X-ray sources in old stellar clusters: the contribution of ROSAT

Frank Verbunt
Astronomical Institute, Postbox 80 000, 3508 TA Utrecht, the Netherlands (verbunt@phys.uu.nl)

Abstract. Two new bright X-ray sources in globular clusters, and many less luminous ones in globular clusters and in old open clusters, have been discovered with ROSAT. Accurate positions obtained with ROSAT help identification with optical objects, which however is still very incomplete in globular clusters. One dim globular cluster source has been identified with a recycled radio pulsar; several others may be cataclysmic variables. The four brightest X-ray sources identified in the old open cluster M 67 are puzzling, as we do not understand why they emit X-rays. In comparison with the two old open clusters studied so far, globular clusters are remarkably underluminous in X-rays.

0. First

I am grateful to the organizers of this meeting for the opportunity to contribute to this celebration of the 65th birthday of Joachim Trümp. During my years (1985-1989) at the Max Planck Institut für extraterrestrische Physik, I have always felt very much at home, as if an 'honorary German', and I thank Joachim and my other colleagues for this. I was impressed with the width and depth of Joachim Trümp's interests, and thoroughly enjoyed my many discussions with him.

The deadline for the first Announcement of Opportunity for observing with ROSAT was on a Sunday evening, at midnight (in checking the date, I find it was on my birthday!). Joachim Trümp was in his office that night, to sign proposals until just before the deadline, or almost, as 11 copies needed to be made for submission. Some of the proposals he signed that night contributed to the results discussed in this review.

1. Introduction

Two types of stellar clusters are commonly discriminated. Globular clusters are distributed spherically around the Galactic Center, have metal abundances $\lesssim 0.1$ of the solar abundances, contain each up to $10^6 - 10^7$ stars, and are very old (in danger in fact of being older than the Universe...), $11.5 \pm 1.5$ Gyr (Chaboyer et al. 1998). Open or galactic clusters are located in the disk of the Milky Way, have metallicities comparable to solar, contain each some $10^3 - 10^4$ stars, and in age range from very young ($\sim$Myr) to fairly old $\lesssim 6$ Gyr). Open clusters have been found only relatively nearby, and it is quite possible that open clusters exist with star numbers and ages closer to those of globular clusters.

The study of clusters with different ages has taught us much about the evolution of single stars; with large numbers of binaries now being detected in clusters we may hope to learn much also about the evolution of binaries. There is an interesting interplay between the evolution of a cluster as a whole and the evolution of the individual stars in it (as reviewed by Hut et al. 1992). For example, sudden mass loss by many of the stars (e.g. due to supernovae in a very young cluster) can dissolve the cluster. Close encounters between single stars and binaries can increase the velocity dispersion of the stars in the cluster. And finally, collisions between stars or exchange encounters (in which a single star kicks a binary star out of its orbit and takes its place) can lead to peculiar stars and binaries that could not arise from isolated (binary) evolution.

The high stellar density in globular clusters implies that encounters between stars in them are common; the lower density in open clusters imply that such encounters are less frequent there, although they may have occurred more often in the past. In this article I will illustrate how X-ray observations with ROSAT contribute to the study of and comparison between binaries in globular clusters and in old open clusters. X-ray emission identifies stars which are, or have been, interacting with other stars. Followup studies at optical and ultraviolet wavelengths may explain the nature of the interaction.

In Sect. 2 I discuss the observations of globular clusters and the detection of bright and of less luminous X-ray sources in them. 47 Tuc and NGC 6397 are discussed as examples of efforts to optically identify dim X-ray sources in the cores of globular clusters. In Sect. 3 I discuss the discovery of X-ray sources in the old open clusters M 67 and NGC 188, and of followup observational and theoretical work. Sect. 4 summarizes the conclusions.
2. Globular clusters

2.1. Bright X-ray sources

Since the discovery of the first bright ($L_x \gtrsim 10^{36}\text{erg/s}$) X-ray sources in globular clusters with UHURU, twelve such sources have been found, five of which are transients (see the review by Hut et al. 1992). An X-ray source at these luminosities must be a neutron star or a black hole accreting from a binary companion. X-ray bursts due to thermonuclear fusion on the surface of a neutron star have been detected in ten cluster sources, the last one with SAX (in’t Zand et al. 1998b). Binary periods have been found for four sources, the last one in NGC 6712 (Homer et al. 1996). Remarkably, two of these are extremely short, 11.4 min (source in NGC 6624) and 13.2 or 20.6 minutes (in NGC 6712), indicating that the mass donor is a white dwarf with mass $M_{\text{wd}} < 0.1 M_\odot$. No such short-period X-ray binaries have been found in the Galactic Disk. Repeated ROSAT observations show that the lightcurve of the 11.4 minute binary is variable, complicating the effort to derive a period derivative for this system (Van der Klis et al. 1993).

The globular cluster system contains only $\sim 0.1\%$ of the stars of our Galaxy, but 10% of the bright X-ray sources. This indicates that bright X-ray sources are formed in globular clusters by stellar collisions or by exchange encounters between neutron stars and binaries.

In agreement with this suggestion is the observation that the bright X-ray sources are located in the cores of the clusters. ROSAT has increased the number of accurate source positions on which this statement is based (Figure 1).

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Fig. 1. Distances $\Delta$ to the cluster centers for the bright sources in globular clusters. For ordinary clusters (above) the distance is in units of the core radii $r_c$; for collapsed clusters (below) in units of 0.1 pc. • indicates a position determination with ROSAT. For NGC 6440 it has been assumed that the dim source is the transient in quiescence. Adapted from Johnston et al. (1995).

Fig. 2. Luminosity distributions of the cores of globular clusters, showing detections (middle frame) and upper limits (upper frame), as well as the derived most-likely intrinsic luminosity function (lower frame). Luminosities refer to the 0.5-2.5 keV band; pre-ROSAT data (from Einstein and HEAO1) are shown as dotted lines, ROSAT data as dashed lines and the combined data as solid lines. From Verbunt et al. (1995).
2.2. Dim X-ray sources

2.2.1. Census of dim sources

The Einstein satellite discovered low-luminosity or dim ($L_x \lesssim 10^{35}$ erg/s) X-ray sources in the cores of nine clusters, one of which (in NGC6440) may be the quiescent counterpart of the bright transient in this cluster (Hertz & Grindlay 1983). Sources were also discovered outside the cores of ωCen and NGC6656 but these have turned out to be fore- or background sources (Cool et al. 1995a). ROSAT observations added substantially to this sample, bringing the total to more than thirty (for a list, see Johnston & Verbunt 1996), and has found multiple sources in the cores of NGC6397 (Cool et al. 1993), 47 Tuc (Hasinger et al. 1994, Verbunt & Hasinger 1998), ωCen (Johnston et al. 1994), and NGC6652 (Bailyn 1995).

Combination of the detections with the upper limits (many of which are from the Rosat All Sky Survey) gives the most likely X-ray luminosity distribution of these sources, $dN(L_x) \propto L_x^{-1.5}dL_x$, down to $\sim 10^{31.5}$ erg/s (Figure 2). This distribution implies that the total X-ray luminosity of each cluster is dominated by a few bright sources rather than by large numbers of undetected less luminous ones (Johnston & Verbunt 1996). This is confirmed by the observation of the unresolved X-ray flux in spatially resolved cores, which is low or even undetectable.

Several sources have been shown to be variable, including one with an extremely soft spectrum ($kT \sim 40$ eV) in M3 (NGC5272 (Hertz et al. 1993)).

The number $N$ of sources in a cluster scales with core mass $M_c$ and density of its core $\rho_c$ as $N \propto M_c\rho_c^{0.5}$ (Johnston & Verbunt 1996). This dependence of the number of sources is between the proportionalities with mass $M_c$ and that expected for pure tidal capture $M_c\rho_c$, a result that was earlier found to hold for radio pulsars in globular clusters (Johnston et al. 1992). This may be the cause of the destruction of binaries formed by close encounters in subsequent encounters in the densest clusters; or because the sources are a mixture of binaries evolved from primordial binaries and binaries formed by close encounters.

2.2.2. Nature of the dim sources

The cores of globular clusters are known to harbour soft X-ray transients in the low state (Sect. 2.1), cataclysmic variables, and millisecond radio pulsars; they probably also harbour chromospherically active close binaries, RS CVn systems. All of these have been suggested as possible counterparts for the dim X-ray sources. One way to investigate these suggestions is by comparing the X-ray luminosities of the dim sources in globular clusters with those of individually identified quiescent transients, cataclysmic variables, millisecond radio pulsars and RS CVn systems in the Galactic Disk (Figure 3). It is seen that the relatively bright X-ray sources, at luminosities $L_x \gtrsim 10^{32}$ erg/s are matched in luminosity only by the quiescent X-ray transients. Millisecond radio pulsars, cataclysmic variables and RS CVn systems are found in the Galactic Disk at $L_x \lesssim 10^{32}$ erg/s. Indeed, at least part of the X-ray emission of the globular cluster M28 is due to the millisecond pulsars in it (Danner et al. 1994, 1997).

Dim X-ray sources have also been detected at positions compatible with the known dwarf nova in M5 (= NGC5904) and the known old nova T Sco 1860 in M80 (= NGC6093); if these are indeed the counterparts the X-ray to optical flux ratio of the dwarf nova in M5 falls in the range of cataclysmic variables in the Galactic Disk, but that of T Sco 1860 is rather higher (Figure 4).

Efforts to identify the multiple dim sources in 47 Tuc and NGC6397 are described in the following subsections.

2.3. 47 Tuc

The globular cluster 47 Tuc (= NGC104) has been observed six times with the ROSAT HRI between 1992 and 1996. Using four X-ray sources – not related to the cluster – detected in most of these observations to align them precisely, Verbunt & Hasinger (1998) obtain an added 58,000s image of the core of 47 Tuc. Contour plots of this image
are shown in Figure 5. A multiple-source algorithm detects five significant sources in the core.

Two of the four sources outside the cluster which were used in the alignment can be identified optically (with a G5 V star and with a galaxy, Geffert et al. 1997), which provides a tie of the X-ray coordinate frame to the optical J2000 coordinate system with an estimated accuracy of \( \lesssim 2" \). This reduces the number of possible optical counterparts to the dim X-ray sources in the core, as compared to the number previously allowed by the 5" positional accuracy. In particular, the remarkable ultraviolet variable and binary AKO 9 (Minniti et al. 1997) is not a counterpart to any of the individually detected X-ray sources.

Looking for counterparts among the blue stragglers, blue variables, and eclipsing binaries, we find that the suggested cataclysmic variables V1 and V2 are possible counterparts for X9 and X19 respectively, whereas an eclipsing binary, star 12 from Edmonds et al. (1996), is a possible counterpart to X10. It should be noted, however, that there is a sizable probability that all coincidences are due to chance: for the three X-ray sources in the central 20" \times 20" region of the cluster, 22 counterparts are investigated, each acceptable as counterpart in an area 4" \times 4".

**2.4. NGC 6397**

The globular cluster NGC 6397 also contains multiple sources in the center, as shown by the X-ray contours in Figure 6. Cool et al. (1993) analyze the 1991-1992 data, and conclude that there are (at least) three sources close to the core; another source is about 25" to the North of the cluster center. Three H\(\alpha\) emission stars, and various blue stars, are suggested as possible counterparts by Cool et al. (1995b). Spectroscopy with the Hubble Space Telescope shows that the H\(\alpha\) emission stars have spectra like (magnetic) cataclysmic variables (Grindlay et al. 1995).

In Figure 6 I show the optical positions of the proposed counterparts on top of the X-ray contours, in a hitherto unpublished 1995 observation. Within the likely error of \( \sim 2" \) two H\(\alpha\) candidates are acceptable; the third (rightmost) one is less obvious.

**3. Old open clusters**

**3.1. M 67**

Following the discovery of a cataclysmic variable of the AM Her type in the old open cluster M 67 (Gilliland et al. 1991), ROSAT observations of this cluster were obtained,
orbits and binary periods explain the X-ray emission of three binaries with circular due to magnetic activity. Magnetic activity is also likely to explain some sources whose X-ray emission is due to magnetic activity; however, this white dwarf was subsequently found in the ultraviolet; it is undermassive, at ~0.2$M_\odot$, and has an effective temperature $T_{\text{eff}} = 16160$ K (Landsman et al. 1997).

The white dwarf is too cool to be responsible for the X-ray emission. The ultraviolet spectrum shows the Mg II λ2800 line in emission (Landsman et al.), and a blue optical spectrum shows emission cores in the Ca II H and K lines (Van den Berg et al. 1998b), both a sign of chromospheric activity on the giant star. This indicates that the X-ray emission is due to magnetic activity; however, S 1040 doesn’t rotate fast, and it is not clear why it would be magnetically active.

### 3.1.2. S 1063 and S 1113: stars below the subgiant branch

The next two brightest X-ray sources in M 67 are two stars which are located below the subgiant branch in the colour magnitude diagram of M 67, number 1063 and 1113 in Sanders’ list. Both are binaries, one with a circular orbit, and one with an eccentric orbit (Table 1). The binary periods are too long, and the binaries are too far above the main sequence, for these stars to be contact binaries. Optical spectra show emission cores in the Ca II H and K lines of both binaries (Van den Berg et al. 1998b), suggesting that the X-ray emission could be due to magnetic activity. In addition there is evidence for H α emission (Figure 8).

We do not understand the location of these stars below the subgiant branch. In principle, mass transfer can
cause a star to become subluminous (because readjusting hydrodynamical equilibrium for a mass-losing star drains its stellar luminosity), but one expects very rapid circularization for a Roche-lobe-filling star (Verbunt & Phinney 1995). Interestingly, the periastron distance in S 1063 is such that tidal forces can have brought a slightly evolved star into corotation at periastron without (as yet) having circularized the orbit (Van den Berg et al. 1998a); this could explain the chromospheric emission of the spun-up star, but not why it is underluminous. The X-ray flux of S 1063 is variable, being 8.1 ± 0.9 counts/ksec in November 1991, and 4.7 ± 0.6 counts/ksec in April 1993 (Belloni et al. 1998).

3.1.3. S 1072 and S 1237: wide eccentric binaries

Two X-ray sources are wide binaries, with orbital periods of about 1500 and 700 d respectively, and with significant eccentricities. Both binaries are in the yellow straggler region of the colour magnitude diagram. Their optical spectra do not show significant emission in the CaIIH and K lines (Van den Berg et al. 1998b). The eccentricity of the orbits indicate that no significant tidal interaction is occurring or has occurred in these binaries. We do not understand why these two binaries would emit X-rays.

3.1.4. S 1082: a blue straggler binary

Star 1082 in Sanders’ list is a blue straggler, the only one in this cluster to be detected in X-rays. From an ultraviolet excess, Landsman et al. (1998) conclude that it is a binary with a subdwarf O star. Optical spectra taken by Van den Berg et al. (1998b) show variability in the Hα line, which may be related to the binarity. The radial velocity of the star shows some variation (Mathieu et al. 1986), but no orbital period has been found so far; the orbital period of about 1 day suggested from photometric data by Goranskii et al. (1992) in particular is not present in the radial velocity data, contrary to expectation in a short-period eclipsing binary. Again, we do not know why this binary emits X-rays.

3.2. NGC 188

Another old open cluster, NGC 188, has also been observed with ROSAT, and two sources have been detected in it (Belloni et al. 1998). Their location in the colour magnitude diagram of NGC 188 is shown in Figure 9. The brightest source, at $L_x(0.1 - 2.4 \text{keV}) \approx 1.7 \times 10^{31} \text{erg/s}$, is a rapidly rotating single giant, a star of the FK Com type. Such stars possibly are the result of a merger of two stars into a single, rapidly rotating star. The other X-ray source, three times less luminous, is identified with a star which is a short-period velocity variable, as well as a rapid rotator. The X-rays of both detected members of NGC 188 can therefore be explained in terms of magnetic activity of rapidly rotating cool stars.

4. Summary, questions and outlook

Whereas the nature of the bright X-ray sources in globular clusters is clear – at least 11 of the 12 known are accreting neutron stars – the nature of many of the less
luminous sources is still unknown. At least one dim source is a radio pulsar; one (in M5) is likely a dwarf nova, and several others (in 47 Tuc and in NGC 6397) quite possibly are cataclysmic variables.

The comparison of the old open clusters with the globular clusters shows that the open clusters are surprisingly bright in X-rays. The added X-ray luminosity of the M67 clusters shows that the open clusters are surprisingly luminous, and of binaries (like cataclysmic variables) that have evolved from wide binaries, can be understood from the efficiency with which wide binaries are ionized in encounters with third stars (e.g. Davies 1997). Theoretical formation and evolution scenarios of cataclysmic variables in globular clusters (Di Stefano & Rappaport 1994) nonetheless predict much larger numbers than appear to be present according to optical or ultraviolet observations (Shara et al. 1996). This indicates that our understanding of the formation (via tidal capture) and of the evolution of cataclysmic variables, as well as their phenomenology is far from complete. The absence of close binaries, like RS CVn systems, also is not readily understood. An alternative line of reasoning is that open clusters like M67 have already lost many of the stars originally in them, but retained a relatively larger fraction of the binaries. Investigation into this line of reasoning again can be made with N-body computations that include stellar evolution.

The near future will bring X-ray satellites that can study more X-ray sources in old open and globular clusters, like AXAF, or that can study the X-ray spectra of these sources, like XMM. Together with theoretical and optical followup, these observations will hopefully contribute answers to the questions about X-ray sources in old clusters, that have been raised thanks to ROSAT.

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Fig. 9. Colour-magnitude diagram of NGC188 in which the stars detected in X-rays are shown with +. From Belloni et al. (1998).
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