X-RAY SOURCES IN INTERMEDIATE-AGE AND OLD OPEN CLUSTERS

T.BELLONI[1],

[1] *Astronomical Institute "A. Pannekoek", University of Amsterdam, and Center for High-Energy Astrophysics, Kruislaan 403, 1098 SJ Amsterdam, The Netherlands*

ABSTRACT. I review here the results of X-ray observations of stellar clusters older than 1 Gyr, performed with the ROSAT satellite. Since stellar activity decreases with age, single stars are not expected to emit above the detection threshold of current X-ray missions. Therefore, these campaigns are aimed to the detection of active binaries, whose rotation (and therefore activity) is kept at a high level by the orbital angular momentum. The final goal of these project is to study homogeneous samples of active binaries. A large number of the detected sources is identified with known binaries in the clusters, but some of them have surprising long orbital periods and high eccentricities. These detections have still to be explained. In addition, peculiar systems are also detected, such as blue stragglers and sub-luminous giants: their X-ray emission can provide an insight on their nature.

1. Introduction

Why observe old clusters in X-rays? There are a number of reasons that would not make them promising targets. Old clusters are generally distant and affected by considerable interstellar absorption, making the threshold for X-ray detection high. Moreover, stellar activity depends on stellar rotation (see Pallavicini et al. 1981), which decreases with age due to magnetic braking. As a consequence, single stars older than 1 Gyr are not expected to be above threshold in observations with current X-ray instruments. There is however a class of objects which is expected to show rapid rotation: stars in close binary systems, where the angular momentum of the star is maintained by tidal interaction. Indeed, RS CVn and W UMa systems are known to be strong X-ray emitters (see e.g. Fleming et al. 1989). Therefore, old open clusters offer the opportunity to study homogeneous samples of such binaries in the same way as it is done for single stars, decoupling parameters like distance, age and metallicity. Here I review the results of two ongoing ROSAT campaigns: one to observe old (age $>$ 2 Gyr) open clusters (Belloni, Verbunt & Schmitt 1993, Belloni & Verbunt 1996, Belloni et al. 1998), and another to cover the age gap between those and the Hyades (Belloni & Tagliaferri 1997, Tagliaferri & Belloni 1997, Belloni & Tagliaferri 1998).

2. The clusters

The selection of clusters for the projects has been made following three main criteria: old age ($>$ 1Gyr), low distance ($<$1000 pc, with the exception of NGC 188) and moderate reddening. The main parameters of the six clusters observed so far (age, distance, number of X-ray detected members and number of X-ray detected binaries) are shown in Table 1

Tab. 1 - Old and intermediate-age open clusters observed with ROSAT

Cluster	Age (Myr)	Distance (pc)	Members	Binaries
NGC 188	9000	1600	3	1
M 67	5000	800	22	17
NGC 752	2500	400	6	4
IC 4651	2000	800	2	1
NGC 3680	2000	800	?	?
NGC 6940	1000	800	4	3

After these observations we have a general view of what we can expect from old clusters. Below I summarize the results (the results on NGC 3680 are still too preliminary and will not be included here). I remark that additional optical work is needed in order to complete the identification of the X-ray sources, and therefore additional X-ray identifications with members will be possible. In particular, while clusters like M 67 and NGC 752 are very well studied, much less information is available on clusters like IC 4651: for this cluster, for instance, no radial velocity nor proper motion studies are available in the literature, making the identification work more uncertain.

2.1. M 67

Two partially overlapping ROSAT PSPC pointings to M 67 have been performed (Belloni, Verbunt & Schmitt 1993, Belloni et al. 1998). A total of 59 X-ray sources have been detected in the field, 22 of which are identified with known members of the cluster. Seventeen of these are known binary systems. As expected, most of them have relatively short orbital periods, below 50 days, and most of them are circular. However, three systems have long periods (266, 697 and 1495 days), and four systems have non-zero eccentricity, up to 0.64. Since binaries are expected to circularize before synchronization (but see van den Berg 1998), and since of course we can expect circularization to be effective only on short-period systems, we would expect to detect only circular systems with rather short period. Some of the detections are therefore puzzling. Moreover, four known binaries with periods shorter than 10 days are not detected, although they are within the field of view. In addition to normal binaries, we also detected a number of different systems: a cataclysmic variable, a hot white dwarf (see Pasquini, Belloni & Abbott 1994) and a blue straggler. The cataclysmic variable, a magnetic system with a $\sim$2 hours period is of the AM Her type (Gilliland et al. 1991, Pasquini, Belloni & Abbott 1994). The period is clearly detected in X-rays. Unfortunately, the fact that the distance to this CV is well known, the estimate of its X-ray luminosity is made uncertain by the interstellar absorption. The blue straggler is the first one detected in X-rays. None of the other blue stragglers in the cluster is detected.

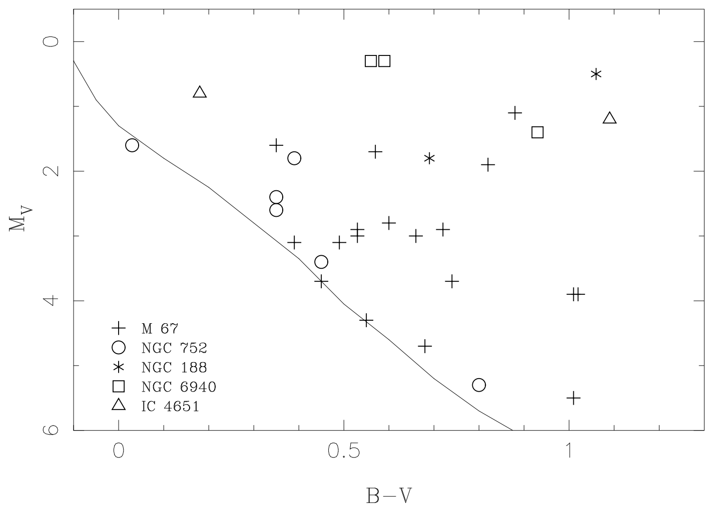

Fig. 1. Color-magnitude diagram containing all the binaries detected in the clusters in the sample. The line is the zero-age main sequence.

2.2. NGC 752

Six known members are currently identified with ROSAT sources (Belloni & Verbunt 1996). Again the majority of them, four, are known to be binaries, and an additional one shows high rotation in its spectral lines. In contrast to M 67, all the detected binaries have very short periods, below 2 days, and are circular. Interestingly, we also detect the only blue straggler of the cluster. Unlike in the case of M 67 (and of the other clusters, see below), none of the red giants is detected.

2.3. NGC 188

This is the oldest cluster in the sample. It was included in the sample despite its large distance (and reddening) in order to extend our study to older ages. Because of this, the angular size of the cluster is small, and the detection threshold is high. We detected three known members (Belloni et al. 1998). Two of them are giants, one of which is a probable FK Com system, while another is a contact system. Eight contact systems are known, out of which we detect the one with the longest period (2.8 days). This is not surprising, as all the others lie on the main sequence and are most likely below the detection threshold because of their lower saturation level (see below).

2.4. NGC 6940

Four members are detected in the PSPC observation (Belloni & Tagliaferri 1997, Tagliaferri & Belloni, 1997). Out of these, three are known binaries. While two of them are the shortest binaries known in the cluster (periods 54 and 83 days) and are circular, the third one is surprisingly the one with the longest period (3595 days) and has an eccentricity of 0.3.

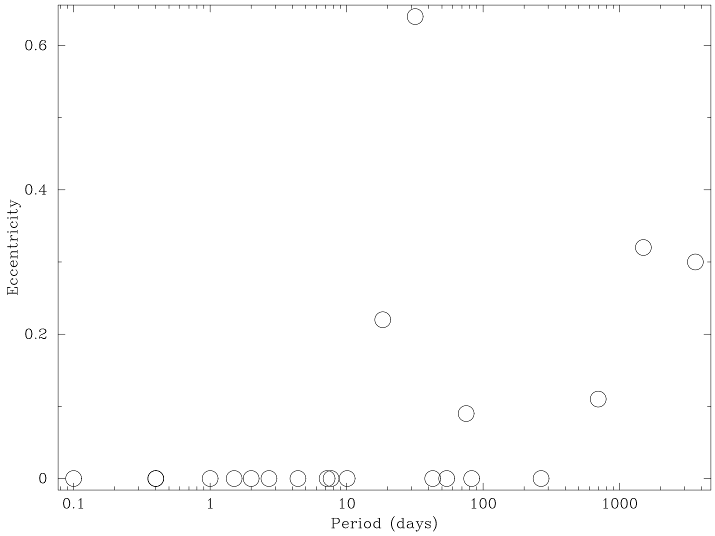

Fig. 2. Distribution of period and eccentricity for the binaries discussed in the text.

2.5. IC 4651

Only two members are detected in this cluster. (Tagliaferri & Belloni, 1997, Belloni & Tagliaferri 1998). Both of them are interesting systems: one is a binary with a period of 75 days and a small eccentricity, the other is a blue straggler, possibly also a binary system.

3. Discussion

Overall, our knowledge of X-ray active binaries in old open clusters is still poor. Even with the current wealth of data, a large effort of optical follow-up is needed before reaching the goal of studying the phenomenon of coronal activity in homogeneous samples. A complete identification effort is needed. The current identifications, based only on spatial coincidence, have to be confirmed, ruling out the possibility of, say, background extragalactic sources. Spectroscopic observations are necessary to look for signs of binarity in those stars where no binary period has been found (or looked for), for indications of the presence of a third star in those known as binaries, and for the detection of indicators of chromospheric activity. Optical follow-up observations have been started for M 67 (see Pasquini, Belloni & Abbott 1994, Pasquini & Belloni 1994, Pasquini 1997, Pasquini & Belloni 1998) and more campaigns are currently planned.

Nevertheless, a number of considerations can be already made, although most of them are questions rather than answers. In Figure 1 a color-magnitude diagram containing all the detected binaries in the five clusters is shown. The diagram is so well populated that it is easy to recognize the turnoff points for M 67 and NGC 752. Binaries are detected from all parts of the color-magnitude diagram, even on the blue straggler part and on regions where no stars would be expected.

Most of the cluster members that are detected are binaries. In binary systems, tidal interaction acts to synchronize the stars' rotation to the orbital revolution and to circularize the orbit. For this to happen, the period must be short, less than 8–10 days for main-sequence stars and less than 150 days for binaries containing a giant (see Verbunt & Phinney 1995). It is therefore rather surprising to detect systems with periods as large as 10 years, and with large eccentricities. The distribution of periods and eccentricities for the binaries for which a period is known is shown in Figure 2. All detected binaries with period shorter than 10 days are circular, while above 10 days non-zero eccentricities start to be found. Additional optical investigation is needed in order to rule out the possibility of the presence of a third star in these systems, and to confirm the identification. The detection of such binaries is not understood.

Figure 3 contains the same data as Figure 1, but with symbol size proportional to the X-ray luminosity in the ROSAT band. As in the case of RS CVn systems in the field (Dempsey et al. 1993), one can see that the higher X-ray luminosities come from evolved stars (see Belloni & Verbunt 1996). This is in agreement with the presence of a saturation effect: if the X-ray flux per unit area reaches saturation at high rotation rates, the larger the surface of the star, the higher its total saturation luminosity will be (Vilhu 1987).

Are all the detected members binaries? Some of them have been included in binary searches, with negative results (for instance, the blue straggler S1082 in M 67 and VR108 in NGC 6940). It is possible that these stars are indeed single, in which case their high level of X-ray emission would not be explained.

All the binaries in the sample have X-ray luminosities in the range 0.7–8.0 $\times 10^{30}$ erg/s (in the 0.1–2.4 keV band), with the exception of the CV n M 67 (3.5×10^{31}erg/s, L241 in IC 4651 and the exceptionally bright contact system V8 in NGC 188 (1.3×10^{32} erg/s).

It is now clear that, besides binaries, X-ray surveys of old and intermediate-age open clusters lead to the detection of a number of peculiar systems. Besides the how white dwarf and the magnetic CV in M 67 (see above), three blue stragglers are now detected by ROSAT. If these are short period binaries, the same argument outlined above would apply to explain their X-ray luminosity. H45 in NGC 752 is indeed a binary (Latham, private communication), and S1082 has been claimed to be an eclipsing binary with a 1 day period (Goranskij et al. 1992) although this has not been confirmed by radial velocity measurements. However, a correspondingly high level of chromospheric emission has not been found for S1082 (Pasquini & Belloni 1998), and all the other blue stragglers in M 67 and IC 4651 have not been detected. In any case, the detection of X-ray emission from blue straggler might be of help in determining the reason for their peculiar position in the C-M diagram.

As an example of a peculiar system among the detected X-ray sources one can look at the case of S1040 in M 67, located to the left of the giant branch (see e.g. Belloni, Verbunt & Schmitt 1993). It has a period of $\sim$42 days and zero eccentricity. The companion of the observed giant has recently been found to be a white dwarf (Landsman et al. 1997), as already suggested by Verbunt & Phinney (1995) in order to explain the circularization of the orbit. This system has probably undergone a complex evolution, passing through a phase of mass-transfer blue straggler. The observed X-rays are coming from the active giant.

Although the case of S1040 is now understood, other systems still are in need of

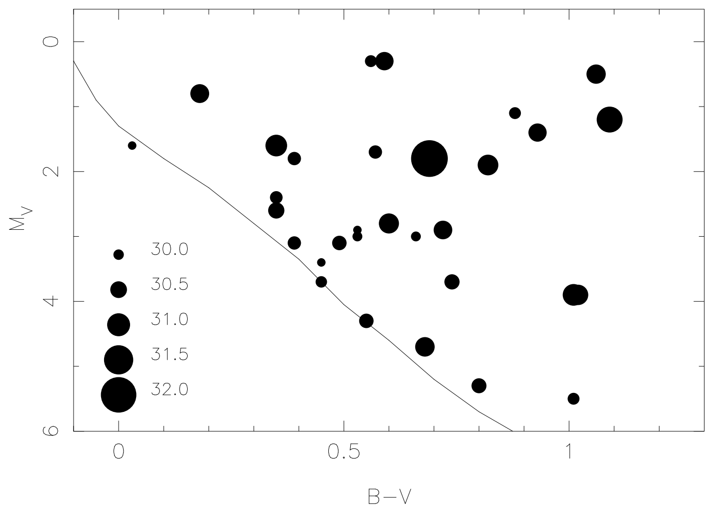

Fig. 3. Same as Figure 1, but with the symbol size proportional to the X-ray luminosity in the ROSAT band (0.1–2.4 keV).

an explanation. Particularly interesting is the case of the two sub-luminous giants in M 67, S1113 and S1063, both detected in the ROSAT observations (Belloni et al. 1998). They can easily be identified in Figure 1 as the two close crosses at B–V∼1. S1113 has a period of a few days and is circular (Mathieu, priv. comm.). Spectroscopically it has been seen that one star rotates very fast (van den Berg et al. 1998). Its position in the color-magnitude diagram can be explained as the result of ongoing mass transfer (see Kippenhan & Weigert 1967). The case of S1063 is more difficult to explain. It has a period of 18 days and it is quite eccentric (Latham et al. 1992). The difficulty is to reconcile X-ray emission, sub-luminosity and eccentricity. Mass transfer can explain the first two, but not the third. Alternatively, the system can be already synchronized without being circularized (see van den Berg et al. 1998). This would account for X-rays and eccentricity, but would leave the sub-luminosity problem open. This source is still puzzling.

4. Conclusions

With ROSAT we have obtained a sizeable sample of X-ray emitting binaries in old and intermediate-age open clusters, and further identifications will certainly increase their number. Some of them are precisely the type of systems we expected, but some of them have properties that would not make them strong X-ray emitters according to our present knowledge. Furthermore, some of the systems that we would expect to detect are not in the sample. It is clear that a large amount of optical follow-up will be necessary before we are able to draw firm conclusions on the X-ray properties of homogeneous samples of active binaries.

Acknowledgements

This work was supported in part by the Netherlands Organization for Scientific Research (NWO) under grant PGS 78-277

References

Belloni, T., Verbunt, F., Schmitt, J.H.M.M.: 1993, *Astron. Astrophys.* **269**, 175
Belloni, T., Verbunt, F.: 1996, *Astron. Astrophys.* **305**, 806
Belloni, T., Tagliaferri, G.: 1997, Astron. Astrophys., in press.
Belloni, T., et al.: 1998, in preparation.
Dempsey, R.C., Linsky, J.L., Schmitt, J.H.M.M., Fleming, T.A.: 1993a, *Astrophys. J.* **413**, 333
Dempsey, R.C., Linsky, J.L., Fleming, T.A., Schmitt, J.H.M.M.: 1993b, *Astrophys. J. Suppl.* **86**, 59
Fleming, T.A., Gioia, I.M., Maccacaro, T.: 1989, *Astron. J.* **98**, 692
Goranskij, V.P., et al.: 1992, *Astron. Astrophys. Trans*, **2**, 201
Kippenhan, R., Weigert, A.: 1967, *Zeits. f. Astroph.*, **65**, 251
Landsman, W., Aparicio, J., Bergeron, P., Di Stefano, R., Stecher, P.: 1997, *Astrophys. J.* **481**, L93
Latham, D.W., Mathieu, R.D., Milone, A.E.A, Davis, R.J.: 1992, in *Binaries as Tracers of Stellar Formation*, A. Dunquennoy & M. Mayor (eds.), Cambridge Univ. Press, Cambridge, p132
Pallavicini, R., Golub, R., Rosner, R.:1981, *Astrophys. J.* **248**, 279
Pasquini, L., Belloni, T., Abbott, T.M.C.: 1994, *Astron. Astrophys.* **290**, L17
Pasquini, L., Belloni, T., 1994, in *Cool Stars, Stellar Systems, and the Sun*, J.-P. Caillault (ed.), ASP Conference Series, 64, 122
Pasquini, L.: 1997, these proceedings
Pasquini, L, Belloni, T.: 1998, in preparation.
Tagliaferri, G., Belloni, T., 1997: these proceedings.
van den Berg, M., et al.: 1998, in preparation.
Verbunt, F., Phinney, E.S.: 1995, *Astron. Astrophys.* **296**, 709
Vilhu, O.: 1987, in *Cool Stars, Stellar Systems, and the Sun*, J.L. Linsky & R.E. Stencel (eds.), Lect. Notes in Phys., Springer Verlag, Berlin, p. 291