COMPARISON OF X-RAY SOURCES
IN OLD OPEN AND IN GLOBULAR CLUSTERS

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Abstract. Twelve bright ($L_x \gtrsim 10^{36}$erg/s) X-ray sources have been detected in globular clusters: they are accreting neutron stars. Five of these are transients. Thirty less luminous sources have been detected in eighteen globular clusters. The luminosity function of these sources does not rise rapidly towards lower luminosities. The sources with $L_x \sim 10^{33}$ erg/s are probably transients in their low state; the least luminous sources currently detected may be cataclysmic variables. The old open cluster M 67 harbours chromospherically active binaries, with $L_x \sim 10^{30-31}$erg/s. Globular clusters contain fewer of these binaries than estimated by scaling with mass from M 67.

1. Introduction

X-ray sources in globular clusters are amongst the brightest in the sky, and were discovered with the earliest X-ray instruments. The more recent highly sensitive X-ray satellites Einstein and, in particular, Rosat enable the study of less luminous sources in globular clusters. Such less luminous sources have also been discovered in old open clusters.

In this review I describe these sources, the bright X-ray sources in globular clusters in Section 2, and the less luminous sources in old open and globular clusters in Sections 3 and 4, respectively. In Section 5 the X-ray sources in old open and in globular clusters are compared.

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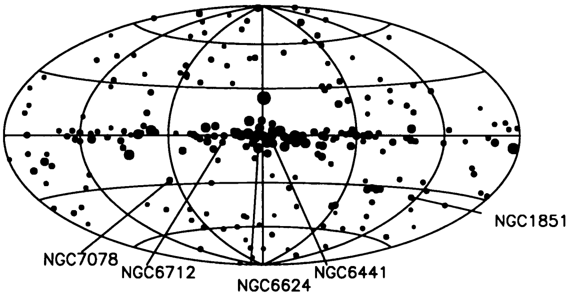

Figure 1. Distribution over the sky of the X-ray sources contained in the third catalogue of the Ariel V satellite (McHardy et al. 1981). The size of the symbols indicates the flux of the X-ray sources. The central horizontal line is the Galactic Plane, with the Galactic Center in the middle. The sources are clearly concentrated towards the Galactic Center. Amongst the sources in our Galaxy, five can be identified with globular clusters.

2. Bright sources in globular clusters

Figure 1 shows the distribution in the sky of the brightest X-ray sources, as detected with the early X-ray satellite Ariel V. These sources are clearly concentrated towards the Galactic Plane, and in this plane, towards the Galactic Centre. Amongst the $\sim$ 200 sources detected by Ariel V near the Galactic Plane, five can be identified with globular clusters.

The bright X-ray sources in globular clusters, with luminosities $L_x(2-10\,\mathrm{keV}) \gtrsim 10^{36}$erg/s, are low-mass X-ray binaries, in which a neutron star accretes matter from a low-mass companion star and emits the liberated energy as X-rays. Pointed Einstein and Rosat observations have discovered a bright X-ray source in some thirty globular clusters of M 31 (Trinchieri and Fabbiano 1991; Magnier 1994). The high incidence in globular clusters of X-ray binaries is ascribed to the occurrence in their dense cores of formation processes of such binaries that do not operate in the Galactic Disk, viz. tidal capture of a neutron star by a passing main-sequence star (Fabian et al. 1975, see also Mardling these proceedings) or an encounter between a binary and a neutron star, in which the neutron star takes the place of one of the binary stars in an exchange encounter (Hills 1976).

Following the discovery with UHURU of six X-ray sources in globular clusters, six more have been found with later satellites; the most recent additions were detected in the Rosat All Sky Survey, in NGC 6652 and in Terzan 6 (Verbunt et al. 1995). The source in NGC 6652 was detected already with the HEAO-1 satellite, but the positional accurracy was insufficient for identification with the cluster (Hertz and Wood 1985). The source in Terzan 6 was not detected with HEAO-1, which indicates that it must have been much brighter in 1991 than a decade before. Comparison between the observations of the cluster sources obtained with various satellites show that at least five of them have been at luminosities below the detection limits of the early satellites, i.e. at $L_x(2 - 10\,\text{keV}) \lesssim 10^{35.5}$erg/s at one time or other. Such sources are called transients.

All well-studied bright X-ray sources in globular clusters have shown X-ray bursts, which proves that they are accreting neutron stars, rather than black holes. Low-mass X-ray binaries with neutron stars have spectral energy distributions characterized by blackbody (X-ray colour) temperatures $\lesssim 5\,\text{keV}$. This is true also for the sources in globular clusters.

A source of a new class, which emits photons mainly at energies $\lesssim$ 0.5 keV has been detected in the Rosat All Sky Survey in NGC 5272. The nature of this source is not clear. For an assumed black-body temperature of 40 eV the bolometric luminosity during the Survey was $\sim 10^{35}$ erg/s (Verbunt et al. 1995). Repeated observations with the Rosat High Resolution Imager (HRI) show that this source is variable by at least a factor 30 (Hertz et al. 1993).

Rosat HRI positions show that all bright X-ray sources are in or close to the core of the globular cluster (Johnston et al. 1995a).

3. Dim sources in old open clusters

Rapidly rotating stars with convective envelopes have active chromospheres and emit X-rays. As they age, such stars lose their rapid rotation, and with it their chromospheric activity. As a consequence, relatively young clusters are usually selected for the study of stellar X-ray emission (e.g. Pye et al. 1994, Stern et al. 1993). If a star is tidally locked in a short-period binary, however, it may remain in rapid rotation even as it ages.

In a Rosat observation of M 67, an open cluster with an age of $\sim$ 5 Gyr, a fair number of X-ray sources have been detected, and from their optical identifications it appears that most of these are indeed binaries (Figure 2). Because tidal forces on convective stars circularize a binary on a time scale given by $e/\dot{e} \propto (a/R)^8$, where a is the semi-major axis, and R the radius of the star (Zahn 1966), one expects short-period binaries with large, bright stars to be circularized and thus to be magnetically active X-ray sources. The brightest X-ray sources in M 67 are indicated in Figure 2 with nos. 4, 7, 8, 10 and 13 and have X-ray luminosities in the 0.5-2.5 keV bandpass of 5.5, 4, 8, 3.5 and 3 $\times 10^{30}$ erg/s, respectively. Of these, only X4, the blue straggler, is not known to be a binary. For X7, the radial velocity is known to vary, but the orbital period has not yet been determined. X8 was suggested by Belloni et al. (1993) to be a binary in the stage of mass-transfer. The eccentricity of its orbit appears to exclude this model, unless

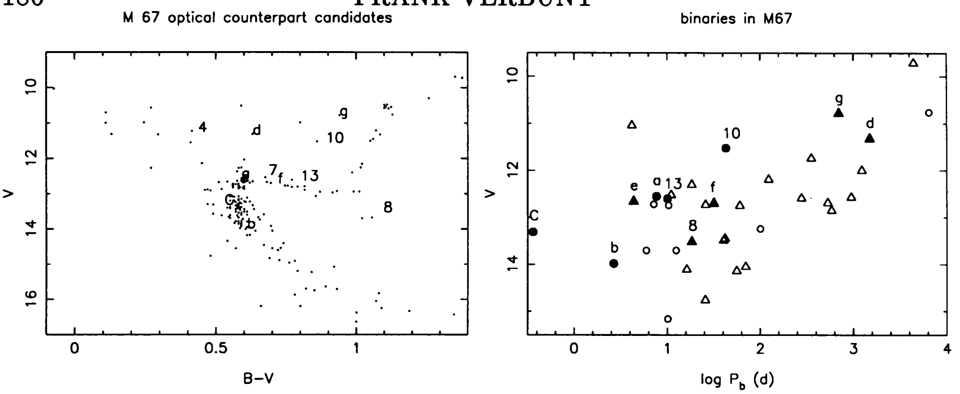

Figure 2. Left: Hertzsprung-Russell diagram of the old open cluster M 67. Optical counterparts of the X-ray sources are indicated with numbers for detections in a first observation (Belloni et al. 1993), and with letters for new detections in a longer, more recent observation (Belloni et al., in preparation); these include a contact binary (C). Right: Visual magnitude as a function of orbital period for known binaries in M 67 (data from Latham et al. 1992). Circles indicate binaries with (almost) zero eccentricity, triangles binaries with eccentric orbits. Filled symbols indicate binaries detected in X-rays.

the observed eccentricity is the consequence of distortion of the spectral lines by contribution of the gas stream.

It has been shown that eccentric orbits of short-period binaries and circular orbits of long-period binaries in open clusters can be understood if the dependence of the circularization time scale of the stellar radius R is taken into account (Verbunt and Phinney 1995). Many of the X-ray-active binaries in M 67 have circular orbits, as expected, including the contact binary AH Cnc; a few of the least luminous sources, however, have eccentric long-period orbits (Figure 2). This is contrary to expectation, and we currently do not understand why these binaries are X-ray sources.

Two of the sources in M 67 have very soft X-ray spectra. One of these is a magnetic cataclysmic variable (Gilliland et al. 1991), for which the observation of M 67 was originally intended; the other one has been identified with a single hot white dwarf (Pasquini et al. 1994). In general, the X-ray luminosities of the chromospherically active binaries in the old open clusters M 67 and NGC 752 (with an age of ~ 2 Gyr) appear to be in agreement with those of similar binaries in the Galactic Disk (Belloni and Verbunt 1995). The total X-ray luminosity of M 67 is about 3×10^{31} erg/s.

4. Low-luminosity sources in globular clusters

Observations with the Rosat High Resolution Imager (HRI) have resolved the core of several globular clusters and shown that they contain multiple sources. Examples are NGC 6397 and NGC 6752 (Cool et al. 1993, Grindlay 1993). A total of some 30 dim sources, either single or multiple, have

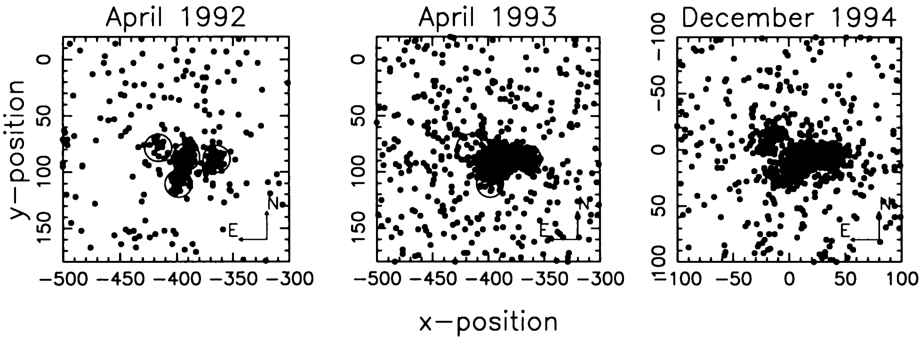

Figure 3. Photons in the inner 100 × 100 arcsec area of 47 Tuc detected in three ROSAT HRI observations showing the variability of the sources. To guide the eye, circles in the left two frames encircle photons of the four sources detected in the first observation.

now been detected in or near the the cores of 18 globular clusters, with luminosities in the range of $10^{31} - 10^{34}$erg/s (Johnston and Verbunt 1996).

Repeated observations of the core of 47 Tuc show that the dim sources are highly variable: of the four sources detected in April 1992, only two are detected again in April 1993 together with a new source (Hasinger et al. 1994). One of the disappeared sources had reappeared when a third observation was obtained, in December 1994 (Figure 3). The absolute positional accuracy of the ROSAT HRI is about 5 arcsec; this precludes certain identification of any of the ROSAT sources with either the single X-ray source detected in 47 Tuc with the Einstein satellite (Hertz and Grindlay 1983) or with the ultraviolet variables detected with HST (Paresce et al. 1992, Paresce and DeMarchi 1994).

The accurate imaging of the ROSAT HRI allows subtraction from the image of the point sources. When this is done, a remaining extended emission is found in 47 Tuc, presumably due to unresolved, fainter point sources. The total luminosity of the extended emission is small, about 10^{33}erg/s, similar to the luminosities of individually detected sources, $L_x = 0.5 - 1.6 \times 10^{33}$erg/s. ROSAT PSPC observations of ten clusters with large apparent cores find marginal evidence of extended emission in only two, viz. NGC 6254 and NGC 6352 (Johnston et al. 1996).

The ROSAT PSPC provides some information about the energy distribution of the X-ray photons. The sources in some clusters, e.g. ω Cen, have spectra that may be characterized with black body colour temperatures of $\gtrsim 0.5$ keV; those in others, e.g. 47 Tuc, have slightly softer spectra, of ~ 0.2 keV. For yet other sources only an upper limit to the colour temperature is obtained, and it cannot be excluded that these sources are as soft as the source in NGC 5272 (Johnston et al. 1994, Verbunt et al. 1995).

The X-ray luminosities of the dim sources in globular cluster cores pro-

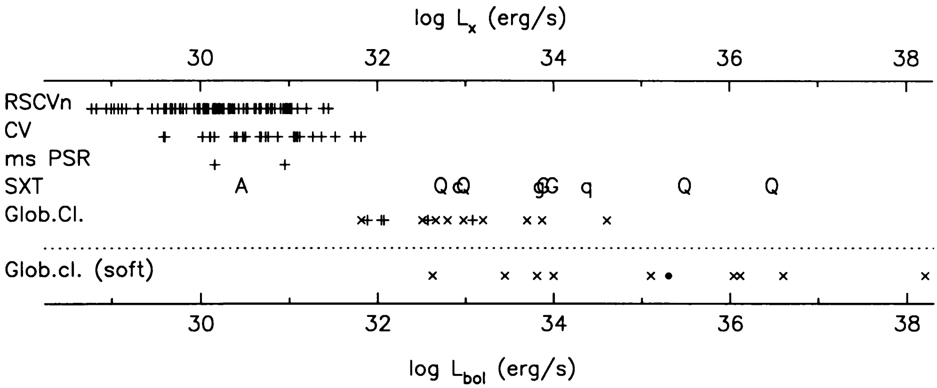

Figure 4. Luminosity distributions (L_x between 0.5 - 2.5 keV) for chromospherically active binaries (RS CVn), cataclysmic variables, recycled radio pulsars (msec PSR), and soft X-ray transients (SXT) in the Galactic Disk, compared with the luminosity of the dim sources in globular clusters. Cluster sources marked with $\times$ only have upper limits to their X-ray colour temperature; their X-ray luminosity is shown for an assumed bremsstrahlung spectrum with $kT \sim 3$ keV, and their bolometric luminosity for an assumed blackbody with $kT = 40$ eV. (From Johnston et al. 1995b.)

vide a first clue to their identity. In Figure 4 we compare the luminosities of soft X-ray transients, recycled radio pulsars, cataclysmic variables, and chromospherically active close binaries (RS CVn systems), all detected in the Galactic Disk, and thus securely identified, with those of the dim sources in globular clusters. It is seen that only the soft X-ray transients cover the same luminosity range as the dim cluster sources.

A few words of caution are in place here. First, we know now that some sources previously detected as single sources are in fact multiple, and obviously the individual luminosities are smaller. This has been taken into account as far as possible in making Figure 4, but some sources may still be multiples. Second, the luminosity distributions of the cataclysmic variables and recycled pulsars in the Galactic Disk are incomplete. For many cataclysmic variables the distances are unknown; it is quite possible that some of them are faraway, luminous sources. The two recycled pulsars in the plot have relatively low rotational-energy loss-rates; it may well be that more rapidly rotating pulsars with larger period derivatives also have higher X-ray luminosities. It has, in fact, been plausibly suggested that the dim source in M 28 is the radio pulsar PSR 1821-24 in that cluster (Danner et al. 1994).

The luminosity distribution of cataclysmic variables in the Galactic Disk overlaps with lower end of the luminosity distribution of the dim X-ray sources in globular clusters. In NGC 6752, three dim X-ray sources have been optically identified with the Hubble Space Telescope, on the basis

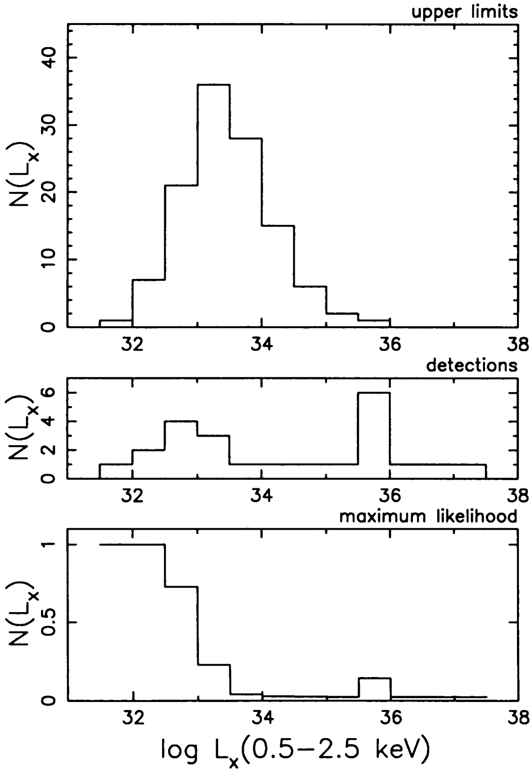

Figure 5. Luminosity distributions of X-ray sources in globular clusters obtained by combining Einstein and Rosat data. Top: upper limits. Middle: detected sources. Below: Maximum likelihood distribution derived from upper two graphs. After Verbunt et al. (1995).

of their H α emission (Cool et al. 1995). Their spectra, also obtained with HST, are very similar to one another, and to those of cataclysmic variables. They are also rather similar to optical spectra of soft X-ray transients in quiescence ... (Grindlay et al. 1995). For the moment, it appears reasonable to conclude that the dim X-ray sources in globular clusters with $L_\mathrm{x} \gtrsim 10^{33}$erg/s are probably soft X-ray transients in their low state. After all, we know that X-ray transients exist in globular clusters (as discussed in Section 2). The least luminous sources currently detected, such as those in NGC 6397 and NGC 6752, may well be cataclysmic variables.

With the growing number of dim sources detected in the cores of globular clusters, we can start drawing conclusions about their luminosity function. First, the ROSAT All Sky Survey has put stringent upper limits to the integrated X-ray luminosities of many globular cluster cores. More specifically, most globular cluster cores do not contain single or multiple sources with X-ray luminosities totalling more than 10^{33}erg/s. Combination of the upper limits with the known detections gives a maximum likelihood luminosity distribution

$$dN(L_\mathrm{x}) = N_o {L_\mathrm{x}}^{-\alpha} d\ln L_\mathrm{x} \tag{1}$$

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with $\alpha \sim 0.7$ (see Figure 5). Second, from the observation that the extended emission due to unresolved point sources is less that that of individually detected sources, we derive that $\alpha < 1$.

A more sophisticated analysis may be made on the basis of the distribution of the detected luminosities with respect to the detection limits. In a flat luminosity distribution, i.e. equal numbers of sources in logarithmic luminosity intervals, we expect a homogeneous distribution of sources above the detection limit; in a skewed distribution in which most sources have low luminosities, most sources will be detected close to the detection limit. The analysis of the luminosity distribution of the dim X-ray sources in 11 globular clusters indicates $\alpha \simeq 0.5$. This value for α is compatible with the luminosity distributions in 47 Tuc and NGC 6752 (Johnston and Verbunt 1996).

The constant N_o in Eq. 1 is proportional to the formation rate of dim X-ray sources in globular clusters. If such sources are formed by two-body encounters in the cluster core, their formation rate should be proportional to $\rho_c^2 r_c^3$, where ρ_c and r_c are the number density of stars in the cluster core, and the core radius, respectively (Verbunt and Hut 1986). More generally, one can write $N_o \propto \rho_c r_c^3 \rho_c^\gamma \propto M_c \rho_c^\gamma$ where M_c is the mass of the core. Comparison of the collision numbers $M_c \rho_c^\gamma$ for various values of γ with the distribution of the dim X-ray sources over the clusters indicates that $\gamma \simeq 0.5$ (Johnston and Verbunt 1996). A similar value of γ has been found for the recycled pulsars in globular clusters (Johnston et al. 1992).

5. Old open clusters compared with globular clusters

Dim X-ray sources occur both in globular clusters and in old open clusters. The dim X-ray sources in old open clusters are binaries. The four brightest sources in M 67 are binaries with orbital periods that are sufficiently short that one expects such a binary to survive in a globular cluster (Figure 2). Naively, one may expect that the number of such chromospherically active close binaries in a globular cluster would scale with the mass of the cluster. As the mass of a typical globular cluster is more than a thousand times the mass of M 67, one would predict a number of chromospherically active binaries in the globular clusters more than a thousand times that in M 67, and thus an integrated X-ray luminosity in excess of $10^3 \times 3 \times 10^{31}$ erg/s. As shown in Figure 5, the ROSAT All Sky Survey puts an upper limit to the X-ray luminosity of the majority of globular clusters well below this predicted value.

As possible explanations for this surprising result, one may argue 1) that the binaries detected as X-ray sources in M 67 are *not* ordinary chromospheric binaries, or 2) that open clusters have lost a larger fraction of

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their initial mass than globular clusters, or 3) that binaries are less frequent in globular clusters than in open clusters. At the moment, we do not know which of these possibilities, if any, is the correct answer.

As an aside I would like to point out that there are probably rather many old open clusters in our Galaxy, quite possibly as many as globular clusters. After all, several of the oldest open clusters, like M 67 and NGC 188 are fairly close to the Sun, at 750 pc and 1500 pc, respectively, which suggests that many such clusters may exist at larger distances from the Sun. This relates to the question whether the formation of clusters has been continuous since the formation of our Galaxy, or alternatively that an initial period of formation of globular clusters ended well before the subsequent formation of open galactic clusters. If many old open clusters in our Galaxy exist, some of them may have masses rather larger than those of M 67 and NGC 188. If so, the suggestion by Mardling (these proceedings) that the low-mass X-ray binaries in the Galactic Disk were formed in open clusters gains in plausibility.

6. Summary and Conclusions

X-ray sources have been found both in globular clusters and in old open clusters. The bright sources in globular clusters are accreting neutron stars. A source with an extremely soft spectrum, highly variable, was detected in NGC 5272; the nature of this source is not known.

Most dim sources in open clusters are close, chromospherically active binaries, in which stars co-rotate with the orbit. Surprisingly, some very wide binaries, with eccentric orbits, have now also been detected as X-ray sources.

Dim X-ray sources in globular clusters are multiple and variable. After subtraction of the individually detected sources, little extended emission remains, and the total X-ray luminosity of a globular cluster is dominated by the brightest sources in it. The X-ray luminosity function of globular cluster sources may be written

$$dN(L_{\rm x}) \propto M_c \rho_c^{0.5} {L_{\rm x}}^{-0.5} d\ln L_{\rm x} \tag{2}$$

Some of the dim sources, especially the relatively luminous ones with $L_{\rm x} \gtrsim 10^{33}$erg/s, are probably soft X-ray transients in their low state, i.e. neutron stars accreting at low rates. Others, especially the fainter ones with $L_{\rm x} \lesssim 10^{32}$erg/s, may be cataclysmic variables.

Globular clusters in general have X-ray luminosities which are smaller than one would predict by multiplying the X-ray luminosity of M 67 with the ratio of the mass of a globular cluster to that of M 67. This indicates that chromospherically active binaries are relatively less frequent in globular clusters than in M 67.

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