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X-ray sources in globular clusters

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Abstract The study of X-ray sources in globular clusters is in very rapid progress, thanks to the combined observations of Chandra and XMM X-ray observatories, and the Hubble Space Telescope. In addition to the low-mass X-ray binaries known since the early 1970s, quiescent X-ray binaries, cataclysmic variables, radio pulsars, and magnetically active binaries can now be identified and studied in X-rays and optical. This improves our knowledge of the population of binaries in globular clusters.

Key words: stars: X-ray sources – globular clusters

1 INTRODUCTION

As their name implies, globular clusters are conglomerates of stars in a roughly spherical distribution. The evolution of the cluster is driven by the gravitational interaction of its members. In the 1960s it became clear, thanks to Hénon, that such a stellar distribution is unstable (e.g. Hénon 1961). Somewhat simplified, the instability is as follows. In the center of the cluster, stars in the high tail of the quasi-thermal velocity distribution escape to the outer regions of the cluster. As a result, the core loses energy, and shrinks. The virial theorem implies that as a consequence the stellar velocities in the core become higher(!), and more stars escape. Thus the core collapses, and the outer regions of the cluster expand.

The presence of binaries in the cluster can stop the collapse: when a single star passes a binary, the three velocities after the encounter tend to be more similar to each other than before. In a close binary the stars have higher velocities than passing single stars, and the encounter shrinks the binary, and gives the passing star a higher velocity. Thus energy is added from the binary to the cluster core, and the collapse is reversed (e.g. Hut et al. 1992). The puzzle that faced the astronomers in the 1960s is that no binaries in globular clusters were known.

X-ray astronomy has changed this. The first satellites in the 1970s showed up a dozen bright X-ray sources in globular clusters, very similar to low-mass X-ray binaries, i.e. neutron stars accreting from a low-mass companion. The Einstein satellite added nine low-luminosity sources, a number which was extended by ROSAT to 47, and in the first observations with Chandra to several hundred. For example, 47 Tuc showed 1 Einstein source, 9 ROSAT sources, and more than 100 Chandra sources (see Fig.2). In this review I discuss first the observations of bright sources, and then the observations of the dim sources. A brief look at the theoretical implications ends the paper.

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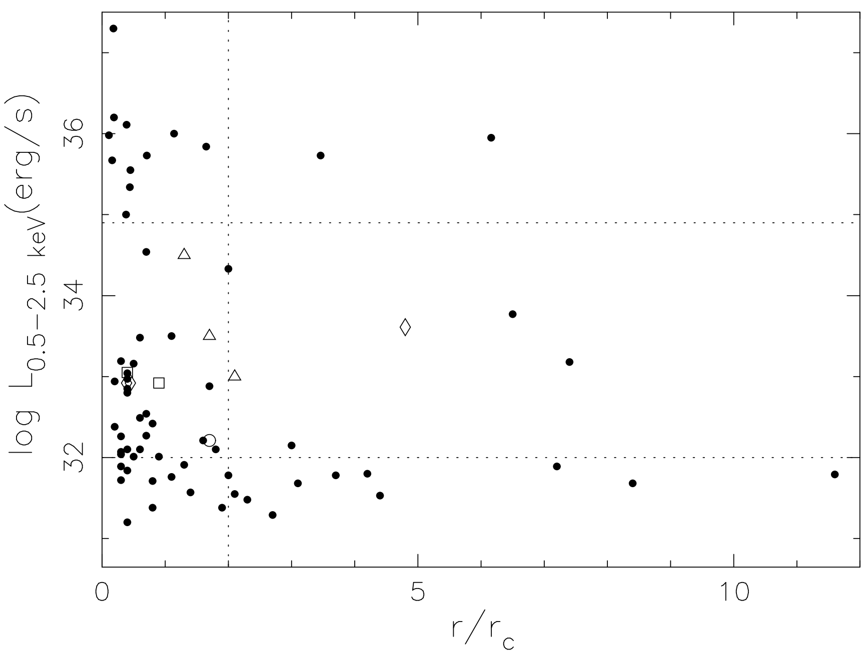

Fig. 1 ROSAT positions • of X-ray sources in globular clusters. Some early positions determined with Chandra are indicated with other symbols. Most sources are within two core radii ($r < 2r_c$).

2 THE BRIGHT SOURCES AND RADIO PULSARS

Before Chandra, twelve bright ($L_\mathrm{x} \gtrsim 10^{36}\,\mathrm{erg\,s^{-1}}$) X-ray sources were known in as many globular clusters (e.g. list in Verbunt et al. 1995). An early observation with Chandra showed that the source in M 15 (NGC 7078) in fact consists of two sources, thus bringing the total to thirteen sources (White & Angelini 2001). Comparison of the X-ray flux levels and spectral energy distribution indicates that these bright sources are similar to the low-mass X-ray binaries in the galactic disk, which are neutron stars or black holes accreting from a low-mass companion star. In globular clusters, thermonuclear X-ray bursts have been observed of 12 from the 13 sources. Such bursts are caused by the fusion of hydrogen into helium, and/or helium into carbon on the surface of a neutron star. Thus, bursters are accreting neutron stars. The one source from which no burst has as yet been seen, the brighter of the two sources in M 15, has a spectral energy distribution indicative of a neutron star as well, and thus all bright X-ray sources in the globular clusters of our galaxy are accreting neutron stars.

Einstein observations give positions with $\sim 2''$ accuracy, and thereby showed that the bright sources are clearly concentrated towards the cluster core (Hertz & Grindlay 1983). This is in agreement with the notion that they are formed via close encounters of neutron stars with field stars, or with a binary: virtually all close encounters between stars happen in the core, because the number densities of stars is highest in the core, and drops rapidly with distance from the core. An update of the radial distribution of X-ray sources in globular clusters, including some new Chandra positions, can be seen in Fig.1, where the bright sources are those above the upper horizontal dotted line, i.e. have $L_\mathrm{x} \gtrsim 10^{35}\,\mathrm{erg\,s^{-1}}$.

In the galactic disk, radio pulsars have been discovered in circular orbits with an undermassive white dwarf. Such pulsar binaries are the expected end-stages of low-mass X-ray binaries in which a (sub)giant transfers mass to a neutron star. The mass transfer probably lowers the magnetic field strength of the accreting neutron star, and adds angular momentum, causing the neutron star to rotate more and more rapidly. Tidal forces in such a binary circularize any initially non-circular orbit very quickly. The mass loss from the (sub)giant prevents growth of its helium core to the value it would reach in a single star. Thus, once the total envelope is transferred, an undermassive helium core is in a circular orbit around a rapidly spinning neutron star with a low magnetic field. The presence of a relatively large number of low-mass X-ray binaries in globular clusters thus led to the prediction that these clusters also harbour pulsar binaries, and indeed many such have been found (list in Freire 2004). There are also a sizable number of single, rapidly rotating pulsars; these are thought to originate from X-ray binaries as well. Perhaps the companion has been released from the binary in a close encounter (in wide binaries); or it has been hit by the energy emitted by the pulsar and is evaporated by it (in close binaries). An interesting puzzle is set by the large number of radio pulsars compared to the number of low-mass X-ray binaries. Since pulsar binaries evolve from low-mass X-ray binaries, their birth rate is at best equal to, and more likely much less than, the birth rate of X-ray binaries. Since the life times of X-ray binaries and radio pulsars are similar ($\sim 10^9$ yr), it is hard to explain that a single cluster like 47 Tuc contains 22 pulsars (14 in binaries, 7 single), and not a single bright X-ray binary (Freire et al. 2003). The solution is possibly that most radio pulsar binaries were formed from binaries with $\gtrsim 2\,M_\odot$ donor stars, in the distant past of the globular cluster (Davies & Hansen 1998). Since globular clusters no longer contain main-sequence or (sub)giant stars more massive than $0.8\,M_\odot$, the typical progenitor of a radio pulsar binary is no longer present in it; and the current number of X-ray binaries is not related to the number of the radio binary pulsar progenitor population.

3 DIM SOURCES

The combination of better spatial resolution and better sensitivity has led to the discovery with Chandra of a very large number of X-ray sources. In some clusters, especially those which have large (in angle) cores, the brightest ROSAT sources correspond to individual Chandra sources, but Chandra discovers many new ones. An example is 47 Tuc (Grindlay et al. 2001a, see also Fig.2). In other clusters, especially those with smaller cores, the ROSAT sources have been resolved in multiple sources, and new sources have been added as well. An example is NGC 6440 (Pooley et al. 2002b). As a result several hundred dim sources are now known.

Different types of objects have been detected in globular clusters as low-luminosity sources:

- quiescent low-mass X-ray binaries. These are neutron stars that accrete matter from a companion star. They have characteristic soft X-ray spectra, with blackbody color temperatures of ~ 0.3 keV. When fitted, more appropriately, with a neutron-star model atmosphere, they are found to have radii ~ 10 km, as expected for a neutron star. This indicates that their X-ray luminosity is thermal emission from the neutron star surface (Rutledge et al. 1999).
- millisecond radio pulsars. These are old neutron stars that have been brought into rapid rotation by the accretion of matter in a binary. Their X-ray emission is partially thermal emission from the hot surface near the magnetic poles, and partially non-thermal, hard emission from relativistic electrons in the magnetosphere. They can, but need not, have hard spectra (e.g. Becker et al. 2003).
- cataclysmic variables. These are white dwarfs that accrete from a binary companion. The hardness of their X-ray spectrum depends among others on the accretion rate, and on the strength of the magnetic field of the white dwarf. In general, their spectrum extends to 10 keV and often beyond (Kuulkers et al. 2004).

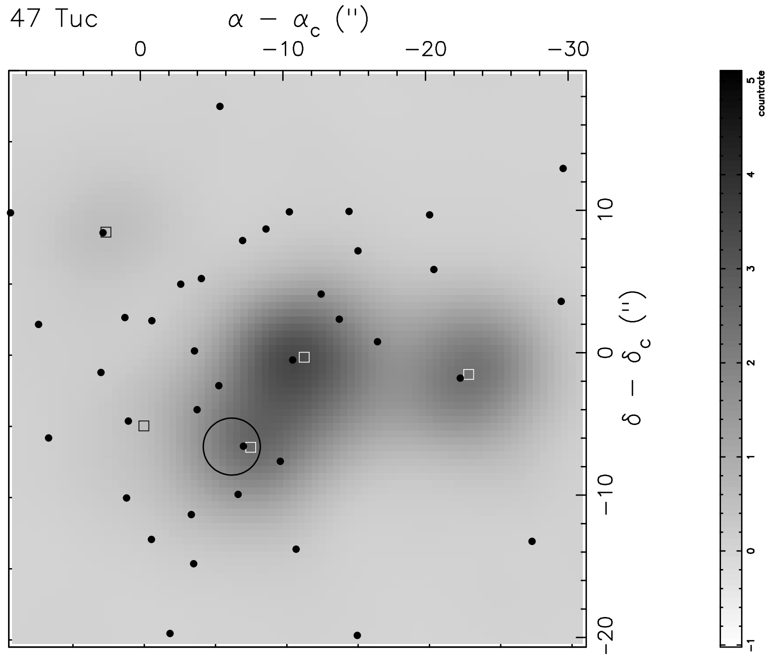

Fig. 2 Central area of 47 Tuc in X-rays. The grey scaled image gives the ROSAT HRI countrates, smoothed with a 2″ Gaussian. The circle indicates the position of the only source seen with Einstein (Hertz & Grindlay 1983); squares indicate the five ROSAT sources (Verbunt & Hasinger 1998) and the black circles the 39 Chandra sources in the cluster center (Grindlay et al. 2001a).

– magnetically active binaries. These are close binaries, in which one or both stars are kept in corotation with the orbit; the rapid rotation combines with the convective motion to act as a dynamo which enhances the magnetic field. The loops of the magnetic field sticking out of the stellar surface contain hot, X-ray emitting gas. In principle, single stars can be rapid rotators, but in an old globular cluster all single stars have slowed down long ago, and only binary stars are magnetically active. Thereby X-ray emission is an efficient way of detecting close binaries in a cluster (e.g. M 67: Belloni et al. 1998, Van den Berg et al. 2004).

The low-luminosity sources are also concentrated towards the center of the globular cluster, although some sources are found further from the core, as illustrated in Fig.1. Sources with an X-ray luminosity $L_x \gtrsim 10^{32}\,\mathrm{erg\,s^{-1}}$ (in the 0.5–2.5 keV range) and a soft X-ray spectrum can be confidently classified as quiescent low-mass X-ray binaries. They are more concentrated towards the cluster center than the less luminous sources (Fig.1). Sources with luminosities $10^{31}\,\mathrm{erg\,s^{-1}} \lesssim L_x \lesssim 10^{32}\,\mathrm{erg\,s^{-1}}$ are mainly cataclysmic variables. With Chandra, less luminous sources are now detected, e.g. down to $L_x \sim 10^{29}\,\mathrm{erg\,s^{-1}}$ in NGC 6121 (Bassa et al. 2004); at these low flux levels most sources are magnetically active binaries. Millisecond radio pulsars can have luminosities up to $10^{32}\,\mathrm{erg\,s^{-1}}$ (the pulsar in M 28, Becker et al. 2003), and have been detected down to $\lesssim 10^{30}\,\mathrm{erg\,s^{-1}}$ (in 47 Tuc, Grindlay et al. 2002); these objects are rare, however, in most clusters.

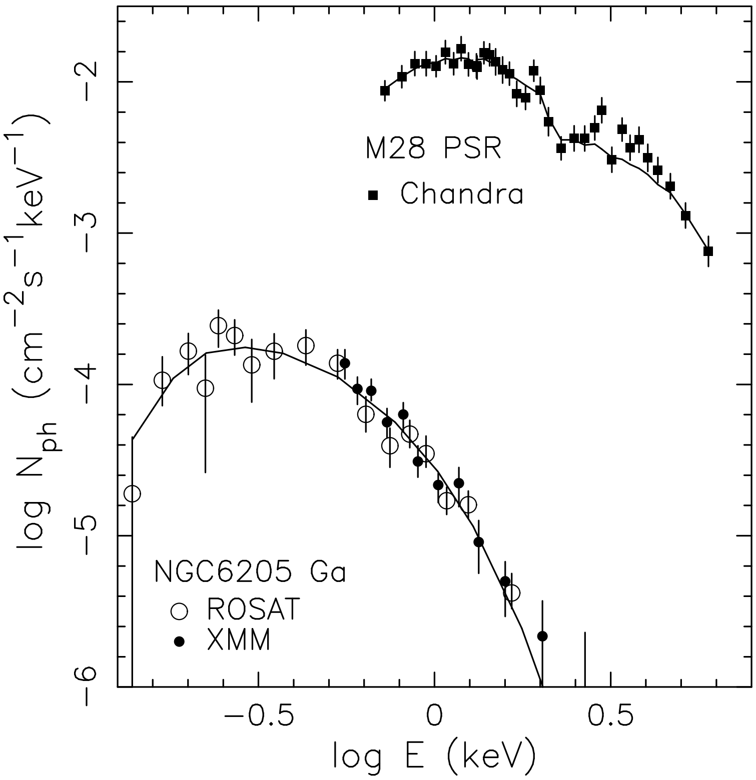

Fig. 3 Comparison of the soft X-ray spectrum of a quiescent low-mass X-ray binary (source Ga in NGC6205, Verbunt 2001, Gendre et al. 2003b) with the hard spectrum of a millisecond pulsar (in M28, Becker et al. 2003). It is seen that ROSAT was sensitive to lower-energy photons.

4 OPTICAL IDENTIFICATION AND ABSOLUTE ASTROMETRY

To discriminate between cataclysmic variables and magnetically active binaries, it is useful to study the object at optical wavelengths. However, in the crowded centra of globular clusters, very accurate positions of the X-ray sources are required. Now that Chandra is making these available, at accuracies $\lesssim 0.2''$, many counterparts are being found. In particular in 47 Tuc, NGC 6752, NGC 6397, and in NGC 6121, a large fraction of the X-ray sources has now been securely identified with an optical counterpart (Edmonds et al. 2003, Pooley et al. 2002a, Grindlay et al. 2001b, Bassa et al. 2004). To illustrate this, we describe our (re-)analysis of the optical data for NGC 6752. The X-ray positions as determined with Chandra are published by Pooley et al. (2002a). The relative accuracy (i.e. the positions of sources with respect to one another) of Chandra is $\lesssim 0.1''$, depending on the number of counts detected and somewhat on the location of the source image on the detector. However, the absolute accuracy (i.e. the source position with respect to an absolute system like the International Celestial Reference System ICRS) is uncertain by about $0.6''$. The HST-WFPC2 images also have excellent relative positions, but a large – in terms of our requirements – uncertainty in the absolute positions, of $1''$ and sometimes much more (e.g. Ransom et al. 2004). Thus, the optical counterpart of a

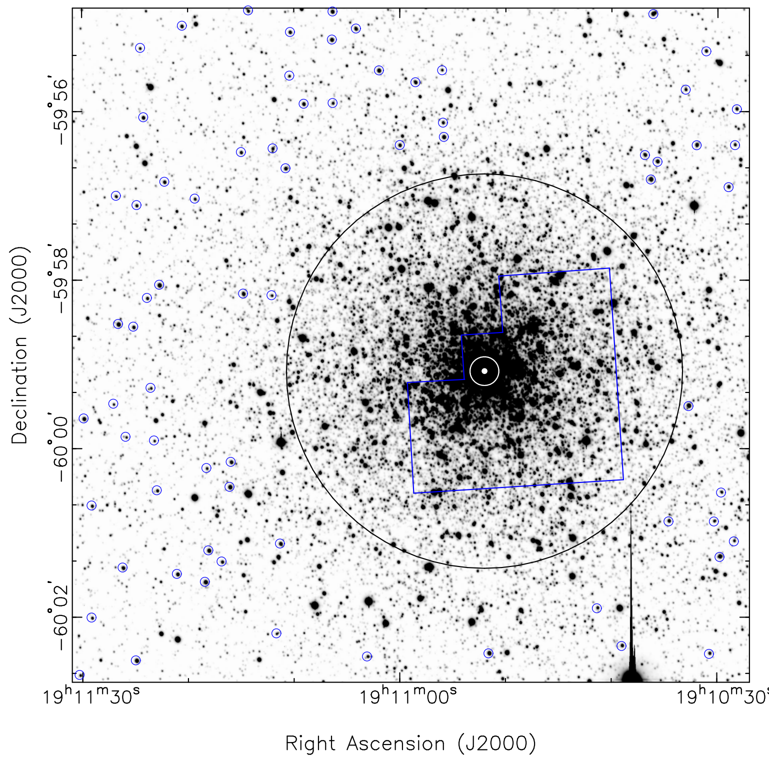

Fig. 4 The V image of NGC 6752 and surroundings on (part of) an ESO 2.2m Wide Field Camera image. The large circle indicates the radius within which half of the cluster mass is contained, the small circle and dot give the core radius and cluster center. The outline of the HST image is also given. The encircled stars in the outer regions have been identified with objects in the USNO CCD Astrograph Catalog, and are used to obtain absolute astrometry.

Chandra source can be found in a circle with a radius (1 sigma) out to $\sqrt{0.6^2 + 1.0^2} = 1.2''$; and out to about $2.5''$ for 2 sigma. In a globular cluster, this corresponds to many optical objects (see Fig.5).

To reduce the error circle, we proceed as follows. We first analyse a groundbased wide-field image, in this case obtained with the Wide Field Imager on the ESO 2.2 m telescope (Fig.4). The stellar positions in this image are correlated with standard astrometric stars in the USNO CCD Astrograph Catalog (UCAC; Zacharias et al. 2000). This enables us to provide absolute positions for the stars in the WFI image to an absolute accuracy of $\lesssim 0.07''$ in both right ascension and declination. In the second step, we correlate stars in the HST-WFPC2 image with stars in the WFI-image. This enables us to obtain absolute positions for the HST stars with an accuracy of $\lesssim 0.1''$ (1 sigma). This is much less than the absolute pointing accuracy of Chandra, which therefore dominates when we try to find an optical counterpart for an X-ray source. The radius of the error circle is effectively halved, its area reduce by a factor 4. The overall error of the optical positions in the ICRS then is composed of a) error between UCAC astrometry and ICRS ($0.02''$) b) error between WFI-image and UCAC ($0.07''$) c) error between WFI and HST ($0.08''$).

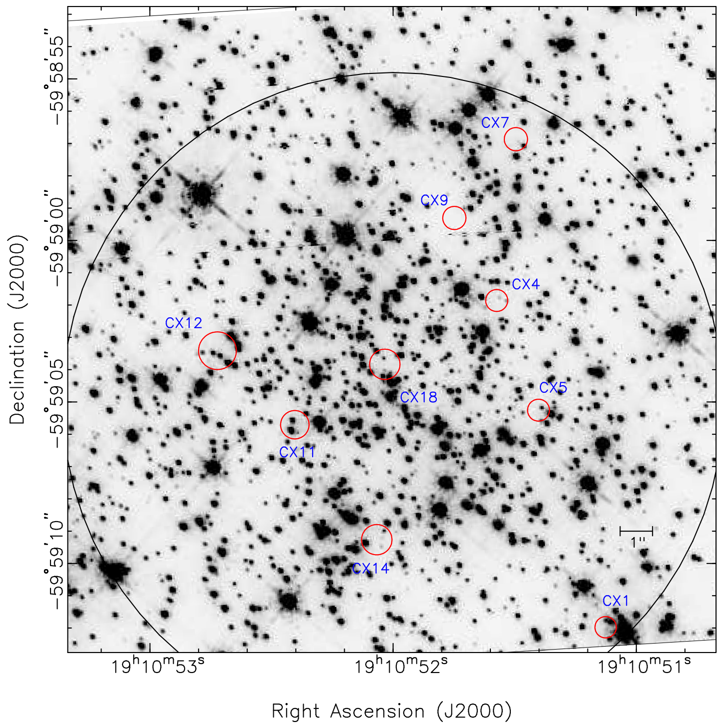

Fig. 5 The image of the center of NGC 6752 in R obtained with HST-WFPC2. The large circle indicates the core radius. The smaller circles give the 95% confidence region within which the optical counterparts of the Chandra X-ray sources must lie. The errors are small because i) the HST image has been brought on absolute astrometry ii) one Chandra source has been identified with a pulsar that has an accurate absolute position.

The largest remaining error is then the error in the pointing direction of Chandra. This error can be reduced once we succeed in securely identifying at least one X-ray source. In the case of NGC 6752 this is a recycled pulsar, PSR 6752 D. This pulsar has an accurate position on the ICRS from radio timing.

The final error circles then are determined by a) the error in the optical positions b) the error in the Chandra pointing direction, determined by the accuracy of the pulsar position on the X-ray image in the Chandra frame and c) for each individual source: the error of the X-ray image in the Chandra frame. The latter error depends on the number of counts (and somewhat on the location in the frame) but usually is less than $0.2''$.

The final identifications are now obtained by inspecting the stars within the error circles in the colour magnitude diagram and in the H α magnitude diagram (Fig.5). Cataclysmic variables are known from studies in the galactic disk to be blue, and often to show the H α line in emission. This puts them to the left of the main-sequence in both frames of Fig.6. Encircled stars in those regions, i.e. those within X-ray error circles, are thus good candidates for being cataclysmic variables. Stars above the main sequence in a colour magnitude diagram are often binaries. Those within an X-ray error circle are good candidates for being magnetically active close binaries.

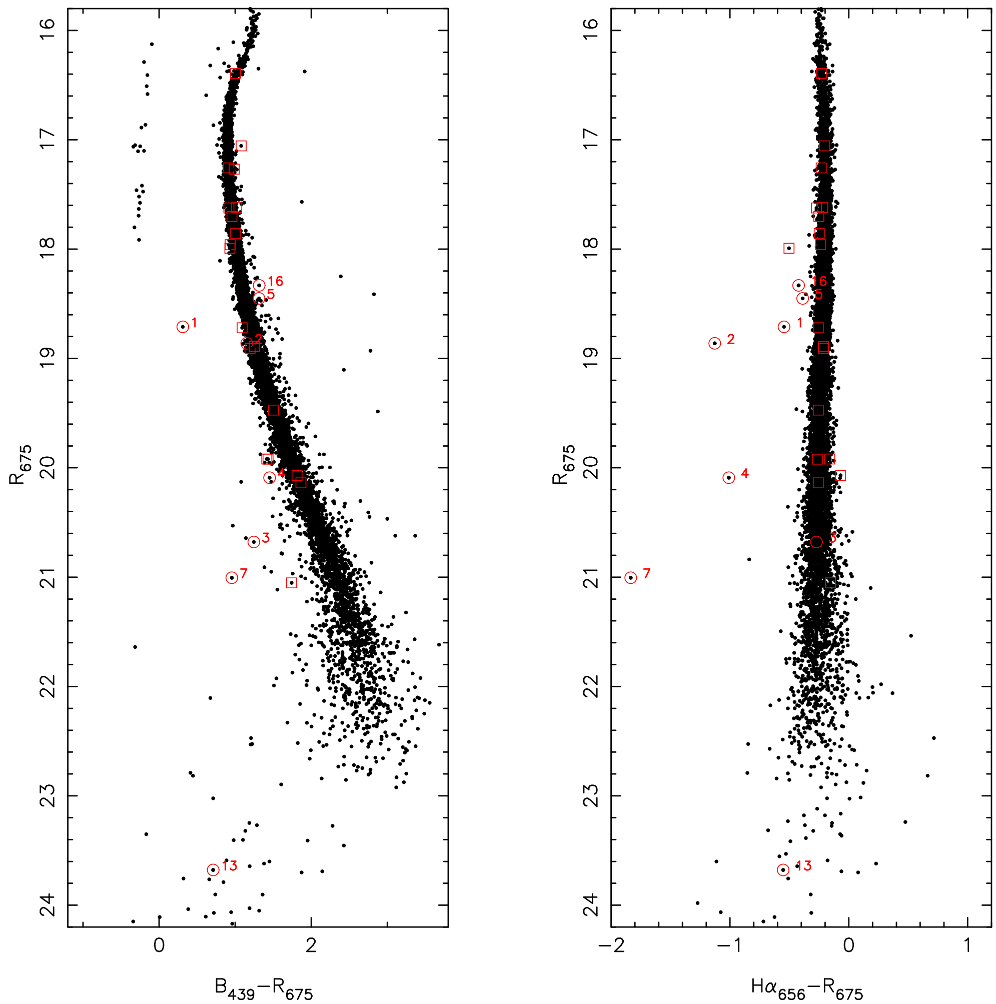

Fig. 6 Colour magnitude diagram (in blue and red, left) and the H α magnitude diagram (in which the strength of the H α line is estimated by comparing the magnitude in the H α filter with that in the broad red filter) of the central region of NGC 6752. Stars within the error circles of X-ray positions are encircled; the numbers refer tot the corresponding X-ray source. Stars to the left of the main sequence in $B-R$ and H$\alpha-R$ are blue and have H α emission, and are probable cataclysmic variables. Encircled stars above the main sequence in $B-R$ are probable magnetically active binaries.

5 EVOLUTION AND FORMATION

The different types of X-ray sources in globular clusters have different evolutionary histories and futures (see reviews by Hut et al. 1992, Verbunt 2003).

The magnetically active binaries are active because tidal interaction forces (one of) the member stars to co-rotate with the orbit. The rapid rotation combines with convection in the star in a dynamo to produce strong magnetic fields, and the loops sticking out of the stellar surface retain hot, X-ray emitting gas. The tidal forces are strong when the radius of the star is a sizable fraction of the distance between the stars, i.e. in close orbits or in binaries with a giant. Remarkably, the magnetically active binaries identified with X-ray sources in globular clusters so far are all main-sequence binaries. They do not evolve much in a Hubble time.

The low-mass X-ray binaries contain neutron stars (or black holes) which accrete matter from a companion that fills its Roche lobe. The mass transfer can be driven because loss of angular momentum shrinks the orbit, in which case $\dot{M}/M \simeq \dot{J}/J$, where M is the mass of the donor, J the angular momentum of the orbit, and the dot indicates a time derivative. In this case the orbit shrinks, and the donor shrinks with it by transferring its outer layers to the compact companion. The orbital period for such binaries is less than 7 hours, for the donor stars in globular clusters which must have masses less than about $0.8\,M_{\odot}$. The mass transfer in wider orbits is driven because the donor star expands as it evolves into a subgiant and giant. In that case $\dot{M}/M \simeq -\dot{R}/R$, where R is the radius of the donor. The binary expands with the donor. At some point, the outer layers of the donor have been transferred in full, and the core then cools into a white dwarf. If the compact star is a neutron star, it has been affected by accretion in three ways: i) its mass has grown ii) its magnetic field has decreased iii) its rotation period has become much shorter. The combination of ii) and iii) implies that the neutron star switches on as a millisecond pulsar when the mass transfer stops. There is appreciable uncertainty about the details of all three effects. First, it is not clear that all the mass lost by the donor actually is added to the neutron star; mass can also be lost from the binary. Second, the physics of field reduction by accretion is not well understood. Third, the spin-up depends on details of the accretion history of the neutron star, which are not clear.

In general the period distribution of low-mass white dwarfs with millisecond companions is such that for many systems the orbit cannot have expanded quite as much as implied by conservation of mass and angular momentum within the binary. This indicates that loss of mass and angular momentum from the binary are important, but we do not understand the details.

Cataclysmic variables in principle evolve along the same lines as low-mass X-ray binaries, except that the accreting star is a white dwarf. More or less by definition, only systems with shrinking orbits are called cataclysmic variables. If the donor is an expanding giant, we refer to the binary as a symbiotic binary. So far, several dozens of cataclysmic variables have been identified in globular clusters, but to our knowledge no symbiotic binaries. One system, AKO 9 in 47 Tuc, has a donor which is larger than a main sequence star, but it may well be that the system will contract after an initial expansion of the orbit.

The formation of the various types of X-ray sources in globular clusters also is varied (e.g. Verbunt 2003). The magnetically active binaries are presumably all primordial binaries, formed with the current members.

In contrast, the low-mass X-ray binaries are formed in dynamical stellar interactions. A field star is deformed by the tidal force of a passing neutron star, and the energy deposited in the tidal bulges is taken from the relative orbital energy: if sufficiently high, this energy transfer can bind the orbit (Fabian et al. 1975). This process is called tidal capture. A neutron star can also take the place of a member in a binary in a close encounter, and this is called an exchange encounter (Hills 1976).

Cataclysmic variables in globular clusters can in principle be formed by the evolution of a primordial binary. Alternatively, the white dwarf can be caught tidally or be exchanged into a binary.

The observation that the number of X-ray sources with luminosities $L_{\rm x} \gtrsim 4 \times 10^{30}\,{\rm erg\,s^{-1}}$ in a globular cluster scales with the estimated number of encounters in the cluster indicates that those X-ray sources are indeed formed via dynamical processes (Pooley et al. 2003). The brighter ($L_x \gtrsim 10^{32}\,\mathrm{erg\,s^{-1}}$) X-ray sources are low-mass X-ray binaries; the other X-ray sources with $L_x \gtrsim 4 \times 10^{30}\,\mathrm{erg\,s^{-1}}$ are mainly cataclysmic variables. Apparently cataclysmic variables in globular clusters are formed mainly via dynamical processes.

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