X-ray sources in globular clusters of other galaxies

Walter H.G. Lewin* and Frank Verbunt†

*Massachusetts Institute of Technology, Physics Department Center for Space Research, MA 02139, USA
†Astronomical Institute, Postbox 80.000, 3508 TA Utrecht, the Netherlands

Abstract. A large number of X-ray sources in globular clusters of galaxies other than the Milky Way has been found with Chandra. We discuss three issues relating to these sources. The X-ray luminosity function (XLF) of the sources in globular clusters of M31 is marginally compatible with the XLF of globular clusters of the Milky Way. The individual XLFs of a dozen elliptical galaxies, after correction for incompleteness, are compatible with one another and show no break; however, the XLF found by adding the individual XLFs of elliptical galaxies has a break at $L_x \approx 5 \times 10^{38}$ erg s$^{-1}$. For the moment there is no evidence for a difference between the XLFs of sources inside and outside globular clusters of elliptical galaxies. It is not (yet?) possible to decide which fraction of low-mass X-ray binaries in elliptical galaxies outside globular clusters have formed inside globular clusters.

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INTRODUCTION

Observations with Chandra of an increasing number of nearby galaxies are revealing a sizable population of bright X-ray sources, many of which are in globular clusters. In elliptical galaxies, as many as half of all bright X-ray sources are in globular clusters; in spiral galaxies a smaller fraction of the bright sources is in globular clusters. The absence of recent star formation in elliptical galaxies implies that the X-ray sources in them are mainly low-mass X-ray binaries. Some questions that have arisen from early research are whether globular clusters do contain black holes? and whether the sources in elliptical galaxies outside globular clusters originate in globular clusters?

Elliptical galaxies are a good target for the study of X-ray sources in globular clusters, because many have 5000 to 10000 globular clusters. The central galaxy of the Virgo cluster, M 87, has 13500 globular clusters! The X-ray sources detected so far in the faraway galaxies are of necessity very bright, typically $L_x > 5 \times 10^{37}$ erg s$^{-1}$. Early studies indicate that about 4% of the globular clusters contains an X-ray source above this limit, roughly corresponding to 1 source per $5 \times 10^6 L_{\odot}$ (Sarazin et al. 2003, Kundu et al. 2003).

We have given an overview of the early papers on this topic in Verbunt & Lewin (2005). Comparison between studies is difficult, as they have different detection limits and compute X-ray luminosities in different energy bands based on different assumed spectra. The study of Kim & Fabbiano (2004) remedies this, and provides a first consistent comparison between a fair number (14) of different elliptical galaxies; we discuss
this important study in Sect. 3. In Sect. 2 we compare the X-ray luminosities of globular clusters in our galaxy and in the Andromea nebula. In Sect. 4 we discuss the question whether sources outside globular clusters can have formed inside them.

GLOBULAR CLUSTERS IN THE MILKY WAY AND IN M31: DIFFERENT OR THE SAME?

The Andromeda Nebula, a.k.a. M 31, was found with Einstein to have rather more bright X-ray sources in globular clusters than our Milky Way (Van Speybroeck et al. 1979). Since this discovery it has been debated whether this simply reflects the larger number of globular clusters of M 31, or an X-ray luminosity function with a higher fraction of bright sources in M 31 (e.g. Verbunt et al. 1984). The debate continued in the ROSAT and Chandra era (Magnier et al. 1992, Supper et al. 1997, Di Stefano et al. 2002). In Figure 1 we show the cumulative X-ray luminosity functions for globular clusters of our Milky Way and of M 31. A 2-sided Kolmogorov-Smirnov test gives a probability of 3% that both distributions are the same. Thus, the evidence that the luminosity functions are intrinsically different is at the 2-sigma level: suggestive, but not conclusive.

The X-ray luminosity functions of the globular clusters in M 31, and the bulge in M 31 (Kong et al. 2002, 2003) are both roughly compatible with the X-ray luminosity function of elliptical galaxies (see next Section), an indication that the X-ray sources in all these old stellar populations are similar. (With a population of eight persistent sources and 5 transients, the globular cluster system of our galaxy has too few bright X-ray sources to...
X-RAY LUMINOSITY FUNCTIONS OF GLOBULAR CLUSTER SYSTEMS OF ELLIPTICAL GALAXIES

Kim & Fabbiano (2003) investigated the incompleteness at the low-luminosity end of the X-ray luminosity function of the elliptical galaxy NGC 1316, and showed that the apparent break in the XLF disappears when appropriate corrections are made. They then investigated XLFs of 13 more elliptical galaxies, and showed that none of these shows a significant break after correction (Kim & Fabbiano 2004, see also Gilfanov 2004). The elliptical galaxies comprise 7 galaxies of the Virgo cluster (at 17 Mpc), 2 of the Fornax cluster (19.9 Mpc), and 5 others (between 11 and 29 Mpc). The effects leading to incomplete detection efficiency at low X-ray luminosities are

- the presence of diffuse emission of the hot interstellar medium in E and S0 galaxies
- the Eddington bias, enhancing the number of sources near the detection threshold
- source confusion
- the larger point-spread function near the detector edge

The X-ray luminosities are determined in the energy range 0.3-8.0 keV; and sources are counted outside the innermost region of each galaxy \((r > 20''\) but within the 25 mag isophote. Corrections for the source numbers and total X-ray luminosity of the galaxy are made on the assumption that they scale as the optical luminosity, i.e. with \(r^{1/4}\); this affects the normalization, but not the slope of the luminosity function. It should be noted that Kim & Fabbiano (2003, 2004) do not discriminate between sources within and outside globular clusters, and give the XLFs of all sources related to elliptical galaxies. They find that the XLF of every individual elliptical galaxy is compatible with a power law \(N(L_x) \propto L_x^{-\beta}\), with \(\beta = 2.0 \pm 0.2\). The variation between the \(\beta\)-values of different ellipticals can be ascribed to small-number statistics. In studies of individual elliptical galaxies it is found that the XLF for sources in globular clusters is the same as the XLF for sources outside globular clusters (Maccarone et al. 2003, Sarazin et al. 2003, Jordán et al. 2004, see Fig. 1). Thus, we may take the overall XLF as a proxy for the XLF of the globular cluster sources.

Since the individual X-ray luminosity functions appear to be the same, they can be added. The added XLF, at luminosities in the 0.3-8.0 keV band \(L_x > 6 \times 10^{37}\) erg s\(^{-1}\), of all 14 elliptical galaxies is marginally compatible with a single power law with \(\beta = 2.1 \pm 0.1\). A broken power law gives a somewhat better fit, and is shown in Figure 2. The best-fit break luminosity is \((5.6 \pm 1.6) \times 10^{38}\) erg s\(^{-1}\), and the values for \(\beta\) at lower and higher luminosities are 1.8\(\pm\)0.2 and 2.8\(\pm\)0.6, respectively. Remarkably, the break is at about the flux where the luminosity function of AGNs and quasars also shows a break. Whereas background sources typically comprise about 5% of the sources within the 25 mag isophote, they are unlikely to cause the break in the added XLF of the elliptical galaxies, which has been corrected for the background sources (Kim & Fabbiano 2004).

The break is at a luminosity which is about twice the Eddington limit for hydrogen-rich material, and comparable to the Eddington limit for hydrogen-poor material (see
FIGURE 2. Left: total corrected number of sources in 14 elliptical galaxies as a function of X-ray luminosity in the 0.3-8.0 keV range. Right: corrected total X-ray luminosity of elliptical galaxies as a function of their absolute K-band magnitude $M_K$. The total X-ray luminosity is computed from the corrected X-ray luminosity function, extrapolated downwards to $L_x = 10^{37}$ erg s$^{-1}$. The size of the symbols scales with the number of globular clusters per unit luminosity of the galaxy $S_N$. • indicates a galaxy for which $S_N$ is not known. (After Kim & Fabbiano 2004.)

also Kuulkers et al. 2003). From their high X-ray luminosity and soft X-ray spectrum, it has been argued that the sources above the break are accreting black holes (e.g. Angelini et al. 2001). As regards the sources below the break, Bildsten & Deloye (2004) note that the assumption that most very luminous X-ray sources are ultracompact binaries, in which the donor star is a hydrogen-depleted degenerate star, explains the location of the break at the Eddington limit of hydrogen-poor material, the high X-ray luminosities, the source incidence (or birth rate), and the X-ray luminosity function. The model does not explain why sources outside globular clusters, which are less likely to be ultracompact binaries (if our own Milky Way is a guide), have the same X-ray luminosity function. This brings us to the question whether sources outside globular clusters could have formed inside them.

OUTSIDE AND INSIDE GLOBULAR CLUSTERS

In elliptical galaxies it is found that the spatial distribution of X-ray sources outside globular clusters is similar to the spatial distribution of globular cluster X-ray sources (e.g. Jordán et al. 2004 for M 87). Similarly, the X-ray luminosity functions of globular cluster sources and other sources are very similar (Fig. I). This has led to the revival of a suggestion by Grindlay & Hertz (1985) that all low-mass X-ray binaries, including those now outside globular clusters, were formed inside globular clusters (White et al. 2002).

In the Milky Way and in M 31 there are about 10 bright low-mass X-ray binaries in the disk for each one in a globular cluster. In elliptical galaxies, there is about 1 source outside globular clusters for each one in them. This suggests that the majority of low-
mass X-ray binaries in the disk of the Milky Way, M31 and by generalization in spiral galaxies are formed in the disk, and not in globular clusters (Verbunt & Lewin 2005). It should be noted that we cannot compare fractions inside and outside globular clusters for the Milky Way and M31 on one hand and elliptical galaxies at the other hand at the same luminosities, because there are very few X-ray sources in the Milky Way and M31 above $L_x \sim 5 \times 10^{37}$ erg s$^{-1}$, which is the lower limit of detectable sources in ellipticals (see Fig. 1).

The total X-ray luminosity of low-mass X-ray sources in elliptical galaxies scales with the luminosity (hence presumably stellar mass) of the elliptical galaxy (Figure 2). This is expected for sources formed outside globular clusters. It is also expected if the sources are mainly formed in globular clusters, because the number of globular clusters is on average higher in large elliptical galaxies than in small ones. Correlations of the total X-ray luminosity have been made with the specific frequency $S_N$ of globular clusters (i.e. the total number of globular clusters divided by the luminosity of the galaxy). We refer to this here as the "global" specific frequency which includes all globular clusters in the entire galaxy. These correlations greatly suffer from a serious problem related to our lack of knowledge of the global $S_N$. Reliable values for the number of globular clusters, in general, come from HST-WFPC2 with a very small (5.7 square arc minutes) field of view. This provides only a reliable local value for $S_N$ but not the global value (see the discussion in Section 8.3 of Verbunt & Lewin 2005).

Kim & Fabbiano (2004) note that the correlation between the total X-ray luminosity (of low-mass X-ray sources) and the infrared luminosity of elliptical galaxies has a scatter which is larger than the measurement accuracy. In Fig. 2 we indicate the elliptical galaxies with a large $S_N$ with a large symbol. We see that the elliptical galaxies brighter in X-rays than the average correlation indeed have a tendency to have a higher $S_N$. This indicates that globular cluster sources contribute significantly to the total X-ray luminosity of the galaxy; to argue that sources outside globular clusters originate inside globular clusters, one would have to show that the total X-ray luminosity (or better, number) of the sources outside globular clusters separately scales with specific frequency $S_N$. In the sample of galaxies studied by Kim & Fabbiano (2004) there is no correlation between $M_K$ and $S_N$ (see Fig. 2).

**CONCLUSIONS AND OUTLOOK**

The conclusions drawn above, i.e. that the X-ray luminosity function of the X-ray sources in old populations is universal and has a break at $L_x \sim 5 \times 10^{38}$ erg s$^{-1}$, are based on a study which does not discriminate between sources inside and outside globular clusters. With the increasingly large sample of sources it is possible and necessary to repeat this study for the globular cluster sources separately. This may also help in addressing the question which fraction of the sources outside globular clusters were actually formed inside them. The location of the break suggests that the sources above the break are accreting black holes. The sources below the break may be dominated by ultracompact sources (Bildsten & Deloye 2004).

There are two important areas of further study not discussed above. The first is the question why clusters with a high metallicity have a higher probability of containing
FIGURE 3. The number of neutron stars per solar mass formed from an initial mass distribution $N(m) \propto m^{-\alpha}$ as a function of the index $\alpha$. The initial range of stellar masses is taken to be from 0.08 to 80 $M_\odot$, and of neutron-star progenitors from 8 to 80 $M_\odot$. The solid curve is normalized on the initial mass of the cluster, the dashed curve on the current luminous mass, assuming that stars from 0.8 to 8 $M_\odot$ have evolved into white dwarfs.

Jordán et al. (2004) discuss the number of neutron stars per unit of initial mass of the cluster, i.e., they take $m_b = m_2$. This ratio, for values $m_a = 0.08$, $m_b = m_2 = 80$ and $m_1 = 8$, is shown as a solid line in Fig. 3 as a function of $\alpha$. If $\alpha$ is lower at higher metallicity, i.e., metal-rich clusters have a shallower initial mass function, then metal-rich clusters have a relatively higher number of neutron stars. We may add that this effect is even stronger if we scale not on the initial mass, but on the current luminous mass, i.e., the stars that determine the observed $K$ magnitude. Eq. 1 for $m_2 = 80$ as before, but with $m_b = 0.8$, is shown in Fig. 3 as a dashed line. (Stars in the range $0.8 < m < 8$ have evolved into white dwarfs.) This deserves further study, in particular whether the required dependence of the slope of the IMF on metallicity can be more firmly established.

The second research area is the indication that the probability for a globular cluster to contain an X-ray source increases slower with density than the number of collisions an X-ray source, even if the number of collisions in them is the same. An interesting calculation by Jordán et al. (2004) shows that a moderate dependence on metallicity of the slope of the Initial Mass Function leads to a difference in the numbers of neutron stars in metal-rich and metal-poor clusters (per unit mass) which is large enough to explain the observed preference for high-metallicity clusters (see Fig. 3). Briefly, if we write the number of stars at mass $m \equiv M/M_\odot$ as $N(m) = Km^{-\alpha}$, we have for the number of stars with initial mass between $m_1$ and $m_2$ (that have evolved into neutron stars) per unit mass between $m_a$ and $m_b$:

$$
\frac{N(m_1, m_2)}{M(m_a, m_b)(M_\odot)} = \frac{2 - \alpha}{1 - \alpha} \frac{m_1^{1-\alpha} - m_2^{1-\alpha}}{m_a^{2-\alpha} - m_b^{2-\alpha}}
$$

(1)

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The second research area is the indication that the probability for a globular cluster to contain an X-ray source increases slower with density than the number of collisions
occurring in the cluster (Jordán et al. 2004). The models for formation and evolution of X-ray sources in globular clusters must address these questions.

REFERENCES

1. Angelini, L., Loewenstein, M., and Mushotzky, R., 2001, ApJ 557, L35
2. Bildsten, L. and Deloye, C., 2004, ApJ 607, L119
3. di Stefano, R., Kong, A., Garcia, M., and et al., 2002, ApJ 570, 618
4. Gilfanov, M., 2004, MNRAS 349, 146
5. Grindlay, J. and Hertz, P., 1985, in D. Lamb and J. Patterson (eds.), Cataclysmic Variables and Low Mass X-ray Binaries, pp 79–91, Reidel, Dordrecht
6. Jordán, A., Côté, P., and Ferrarese, L. e. a., 2004, ApJ 613, 279
7. Kim, D.-W. and Fabbiano, G., 2003, ApJ 586, 826
8. Kim, D.-W. and Fabbiano, G., 2004, ApJ 611, 846
9. Kong, A., Di Stefano, R., Garcia, M., and Greiner, J., 2003, ApJ 585, 298
10. Kong, A., Garcia, M., Primini, F., and et al., 2002, ApJ 577, 738
11. Kundu, A., Maccarone, T., Zepf, S., and Puzia, T., 2003, ApJ 589, L81
12. Kuulkers, E., den Hartog, P., in ’t Zand, J., Verbunt, F., Harris, W., and Cocchi, M., 2003, A&A 399, 663
13. Maccarone, T., Kundu, A., and Zepf, S., 2003, ApJ 586, 814
14. Magnier, E., Lewin, W., van Paradijs, J., and et al., 1992, A&AS 96, 379
15. Sarazin, C., Kundu, A., Irwin, J., and et al., 2003, ApJ 595, 743
16. Supper, R., Hasinger, G., Pietsch, W., and et al., 1997, ApJ 317, 328
17. van Speybroeck, L., Epstein, A., Forman, W., Giacconi, R., Jones, C., Liller, W., and Smarr, L., 1979, ApJ 234, L45
18. Verbunt, F., Bunk, W., Hasinger, G., and Johnston, H., 1995, A&A 300, 732
19. Verbunt, F. and Lewin, W., 2005, in W. Lewin and M. van der Klis (eds.), Compact stellar X-ray sources, p. in press, Cambridge University Press
20. Verbunt, F., van Paradijs, J., and Elson, R., 1984, MNRAS 210, 899
21. White, N., Sarazin, C., and Kulkarni, S., 2002, ApJ 571, L23