Mon. Not. R. Astron. Soc. **000**, 000–000 (0000) Printed 11 February 2003 (MN LaTeX style file v1.4)

A search for X-ray variability in the open cluster NGC 2516

Gavin Ramsay, Louise Harra, Hilary Kay
Mullard Space Science Laboratory, University College London, Holmbury St. Mary, Dorking, Surrey, RH5 6NT, UK

Received:

ABSTRACT

We present the results of a search for X-ray variability in the galactic open cluster NGC 2516. This cluster has been observed on 8 occasions using *XMM-Newton* making it an excellent target for such a study. We find 4 sources which show significant variability, implying the detection of one significantly variable source every 25ksec. All sources exhibit spectra which can be fitted using an absorbed one or two temperature thermal plasma model. The brightest of these flares also show a prominent Iron line near ∼7.0keV. All 4 sources lie near the observed main sequence of NGC 2516 suggesting they are cluster members. We propose that at least 3 of the 4 objects are RS CVn systems. We compare the properties of the brightest flare with those of solar flares.

Key words: Sun: flares – stars: activity, coronae – Galaxy: open clusters and associations: individual: NGC 2516 – X-rays: stars, binaries

1 INTRODUCTION

NGC 2516 is a rich, well studied, galactic open cluster. It has a low metallicity (eg Cameron 1985, Jeffries, James & Thurston 1998), is nearby (∼387pc; Jeffries, Thurston & Pye 1997), is young ($\sim 10^8$ years; eg Feinstein, Marraco, Mirabel et al 1973) and has a relatively low line of sight extinction. Because of its low metallicity, it is an excellent target to test how coronal activity and stellar structure depend on metal content.

NGC 2516 has been the subject of several studies in the X-ray band. It was observed using *ROSAT* by Dachs & Hummel (1996), Jeffries, Thurston & Pye (1997) and Micela et al (2000). More recently it was the subject of a study using *XMM-Newton* (Sciortino et al 2001) and also *Chandra* (Harnden et al 2001). These studies have concentrated on determining the cluster X-ray luminosity function: Sciortino et al (2001) found that dwarf G and K stars in NGC 2516 were less luminous than those in the Pleiades (which has a similar age but solar metallicity ratio). In contrast, the luminosity function of dwarf M stars in NGC 2516 and the Pleiades were indistinguishable.

In this paper, we show the results of a search for X-ray variable objects in NGC 2516 using *XMM-Newton* data. With the relatively large number of X-ray objects it is an excellent target to determine the frequency of stellar flaring activity in a young, metal poor cluster. Further, NGC 2516 has been observed on 8 occasions with *XMM-Newton* since it has been used as a calibration target.

Date	Orbit	ObsId	Clean Time (ksec)
2000-04-06	060	0113891001	17.6
2000-04-06	060	0113891101	15.0
2000-06-10	092	0126511201	26.1
2000-10-31	164	0113891201	0.5
2001-01-29	209	0134531201	17.0
2001-01-29	209	0134531301	5.0
2001-06-24	272	0134531301	0.0
2001-10-29	346	0134531501	16.7

Table 1. The observation log of *XMM-Newton* observations of NGC 2516. We show the *XMM-Newton* orbit number and the observation id.

2 OBSERVATIONS

The satellite *XMM-Newton* was launched in Dec 1999 by the European Space Agency. It has the largest effective area of any imaging X-ray satellite. The EPIC instruments have imaging detectors covering the energy range 0.15–10keV with moderate spectral resolution. The observation log is shown in Table 1. The first two observations were centered at $7^h\ 58^m\ 20^s$, $-60^\circ\ 52'\ 13''$ (2000), and the rest at $7^h\ 58^m\ 22^s$, $-60^\circ\ 45'\ 36''$ (2000). (We do not discuss the data taken using the Reflection Grating Spectrometer since the sources

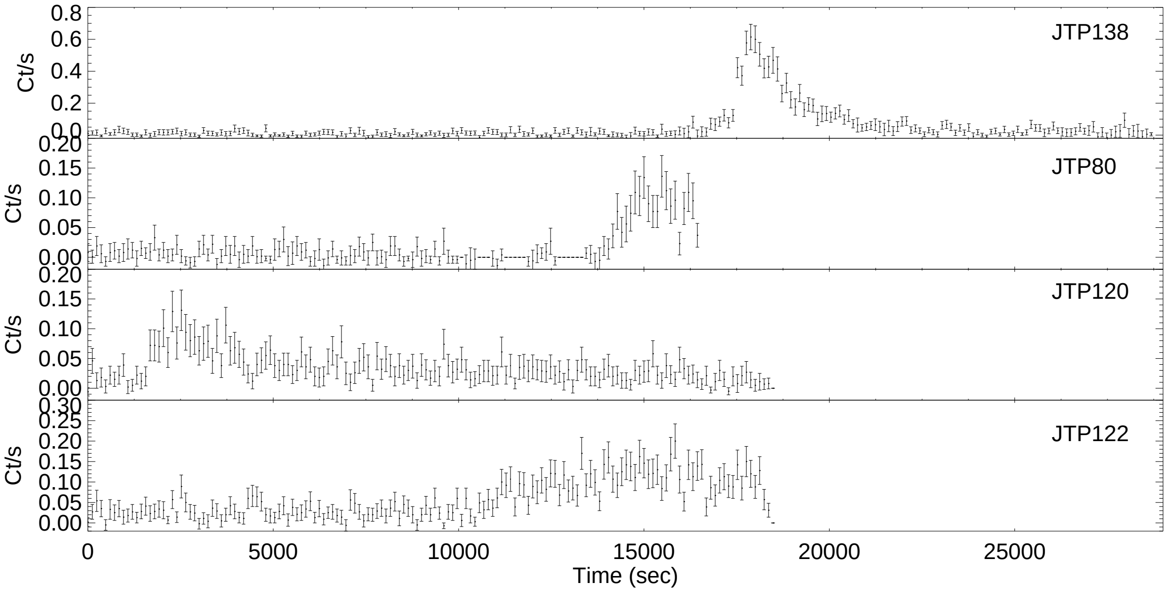

Figure 1. The background subtracted X-ray light curves for each of the 4 sources which showed significant variability. The bin size is 120 sec and covers the energy range 0.2-10.0keV.

were comparatively faint and source confusion would be a problem. The Optical Monitor was in blocked mode).

The data were processed using the *XMM-Newton Science Analysis Software* (SAS) v5.3.3. An image was generated from each dataset in the energy range 0.2-5.0keV. We removed data at the edge of the detector furthest from on-axis since these rows had increased noise. We also selected those events which were tagged as `FLAG=0`: this excludes events close to, for instance, hot pixels and chip edges. Time intervals which showed high levels of particle background were excluded. The resulting images were then source searched using standard SAS tasks. Events were then extracted around a specified radius from the source positions. The events for each source were then subject to a Discrete Fourier Transform in the time interval of 1min to 0.7×Exposure length. All power spectra which showed a peak above a certain criteria above the mean power were flagged and inspected by eye. We also had a second flagging procedure which indicated which objects had a count rate which varied over a certain value.

After the completion of this process, 4 sources were found to show significant variability in their X-ray light curves. Their X-ray positions were compared to the list of X-ray sources in NGC 2516 and their corresponding optical counterparts (Jeffries, Thurston & Pye 1997). We found counterparts for all 4 sources: the offset between the *XMM-Newton* and optical counterpart was typically better than $6''$ (which is the FWHM of sources in the EPIC pn). We show their X-ray positions along with their counterpart of the X-ray catalogue of Jeffries et al (1997) in Table 2. For each source we examined the other datasets to determine if the source was also detected at other epochs. In each case the source was detected but at low count rates (typically 0.01-0.02 ct/s). However, they showed no significant variation in these other datasets.

We show the (background subtracted) X-ray light curves for each source in Figure 1. Three of the sources show evidence for a rapid flare, although in one of those (JTP80) the observation ends shortly after the start of the flare. The other source (JTP122) shows a more gradual rise in brightness. The most dramatic source is JTP138 which shows a gradual rise in flux lasting ~12 min followed by a sharp increase in flux taking place in less than 2 min. After reaching maximum, it reaches half its maximum intensity after ~20 mins. The duration of the flare lasts around 90 min. We show in Figure 2 the light curves in the 1–3keV and 3–10keV energy bands for JTP 138 in time bins of 500 sec together with its softness ratio. Although the hardness ratio curve shows some evidence for a softening over the duration of the flare, it has large errors. However, there is some evidence for a small increase in flux in the 1–3keV light curve just before the sharp rise that is not seen in the 3–10keV light curve, although again this may just be due to the low signal to noise.

JTP	RA	Dec	V	$(B-V)$	ObsId
80	07 57 58.5	-60 56 53	12.84	0.63	0113891101
138	07 59 20.1	-60 34 44	11.96	0.51	0126511201
114	07 58 43.3	-60 55 24	13.97	0.87	0134531501
122	07 58 50.8	-60 38 35	9.51	0.08	0134531501

Table 2. The X-ray sources which showed significant X-ray variability. JTP refers to the X-ray source number of Jeffries, Thurston & Pye (1997), the X-ray position (2000) is the position from the XMM-Newton EPIC images and the optical counterparts are taken from Jeffries et al. We also indicate the observation number (cf Table 1) in which the source variation was detected.

3 SOURCE SPECTRA

We extracted spectra from each of the 4 variable sources: only the time interval of the flare duration and single and

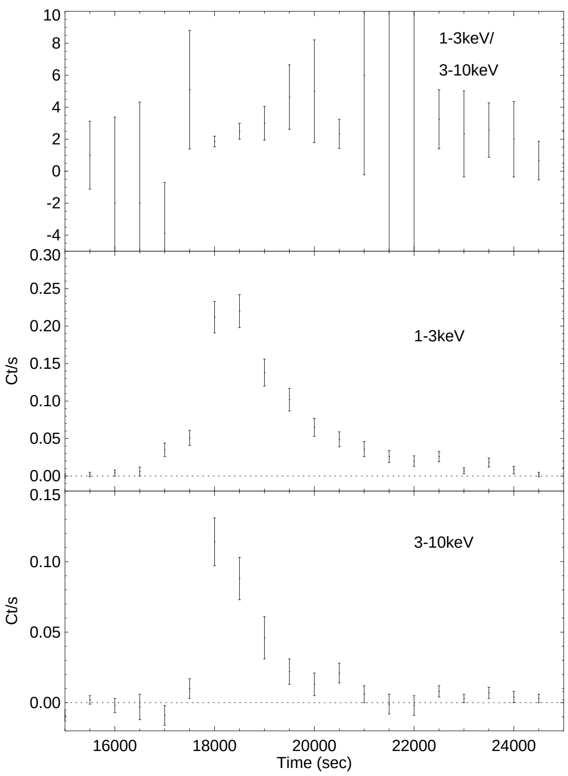

Figure 2. The flare seen in JTP138 in the 1–3keV (middle panel) and 3–10keV (bottom panel) energy band and the 1–3keV/3–10keV softness ratio (top panel).

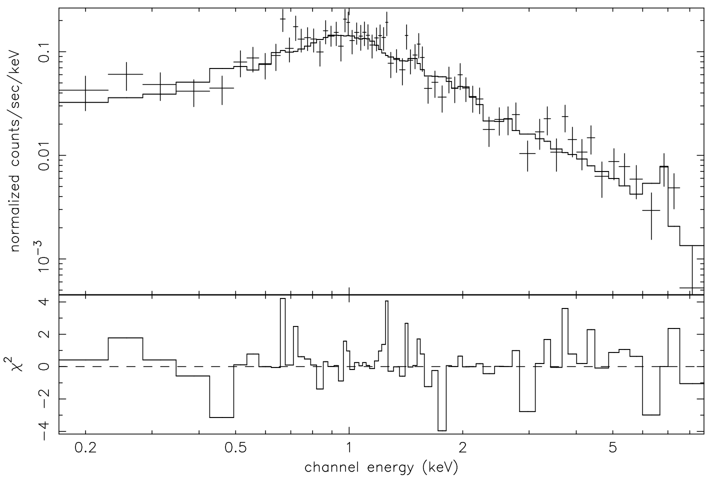

Figure 3. The EPIC pn spectra of source JTP138. The best fit - shown as a solid line - is an absorbed two temperature plasma model.

double events were used. We also extracted background spectra from a nearby source free area off the detector. We used the 'canned' response files appropriate to the location of the source on the detector and generated an auxiliary file using the SAS task `arfgen`. We fitted the spectra using the X-ray fitting package `XSPEC` (Dorman & Arnaud 2001).

All spectra could be fitted using an absorbed one or two temperature plasma model (we used the `MEKAL` model in `XSPEC`). We show the spectrum of the brightest flare (JTP138) in Figure 3: the fit is good with no evidence for significant residuals at particular energies. This source also showed evidence for an Fe line at 7.0±0.2keV (the other sources did not). We show the spectral fits in Table 3.

All spectra show a moderate amount of absorption, typically $\sim 5 \times 10^{20}$ cm^{-2}, and temperatures of a few keV. In determining their luminosity we assume that all 4 sources are members of NGC 2516 and its distance is 387 pc (Jeffries, Thurston & Pye 1997). In the case of JTP138, where we observe the total duration of the flare, the energy released was 8×10^{34} ergs. In the case of JTP80, where we observed only the start of the flare, the energy released was greater than 1×10^{34} ergs. There was a similar energy release observed in JTP114 where most of the flare was observed.

4 THE NATURE OF THE SOURCES

We have identified each of the 4 X-ray variable sources with an optical counterpart (Table 2). Jeffries et al (1997) identify JTP122 as having an AOV spectral type: the other 3 sources have not been classified spectroscopically. Further, JTP138 and JTP122 were both classed as cluster members by King (1978) from a proper motion survey. To determine the likelihood of the other two sources being cluster members we plotted the $V, B-V$, data of Sung et al (2002) and traced the position of the main sequence. We then over-plotted the optical colours of our X-ray variable sources (Figure 4). All 4 sources lie close to the main sequence of NGC 2516: we conclude that each source is likely to be a cluster member.

Stellar coronal activity is common in stars which have a convective layer and a relatively rapid rotation period. Enhanced levels of activity are often seen in close binary systems, for example the RS CVn systems which typically consist of a giant or sub-giant primary with a main-sequence or sub-giant companion. In many RS CVn systems the rotation of one of the components is synchronised with the orbital motion, leading to enhanced rotation and high levels of activity, seen as large spot coverage and flares in X-ray, optical and radio bands. Additionally X-ray activity has also been seen on early-type stars, such as Castor A and B. Here it is thought the flaring component may originate from low-mass, late-type companions (Güdel at al. 2001). X-ray flares have also been reported in pre-main sequence stars (eg Schmidt 1994) and single solar type stars (eg Landini et al 1986).

The energy released in the X-ray flares we observed in NGC 2516 were $\sim \times 10^{34-35}$ ergs and lasted around 1–2 hrs. This contrasts to the energy released on a flare seen on Algol (7×10^{36} ergs) which lasted over a day (Ottmann & Schmitt 1996). In dwarf M stars flares have been seen in the U band (eg Byrne, Doyle & Butler 1984) although they are relatively rare and last several 10's of minutes. In X-rays, dwarf M stars show flares of energies typically $\sim 10^{30-34}$ ergs with a duration less than 1 hour (eg Cheng & Pallavicini 1991). We consider that it is unlikely that the flares originate from pre-main sequence stars since NGC 2516 is not a star forming region. Solar type stars have also been found to show flares in various energy bands with energies $\sim 10^{33-38}$ ergs, although they are very rare (eg Schaefer et al 2000).

In contrast, flares have been seen on RS CVn systems

JTP	N_H	kT_1	kT_2	Observed flux	Bolometric luminosity		χ^2_ν
	$\times 10^{20}$ cm^{-2}	(keV)	(keV)	ergs s^{-1} cm^{-2}	10^{30} ergs s^{-1}	10^{34} ergs	(dof)
80	$5.4^{+6.0}_{-4.3}$	$3.1^{+2.1}_{-0.6}$		$3.1^{+0.5}_{-0.6} \times 10^{-13}$	$5.5^{+0.9}_{-1.1}$	1.2 ± 0.2	0.64 (39)
138	$9.5^{+5.0}_{-3.5}$	$0.8^{+0.4}_{-0.5}$	$5.3^{+3.1}_{-1.4}$	$1.05\pm0.14 \times 10^{-13}$	$1.9^{+2.1}_{-1.6}$	$8.0^{+0.8}_{-1.3}$	0.97 (64)
114	7^{+8}_{-6}	$1.8^{+0.9}_{-0.3}$		1.64×10^{-13}	$4.9^{+0.8}_{-1.3}$	$1.1^{+0.2}_{-0.3}$	1.27 (16)
122	$5.5^{+15}_{-4.5}$	$1.0^{+0.7}_{-0.5}$	$3.7^{+2.7}_{-1.7}$	$3.0\pm0.6 \times 10^{-13}$	$8.0^{+1.2}_{-1.4}$	$5.6^{+0.8}_{-1.0}$	1.67 (33)

Table 3. The spectral fits to the four X-ray varying sources. We have extracted events covering only flare time interval. When determining the luminosity of the flare we assume a distance of 387pc and a solar metallicity.

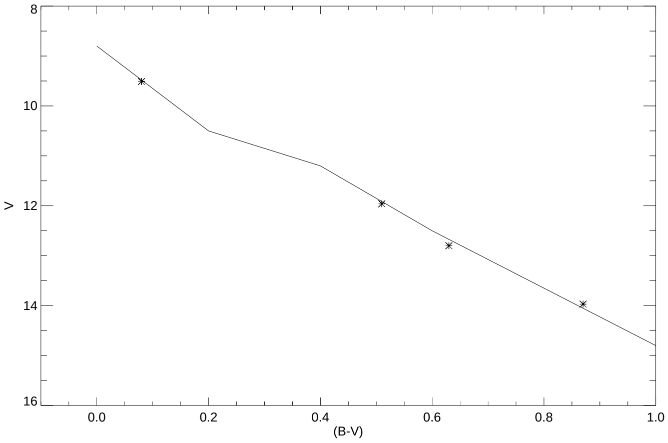

Figure 4. We plot the location of the optical counterparts of the X-ray flaring sources in the $V, B-V$ plane. We also show the location of the main sequence in NGC 2516 taken from the data of Sung et al (2002).

which share similar characteristics to the flares we have observed. van den Oord, Mewe & Brinkman (1988) estimated the energy released in a flare on the RS CVn system σ^2 CrB was 2.4×10^{34} ergs and lasted $\sim$ 90 mins. Further, they found clear evidence for a softening of the light curve after the sharp rise in flux. This is comparable to the RS CVn system II Peg which released $> 5 \times 10^{34}$ ergs in a flare lasting more than several hours (Doyle et al 1991, Doyle, van der Oord & Kellett 1992). Their X-ray spectra are well modelled using a thermal plasma of a few keV. Further, there are several instances where Fe Kα emission has been seen in stars with active stellar coronae (eg Tsuru et al 1989, Güdel et al 2001).

We suggest that JTP 138, JTP 80 and JTP 114 are good candidates for RS CVn systems. The fact that JTP 122 has been classified as AO V spectral type may indicate that it has a dwarf M star as a companion. Followup spectroscopy will be able to test these assertions.

5 THE FREQUENCY OF FLARING ACTIVITY

NGC 2516 has been observed using *XMM-Newton* for 97.4 ksec (cf Table 1). We detected 4 significantly variable X-ray sources over this time implying the detection of one X-ray variable source every $\sim$25ksec. The first two observations were offset from the other observations by $\sim 7^{'}$ (cf Table 1). In this first field we detected 113 X-ray sources and in the second 151 (using the longest exposures in these fields). We detected 1 variable source in field 1 and 3 in field 2. This gives 2.7×10^{-4} variable X-ray sources per ksec per X-ray source in field 1 and 3.0×10^{-4} in field 2. Although simplistic, if every source in the field was a potential X-ray variable source, then these rates would imply that each source would show a flare every $\sim$40 days.

6 COMPARISON WITH SOLAR FLARES

Flaring activity has been seen on the Sun at many wavelengths and timescales. We have searched for solar flares that have a similar temporal profile to 'JTP 138' using the Geostationary Operational Environmental Satellites (GOES). The satellites are in geostationary orbit, their purpose being to monitor the Sun's X-ray emission continuously.

We have identified several solar flares which have similar timescales to that seen in JTP 138. Figure 5 (curve a) shows the light curve of a 'small' solar flare which has an intensity several orders of magnitude lower than the largest flares in the current solar cycle. Like JTP 138 it shows a small increase in flux (lasting $\sim$10 mins) before a rapid rise which takes around 10 mins to reach maximum flux. We have estimated its temperature using ratios of the low energy channel on GOES (1-8Å, 1.5–12.4keV) with the high energy channel (0.5-4Å, 3–25keV). The temperature reached a maximum of 0.6 keV, with a luminosity of 7×10^{25} ergs s^{-1}. The second example solar flare is also shown in Figure 5 (curve b). This flare is brighter, and reaches a temperature of 0.8 keV, with a luminosity of 2×10^{26} ergs s^{-1}. In contrast to the small solar flare and JTP 138, there is no evidence for a pre-flare increase in flux. Both solar flares last around 1–1.5 hrs, similar to JTP 138. In Figure 6 we show the energy resolved light curve of the small solar flare. Similar to the flare seen in JTP 138, the solar flare reaches a maximum in hard X-rays earlier than in soft X-rays.

Although the shape and duration of these solar flares are similar to that of JTP 138, they have lower temperatures and much lower luminosities. The luminosity may simply be a reflection of the volume of the emitting plasma. In the case of RS CVn systems, the flare size can extend to the size of the binary system (or indeed, originate in the intra-binary region as seen in the RS CVn system CF Tuc, Gunn et al 1997). For reasonable system parameters and an orbital period of 2 days, the separation is $\sim 5 \times 10^{11}$ cm. Moreover, the Suns rotation rate has been slowing down since it joined the main sequence. It therefore has lower magnetic activity compared to stars which have recently joined the main sequence (as in the case of stars in NGC 2516).

Numerous explanations for the triggering mechanism of solar flares have been developed over the years. The most

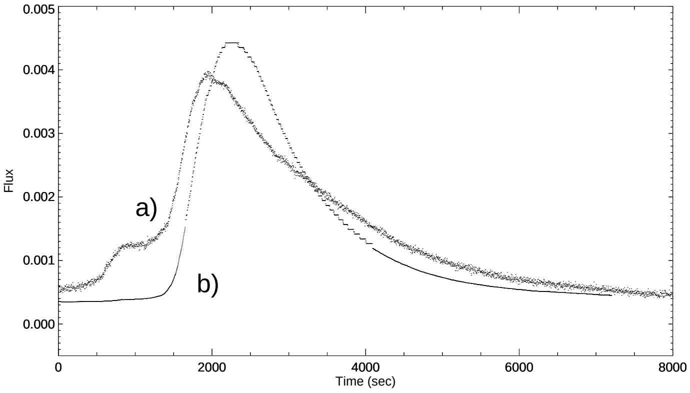

Figure 5. Two solar flares in the wavelength range (1-8Å). Flare a) which took place on 3 Sep 1996 is a relatively small solar flare, which lasts for approximately 1.5 hrs. It shows prominent pre-flare activity. The flux has been multiplied by 10. Flare b) (12 Feb 2001) is an average intensity solar flare. The units for flux is ergs/s/cm^{-2}.

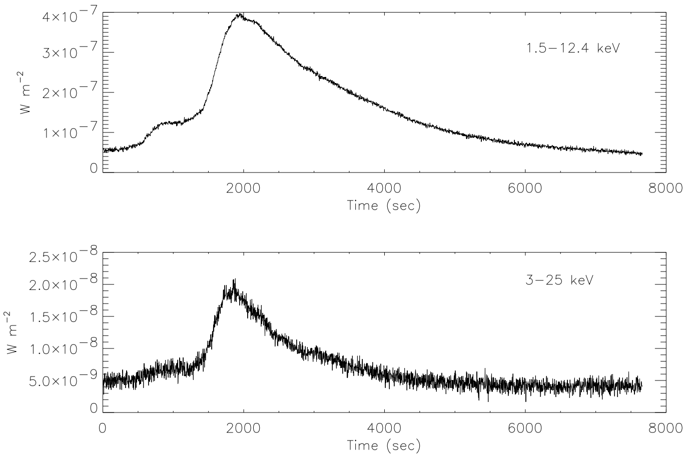

Figure 6. We show the light curve of the flare a in Figure 5 split into soft and hard X-ray bands. Like the flare seen in JTP 138 the hard flux drops more rapidly than at softer energies and maximum hard flux is reached earlier than at softer energies.

popular current theory for converting magnetic energy into kinetic and thermal energies is that of magnetic reconnection (eg Priest & Forbes 1999). The site of the reconnection takes place high in the solar corona above magnetic loops, or between at least two loop systems that interact. At the reconnection site, the electrons are accelerated and move along the loops with a high velocity ($v \sim 0.5c$). Some of these electrons will bombard the chromosphere which is denser and cause this plasma to be heated. This plasma will then evaporate into the loops causing the soft X-ray emission such as is shown in Figure 5 (cf Harra 2000 for more details). Although the details are still uncertain, observations support this view.

Feldman, Laming & Doschek (1995) found a correlation between solar and stellar flare temperatures and emission measures. Shibata & Yokoyama (1999) proposed a model based on a magnetic reconnection model with heat conduction and chromospheric evaporation to account for this correlation. Based on our spectral fits to JTP 138, we find an emission measure of 7×10^{53} cm^{-3} for JTP 138. For a temperature of 6×10^{7} K for the hot component, Figure 1 of Shibata & Yokoyama (1999) suggests a magnetic field strength of $\sim$100 G for this source. Measuring stellar magnetic field strengths is difficult. However, observations of various RS CVn systems show evidence for magnetic field strengths of the order $\sim$100–1000 G (eg Donati 1999), indicating that a field strength of 100 G for JTP 138 is reasonable.

7 CONCLUSIONS

We have performed a X-ray time variability survey of the open cluster NGC 2516. We have found 4 systems which have shown significant variability. Three of these systems show light curves which are characteristic of stellar flaring activity. Based on the flare duration and their spectral properties we suggest that they are RS CVn systems. The fourth system has been identified with a AO V type star and propose that it may have an unseen dwarf M star which shows flaring activity. An optical spectroscopic study of these objects is required. Finally, this study shows that open clusters are excellent objects to search for stellar flaring activity and may be relatively common.

8 ACKNOWLEDGMENTS

This paper is Based on observations obtained with XMM-Newton, an ESA science mission with instruments and contributions directly funded by ESA Member States and the USA (NASA). We thank Mat Page for the use of some of his software. We acknowledge the use of the WEBDA database of galactic clusters.

REFERENCES

Byrne, P. B., Doyle, J. G., Butler, C. J., 1984, MNRAS, 206, 907
Cameron, L. M., 1985, A&A, 147, 39
Cheng, C.-C., Pallavicini, R., 1991, ApJ, 381, 234
Dachs, J., Hummel, W., 1996, A&A, 312, 818
Donati, J. -F., 1999, MNRAS, 302, 457
Dorman, B., Arnaud, K. A., 2001, ASP Conference Proceedings, Vol. 238, p415
Doyle, J. G., et al, 1991, MNRAS, 248, 503
Doyle, J. G., van der Oord, G. H. J., Kellett, B. J., 1992, A&A, 262, 533
Feinstein, A., Marraco, H. G., Mirabel, I., 1973, A&AS, 9, 233
Feldman, U., Laming, J. M., Doschek, G. A, 1995, ApJ, 451, L79
Güdel, M., Audard, M., Magee, H., Franciosini, E., Grosso, N., Cordova, F. A., Pallavicini, R., Mewe, R., 2001, A&A, 365, L344
Gunn, A. G., Migenes, V., Doyle, J. G., Spencer, R. E., Mathioudakis, M., 1997, MNRAS, 287, 199
Harnden, F. R., et al, 2001, ApJ, 547, L141
Harra, L.K., 2000, Phil. Trans. R. Soc. Lond. A., 358, 1
Jeffries, R. D., Thurston, M. R., Pye, J. P., 1997, MNRAS, 287, 350
Jeffries, R. D., James, D. J., Thurston, M. R., 1998, MNRAS, 300, 550
King, D. S., 1978, Sydney Obs Papers, 81
Landini, M., Monsignori Fossi, B. C., Pallavicini, R., Piro, L., 1986, A&A, 157, 217
Micela, G., Sciortino, S., Jeffries, R., Thurston, M., Favata, F., 2000, A&A, 357, 909

Ottmann, R., Schmitt, J. H. M. M., 1996, A&A, 307, 813
Priest, E., Forbes, T., 1999, Magnetic Reconnection, Cambridge University Press.
Sciortino, S., et al, 2001, A&A, 365, L259
Schmitt, J. H. M. M., 1994, ApJS, 90, 735
Schaefer, B. E., King, J. R., Deliyannis, C. P., 2000, ApJ, 529, 1026
Shibata, K. & Yokoyama, T., 1999, ApJ, 526, L49
Sung, H., Bessell, M. S., Lee, B.-W., Lee, S.-G., 2002, AJ, 123, 290
Tsuru, T., 1989, PASJ, 41, 679
van den Oord, G. H. J., Mewe, R., Brinkmann, A. C., 1988, A&A, 205, 181