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ASTRONOMY AND ASTROPHYSICS

Optical identification of ROSAT sources in M 67: activity in an old cluster*

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Abstract. We present optical identification and high-resolution spectroscopy of ROSAT sources in the field of the old open cluster M 67. For the first time it is possible to analyze coronal and chromospheric activity of active stars in a solar-age cluster, and to compare it with field stars. ROSAT observed the high X-ray luminosity tail of the cluster sources. In agreement with what expected from studies of field stars, most of the detected X-ray sources are binaries, preferably with short periods and eccentric orbits. In addition, several of the M 67 ROSAT sources have peculiar locations in the cluster colour-magnitude diagram. This is most likely due to rather complex evolutionary histories, involving the presence of mass transfer or large mass losses.

The X-ray luminosity of the sources does not scale with the stellar parameters in an obvious way. In particular, no relationship is found between coronal emission and stellar magnitude or binary period. The Ca II K chromospheric flux from most of the counterparts is in excess to that of single stars in the cluster by one order of magnitude. The X-ray luminosity of the sources in the old M 67 is one order of magnitude lower than the most active active binaries in the field, but comparable to that of the much younger binaries in the Hyades.

Key words: stars: binaries: close – stars: coronae – stars: chromospheres – open clusters and associations: individual: M 67 – X-rays: stars

1. Introduction

The study of chromospheric and coronal activity has progressed impressively in the last two decades, thanks to the launch of X-ray satellites. Coronal sources have been detected in X rays all over the cool part of the H-R diagram (Vaiana et al. 1980) and active binaries of the RS CVn type have soon been recognized as powerful X-ray emitters (Walter et al. 1980).

With the advent of the ROSAT satellite and its all-sky survey, a complete X-ray study of known active binaries has been possible (Dempsey et al. 1993a,b). A large number of previously unknown coronal active stars is becoming available (see e.g. Metanomski et al. 1998), with interesting consequences on our understanding of the population of young stars in the solar neighborhood (Guillout et al. 1998).

While the general framework of dependence of X-ray emission on stellar rotational velocity (and then stellar age) has been established long time ago (Pallavicini et al. 1981), there still remain many uncertainties about which stellar parameters affect the coronal emission in late-type stars.

We know, for instance, that old stars may preserve a high level of X-ray emission if they are in binary systems, where a high rotational velocity can be maintained through tidal interaction, but it is not clear which role stellar mass, radius, orbital period and eccentricity play in determining the level of activity.

One of the most relevant limitations is that, since most studies are performed in field samples, it is difficult to determine precisely the characteristics of the studied objects. Stars with different (but poorly determined) masses, ages and possibly evolutionary histories are often compared.

The study of clusters, where ages, masses, and evolutionary status of the counterparts of X-ray sources can be well established, is a necessary step forward. In this framework, not only ROSAT observations of young clusters have provided new insight to the discussion on the age-activity relationship (see e.g. Randich and Schmitt 1995), but for the first time it has also been possible to detect coronal sources in old clusters, i.e. with ages comparable with the Sun.

With the ROSAT observations of M 67 and other intermediate age clusters, Belloni et al.(1993, 1996, 1997) allowed to extend the study of the evolution of coronal activity to systems with age up to $\sim$ 6 Gyrs. By examining these coeval samples, these observations allow the study of active coronae from a different, unique perspective: it is possible to investigate which stars (or stellar systems) show the highest activity level in samples so old that the emission from single, solar-type stars is expected to be very low.

The ROSAT observations require a follow up at different wavelengths, in order to :

– Confirm the identification of the optical counterparts. In these clusters the stellar density is rather high, and more than one source may be contained in the ROSAT error box.

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* Based on observations collected at ESO, La Silla

As an example of the relevance of this issue, the reader can compare the results of the present work (summarized in Table 1) with those of Belloni, Verbunt & Schmitt (1993), based only on X-ray and general optical information, but not on a detailed follow up.
– Study in more detail the characteristics of the sources, their binary nature, X-ray and chromospheric emission.
– Compare the observed characteristics with those of field stars.

In this work, we present the identification and the study of the ROSAT counterparts of the old open cluster M 67 (Belloni, Verbunt & Schmitt 1993). A second, longer ROSAT pointing to M 67 has been performed (Belloni, Verbunt & Mathieu in preparation): where possible, the results from this observation have been included in the present paper.

M 67 is a very interesting target, not only because its age and metallicity are similar to those of the Sun, but also because the cluster has been subject to several photometric and spectroscopic studies which have led to detailed membership determinations (Sanders 1977, Girard et al. 1989), a large amount of data on binary stars (Latham et al. 1992), photometric variables, W UMa candidates (Gilliland et al. 1991), and blue stragglers (Mathys 1991).

This large body of ancillary data makes M 67 one of the best studied clusters; one AM Her system and a hot white dwarf belonging to the cluster have already been confirmed within this identification project (Pasquini et al. 1994a).

2. The observations

The observations were carried out at ESO, La Silla, over the period 1992-1995, using a variety of instruments and telescopes. We stress that, being mainly interested in the coronal counterparts of ROSAT detections, we did not attempt a complete identification of all the sources, but only of the possible coronal cluster members. This implies that, when only optically faint candidates are within the ROSAT error box, observations were not always pursued further.

First, observations were carried out at the ESO 1.52m telescope equipped with the B&Ch spectrograph (Turatto 1997): with a resolution of 2 Å/pixel and a 2048 pixel CCD, the range 3700-7600 Å was covered. All objects within the reach of the telescope-spectrograph combination were observed, within $\sim 40''$ from the nominal ROSAT source in order to be confident that no possible counterpart would be missed. A posteriori, we found this radius exceedingly large and we could confirm the good accuracy of the ROSAT error box.

Bright stars within fields with no obvious counterpart have been observed even if located at a comparatively large distance from the X-ray position.

The low-resolution spectra were inspected to derive (or check) spectral types or spectral anomalies, but mostly to find signatures of high chromospheric emission, like filling-in or emission of the Balmer lines. Most of the stellar candidates were selected in this way. Additional observations at low resolution needed for the identification of some of the fainter counterparts were performed using the 3.6m telescope with the EFOSC spectrograph (Benetti et al. 1997; see also Pasquini et al. 1994a).

Finally, the 3.6m telescope with the CASPEC spectrograph (Randich and Pasquini 1996) and the NTT with the EMMI spectrograph were used to obtain intermediate- and high-resolution spectroscopy of the pre-selected candidates. This last step is required to allow a firm identification of the targets and to derive absolute chromospheric fluxes at the stellar surface. The observations were centered in the Ca II H and K region, and in the Hα region. CASPEC spectra have a resolving power R=18000. The EMMI spectra were obtained in dichroic mode: blue and red spectra were recorded simultaneously. Blue spectra were acquired with a holographic grating at R=6000 (Pasquini et al. 1994b), while red spectra were obtained with a resolution R=20000 or R=3000, depending on the stellar apparent magnitude. The spectra have been reduced using the MIDAS package (Banse et al. 1988).

When a candidate showed enhanced chromospheric activity and acceptable positional coincidence, it was accepted as counterpart. However, for some of the fields no star fulfilled both conditions. For these fields, we obtained low resolution spectroscopy of fainter candidates, and when no acceptable alternatives were found, the original stars were accepted as (possible) candidates.

3. Optical identification: results

Belloni, Verbunt & Schmitt (1993, hereafter BVS) list 22 sources detected in the central 20 arcmin of a ROSAT PSPC field centered on a position $\sim 12'$ east of the center of M 67.

The ROSAT sources with firm or possible optical counterparts are summarized in Table 1: the numbering scheme is the same as in BVS. Source number 11 was recognized by BVS as a blend of a hard and a soft source. In the analysis of the new ROSAT observation of M 67 (Belloni, Verbunt & Mathieu, in preparation), the two sources could be resolved and they are listed separately (sources 11a and 11b). The optical positions are from Girard et al. (1989) when available, while the coordinates for the remaining objects are from the Digitized Sky Survey. For these, distances are accurate only to a few arcsecs.

For optical identification, we adopted the results obtained by similar studies in the field (see e.g. Stocke et al. 1991). QSO's and emission-line galaxies, when close to the nominal error box were accepted as counterparts; in particular, in the error boxes of the 3 extragalactic sources identified with X-ray sources, no known M 67 member exists. For the ten ROSAT fields with no identification, EFOSC images were acquired, but no stellar counterpart was found down to magnitude limits in excess of those expected for values of L_x/L_v typical for coronal sources.

In Fig. 1, low resolution spectra of the extragalactic sources and of some of the most interesting objects in the fields with doubtful or no optical identification are shown. Note that the shape of the continuum may not represent the true continuum of the objects, since in order to gain spectra of several objects

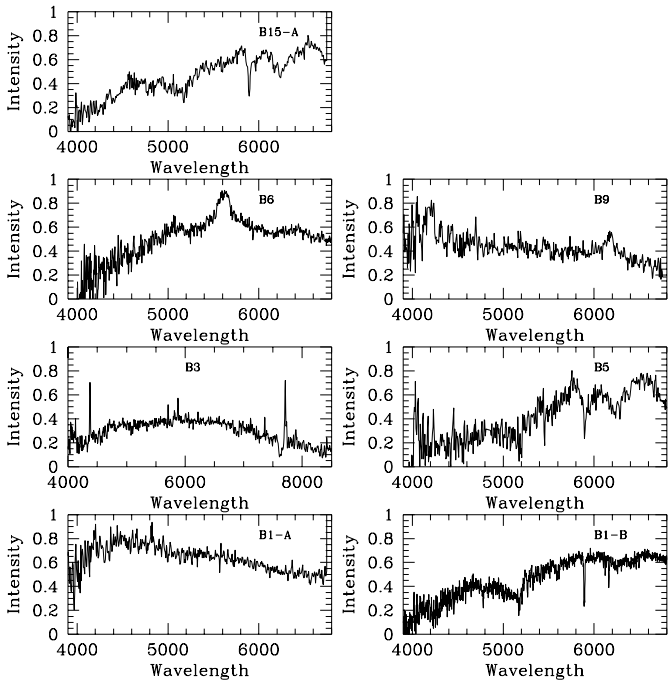

Fig. 1. Low resolution spectra of the extragalactic optical counterparts and of the objects in the fields with doubtful or no optical identification. Flux is in arbitrary units

simultaneously, in most cases the slit could not be aligned with the parallactic angle.

Thanks to the boresight correction applied by BVS, the optical and X-ray positions for most candidates agree extremely well, with differences often smaller than 10 arcsec, which is the typical nominal ROSAT error box (BVS). Therefore, we consider the 2 proposed counterparts having larger distances from the X-ray source (B1, B15) only as possible, but not likely candidates. For B19, the uncertainty in the identification is given by the fact that, although the X-ray and the optical position of the star S364 match quite well, the high-resolution spectra obtained do not show any sign of enhanced chromospheric activity (cfr. Sect. 5.2). This, according to the previously mentioned criteria, does not make this star a firm counterpart.

Out of 23 sources, one has been recognized as spurious, and 13 have been firmly identified. Of these, 9 are cluster members, 3 are extragalactic objects and one is a non-member star. Three additional cases remain unclear, in the sense that they do not meet all the requirements for a firm identification.

As explained in detail below, of the identified sources, seven are definitely coronal emitters and belong to the cluster. Relevant for the aim of this work is that we can be confident that none of the unidentified sources are coronal emitters belonging to the cluster. This confidence is supported by three arguments:

– All unidentified sources have faint optical counterparts. This would imply an exceptionally high L_x/L_v ratio if they were coronal sources. Only in the case of B12 there are possible coronal candidates the error box, but their cluster membership is uncertain.

Table 1. Summary of the identification of ROSAT sources. For each X-ray source we list: identifier, name of the possible optical counterpart, distance between them, 90% error radius (from BVS), and a comment on the object.

B#	Name	d ($''$)	r ($''$)	Comments
1	—	38	17.8	DISTANT
3	—	17	14.4	Galaxy Z=0.174
4	S 1082	9	10.5	Blue Straggler
6	—	4	7.8	QSO Z=1
7	S 1077	4	8.2	
8	S 1063	2	6.6	
9	—	22	18.3	QSO Z=1.2
10	S 1040	7	12.5	
11a	S 1019	7	14.4	
11b	G 152		14.4	WD (Pasquini et al. 1994a)
13	S 999	3	14.2	
14	S 759	6	13.0	
15	—	31	7.8	DISTANT
16	G 186		15.5	AM Her (Pasquini et al. 1994a)
17	S 972	12	20.8	
19	S 364	16	16.0	POSSIBLE

– Most of the ROSAT detections in the central part of the cluster have been identified; the unidentified sources are located in the external parts of the cluster, where the membership probability is lower.
– As pointed out by BVS, on the basis of the LogN-LogS function (Hasinger et al. 1998), $\sim$ 12-16 sources out of the 23 detected sources are expected to be background objects.

However, we cannot exclude that some non coronal systems belonging to M 67 are present among the unidentified ROSAT sources. Systems with a high L_x/L_v ratio, like white dwarfs (WD), cataclysmic variables (CV), or low mass X-ray binaries (in quiescence) could be present, but not identified in the present program. WD's and polar CVs are very unlikely cases, since they would show very soft hardness ratios (Fleming et al. 1996), which are not observed (BSV), but we cannot exclude the presence of a weakly-magnetized CV or a LMXB in quiescence.

Below, we discuss the single sources in detail:

B1: The proposed possible counterpart (star B1-B in Fig. 1) is not in the list by Sanders (1977). Its coordinates are: α(2000)= 08 49 53 δ(2000)= 12 02 06. At 2 Å resolution the star shows Hα filling-in. No other star in the field shows signatures of activity. We derive a spectral type K5: with a magnitude of V$\sim$16.4, the star could be a member of the cluster. However, it is distant from the X-ray position. A stellar object of magnitude V$\sim$20.4 and position α(2000)= 08 49 54 δ(2000)= 12 01 48, lies only 16 arcsec away from the X-ray position (B1-A in Fig. 1). Its spectrum resembles that of an F dwarf (although with unusually faint Balmer lines). With this combination of magnitude and spectral type, the star does not belong to the cluster, and the exceedingly high L_x/L_v would exclude it as a coronal counterpart.

B2: Two stars are found at (α(2000)=08 50 14.8; δ(2000) = 12 00 37) and (α(2000)=08 50 14.6; δ(2000)= 12 01 45), at a distance of 28 and 42 arcsec from the X-ray position respec-

tively. Their spectra are those of a M1 and a K4 dwarf with no special features. An additional object lies very close to the X-ray position, possibly with and emission line at ∼6500 Å, but the signal to noise ratio is too low to derive any firm conclusion.

B3: A galaxy with coordinates α(2000)= 08 49 22.6 δ(2000)= 11 54 57.6. The two strongest emission lines are consistent with being [OII]3727 and Hα at redshift 0.174 (see Fig. 1).

B4: This field has not been extensively studied. The agreement of S1082 with the X-ray coordinates is very good and the brightness of the star makes the study of nearby faint objects difficult. Low resolution spectra for stars S1072, S1075 and S1079 were obtained. They do not show signatures of enhanced activity. The high resolution spectrum of S1082 shows a composite Hα, with a broad and a narrow component (cfr. Fig. 2). Such a spectrum was also observed by Mathys (1991).

B5: A faint object is in good agreement with the X-ray position (α(2000)=08 50 08.8 δ(2000)=11 53 27, d=15 arcsec). However, from visual magnitude and spectral type of the star (M1 V, see Fig. 1), Balmer lines in emission are expected for it to be the optical counterpart. The nearest S star (S490) shows no special features. The counterpart is therefore not confirmed. Among all the BSV sources, this is the only one which has not been confirmed by the new M 67 pointings (Belloni, Verbunt & Mathieu, in preparation) and it should probably be considered spurious.

B6: A QSO with coordinates α(2000)=08 49 54.2 δ(2000)= 11 53 17. The redshift has been computed identifying the strong emission line as Mg II. (see Fig. 1).

B7: S1077 shows indications of activity. At low resolution the nearby S2224 does not show any peculiar signature.

B8: S1063 not only coincides very well with position, but also shows a very pronounced Ca II H & K emission. This star is located below the subgiant branch (cfr. Sect. 5.3).

B9: The bright star in the field (S258) was observed at high resolution: it does not show signs of activity, and it lies at a large distance from the X-ray position. A QSO at Z=1.2 is found at α(2000)=08 49 36, δ(2000)=+11 50 56. The two emission lines (see Fig. 1) correspond to CIII and MgII.

B10: S1040 shows Ca II H&K emission. The fainter star S2216 does not show particular features at low resolution.

B11a: The most difficult field: a crowded region, with several known binaries. The best candidate is S1019, with spectacular Ca II H&K emission, and Hα filling. Other brighter candidates have been observed also at high resolution, but do not show evidence for enhanced activity (S1010, S1045, S1024) (However, note that, even though it does not show Ca II emission, the Ca II flux of S1024 may still be quite high because to its rather hot temperature, cfr. Table 3).

B12: Two stars lie within 25 arcsec from the ROSAT position: S613 (V=15.45) and S614 (V=15.50), but neither shows peculiar characteristics at low resolution. Their membership probability is given as low/intermediate by Girard et al. (1989) (47 and 60 % respectively) and by Sanders (47 and 22 % respectively). We do not consider them as good candidates. High resolution spectroscopy is needed to reach a firm conclusion.

B13: S999 shows Ca II core emission at high resolution. At low resolution, neither of the other possible candidates (S995, S997, S998) show special features.

B14: The Ca II spectrum of S759 shows enhanced emission, but the S/N ratio of the spectrum is not very high. The nearby S756, S757 do not show special features at low resolution. S759 is given zero probability of membership by Sanders (1977).

B15: A late K star. At intermediate resolution, we could only obtain a low S/N spectrum: the star might show Ca II H&K emission, but the distance from the X-ray source makes the identification uncertain. A fainter star (V∼18.5) at α(2000)= 08 50 55.9 δ(2000)= 11 45 54 (d=17.5 arcsec) shows an M1 dwarf spectrum (see Fig. 1), but the absence of Balmer-line emission makes it an unlikely counterpart.

B16: AM Her (Gilliland et al. 1991, Pasquini et al. 1994a)

B17: Two stars (S972 and S973) are close to the X-ray source: intermediate and high resolution spectra show strong Ca II H&K in S972 but not in S973, which is a brighter (V=13.49) binary (Orbital Period=40.4 days, Latham et al. 1992). S972 is listed by Sanders (1977) with a moderate (42%) probability of membership.

B18: No spectroscopic observations.

B19: The bright giant S364 (α(2000)= 08 49 57 δ(2000)=11 41 36) is within the ROSAT error box. Its membership probability is listed as 82% by Sanders (1977). Low resolution spectra were obtained for two other possible counterparts (no S numbers) distant 47 and 24 arcsec respectively. Neither shows special features. The fact that S364 does not show any enhanced activity either in the Ca II K or in the Hα lines (see Fig. 2 and Sect. 5.2) makes its identification with the ROSAT source uncertain.

B20-22: No spectroscopic observations. No stars bright enough to be obvious coronal counterparts are visible in the fields.

4. Intermediate- and high-resolution spectra

The Ca II and Hα high-resolution spectra are shown in Fig. 2. It is relevant to note that we observed at high resolution not only the proposed optical candidates, but also several stars with similar characteristics. In Table 2, the optical characteristics of the coronal optical counterparts are given, together with the X-ray luminosity. The X-ray luminosities differ by a factor ~ 2 from those given by BVS, because in this early work a too low conversion factor was used. Here we adopt a the same model of Belloni, Verbunt & Mathieu (in preparation) with N_H=1.7×10^{20}cm^{-2}. This corresponds to a conversion factor between counts/sec and 0.1–2.4 keV flux in erg cm^{-2}sec^{-1} of 1.8×10^{-11}.

The properties of the 'comparison' stars observed at high resolution are summarized in Table 3. Some of these stars turned out to be likely detected in the new M 67 observations of Belloni, Verbunt & Mathieu, in which case the X-ray luminosities and fluxes are given for sake of completeness. However, since these detections refer to a pointing having different sensitivity and the analysis of the optical counterparts has not yet been performed

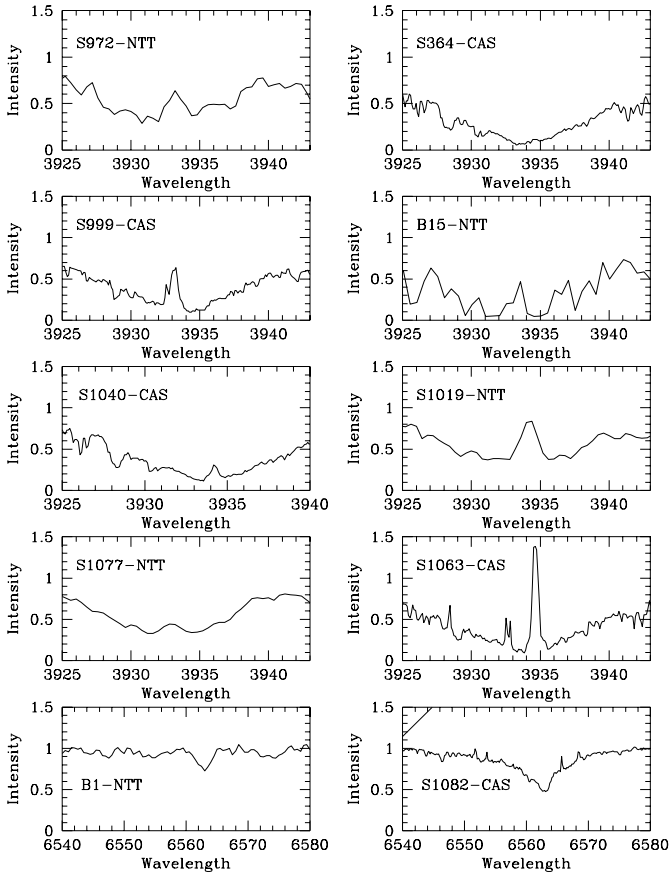

Fig. 2. High- and intermediate-resolution Ca II and Hα spectra of the proposed candidates

as in the present analysis, they are treated separately from the stars of Table 2, which form the bulk of the present work.

We used the high-resolution spectra to compute Ca II K line fluxes using the procedure of Pasquini et al. (1988), based on the (V-R) colour index. For stars having (V-R) colours measured by Gilliland et al. (1991) in the Cousin system, the Johnson (V-R)$_o$ colour has been derived by using the transformation formulas given by Taylor (1986). For the other stars, the (V-R)$_o$ colour has been computed using (B-V)-(V-R) standard transformations (Johnson 1966).

For a few stars, both high (R=20000) and intermediate (R=6000) resolution spectra were acquired. Chromospheric fluxes were computed by using both high and intermediate resolution spectra and the results were compared to evaluate the effects of the different resolution on the flux estimates. The A_k indices (the ratio between the Ca II core emission and the pseudocontinuum at 3950 Å, see Pasquini et al. 1988) derived from low resolution spectra are systematically larger by a factor 2 than those measured from the high resolution ones. Such an effect is expected, as discussed in Pasquini et al. (1989). The A_k values given in Tables 2 and 3 have been corrected for this difference. The uncertainties in the chromospheric fluxes are of the order of 50%. For a few stars, marked with ':' in Tables 2 and 3, the uncertainties may be even higher, due either to the low signal-to-noise ratio of the data, or to problems in defining accurately the K1 minima.

In Fig. 2, high and intermediate resolution Ca II K line spectra are shown. The spectra are normalized to the 3950 Å pseudocontinuum.

In Tables 2 and 3, the derived chromospheric fluxes are also given. No attempt was done to separate the different components of a binary system, since they are never clearly separated in our spectra.

5. Discussion

The aim of this work is to discuss the nature of the coronal sources belonging to M 67 detected in the ROSAT observation of BVS. For this purpose we concentrate mostly on the firmly identified sources.

5.1. Which parameters determine X-ray emission in a 4Gyr old cluster?

It is important to remember that the observations by BVS could only detect the high X-ray luminosity tail of the cluster. The longer, more recent ROSAT observations reveal more sources, confirming that cluster X-ray emitters might exist at lower levels than the one analyzed here (Belloni, Verbunt & Mathieu, in preparation).

Of the 8 known members of Table 2, six are either known binaries or show clear signs of duplicity, like photometric modulation or displaced position in the colour-magnitude diagram of the cluster. Of the remaining two, S1077 is reported by BVS as a multiple system with short period, while S364 is not included in the current list of binaries. Jones and Smith (1984) found anomalous DDO colours for this star, but they concluded that this was probably due to due measurement uncertainties. Once again, we stress that this identification is only considered as 'possible'.

The first conclusion is that in M 67 the strongest coronal sources are binaries. This was expected from the results on field stars and from the age-coronal activity relationships: single, late type stars with ages comparable to the Sun are not expected to emit X-ray in excess to $\sim 10^{29}$ erg/s in luminosity.

In Fig. 3 the colour-magnitude diagram of the cluster is shown, with the X-ray identifications marked. It is striking to notice that a large variety of cases exists: one Blue Straggler (S1082), one peculiar object (S1063), evolved 'normal' binaries (S1077, S999), main sequence binaries (S1019, S972), one Red Straggler (S1040), and possibly a red giant (S364). Among field stars such a comparison can hardly be done, due to the uncertainty in the fundamental stellar parameters.

The second conclusion is therefore that among the M 67 sources there exists a large variety in evolutionary status and composition of binary systems. In particular, several of the strong X-ray emitters are found among objects having peculiar location in the colour magnitude diagram.

This variety makes it difficult to understand which parameters determine the X-ray emission in these binaries. From the

Table 2. Summary of the ROSAT sources with identified optical counterparts. Column 1): ROSAT ID, Column 2): Sanders (1977) number, Column 3): V magnitude, Column 4): B-V colour, Column 5): V-I colour, Column 6): V-R colour, Column 7): Orbital Period (Latham et al. 1992), Column 8): Photometric period, Column 9): Log of X-ray Luminosity, Column 10): Chromospheric index in the Ca II K line, Column 11): Chromospheric flux in the Ca II K line in units of 10^5 erg cm^{-2} sec^{-1}. Column 12): Angular diameter in milliarcsec according to the relationship by Barnes and Evans (1976), Column 13): Stellar radii in units of 10^{10} cm. [a] The star is on the binary sequence of Montgomery et al. (1993), [b] Photometric period from Goranskij et al. (1992), [c] Photometric period from Gilliland et al. (1991). For the derivation of the (V-R) colours and the chromospheric fluxes see text.

Source	Name	V	B-V	V-I	V-R	O.P.	Ph.P.	Log(L_x)	Ak	F'k	Log(ϕ)	R
1	No S#							30.61	/	/	/	
4	S1082	11.25	0.415	0.529	0.35*		1.068[b]	30.98	0.2	40:	-1.4283	21.9
7	S1077	12.47	0.637	0.843	0.50*			30.85	0.5	50	-1.5436	16.8
8	S1063	13.52	1.07	1.199	0.85*	18.24		31.16	0.95	10	-1.4533	20.7
10	S1040	11.55	0.88	0.91	0.67	42.83	7.97[c]	30.79	0.27	7	-1.21374	35.9
11a	S1019	14.32	0.83	0.997	0.67		9.75[c]	30.72	0.75	26	-1.76774	10.0
13	S999	12.60	0.78	0.908	0.62	10.06	9.79[c]	30.68	0.64	30	-1.46664	20.0
14	S759	16.17	0.747	0.828	0.56*			??	0.23:	14:	N.M.	
15	No S#							30.83	0.27:		/	
17	S972	15.37	0.89	1.09	0.67*	[a]		30.54	0.5	18	-1.97774	6.2
19	S364	9.93	1.36	1.30	0.94			30.50	0.15	0.5	-0.65808	129

Table 3. Additional M 67 stars observed at intermediate/high resolution for comparison purposes with stars of Table 2. Columns are the same as in Table 2. [a]: combined colour and magnitude from Latham et al (1992), [b] Photometric period from Gilliland et al. (1991)

Name	V	B-V	V-I	V-R	O.P.	Ph.P.	Log(L_x)	Ak	F'k	Logϕ	R
S1010	10.48	1.11	1.08	.78			/	0.06	0.4:	-0.90536	73
S1024	12.718	0.553	0.685	.43	7.16		30.32:	0.12	10:	-1.65326	13
S1045	12.54	0.591	0.703	.46	7.645		29.82	0.07	3	-1.59192	15
S1113	13.766	1.013	//	0.78*			30.79	1.58	28	-1.56256	16.1
S1242	12.72	0.683	0.807	0.53*	31.78	4.88[b]	29.96	0.20	14	-1.56786	15.9
S1264[a]	11.7	0.92	//	0.69*	353.9		/	0.09	2.2	-1.22658	34.8
S1272	12.514	0.598	0.697	0.47*	11.02		/	0.11	10	-1.57814	15.5

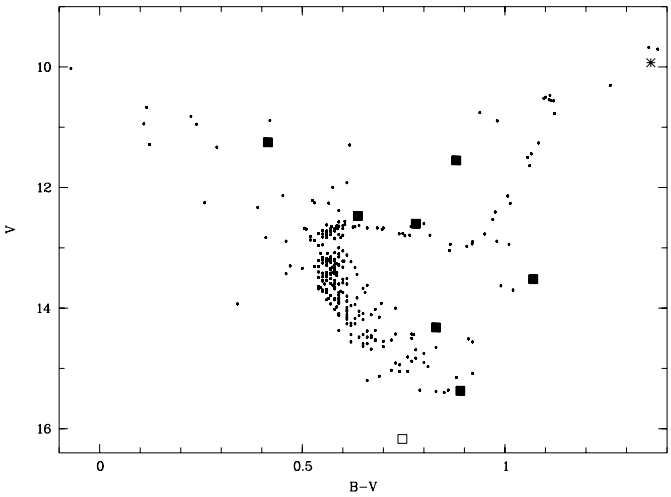

Fig. 3. Colour-magnitude diagram of M 67. Filled squares show the positions of the firm X-ray counterparts. S759 (non member) and S364 (possible counterpart) are indicated respectively as an open square and a star.

study of field active binaries, it emerged that the main parameter determining X-ray luminosity is stellar radius. Therefore, the strongest X-ray emitters would be expected to be among the most luminous systems (Dempsey et al. 1993b). On the contrary, the most luminous X-ray sources in M 67 span over a range in visible luminosity of at least 4 magnitudes (cfr. Table 1). Although S972, which has the lowest X-ray luminosity, is also the faintest established member of the cluster in the optical, other stars (like S1019 or S1063) show the highest X-ray emission, while being relatively faint in the optical.

The third conclusion is therefore that, in this coeval sample, the highest X-ray luminosity is not given by the most luminous stars.

Another interesting point is the dependence of X-ray emission on the orbital (or rotational) period, since X-ray luminosity scales with stellar rotational velocity (Pallavicini et al. 1981), which in turn is related to stellar radius and orbital period. In most cases (and for main sequence stars), it is expected that short period binaries are synchronized, i.e. they have equal orbital and rotational periods. It is also expected that synchronization happens before orbit circularization (Zahn 1977). All 4 stars for which the rotational modulation is known, as inferred from the photometric variability, have rotational periods of less than 10 days. For S1063, only the orbital period is known, but this star may have a special history (see Sect. 5.3). Pending more data on the rotational period of the other objects, we can say that

Not only the X-ray sources in M 67 are binaries, but also most of them have short rotational periods.

On the other hand, do all M 67 short period systems show strong X-ray (or chromospheric) activity ? In M 67, 11 binaries have a measured orbital period shorter than 16 days (Latham et al. 1992), a canonical value for the definition of RS CVn systems, but most of them were not detected in the ROSAT observations. Three of them (S1272, S1284, S1224) where out or at the very border of the ROSAT field; one (S999) was detected, but the remaining (S1045, S1234, S1024, S986, S1009, S1070 S1014, S810) were contained in the ROSAT field but not detected. These systems are likely active, but with X-ray luminosities $L_x \leq 30.3$ (corresponding to the sensitivity of BSV), as it is suggested by the likely detection of some of these stars in the deeper pointing (S1045, S1024, S1234 and S1070, Belloni, Verbunt & Mathieu, in preparation). Since some of the non-detected binaries, like S986, S1009 and S810, have periods of 10 days or shorter, the data collected up to now show that

Among the binaries of M 67, a short orbital period does not necessarily imply a high X-ray luminosity.

Since we are dealing mostly with evolved stars, for which short periods can coexist with eccentrical orbits, eccentricity could be a relevant parameter, because the non-synchronization would allow the possibility of having a rotational period shorter than the orbital period. Of the detected binaries, S1063 and S999 have highly eccentric orbits, but S1040 has an eccentricity comparable with 0. This is surprising, because if the photometric variability detected by Gilliland et al. (1991) really represents the rotational period, than this star would be circularized but not synchronized. On the other hand, S1040 had probably a very complex history, having had mass transfer in the past (Landsman et al. 1997). Considering this star as a special case we, could argue that non-circular binaries are favored among the strongest X-ray emitters. However, in the list of Latham et al. (1992), there are five short-period binaries with eccentricities significantly different from 0 (S1284, S1272, S1234, S1224, S1014). Two of them (S1014 and S1234) were in the ROSAT field of view but were not detected. Therefore, it seems that also a high eccentricity does not represent *per se* a condition for strong X-ray emission.

5.2. Chromospheric activity

The chromospheric flux of the Sun in the Ca II K line is of 3-5$\times 10^5$ erg cm^{-2}sec^{-1} (Pasquini et al. 1988). For the main sequence G stars in M 67, being metallicity and age comparable with those of the Sun, values comparable with this are expected.

Recently, Dupree et al. (in preparation) studied the chromospheric emission in the Ca II lines for a sample of M 67 giants, using calibrations and spectra of similar quality to the ones presented here. In Fig. 4 the Ca II chromospheric fluxes are plotted as a function of the (V-R) colour, both for the stars in Dupree et al. (open squares) and for the X-ray counterparts of Table 2 (filled squares). The ROSAT stars have a level of chromospheric activity one order of magnitude higher than the optically-selected giants in Dupree et al. The only exception is S364, which fits extremely well within normal giants of similar spectral type. For this reason, despite the reasonable agreement with the X-ray position, this star is considered as a doubtful counterpart.

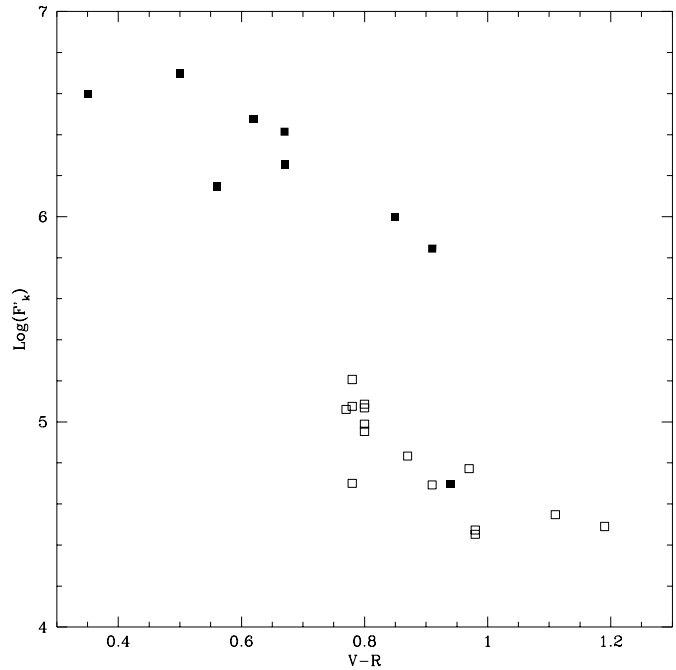

Fig. 4. Ca II chromospheric fluxes vs. (V-R) colour for M67 single stars (Dupree et al., in preparation: open symbols) and ROSAT stars (Table 2 of this work: filled symbols)

In order to perform an unbiased analysis of the relationship between chromospheric and coronal activity, we have to use indicators which express similar quantities, namely fluxes at the stellar surface. We computed the radii of the stars by using the same Barnes-Evans (1976) relationship used to calibrate the Ca II data: Logϕ = 0.4874 - 0.2V$_o$ + 0.858(V-R). Although we know that the resulting radii are probably incorrect (for instance, because the stars are implicitly assumed to be single), the fact that the same relationship is used for computing the Ca II and X-ray fluxes minimizes the presence of possible systematic effects in the comparison. We assumed an absorption A(V)=0.17 and a distance of 785 parsecs (Janes 1984). The resulting diameters and radii are given in Tables 2 and 3 (in units of milliarcseconds and 10^{10} cm respectively). In Fig. 5a, Log(F$_x$) is given as a function of Log F$_k$. The relationship is rather scattered and mostly the presence of the (doubtful) S364 hints to the presence of a trend.

Since the sample contains systems whose evolutionary status is very different from each other, to further investigate this point we plot in Fig. 5b the ratio between the X-ray and chromospheric fluxes versus apparent magnitude. Fainter (i.e. higher gravity) stars have much higher coronal to chromospheric flux ratios than more luminous (i.e. lower gravity) stars.

Although the number of objects is rather low, it appears that dwarfs and giants follow different trends, with dwarfs having higher F$_x$ for a given F'$_k$. This fact has two possible explanations:

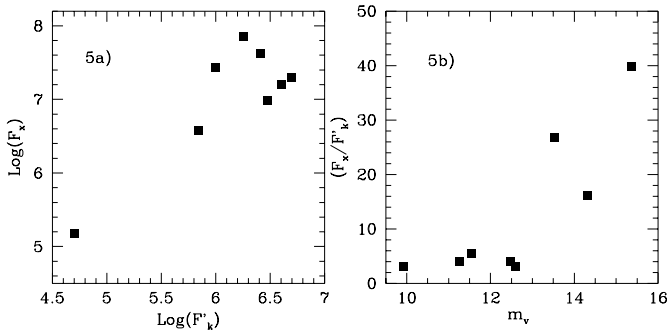

Fig. 5. a Comparison between Ca II and X-ray fluxes for the X-ray counterparts. **b** Coronal to Ca II fluxes as a function of stellar magnitude.

– For comparable chromospheric fluxes, higher-gravity stars are more efficient in heating their coronae than lower-gravity stars. This could indicate the presence of different coronal structures between dwarfs and evolved stars.
– The assumption that the Ca II K fluxes are representative of the whole chromospheric losses may not apply when comparing stars of different luminosity. Giants could for instance have a different balance in the different chromospheric lines than dwarfs.

5.3. S1063 and S1113

Two objects deserve a special attention, due to their peculiar position in the colour-magnitude diagram: S1063 and S1113.

S1113 was was outside the field of the observation by BSV. Because of the strong chromospheric activity observed, we would expect it to show rather strong X-ray emission, which is indeed detected in the new ROSAT pointing (cfr. Table 3).

These two stars are located below the giants branch: they are as red as single subgiants, but almost one magnitude fainter. S1063 is a known eccentric binary with a period of 18.3 days, while S1113 is a short period (2.82 d) circular binary (Latham et al. 1992, Mathieu et al. in preparation). The two stars are classified as members in the proper motion studies of Sanders (1977) and Girard et al. (1989), with a probability higher than 90%. Their peculiar position in the colour-magnitude diagram and their high level of coronal and chromospheric activity make these two object very interesting. It is not possible to simply combine two M 67 stars and obtain the magnitudes and colours of S1063 and S1113. Some mass exchange, or large mass losses in the past history of the systems, possibly still going on, look unavoidable. The high-resolution Ca II spectrum of S1113 shows neither direct evidence of duplicity, nor strong asymmetries in the Ca II core typical of strong mass losses, but not much can be derived with only one optical spectrum for this star.

We stress that the conclusion that these two stars have suffered a special evolutionary history is made possible only by the fact that we they are members of a cluster (and therefore we can firmly position them in the colour magnitude diagram) and by the detailed optical follow-up. How many such systems exist among field binaries? Note that, in absence of detailed studies (e.g. accurate determinations of mass, metallicity and gravity), similar systems in the field cannot be distinguished by otherwise 'normal' RS CVn binaries. A more detailed study in other clusters and possibly the analysis of Hipparcos parallaxes of active binaries will help in understanding how common these systems are. Investigation of their binarity and orbital synchronization will also be crucial to model their possible evolution with time (see i.e. the discussion in Stepien 1995).

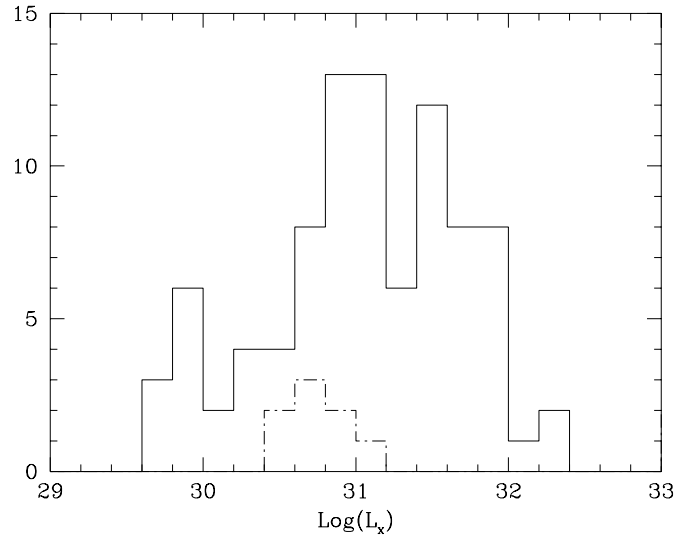

Fig. 6. ROSAT luminosity for the M 67 sources (broken line) and for RS CVn binaries with known distances (continuous line)

5.4. Comparison with ROSAT observations of field RS CVn

One of the aims of this study is the possibility of comparing for the first time active stars in an old cluster with the field population of RS CVn. Dempsey et al. (1993a,b) studied the ROSAT detections of known RS CVn. Their sample, taken from the catalogue of Strassmeier et al. (1988), contains binaries of a large variety of ages, masses and periods. We selected all the stars from Dempsey et al. (1993a) with known distance. We computed X-ray luminosities by converting the PSPC count rates (see also Dempsey et al. 1994) using the same conversion factor used for the M 67 stars. The distribution in luminosity is given in Fig. 6 for M 67 and field RS CVn separately. Although the M 67 sources do overlap well with the main body of field RS CVn's, their emission is not as high as the most active RS CVn systems.

Fig. 6 shows that the high X-ray luminosity tail of binaries in the 4 Gyr old cluster M 67 is about 10 times lower than the high luminosity tail of field RS CVn's.

The reasons for this difference are at the moment not very clear: it could be an effect due to the old age of the cluster and/or to the evolutionary status of the sources, or to a statistical effect caused by the fact that we can only sample a few hundred stars within the cluster. Identifications in clusters of different ages, as well as a detailed analysis of the strongest sources in the field,

will help in understanding this open question. It is interesting to note that in the analysis of the much younger Hyades, Stern et al. (1995) found that binaries are the strongest X-ray emitters in this cluster. Similarities with M67 exist also in that the strongest X-ray source in the Hyades (V471 Tau) is a peculiar system. Finally, Hyades binaries have X-ray luminosities similar or lower than those observed among the M67 sources.

This could indicate that as far as the high-luminosity tail of the X-ray luminosity function is concerned, age is not the primary parameter to determine the X-ray emission in binaries, as pointed out also by Ottmann et al. (1997) in their analysis of Pop II binaries.

We would therefore argue that the extremely active i.e. ($L_x \sim 10^{32}$ erg cm^{-2} sec $^{-1}$) RS CVn systems seem to be very rare and possibly limited to quite exceptional cases. Metanomski et al. (1998), in their study of hundred stars identified over a large area of the ROSAT All-Sky Survey, find results similar to ours: no such a high luminosity coronal source is indeed present in their sample.

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