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Soft X-ray emission from intermediate-age open clusters: IC 4651

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Abstract. We present the results of soft X-ray observations of the intermediate-age open cluster IC 4651 performed with the ROSAT PSPC. We detected 25 sources. Two are identified with a giant binary and a blue straggler respectively, both belonging to the cluster, and two with probable main-sequence members. Two other cases have ambiguous identification. Of the five binaries known in the cluster, the one detected in X rays is the only one whose period is short enough to maintain fast rotation and therefore strong stellar activity at a high age. The detected blue straggler is probably binary, suggesting that binarity is the key to producing a high level of X-ray emission. It is the third blue straggler detected in X rays. The remaining sources need to be identified through optical follow-up.

Key words: stars: activity – open clusters and associations: individual: IC 4651 – X-rays: stars

1. Introduction

Stellar activity depends crucially on the star's rotation rate (Pallavicini et al. 1981), which decreases with age because of magnetic braking (e.g. Skumanich 1972). Thus, open clusters are crucial to distinguish between truly evolutionary effects on stellar activity and effects primarily due to the rotation rate itself. The first X-ray observations of open clusters were carried out with the *Einstein* satellite (Stern et al. 1981, Caillault & Helfand 1985, Micela et al. 1988, Schmitt et al. 1990, Micela et al. 1990), but these observations have been carried out in a more systematic way with the ROSAT satellite (Stern et al. 1992; Stauffer et al. 1994; Patten & Simon 1993; Randich & Schmitt 1995; Randich et al. 1995, 1996a,b). Various clusters of different ages have been studied in order to understand the evolution of stellar activity with age (see Randich 1997 for a review). Before ROSAT, the attention has been concentrated mainly on young clusters (30 to 700 Myr). ROSAT performed the first observations of the old open cluster M 67 (∼5 Gyr, Belloni et al. 1993, Belloni et al. in preparation) and NGC 188 (∼9 Gyr, Belloni et al., in preparation), leading to the detection of a number of sources. Indication of chromospheric activity has been found for most of the optical candidates (Pasquini & Belloni 1994). In contrast to younger clusters, clusters older than ∼ 1 Gyr are not expected to contain rapidly-rotating single late-type stars, and therefore strong X-ray sources. However, there are stars older than ∼ 1 Gyr that show rapid rotation: these are members of close binary systems, where tidal interaction prevents the stars from losing angular momentum; well-known examples are the RS CVn binaries. The observations of these clusters have led to the detection of such binaries, and also to a number of peculiar and interesting objects, such as white dwarfs, cataclysmic variables, blue stragglers and wide/eccentric binaries.

In the framework of a project to cover the X-ray observational gap between old and young clusters, we observed the intermediate age open clusters NGC 752 (∼2 Gyr, Belloni & Verbunt 1996), NGC 6940 (∼1 Gyr, Belloni & Tagliaferri 1997) and IC 4651 (∼2.5 Gyr) with the ROSAT PSPC. Moreover, ROSAT HRI observations of the clusters NGC 3680 (∼2 Gyr) and NGC 2527 (∼ 1 Gyr) were made in 1997 and are currently being analyzed. In the PSPC observation of NGC 752, 49 X-ray sources have been detected; seven of them are identified with optical cluster members, four of which are short period binaries, one is a rapid rotator and one is a blue straggler (Belloni & Verbunt 1996). In the PSPC observation of NGC 6940 18 sources were detected, four of which are identified with members of the cluster with a fifth source a suspected member. In NGC 6940, a high fraction of the detected members are binaries: three out of four of the identified members are among the only six binaries known in the cluster. These observations give also evidence for the presence of a saturation level, at which the whole surface of the star is chromospherically active (see Belloni 1998 for a review).

Here we present the results obtained for IC 4651. This open cluster has an estimated age of ~ 2.5 Gyr and a distance of $\sim 800-900$ pc (Eggen 1971, Anthony-Twarog et al. 1988). It has a relatively constant reddening, estimated to be E(B-V)$=0.15$ by Eggen (1971) and E(B-V)$=0.09$ by Anthony-Twarog & Twarog (1987), and an angular size smaller than $\sim 15'$. The paper is organized as follows: in Sect. 2 we present the PSPC observation and our data analysis, in Sect. 3 we present and discuss the results and in Sect. 4 we compare them with those of other open clusters and discuss the implications.

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2. Observations

We observed IC 4651 with the Position Sensitive Proportional Counter (PSPC) on board ROSAT between 1993 Sep 9th 06:05 UT and 1993 Sep 10th 18:30 UT, for a net observation time of 15200 s. A description of the satellite and the instrument can be found in Trümper (1983) and Pfeffermann et al. (1986) respectively. The data were analyzed using the EXSAS package (Zimmermann et al. 1994). Due to the degradation of the Point Spread Function at large off-axis angles, we limited our analysis to the inner 20′ of the field of view. We followed the standard procedure within EXSAS for the detection of sources. First we produced a background map by removing all possible sources and smoothing the resulting image. Then we ran a Maximum Likelihood (ML) technique to test for deviations from a purely background distribution (Cruddace et al. 1988). The ML threshold for detection was set at 10, corresponding to a single-trial probability of a chance detection of 4.5×10^{-5}. We applied the procedure described above for three PSPC channel bands: 11–240 (total band T, corresponding roughly to 0.1–2.4 keV), 11–40 (soft band S, 0.1–0.4 keV) and 41-240 (hard band H, 0.4–2.4 keV).

With this procedure, we detected 24 sources in the T band, 26 in the H band and 3 in the soft band. A few of these sources turned out to be either double detections (in some case the ML program detects the same source more than once) or very broad excesses due to inhomogeneities of the background (which are too broad to be point sources and too weak to be statistically significant extended sources). After exclusion of these sources we cross-correlated the three lists, producing a final list of 25 sources detected in the inner 20′ of the PSPC detector. A summary of the sources is given in Table 1. The reported positions have been corrected for the offset ($\sim 10''$) between the X-ray detector and the optical star sensor by means of a cross-correlation with stars in the Space Telescope Guide Star Catalog (GSC: Lasker et al. 1990). Since eight sources could be identified with GSC entries, the boresight correction obtained with this procedure is robust and allows us to remove all systematic effects. Therefore, we added only a systematic error of 3″ to the 90% error radii, in order to account for residual uncertainties.

3. Results

3.1. Identifications

As mentioned in the previous section, eight X-ray sources could be identified with GSC stars. In order to obtain identifications with possible members of the cluster, we cross-correlated our source list with the optical catalogs of stars in the field of IC 4651. Four such lists have been presented: Eggen (1971), Lindoff (1972), Anthony-Twarog & Twarog (1987), and Anthony-Twarog et al. (1988). We consider a tentative identification if a catalogued star falls within the 90% error box of an X-ray source and no other stars are present in the error box. From these four lists we found an unambiguous possible counterpart to four X-ray sources. Two additional sources (#11 and #18) have more than one optical star within their error boxes, complicating the identification procedure. For the sources that cannot be identified in this way and for those falling outside the regions covered in the references mentioned above, we used the Guide Star Catalog and examined the Digitized Sky Survey (Postman et al., in preparation). The proposed identifications are summarized in Table 1.

Currently there are neither radial velocity nor proper motion studies published in the literature for this cluster, and therefore no firm determination of membership is available. However, the relative compactness and richness of the cluster (a hundred stars within an angular diameter of $\sim 15'$) ensures that most of the stars within this radius are indeed members, as can be easily seen from the color-magnitude diagram (Fig. 1). Given the angular size of the cluster, it is unlikely that those X-ray sources outside the region covered by optical studies are related to the cluster, even if they have a relatively bright optical counterpart. Anthony-Twarog & Twarog (1987) derive an indication of membership from ubvyH_β photometry. In this way, they can separate probable single members from non-members and binaries, but cannot discriminate between the latter two.

As can be seen from Table 1, six X-ray sources have possible counterparts listed in Lindoff (1972), Eggen (1971) or Anthony-Twarog et al. (1988). Source #8 is identified with the red giant L241; this star is included in a list of five binaries discovered by Mermilliod et al. (1995) in a sample of 20 red giants in the IC 4651 field. It is a single line spectroscopic binary with a period of 75.17 days and an eccentricity of 0.09 ± 0.02. Source #10 is identified with L234 and lies on the cluster main sequence (see Fig. 1), as does source #12, identified with E51. Source #14, is identified with the blue straggler L44. Anthony-Twarog & Twarog (1987) find it to be a binary member of the cluster on the basis of their ubvyHβ photometry. In the X-ray error box of source #18 there are two weak stars studied by Anthony-Twarog et al. (1988). In Fig. 1 the two possible counterparts are represented by triangle symbols. Finally, the position of source #11 coincides with a conglomerate of at least six stars. In Fig. 1 we plot the three brightest of these, which we regard as the most likely counterpart candidates, as crosses. All the sources marked in Table 1 with 'OUT' as optical ID are outside the regions studied by the above authors and probably are not cluster members. We identified four of them with stars from the Guide Star Catalog, one with a SAO star, while to the other six we tentatively assigned a magnitude using the Digitized Sky Survey (Postman et al., in preparation). The remaining eight X-ray sources do not have visible optical candidates in their error boxes and are not listed in Table 1; two of them (#13,21) lie in the central part of the cluster.

IC 4651 is located at low galactic latitude ($b_{II} \sim -8^\circ$). The total galactic interstellar absorption along the line of sight, estimated from radio data, is $N_H \sim 1.7 \times 10^{21} cm^{-2}$ (Dickey & Lockman 1990). To estimate the number of field sources expected, we assumed a typical power-law spectrum with photon index 2.0 and the above value of N_H. With these parameters our limiting count rate of ∼1 ct/ksec translates into a flux limit of 2.0×10^{-14} erg $cm^{-2}s^{-1}$ (in the 0.4–2.5 keV band). From the log N–log S distribution derived from the ROSAT Lock-

Table 1. Sources detected in the IC 4651 field. The columns give source ID number, position, 90% confidence radius, count rate, channel band to which the count rate corresponds (T=11–240, H=41–240), hardness ratio HR2 (see text) for the brightest sources (above 100 detected counts),ID of the optical object (L: Lindoff 1972; E: Eggen 1971; AT: Anthony-Twarog et al. 1988; OUT: outside the optical fields studied by the authors mentioned above), V and $B-V$, X-ray luminosity in the 0.1–2.4 keV band estimated with a typical X-ray spectrum of RS CVn (see text), and remarks.

no.	α(2000)	δ(2000)	Δr	Rate (cts/ks)	B	HR2	Opt. ID.	V	$B-V$	L_X (erg/s)	remarks
1	17h23m15.0s	-49°56′17”	8”	8.4± 1.5	T	–0.27±0.16	OUT	10.60			GSC
2	17h23m38.2s	-50° 0′16”	11”	3.0± 0.6	T		OUT	9.36			SAO 227893
3	17h24m11.4s	-49°44′26”	17”	1.8± 0.5	H		OUT	10.74			GSC
4	17h26m08.0s	-49°44′53”	18”	5.4± 0.8	H		OUT	∼16			POSS
5	17h23m48.3s	-49°45′50”	12”	3.3± 0.6	H		OUT	11.72			GSC
6	17h24m22.8s	-49°46′40”	12”	2.6± 0.5	H						
7	17h25m 4.0s	-49°47′36”	15”	1.4± 0.4	H		OUT	∼14			POSS
8	17h24m56.5s	-49°50′4”	4”	11.3± 0.9	H	0.36±0.08	L241	10.97	1.18	$1.8 \cdot 10^{31}$	P=75d, e=0.09
9	17h23m36.7s	-49°53′34”	17”	1.3± 0.4	H						
10	17h25m29.5s	-49°54′7”	8”	2.7± 0.5	H		L234	14.14	0.63	$4.3 \cdot 10^{30}$	
11	17h24m44.8s	-49°54′58”	13”	1.7± 0.4	H		L11	11.5	0.7	$2.7 \cdot 10^{30}$	
”							L12	11.9	0.4	”	
”							L13	11.8	0.8	”	AT 6
”							L77	13.32	0.60	”	E79
”							AT 50	15.21	1.32	”	
”							AT 60	15.52	0.95	”	
”							AT 119	16.93	0.86	”	
12	17h24m39.1s	-49°56′54”	12”	1.0± 0.3	H		E51	14.82	0.74	$1.6 \cdot 10^{30}$	AT 45
13	17h25m10.2s	-49°55′59”	10”	1.5± 0.4	H						
14	17h25m 5.3s	-49°56′44”	7”	3.1± 0.5	H		L44	10.54	0.27	$5.0 \cdot 10^{30}$	BS (A5)
15	17h23m37.6s	-49°57′16”	13”	1.4± 0.4	H		OUT	∼14			POSS
16	17h26m 9.8s	-49°58′3”	14”	2.0± 0.5	H		OUT	∼16			POSS
17	17h23m25.6s	-49°58′9”	13”	1.9± 0.4	H						
18	17h24m36.6s	-49°59′17”	10”	1.6± 0.4	H		AT 4218	15.15	1.06	$2.6 \cdot 10^{30}$	
”							AT 4219	15.81	0.76	”	
19	17h25m55.3s	-50° 0′5”	6”	7.5± 0.8	H	0.19±0.11					
20	17h26m20.2s	-50° 1′24”	14”	2.4± 0.5	H						
21	17h24m42.1s	-50° 1′42”	10”	1.3± 0.6	H						
22	17h23m46.2s	-50° 2′52”	7”	5.0± 0.6	H		OUT	11.65			GSC
23	17h23m37.7s	-50° 3′15”	6”	11.3± 0.9	H	0.49±0.08					
24	17h25m45.2s	-50° 4′20”	17”	4.3± 0.7	H		OUT	>16			POSS
25	17h25m 0.1s	-50° 5′11”	5”	6.7± 0.7	H	0.33±0.11	OUT	∼13.5			POSS

man hole deep survey (Hasinger et al. 1997), we estimate that roughly 15 detections of extragalactic sources are expected in our observation. All the sources without a POSS optical counterpart are therefore most likely extragalactic, as well as some of the weak identifications outside the region of the cluster.

3.2. X-ray properties

The number of counts detected from most of the sources is too low to produce meaningful hardness ratios. All sources but three are not detected in the soft ROSAT band, due to the relatively large value of the interstellar absorption in front of the cluster. In order to estimate the X-ray luminosity in the ROSAT band for the detected members, we adopted a spectral model typical of RS CVn binaries. Following Dempsey et al. (1993a), who studied the full sample of RS CVn binaries detected in the RASS, we used a two-temperature thin emission plasma model (according to Raymond & Smith 1977). The parameters used are the average of the values in Dempsey et al. (1993a): kT_{low}= 0.175 keV, kT_{high}=1.4 keV, $\mathrm{EM}_{high}/\mathrm{EM}_{low}$=6. For each star we used a value of interstellar absorption $\mathrm{N}_H = 5.6 \times 10^{20}$, as derived from the most recent estimate of E(B–V)=0.09 (see Anthony-Twarog & Twarog 1987). The derived X-ray luminosities, assuming a distance of 850 pc (Eggen 1971, Anthony-Twarog & Twarog 1987), are reported in Table 1. Although the detections correspond to the hard PSPC band (0.4–2.4 keV), the values are given for the full PSPC range 0.1–2.4 keV to allow comparison with other systems. We estimate that the uncertainties on the derived luminosities, due to a different value of the temperatures and/or EM ratio but still within the typical range observed for coronal sources, are up to 50%.

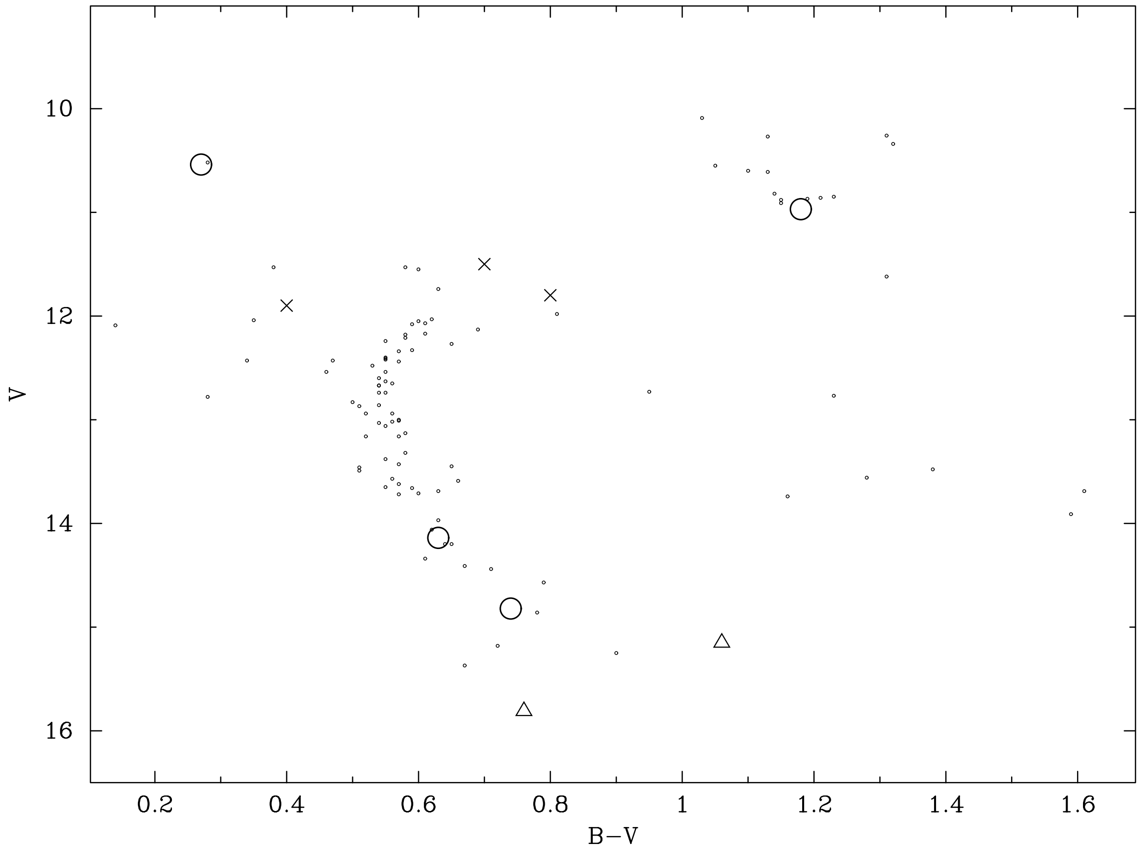

Fig. 1. Color-magnitude diagram for IC 4651 (data from Anthony-Twarog et al. 1988). Circles are X-ray detections with a likely member, crosses and triangles are stars within the X-ray error box of sources #11 and #18, respectively.

For the five brightest X-ray sources we calculated the value of the ROSAT hardness ratio HR2=(D–C)/(D+C), where C and D are the counts in the channel range 52–90 (0.5–0.9 keV) and 91–201 (1.0–2.4 keV) respectively (see Table 1). We expect a value of 0.32 from the model adopted for the flux conversion (see above). As one can see, the detected binary (#8) has a HR2 value compatible with the expectation from active binary sources.

4. Discussion

The age of IC 4651 is about twice that of NGC 6940 and similar to that of NGC 752. As in the case of NGC 752 (Belloni & Verbunt 1996), we expect to detect coronal sources only if they are in binary systems; moreover, due to saturation effects one would expect to detect more easily giant stars than main sequence stars (see discussions in Stauffer et al. 1994; Belloni & Verbunt 1996; Belloni & Tagliaferri 1997). As can be seen from Fig. 1, in IC 4651 there are more than a dozen giants. Five of them are found to be binaries by Mermilliod et al. (1995). However, only one of them has a period short enough to sustain a high level of stellar activity, and this is the binary we detect as an active X-ray source. In this scenario, one expects the stars to co-rotate and therefore the orbit to be circular. This binary is slightly eccentric (e=0.1), but its characteristics are compatible with co-rotation (see Verbunt & Phinney 1995). This is also the brightest source of the six that we suppose to be at the cluster distance, in agreement with the presence of a saturation level, which is higher for evolved stars (see Belloni & Verbunt 1996).

In NGC 6940 we had not detected main sequence stars, but only giants. Of these, two are not classified as binaries; one in particular has been extensively studied (Mermilliod & Mayor 1989) and is very unlikely to be a binary (see Belloni & Tagliaferri 1997). Thus, their detection in the X-ray band is puzzling. On the contrary, in IC 4651 of all known giants only one, a binary, is detected. Two other stars lying on the cluster main sequence are also detected. Given the age of the cluster, we expect them to be binaries. At the bottom end of the cluster main sequence, somewhat offset from it, lie the two possible counterparts of source #18. They could be either field stars or weak members of the cluster.

In the error box of source #11, which is only 13 arcsec, there are at least seven stars, which look like a sub-cluster. The three brightest of these stars are plotted as crosses in Fig. 1. If these stars are all members of the cluster, then one is a blue straggler (i.e. it lies in a region of the color-magnitude diagram occupied by blue stragglers), while the other two are stars in the process of evolving toward the red giant branch. The possibility cannot be ruled out that more than one of these stars contribute to the detected X-ray emission.

Finally, source #14 is identified with a blue straggler, found by Anthony-Twarog & Twarog (1987) to be a binary. This is the third blue straggler detected in the X-ray band, the other two being in M67 and NGC 752 respectively. Of all blue stragglers known in the old and intermediate-age open clusters that we studied, only three are detected in X rays. All three have measurements that indicate binarity (see Belloni 1998), and once again this is probably the key to X-ray emission. These are not the only binaries know among the blue stragglers in these clusters, showing that binarity does not imply strong stellar activity per se. One of the two stars also has to be of late spectral type in order to have an enhanced dynamo activity, like in Algol systems.

For the sources marked with 'OUT' in Table 1 we have no color information; however, from their magnitudes, most of them should be stars. They lie outside the inner 10 arcmin diameter region of the cluster and are probably non-members. We have already planned follow-up optical observations to determine the physical nature of all detected X-ray sources in the IC 4651 field.

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