1</td>
<td>7.0$\pm$1.5</td>
<td>1, 14, 18</td>
</tr>
</tbody>
</table>

12. Adopted distance 8.5 kpc.

In Table 1 we have collected published data on average maximum X-ray burst fluxes. For each source the relative distance $d'$ (determined to within an arbitrary scaling constant) is given according to the standard-candle assumption by $d'=F_{\text{max}}^{1/2}$. Measuring $F_{\text{max}}$ in units of $10^{-8}$ erg cm$^{-2}$ s$^{-1}$ we find average values of $d'\sin l^{14}$ and $d'\cos l^{15}$ of 0.034$\pm$0.050 and 0.497$\pm$0.084, respectively, consistent with a spatial distribution symmetric around the galactic centre. Taking for the distance to the galactic centre a value of 8.5 kpc we thus find for $L_0$ a value of $3.5\pm1.0\times10^{38}$ erg s$^{-1}$.

We can derive an independent estimate of the standard-candle value using distance estimates for globular clusters that contain X-ray burst sources. The relevant data are collected in Table 2. For a number of globulars near the galactic centre region, for which the distance estimates are rather uncertain, we have assumed a distance equal to the galactic centre (8.5 kpc). From these data we find $L_0=4.0\pm0.9$ (m.e.)$\times10^{38}$ erg s$^{-1}$. (Note that we have not included the source in NGC 6441, since according to Li (1979) the two bursts from this source are probably not Type I bursts.)
The value of $L_\alpha$ we derive from the globular-cluster data does not differ significantly from that derived from the sources outside globular clusters. The present results, based upon a more extended database, confirm the conclusion reached previously (van Paradijs 1981a), that the average maximum luminosity of X-ray bursts is substantially larger than the Eddington limit of a 1.4 $M_\odot$ object.

In the following we have adopted for the standard candle a value of $3.7 \times 10^{38}$ erg s$^{-1}$.

2.3 LUMINOSITY DISTRIBUTION FOR DIFFERENT GROUPS OF LMXBs

In the derivation of the persistent X-ray luminosities $L_x$ of low-mass X-ray binaries we have used long-term average X-ray fluxes in the 2–10 keV range, as derived from the 4U, 3A and MX catalogues of X-ray sources (Forman et al. 1978; Warwick et al. 1981; McHardy et al. 1981; Markert et al. 1978). The 3A and MX catalogue directly give the average flux. For many sources the 4U catalogue gives the maximum observed flux and the ratio of maximum to minimum flux. For these sources we have taken the average value of the maximum and minimum 4U fluxes. The final average fluxes used are the straight average of these three catalogue values. They are given in Tables 3–6 for X-ray burst sources, globular-cluster X-ray sources, sources for which the secondary has been observed, and for 'galactic bulge' sources within 10° of the galactic plane and within a 20° galactic longitude interval from the direction of the galactic centre.

In Table 7 we have listed the average values, standard deviations and mean errors of the log $L_x$ distributions of these different groups of sources. Histograms of these distributions are shown in Fig. 1.

2.4 DISCUSSION

It is clear from the results presented in Table 7 and illustrated in Fig. 1 that:

1. For sources outside globular clusters the luminosity distributions (number of sources per unit interval in log $L_x$) based on three different methods to estimate distances, are indistinguishable.

<table>
<thead>
<tr>
<th>Source</th>
<th>$F_x$ (erg cm$^{-2}$s$^{-1}$)</th>
<th>d (kpc)</th>
<th>$\log L_x$ (erg s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1636–536</td>
<td>4.9(-9)</td>
<td>9.2</td>
<td>37.7</td>
</tr>
<tr>
<td>1702–429</td>
<td>1.1(-9)</td>
<td>8.6</td>
<td>37.0</td>
</tr>
<tr>
<td>1715–321</td>
<td>6.3(-10)</td>
<td>10.2</td>
<td>36.9</td>
</tr>
<tr>
<td>1735–444</td>
<td>3.6(-9)</td>
<td>12.8</td>
<td>37.8</td>
</tr>
<tr>
<td>1744–265</td>
<td>8.7(-9)</td>
<td>7.9</td>
<td>37.8</td>
</tr>
<tr>
<td>1812–12</td>
<td>4.3(-10)</td>
<td>6.4</td>
<td>36.3</td>
</tr>
<tr>
<td>1813–140</td>
<td>1.3(-8)</td>
<td>13.1</td>
<td>38.4</td>
</tr>
<tr>
<td>1831–237</td>
<td>1.9(-10)</td>
<td>19.7</td>
<td>36.9</td>
</tr>
<tr>
<td>1837+049</td>
<td>4.3(-9)</td>
<td>12.8</td>
<td>37.9</td>
</tr>
<tr>
<td>1906+000</td>
<td>5.5(-10)</td>
<td>13.1</td>
<td>37.1</td>
</tr>
</tbody>
</table>
Table 4. Persistent luminosities of X-ray sources in globular clusters.

<table>
<thead>
<tr>
<th>Source</th>
<th>$F_x$ (erg cm$^{-2}$s$^{-1}$)</th>
<th>d (kpc)</th>
<th>$\log L_x$ (erg s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0512-401</td>
<td>1.7(-10)</td>
<td>10.8</td>
<td>36.4</td>
</tr>
<tr>
<td>1724-307</td>
<td>4.0(-10)</td>
<td>10.5</td>
<td>36.7</td>
</tr>
<tr>
<td>1728-337</td>
<td>2.6(-9)</td>
<td>8.5</td>
<td>37.3</td>
</tr>
<tr>
<td>1732-303</td>
<td>4.0(-10)</td>
<td>8.5</td>
<td>36.5</td>
</tr>
<tr>
<td>1745-248</td>
<td>4.0(-10)</td>
<td>8.5</td>
<td>36.5</td>
</tr>
<tr>
<td>1746-370</td>
<td>8.2(-10)</td>
<td>10</td>
<td>37.0</td>
</tr>
<tr>
<td>1820-303</td>
<td>4.2(-9)</td>
<td>6.6</td>
<td>37.3</td>
</tr>
<tr>
<td>1850-087</td>
<td>1.5(-10)</td>
<td>7</td>
<td>36.0</td>
</tr>
<tr>
<td>2131+11</td>
<td>1.1(-10)</td>
<td>9.3</td>
<td>36.0</td>
</tr>
</tbody>
</table>

Table 5. Persistent luminosities of sources with individual distance.

<table>
<thead>
<tr>
<th>Source</th>
<th>$F_x$ (erg cm$^{-2}$s$^{-1}$)</th>
<th>d (kpc)</th>
<th>$\log L_x$ (erg s$^{-1}$)</th>
<th>remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>0921-630</td>
<td>5.5(-11)</td>
<td>7.6</td>
<td>35.6</td>
<td>1,5</td>
</tr>
<tr>
<td>1728-247</td>
<td>1.7(-9)</td>
<td>10.5</td>
<td>37.3</td>
<td>2</td>
</tr>
<tr>
<td>2030+407</td>
<td>4.3(-9)</td>
<td>10.0</td>
<td>37.7</td>
<td>3</td>
</tr>
<tr>
<td>2142+380</td>
<td>9.3(-9)</td>
<td>4.4</td>
<td>37.3</td>
<td>4</td>
</tr>
</tbody>
</table>

Remarks

1. Assumed 50% of visual brightness due to F-G III star, with $M_V$=+1.0
2. Distance from infrared colours (I.S.Laas, MNRAS 187,807) and $M_V$=−7.5
3. Distance based on $N_H$ estimate from radio observations
4. Contribution of F III companion to optical brightness 60%;
   $M_V$(F III)=-1; $V$=14.35; E(B-V)=0.35.
5. Not included in average of $\log L_x$, since X-ray source is probably
   occulted by an accretion disc (see van Paradijs, 1983).

Furthermore, the luminosity distribution for the three groups together is flat between
$\log L_x$~38.4 and ~37.0. The total dynamic range spanned by the distributions is more than two
orders of magnitude, much larger than the typical errors in the luminosity determinations of the
individual sources. Below $\log L_x$~37.0 the luminosity function decreases somewhat. For a source
located at the far side of the galactic centre (at ~13 kpc, say) the flux corresponding to $10^{37}$ ergs$^{-1}$
is ~$5\times10^{-10}$ erg cm$^{-2}$s$^{-1}$, which is comparable to the completeness limit in the galactic centre
region of the sky, which region is densely populated with very bright sources. This suggests that

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Table 6. Persistent luminosities of galactic bulge sources.

<table>
<thead>
<tr>
<th>Source</th>
<th>$\bar{F}_x$ (erg cm$^{-2}$ s$^{-1}$)</th>
<th>$\log L_x$ (erg s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1624-490</td>
<td>1.1(-9)</td>
<td>37.0</td>
</tr>
<tr>
<td>1642-455</td>
<td>9.1(-9)</td>
<td>37.9</td>
</tr>
<tr>
<td>1659-489</td>
<td>3.4(-9)</td>
<td>37.5</td>
</tr>
<tr>
<td>1702-363</td>
<td>1.4(-8)</td>
<td>38.1</td>
</tr>
<tr>
<td>1705-32</td>
<td>2.2(-10)</td>
<td>36.3</td>
</tr>
<tr>
<td>1705-440</td>
<td>3.4(-9)</td>
<td>37.5</td>
</tr>
<tr>
<td>1708-23</td>
<td>4.9(-10)</td>
<td>36.6</td>
</tr>
<tr>
<td>1715-39</td>
<td>3.9(-10)</td>
<td>36.5</td>
</tr>
<tr>
<td>1722-30</td>
<td>1.4(-10)</td>
<td>36.1</td>
</tr>
<tr>
<td>1728-169</td>
<td>5.4(-9)</td>
<td>37.7</td>
</tr>
<tr>
<td>1742-294</td>
<td>2.7(-9)</td>
<td>37.4</td>
</tr>
<tr>
<td>1755-33</td>
<td>1.4(-9)</td>
<td>37.1</td>
</tr>
<tr>
<td>1758-205</td>
<td>1.1(-8)</td>
<td>38.0</td>
</tr>
<tr>
<td>1758-250</td>
<td>2.2(-8)</td>
<td>38.3</td>
</tr>
<tr>
<td>1811-171</td>
<td>6.5(-9)</td>
<td>37.8</td>
</tr>
<tr>
<td>1813-14</td>
<td>1.4(-8)</td>
<td>38.1</td>
</tr>
<tr>
<td>1815-26</td>
<td>2.8(-10)</td>
<td>36.4</td>
</tr>
</tbody>
</table>

Table 7. Distributions of $\log L_x$.

<table>
<thead>
<tr>
<th>group</th>
<th>$&lt;\log L_x&gt;$ (erg s$^{-1}$)</th>
<th>standard deviation</th>
<th>mean error</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burst sources</td>
<td>37.33</td>
<td>0.63</td>
<td>0.19</td>
<td>11</td>
</tr>
<tr>
<td>Bulge sources</td>
<td>37.31</td>
<td>0.71</td>
<td>0.17</td>
<td>17</td>
</tr>
<tr>
<td>Total outside clusters:</td>
<td>37.33</td>
<td>0.64</td>
<td>0.11</td>
<td>31</td>
</tr>
<tr>
<td>Globular cluster sources</td>
<td>36.63</td>
<td>0.49</td>
<td>0.16</td>
<td>9</td>
</tr>
</tbody>
</table>

the observed decrease below $10^{37}$ erg s$^{-1}$ of the luminosity function is the effect of incompleteness of the surveys on which our luminosity functions are based.

2. No source with a long-term average luminosity in excess of $10^{37.3}$ erg s$^{-1}$ is located in a globular cluster, whereas 16 of the 31 sources outside clusters fall inside this high-luminosity end of the distribution. In view of the good agreement between the average peak luminosities of X-ray
bursts from sources inside and outside globular clusters (see above) it is very unlikely that this is
due to a systematic error in the distance estimates used. Further, it is highly unlikely that the
absence of X-ray sources with $\log L_x > 37.3$ is due to the fact that a significant number of bright
X-ray sources thought to be outside clusters are actually located inside heavily reddened and
hence as yet not detected globular clusters (Hertz & Grindlay 1983b; Isaacman & van Paradijs, in
preparation).

With a $\Delta$ of 16/31 the Kolmogorov–Smirnov test for the compatibility of two samples gives a
probability of <0.03 that the luminosity distribution of the globular cluster sources (Table 4) is
the same as that for all sources outside clusters (Tables 3+5+6). If the incompleteness at
$\log L_x < 37$ were more serious for the plane sources than for the cluster sources, the
Kolmogorov–Smirnov test would give a slightly higher probability, but not sufficiently higher to
affect our conclusion that the luminosity distributions are significantly different. More
specifically: the luminosity distribution of globular-cluster X-ray sources is probably cut off at a
luminosity level which is about an order of magnitude below that of the luminosity distribution of
the sources outside globular clusters.

2.5 Globular cluster X-ray sources in M31

With the Einstein observatory 19 X-ray sources have been detected in globular clusters of M31
(Van Speybroeck et al. 1979). Their X-ray luminosity distribution based on values given by Long
& Van Speybroeck (1983) is shown in Fig. 1. This distribution is markedly different from that of
the globular clusters in our Galaxy, in that it extends to much higher values (Van Speybroeck et al.
1979). The lower cut-off in the M31 luminosity distribution corresponds to the Einstein detection
limit.

It will be noted that the luminosity distribution of the M31 sources is based on one observation
in the 0.5–4.5keV band, in contrast to the other distributions, which are long-term averaged
luminosities based on the 2–10keV band.
3 Theory of X-ray sources in globular clusters

In this section we try to explain the different upper limits to the luminosity distributions for X-ray sources in the galactic plane, in the globular clusters of our Galaxy, and in those of M31. We assume that the bright X-ray sources in globular clusters, as well as those of Population II in the galactic plane, are binaries in which a neutron star accretes matter transferred from a low-mass Roche-lobe-filling companion [for a review of the developments leading to this view see Lewin & Joss (1983) and references therein]. It is presently not clear which mechanism drives the mass transfer in these systems, but magnetic braking of the rotation of the secondary is an attractive mechanism (Verbunt & Zwaan 1981). Another mechanism that has been proposed is the incipient expansion of a subgiant or giant companion star (Webbink, Rappaport & Savonije 1983). This mechanism can only explain a fraction of the observed bright X-ray sources, since many of the optical identifications and orbital periods exclude the presence of a giant in the system (cf. van Paradijs 1983).

A description of the evolution of a low-mass X-ray binary under the action of magnetic braking has been given by Rappaport, Verbunt & Joss (1983), for different possible braking laws. In all the calculations by these authors the mass-transfer rate is a monotonically increasing function of the mass of the secondary, or equivalently of the orbital period of the system. A correlation between mass-transfer rate and orbital period may have been observed in cataclysmic variables (Patterson 1984; but see Verbunt & Wade 1984), in which the mass transfer is thought to be driven by the same process as in low-mass X-ray binaries.

In view of the uncertainty of our theoretical and observational knowledge about the evolution of low-mass X-ray binaries we consider a correlation between mass-transfer rate and orbital period to be a reasonable hypothesis, rather than an established fact. In Section 3.2 we investigate whether this hypothesis can explain the observed upper limits to the X-ray luminosities.

In Section 3.3 we consider the possible importance of differences in metallicities on the mass transfer rates.

Before we start these discussions, however, we first summarize the relevant data about the clusters in M31. For the globular clusters in our own Galaxy we refer to the reviews by Harris & Racine (1979) and in Hanes & Madore (1981).

3.1 Globular Clusters in M31

One method to obtain information about the age and chemical content of the globular clusters of M31 is the investigation of their integrated colours. When plotted in a $U-B$, $B-V$ diagram the clusters in M31 follow a similar pattern to those in the galaxy (Van den Bergh 1969). A discussion of the $U-B$, $B-V$ plane in terms of age and metallicity has been given by Searle, Wilkinson & Bagnuolo (1980), who compare the LMC and galactic globular clusters. In the galaxy, unlike in the LMC, all the clusters are old (>$10^{10}$ yr) and range from metal rich to metal poor, with a corresponding spread in $U-B$ (metal rich corresponds to large $U-B$). Most clusters in M31 are also old, although a few `young' clusters (<$10^9$ yr) are known. The nature of any correlation between the age and metallicity of a cluster depends on the enrichment history of the galaxy.

Those clusters in M31 which contain X-ray sources and which have UBV measurements are plotted in Fig. 2. Three other X-ray clusters have $B-V$ colours but no $U-B$ colours. Their $B-V$ colours are all $\sim 0.93$ and thus place them in the region occupied by the galaxy clusters. From this coincidence we may conclude that the globular clusters in M31 are old. As the UBV colours depend on chemical composition as well as on the age of the cluster, and also on the enrichment history of the whole galaxy, small differences in age, of a few billion years, say, between the M31 globular clusters and those in our own Galaxy cannot be excluded.
The distribution of the metallicity of the globular clusters in M31 seems to be somewhat more tilted to higher metallicities than the one for the clusters in our own Galaxy (Van den Bergh 1969). Measurements of different metallicity indicators of globular clusters in M31, with special interest for those containing X-ray sources, have been reported by Huchra, Stauffer & van Speybroeck (1982).

3.2 MASS TRANSFER AND THE MASS OF THE SECONDARY

With the hypothesis that the mass-transfer rate in a low-mass X-ray binary is a monotonically increasing function of the mass of the Roche-lobe-filling secondary, one would expect an upper limit to the luminosity distribution if an upper limit to the mass range of the secondaries existed. Such a limit does apply in a globular cluster, and is given by the turn-off mass. Stars in the cluster with masses larger than the turn-off mass have evolved and passed the short-lived giant stage to become compact stars. Hence the mass of the secondary of a low-mass X-ray binary in a globular cluster must be smaller than or equal to the turn-off mass.

In principle, a further limitation to the mass of the secondary could arise from the formation process of X-ray binaries in a cluster through close encounters between neutron stars and single main-sequence stars (Fabian et al. 1975): in most clusters the least massive stars are the most numerous ones (Freeman 1977), and the formation rate of X-ray binaries through tidal capture is proportional to the number density of the main-sequence stars. One has to take into account, however, that virtually all close encounters are expected to occur in the dense core of the cluster, where the more massive stars are relatively well represented due to the mass segregation. Thus, in
the core of M3 main-sequence stars with mass close to the turn-off mass are more numerous than
less massive stars, even though their number in the whole cluster is very small (Gunn 1980; Gunn
& Griffin 1979). In addition, the capture cross-section for a single main-sequence increases with
its mass. In practice, therefore, the formation process of low-mass X-ray binaries in globular
clusters does not impose an upper limit to the secondary masses, lower than the turn-off mass.

If we try to explain the upper limit of the luminosity distribution for the galactic globular-cluster
sources, as shown in Fig. 1, with the upper limit to the mass of their secondaries given by the
turn-off mass, we run into the following problem. The globular clusters in our Galaxy have
turn-off masses of typically \(0.8M_\odot\) (cf. Freeman 1977; Gunn & Griffin 1979). The secondaries in
X-ray sources in the galactic disc cannot have masses much in excess of \(\sim 1M_\odot\). Furthermore,
since the difference in age between the clusters in M31 and those in our Galaxy is at most a few
billion years, the corresponding difference in turn-off mass cannot exceed \(0.1M_\odot\) (see the
evolutionary calculations of Ciardullo & Demarque (1977). For the effect of metallicity on the
turn-off mass see below.) None the less, both the sources in the galactic plane and those in the
globular clusters of M31 have much higher maximum luminosities. The mass-transfer rate would
have to be higher by a factor \(\sim 10\) for a secondary of \(1M_\odot\) and by a factor \(\sim 5\) for a secondary of
\(\sim 0.9M_\odot\) than at secondary mass \(0.8M_\odot\), if the difference between the luminosity distributions
were to be explained with the hypothesis that the mass-transfer rate in a low-mass X-ray binary is
a monotonically increasing function of the secondary mass.

Such a strong variation of \(\dot{M}\) with \(M_2\) is excluded by the flatness of the X-ray luminosity
distribution of both the sources inside and outside the globular clusters (Webbink et al. 1983;
Rappaport et al. 1983). For example, even in the hypothetical case that all low-mass X-ray
binarys are formed with a \(\sim 1M_\odot\) secondary and with the highest \(L_X\), a flat X-ray luminosity
distribution, in the sense that \(dN/(\log L_X)/d(\log L_X)\)=const., only follows if the mass-transfer rate
is proportional to the secondary mass, i.e. \(\dot{M} \propto M_2\). A steeper dependence of \(\dot{M}\) on \(M_2\), such as
mentioned above, would lead to a much greater preponderance of the low-luminosity sources
than is actually observed.

To circumvent this problem one could hypothesize the presence of a mass transfer mechanism
operating efficiently in systems with secondary masses \(M_2 \geq 0.8M_\odot\), but absent in systems with
\(M_2 \leq 0.8M_\odot\). An example of such a mechanism is the incipient expansion of the secondary star as
described by Webbink et al. (1983). As mentioned above this mechanism does not apply to all
bright sources. Thus it does not provide a full solution to the problem.

We conclude that it is unlikely that the difference in maximum luminosities attained by sources
in globular clusters of our Galaxy, of M31, and in the galactic plane can be explained as a result of
a difference in the masses of their secondaries.

### 3.3 Mass Transfer and Metallicity

The metallicity of a globular cluster may affect the mass-transfer rate of low-mass X-ray binaries
contained in it in two ways.

(i) At a given age for the globular cluster the metallicity may affect the turn-off mass.
Evolutionary calculations shows that this effect is very small. In the calculations of Ciardullo &
Demarque (1977) for \(Y=0.20\) and for \(Y=0.30\), for example, the difference in turn-off mass
between clusters with \(Z=0.0001\) and \(Z=0.01\) is smaller than \(0.05M_\odot\). Furthermore, as discussed
in Section 3.2, variations in turn-off mass of globular clusters cannot easily explain the observed
differences in X-ray luminosity functions.

(ii) The metallicity may affect the mechanism that drives the mass transfer. Whether this is an
important effect cannot at present be determined from the scanty theoretical understanding of
the evolution of low-mass X-ray binaries.
The observed metallicity parameters of globular clusters of our Galaxy (e.g. Zinn 1980) and of M31 shows that differences in the metallicity of globular clusters do not provide an explanation for the variation in their X-ray luminosities. As an indicator of the metallicity of the globular clusters of our Galaxy we use the parameter $[\text{Fe/H}]_{\text{Zinn}}$ (Zinn 1980). To compare the cluster sources of M31 with those in our Galaxy we approximate the relation between the Ca ii $K$ line strength and $(V-K)_0$ as given by Huchra et al. (1982) with the formula

$$\text{Ca ii } K = 10.0 + 5.6((V-K)_0 - 2.2)$$

and combine this with the relation (Frogel, Persson & Cohen 1980)

$$(V-K)_0 = 2.96 + 0.43[\text{Fe/H}]_{\text{Zinn}}$$

to find

$$\text{Ca ii } K = 14.38 + 2.2[\text{Fe/H}]_{\text{Zinn}}.$$  

In Fig. 3 we show the X-ray luminosity of the globular clusters in M31 and those in our Galaxy as a function of $[\text{Fe/H}]_{\text{Zinn}}$. The bright X-ray clusters of M31 span the full range of metallicity. We conclude that the high luminosity of the M31 globular-cluster X-ray sources cannot be explained in terms of a higher metallicity.

3.4 DISCUSSION

The absence of long-term averaged bright X-ray sources in the globular clusters of our Galaxy cannot be explained well with theories of binary evolution in which the mass transfer depends on
the secondary mass only, nor with a difference in metallicity. Both conclusions have been reached by investigation of the globular-cluster sources in M31, under the assumption that the luminosity distribution as derived from a single observation in the 0.5–4.5 keV band is not too different from the long-term averaged distribution based on 2–10 keV band observations. New X-ray observations of the M31 clusters will reveal whether this assumption is correct.

4 The low-luminosity X-ray sources in globular clusters

Hertz & Grindlay (1983a, b) have discovered an interesting class of low-luminosity X-ray sources in the globular clusters in our Galaxy. They identify these sources as cataclysmic variables. Indeed, if the formation of low-mass X-ray binaries in globular clusters occurs through capture processes, one predicts the formation of many cataclysmic variables too: for every collision of a cluster main sequence star with a neutron star there are many collisions with white dwarfs, as white dwarfs are more abundant than neutron stars (Hut & Verbunt 1983).

The X-ray luminosity of the dim Einstein sources is high compared to those of cataclysmic variables in the plane, however: few cataclysmic variables in the plane have X-ray luminosities in excess of $10^{32}$ erg s$^{-1}$ (see the review of Cordova & Mason 1983), whereas the low-luminosity cluster sources have luminosities up to $10^{34.5}$ erg s$^{-1}$. If these sources are indeed cataclysmic variables, we are thus confronted with the surprising situation that the low-mass X-ray binaries in globular clusters are systematically less bright than the ones in the galactic plane, whereas for the cataclysmic variables the reverse is true.

Hertz & Grindlay (1983a, b) conclude that a higher X-ray luminosity limit for cataclysmic variables in globular clusters is expected, based on the following arguments.

1. They interpret the factor $\sim 10^5$ difference between the maximum X-ray luminosity of the bright and the dim globular-cluster X-ray sources as being due to a ratio of $\sim 10^7$ between the radii of white dwarfs and neutron stars at a comparable accretion rate.

2. They argue that the maximum luminosity for the dim globular-cluster sources ($L_x \approx 10^{34.5}$ erg s$^{-1}$) is consistent with that observed for the cataclysmic variables in the galactic plane ($L_x \approx 10^{33}$ erg s$^{-1}$ – Cordova & Mason 1983), and due to the fact that the number of cataclysmic variables sampled in the globular-cluster observations is much higher than that of those sampled in the galactic plane, in conjunction with the X-ray luminosity function for cataclysmic variables, which is described as a power law with index $\alpha = 1.2$.

With regard to the first argument we note that it does not take into account that the bulk of the energy emitted by cataclysmic variables is not emitted in the X-ray region as in low-mass X-ray binaries, but at lower energies (cf. van Paradijs & Verbunt 1984). Indeed, observations of cataclysmic variables in the galactic plane have shown that systems with accretion rates much higher than those of the brightest globular cluster X-ray sources, viz. with $\log \dot{M} (M_{\odot} \text{yr}^{-1}) > -8$, have X-ray luminosities $< 10^{33}$ erg s$^{-1}$.

With regard to the second argument we note that the luminosity distribution used in it is derived from all dim globular cluster X-ray sources. Therefore this argument shows that it is not surprising that no sources with $10^{33}$ erg s$^{-1} < L_x < 10^{34.5}$ erg s$^{-1}$ have been observed in the galactic disc, and holds irrespective of whether these sources are cataclysmic variables or not. Although this argument shows that the interpretation of the dim sources by Hertz & Grindlay is consistent, it cannot be used to establish the nature of the brightest dim sources.

As already mentioned by Hertz & Grindlay (1983b), the dim globular cluster sources may not be a pure sample of white-dwarf binaries. We show that there are reasons to believe that such an impurity is especially important for the dim sources with $L_x > 10^{33}$ erg s$^{-1}$. This undermines the derivation of the cataclysmic-variable luminosity function by Hertz & Grindlay.
In Fig. 4 we have plotted the X-ray luminosities \( L_x \) of all globular cluster sources with a well-determined position as a function of their radial distance \( r \) to the cluster centre in units of the core radius \( r_c \). The values of \( L_x \) and \( r/r_c \) are taken from Hertz & Grindlay (1983a). The sources with \( \log L_x>36 \) are the bright low-mass X-ray binaries. Because of the relatively high mass of the neutron star (\( \sim 1.4M_\odot \)) compared to that of the average cluster member (\( \sim 0.35M_\odot \)) these binaries are confined to the core of the cluster, i.e. \( r/r_c \leq 2 \) (Grindlay 1981).

The sources fainter than \( 10^{33}\text{ ergs}^{-1} \) are distributed more or less uniformly as a function of \( r/r_c \). Of the four sources brighter than \( 10^{33}\text{ ergs}^{-1} \) three have a positional error box completely in the core (\( r/r_c \leq 2 \)). The fourth one has a large error box, covering the complete core and a small region outside it (\( r/r_c \leq 4 \)). In analogy with the bright globular-cluster X-ray sources the location in the centre of the four dim sources with \( L_x>10^{33}\text{ ergs}^{-1} \) indicates that the compact star has a mass \( \geq 1M_\odot \). We discuss three possibilities for the nature of these brightest dim sources.

First, they could be cataclysmic variables with a massive white dwarf. Their high luminosity would then be caused by the small radius of a white dwarf close to the Chandrasekhar limit rather than by the high mass-transfer rate. Although this possibility cannot be excluded, we consider it rather unlikely, as none such very bright cataclysmic variable is known in the galactic plane. In particular we note that the X-ray luminosity of SS Cyg, a dwarf nova with a white dwarf of \( \sim 1.3M_\odot \) (Stover et al. 1980), does not exceed \( 10^{33}\text{ ergs}^{-1} \) even at outburst peak (Cordova & Mason 1983).

Secondly, they could be persistent low-mass X-ray sources that seem to have a low-luminosity because they are observed by us at high inclination, so that the neutron star is shielded from us by the accretion disc. In that case they would be similar to sources in the disc as 0921–63, 1822–37 and 2129+47 (see van Paradijs 1983, and references therein). Although it is conceivable that one of the four brightest dim sources is of this nature, it is statistically rather unlikely that all four of them are.

Thirdly, they could be transient low-mass X-ray sources, observed at quiescence. The analogy between soft X-ray transients and dwarf novae makes it likely that soft X-ray transients have a non-zero mass-transfer rate at quiescence (van Paradijs & Verbunt 1984). Therefore, one expects the presence of soft X-ray transients in their quiescent state in the core of globular clusters. One soft X-ray transient has possibly been detected in quiescence, with a luminosity \( L_x=10^{32.8}\text{ ergs}^{-1} \), and is actually located in a globular cluster (Hertz & Grindlay 1983b). For the other soft X-ray transients only lower limits to the ratio between peak luminosity (of \( \sim 10^{38}\text{ ergs}^{-1} \)) and quiescent luminosity are known. These lower limits are compatible with quiescent
luminosities for many of them between $10^{32}$ and $10^{34}$ erg s$^{-1}$. We conclude that the four brightest dim sources may well be quiescent soft X-ray transients.

Additional support for this interpretation comes from the discovery in the Einstein galactic plane survey of a number of sources with similar luminosities $L_x=10^{34}$ erg s$^{-1}$ (Hertz & Grindlay 1984). These sources are interpreted by their discoverers as bright cataclysmic variables. The concentration of these sources towards the galactic bulge (Hertz & Grindlay 1984), however, would be well explained if these sources were soft X-ray transients too: low-mass X-ray binaries are well known to be concentrated towards the galactic bulge.

We conclude that the most likely interpretation for the brightest dim globular cluster X-ray sources is that they are soft X-ray transients. The possibility that these sources are bright cataclysmic variables cannot be excluded yet, however. One could for example explain the extreme brightness of cataclysmic variables both in globular clusters and in the galactic bulge with the ad hoc hypothesis that cataclysmic variables of Population II are brighter than their Population I counterparts.

In this respect the source with $L_x=10^{34.3}$ erg s$^{-1}$ discovered by Hertz & Grindlay (1983a, b) near the globular cluster NGC5824 is crucial. The position of this source is based on an uncertain identification of a 2a HRI source with an IPC source. If our reasoning is correct, the correct position of the IPC source should be in the cluster core, or otherwise the source should not be a cluster member. If the HRI position for the IPC source is correct, we note that this source has the largest distance (in arseconds) to its cluster centre of all globular cluster sources, and that it is the brightest of the dim sources (see Fig. 4). The fact that this source is extreme in both these respects justifies some suspicion as to its cluster membership. We urge a further investigation of this source.

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