X-rays from old star clusters

Frank Verbunt
Astronomical Institute, Utrecht University, Postbox 80.000, 3508 TA Utrecht, The Netherlands; email verbunt@phys.uu.nl

Abstract. A brief overview is given of X-ray observations of old clusters. Most X-ray sources in old open clusters are interacting binaries, formed via evolution of a primordial binary, and emitting X-rays because of magnetic activity; however, a sizable fraction of the cluster sources is not well understood, including some of the most luminous ones. Globular clusters appear to contain fewer magnetically active X-ray sources than expected if one scales from old open clusters by mass.

1. Introduction

The comparison of stellar clusters with different ages has contributed much to our understanding of the evolution of single stars. Large numbers of binaries are being discovered and studied in stellar clusters via radial velocity studies (as reviewed by Mermilliod 1997), and we may hope to learn about the evolution of binaries as well. Another reason to study binaries in clusters is the close interaction between the evolution of the binaries and the evolution of the cluster as a whole (see review by Hut et al. 1992). For example, close encounters between single stars and binaries change the velocity distribution of the cluster stars. Exchange encounters, in which a single star encounters a binary and releases one binary star by taking its place, may lead to strange binaries which would not – or not as frequently – be formed via the evolution of an isolated binary.

In this paper I review the role in these studies of X-ray observations of old (∼ 1 Gyr) clusters. In Section 2 I discuss what types of objects emit X-rays and how these objects – very often binaries – are formed, and give an overview of all X-ray observations of old open clusters (for an earlier review, see Belloni 1997). In Section 3 the bright and dim X-ray sources in globular clusters are discussed, and a comparison with the sources in old open clusters is made in Section 4.

2. X-rays from old open clusters

2.1. A brief overview of close binary evolution

To prepare for our discussion of the X-ray sources in old open clusters, we make a brief detour to binary evolution, illustrated in Figure 1. Consider a primordial binary of two main-sequence stars in a relatively close orbit (Fig. 1-Ia). Unless pre-main-sequence circularization has occurred, the binary will in general have
Figure 1. Schematic outline of the evolution of binaries with an initially close orbit (left) and with an initially wide orbit (right). For details see text.

an eccentric orbit. Loss of angular momentum drives the two stars together, and at some point tidal interaction starts: the larger (i.e. more massive) star first is spun-up to be brought into co-rotation with the orbit at periastron. Subsequently the orbit is circularized. Rapid rotation engenders chromospheric and coronal activity, and with it, X-ray emission (Ib). When loss of angular momentum is severe, or the initial binary very close, the two stars may come into contact (Ic) and may even merge into a single 'FK Com' star (Id). Both contact binaries and FK Com stars are magnetically active X-ray emitters.

When the initial binary is wide (Fig. 1-IIa), loss of angular momentum has no effect, and tidal forces only come into play once one of the binary stars – the more massive one – evolves into a (sub)giant. The subgiant is then brought into corotation, and the orbit circularized; the binary becomes an RS CVn system, in which the rapidly rotating star emits X-rays (IIb). When the giant fills its Roche lobe, mass transfer starts and the binary is an Algol system (IIc), until the complete envelope of the giant has been transferred, leaving a white dwarf into orbit around a companion. The white dwarf is undermassive, because mass transfer has interrupted the ordinary giant evolution; and its companion has been brought into rapid rotation because of the angular momentum it accreted with the mass (IIId). The companion to the white dwarf may evolve to fill its Roche lobe either because it expands into a giant, or because loss of angular momentum lets the orbit shrink. The ensuing mass transfer then dominates the luminosity, and the binary has become a cataclysmic variable. (Note, however,
that the typical progenitor of a cataclysmic variable has a rather wider orbit than characteristic Algols.)

With the exception of the initial binaries, all the evolutionary stages shown in Fig. 2 are X-ray sources. Most of them emit X-rays due to magnetic activity induced by rapid rotation; only in the case of the cataclysmic variable the X-rays are due to the mass accretion onto the white dwarf.

2.2. Optical identification of X-ray sources

To illustrate the optical identification of X-ray sources in old open clusters, we discuss some details of the X-ray analysis of M 67. In Fig. 2a we show the distribution of counts on the ROSAT detector near S1082 and S1072. It is seen that most pixels are empty, some contain a single count, and some two. If we smooth the picture and then plot X-ray contours, three sources show up (Fig. 2b). Overlaying these sources on an optical image, we find that the two brighter ones coincide closely with S1082 and S1063. These identifications may be considered secure. We also find that the X-ray source that Belloni et al. (1998) identify with S1072 has a maximum which is offset with respect to the optical position. The number of photons that defines this X-ray source is small, and the X-ray center has a 90% uncertainty radius of 9\,"; the offset between the X-ray center and S1072 is at this radius, and the identification is feasible. We note from the figure that a circle with a 9\," radius located arbitrarily in the frame has a finite probability of hitting an optical object. Belloni et al. (1998)
estimate that 1 of the 12 identifications of X-ray sources with member binaries of M 67 may be due to chance coincidence; most identifications, possibly all, are correct. In IC 4651 two X-ray sources have multiple optical counterparts of comparable brightness in their error circle; this indicates that the probability of chance coincidence in this cluster is high.

2.3. X-ray sources in old open clusters

Table 1 summarizes the X-ray observations of old open clusters, and the identifications of X-ray sources with optical objects in different categories. The richest harvest has been obtained for M 67. The optical counterparts of the X-ray sources in M 67 are located throughout the colour-magnitude diagram, both near the isochrone for single stars, and away from it (Figure 3). Most sources are known binaries. The smaller number of X-ray sources in NGC 188 is most likely due to the rather higher detection limit in that cluster. The smaller numbers of X-ray sources in NGC 752, IC 4651 and NGC 6940 is due in part because of the smaller number of stars in these clusters; and in part perhaps to the absence of a well-developed (sub)giant branch in these younger clusters (Figure 3). Old clusters were ignored in early X-ray studies of open clusters because old stars do not emit much X-rays – or so it was thought. Ironically, the least luminous sources detected in old clusters are brighter than the most luminous sources in young open clusters (see Randich, these proceedings). The lower limit in the old clusters is set by the detection limit; less luminous sources are certainly present.

We discuss the X-ray sources in old open clusters on the basis of Table 1, starting with those for which the X-ray emission is readily understood. Circular binaries (SB $e=0$ in Table 1) are X-ray sources because of tidal interaction. Those in NGC 752 have orbital periods of 0.41, 1.01, 1.45 and 1.95 d, those in
Figure 3. Colour magnitude diagram of M 67 (left, after Belloni et al. 1998) and IC 4651 (right). Special symbols indicate stars detected in X-rays: circles, triangles and squares indicate binaries with circular, eccentric and unknown orbits, respectively; + stars for which no evidence for binarity was found. The symbol size indicates the (logarithm of the) X-ray luminosity (between 0.1-2.4 keV, in ergs/s).

M 67 of 2.66, 7.65 and 10.06 d; these binaries are probably of the type shown in Fig. 1-Ib. The circular binaries in NGC 6940 have orbits of 54.2 and 82.5 d, and are probably of the type shown in Fig. 1-Ib. Two contact binaries (CB in Table 1; Fig. 1-Ic) are found in M 67, and an FK Com star (FK in Table 1) in NGC 188. Other X-ray sources which we understand (‘oth’ in Table 1) are a cataclysmic variable (Fig. 1-IIe), a hot single white dwarf, and a triple system in which a close binary of the type shown in Fig. 1-Ib is kept at finite eccentricity by a third companion in a wide orbit in M 67; and a rapidly rotating star – probably rotating rapidly because of tidal interaction in a close binary – in NGC 752.

Turning to the sources for which the X-ray emission is less readily understood, we note that a blue straggler (BS in Table 1) has been detected in three of the five old clusters. In each case, the blue straggler is among the brightest X-ray sources in the cluster. Multicolour photometry of the ones in M 67 and IC 4651 indicates that they are binaries (Landsman et al. 1998, Anthony-Twarog & Twarog 1987), and radial velocities indicate that the one in NGC 752 is a binary (Latham, cited in Belloni 1997), but no period is known. It is not clear why the blue stragglers emit X-rays. The brightest X-ray source in M 67 is similar to the binary depicted in Fig. 1-IId (Landsman et al. 1997, see also Verbunt & Phinney 1995), except that the companion to the white dwarf is a slow rotator (van den Berg et al. 1999, & these proceedings). It is seen at $V=11.52$, $V=11.52$.
$B-V=0.88$ in Fig. 3a. If rapid rotation is taken to be pre-requisite for X-ray emission, we do not understand this source. The binary AY Cet is rather similar to this system, and also is a relatively bright X-ray source. The X-ray emission of this system is probably related to its earlier history, which included a phase of mass transfer; magnetic activity is present even in the absence of rapid rotation, but we do not know why. We note that X-ray emission of giants in general is not well related to rotational velocity (Van den Berg et al. 1999).

The next two brightest X-ray sources in M 67 are both binaries, located below the subgiant branch, several magnitudes above the main sequence (at $V \simeq 13.5$, $B-V \simeq 1.1$ in Fig. 3a); no single star or binary can be located there according to our current understanding. Both binaries show Hα emission and emission in the cores of the CaH&K lines, and thus appear to be magnetically active X-ray sources. S1063 has a 18.39 d orbit with eccentricity $e = 0.22$; S1113 has a circular 2.82 d orbit. Both are photometric variables. We do not currently understand their evolutionary status (Van den Berg et al. 1999, & these proceedings).

Several spectroscopic binaries with eccentric orbits have also been detected in X-rays (SB $e>0$ in Table 1). The binary in IC 4651 has an orbit of 75 d, and a relatively small eccentricity ($e=0.09$, Mermilliod et al. 1995); perhaps it is in the process of tidal circularization. One binary in M 67 has an orbit of 31.78 d and a fairly high eccentricity of $e=0.664$ (Mathieu et al. 1990); a photometric period has been detected at 4.88 d (Gilliland et al. 1991), which is exactly the corotation period at periastron, strongly suggestive of tidal interaction. The three other eccentric binaries detected in X-rays have very long orbital periods, 697.8 and 1495 d in M 67 and 3595 d (!) in NGC 6940 (Mermilliod & Mayor 1989). Such wide orbits exclude tidal interaction, as confirmed by the eccentric orbits. One wonders whether these stars could be triple systems, i.e. the giant star that we observe has a close binary as a companion. Triple systems are not uncommon: one X-ray source in M 67 is known to be a triple, and one of the X-ray sources in the same ROSAT field of view as M 67 is identified with HD 75638, a bright F star not related to the cluster (Belloni et al. 1998), which is a triple star (Nordström et al. 1997).

Finally, several spectroscopic binaries with as yet unknown orbits have been detected as X-ray sources; considering that half of the X-ray detected binaries with known orbits are unusual, we may expect more surprises when these binaries are studied further.

3. X-ray sources in globular clusters

Twelve bright ($L_x \gtrsim 10^{36}$ erg/s) X-ray sources have been found in globular clusters; they are neutron stars accreting matter from a companion star. Four of these are bright only occasionally, i.e. they are soft X-ray transients. The number of bright sources in the whole galaxy is of order 100. Since globular clusters contain only ~0.001 of the mass of our Galaxy, the high incidence of bright X-ray sources in them points to a formation process for such sources which operates preferably in globular clusters. This process has been identified with the occurrence of close encounters between stars: if a neutron star passes close to another star it may be captured tidally; alternatively a neutron star may
eject a binary star and take its place in an exchange encounter (for a review, see Hut et al. 1992). The orbital period is known for five bright X-ray sources in globular clusters; for two of them this period is so small (11 and 13 – or 20 – minutes, respectively; Homer et al. 1996) that the mass donor must be a white dwarf. No such systems are known in the galactic disk, again pointing to a special formation mechanism in globular clusters.

The nature of the less luminous X-ray sources discovered in globular clusters, with $L_x \lesssim 10^{35}$ erg/s, is less clear. About thirty dim sources are now known distributed over twenty clusters, their X-ray luminosity distribution is shown in Figure 4. Many more must be present, below current detection limits. The luminosities of the dim sources are such that transients in their low-luminosity state, cataclysmic variables, RS CVn systems, and recycled radio pulsars all are possible counterparts. The only secure identification is with a recycled radio pulsar in M28: the radio period of 3.054 ms is detected also in X-rays (Danner et al. 1997). Various other sources have been tentatively identified with cataclysmic variables. Figure 5 illustrates the problems that optical identification of X-ray sources in the cores of globular clusters entail. The central region of 47 Tuc contains five X-ray sources, and several thousand stars: given the limited accuracy of the X-ray positions, a possible counterpart is always found. Even if one limits oneself to blue and/or variable stars only, the probability of chance coincidence is still appreciable. Thus, X-ray sources C and D in Fig. 4 can tentatively be identified with cataclysmic variables at nearby positions, but chance coincidence cannot be excluded (Verbunt & Hasinger 1998).

NGC 6397 is another cluster containing multiple dim X-ray sources in its core, for which cataclysmic variables have been suggested as counterparts (Cool et al. 1995). The sources are so close together, however, that the whole core of the cluster is covered by their error circles, i.e. any cataclysmic variable (or other star) in the cluster core of necessity falls within an X-ray error circle. Clearly, secure identification can be obtained only if either the positional accuracy is improved (as may be done with AXAF), or if the same periodicity is discovered in the X-ray source and in the suggested optical counterpart.

A statistical analysis of the currently known dim sources in globular clusters, taking into account the detection limit for each cluster, shows that the number of sources $N$ at luminosity $L_x$ in a cluster scales with the density $\rho_c$ and the mass $M_c$ of the cluster core as (Johnston & Verbunt 1996):

$$dN(L_x) \propto M_c \rho_c^{0.5} \times L_x^{-1.5} dL_x$$

This implies that the total luminosity of each cluster core is dominated by a small number of bright sources rather than by a large number of unresolved
very faint sources; in agreement with observation. If the only process of importance is the rate of close encounters between stars in the cluster core, one expects a proportionality of the source numbers \( N \propto \rho_c^2 \propto M_c \rho_c \); for primordial binaries the expected proportionality is with \( M_c \). The fact that the observed proportionality lies between these two indicates that the population of dim sources is a mix of primordial binaries evolved into X-ray sources (e.g. RS CVn systems and cataclysmic variables) and X-ray sources formed via close encounters (X-ray transients and recycled radio pulsars; some cataclysmic variables).

4. **Comparison open and globular clusters; prospects**

In comparing the old open clusters with the globular clusters, we note that the sources in globular clusters detected so far are brighter than the brightest sources found in old open clusters (see Fig. 4). Most of the currently known X-ray sources in globular clusters are the result of past stellar encounters in the cluster cores. Most of the currently known X-ray sources in old open clusters may have evolved from primordial binaries. Some X-ray sources in old open clusters – including all four brightest sources in M 67, and the brightest source in IC 4651 – are not well understood. In general however it may be stated that X-ray observations are very efficient in picking out binaries in old open clusters which are currently interacting.

The brightest X-ray sources in old open clusters are an FK Com system in NGC 188 and a slightly eccentric binary in IC 4651, both with \( L_x(0.1 - 2.4 \text{ keV}) > 10^{31} \text{ erg/s} \). The four brightest sources in M 67 each have \( L_x(0.1 - 2.4 \text{ keV}) \approx 0.75 \times 10^{31} \text{ erg/s} \). There is no obvious reason why such systems couldn’t exist in globular clusters as well. However, if we assume that a globular cluster typically has a hundred to a thousand times more mass than an old open cluster and that the total X-ray luminosity scales with mass, we predict that each globular cluster has an X-ray luminosity well in excess of \( 10^{33} \) to \( 10^{34} \) erg/s, in contrast to observation (Verbunt 1996). We investigate this more closely in Figure 6.
where we compare the X-ray luminosity to mass ratio of globular clusters with that of M 67.

It is seen that most globular clusters have a lower X-ray light to mass ratio than M 67, some by several orders of magnitude. This may indicate that binaries are destroyed efficiently in the cores of globular clusters – as suggested by the X-ray luminosity function discussed in Sect. 3. Since some of the brightest X-ray sources have very short orbital periods and the brightest source in NGC 188 is a single star, this explanation may not be sufficient. An alternative possibility is that M 67 has lost a larger fraction of its mass – in particular single, non X-ray emitting stars – than the typical globular cluster. It is certainly true that the fraction of binaries amongst the giants in M 67 is larger than in the well-studied globular clusters.

Ottmann et al. (1997) find that binaries of population II are less luminous X-ray emitters than their population I counterparts; such a finding would also explain the dearth of X-ray detections of magnetically active sources in globular clusters. It should be noted that the sample on which Ottmann et al. base their conclusion is rather small; and that it includes just one binary with an evolved primary (viz. HD 6286; Pasquini & Lindgren 1994).

The search for X-ray sources in globular clusters has concentrated on their cores, because of confusion problems with background sources away from the core. It may be worthwhile to estimate the X-ray luminosities of globular cluster out to their tidal radius, and then re-do Fig. 6.

The prospects for further work are excellent. AXAF and XMM are ready for launch. AXAF will provide more accurate positions and more secure identifications; XMM will probe clusters to much lower X-ray luminosities, so that magnetically active binaries become detectable in globular clusters. Theoretically the first descriptions of complete cluster evolution, in which stellar and dynamical evolution is combined, are becoming possible with special-purpose computers (Hurley et al, these proceedings).
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