Astron. Astrophys. 335, L101–L105 (1998)

ASTRONOMY AND ASTROPHYSICS

LETTER

Letter to the Editor

RXTE observations of Proxima Centauri

Bernhard Haisch[1], **Vinay Kashyap**[2], **Jeremy J. Drake**[2], **and Peter Freeman**[3]

[1] Solar and Astrophysics Laboratory, Lockheed Martin, H1-12, B252, 3251 Hanover St., Palo Alto, CA 94304, USA
[2] Center for Astrophysics, 60 Garden St., Cambridge, MA 02138, USA
[3] Department of Astronomy & Astrophysics and Enrico Fermi Institute, University of Chicago, Chicago, IL 60637, USA

Received 1 April 1998 / Accepted 14 May 1998

Abstract. We report on Rossi X-ray Timing Explorer (RXTE) observations of the dM5e flare star Proxima Centauri. These were carried out using the Proportional Counter Array (PCA) in three segments totaling 50.87 ks on 1996 February 20, 23 and 25. The star was detected in the three lowest-energy channels (1.75–3.9 keV, 3.9–5.75 keV, 5.75–8.7 keV) with a mean X-ray luminosity of $< L_x >= 7\,10^{26}$ ergs s^{-1}. This is an order of magnitude higher than the mean non-flaring ASCA detection in a similar passband in March 1994. Previous *Einstein Observatory*, EXOSAT and ROSAT detections yielded similar L_x ($\sim 10^{27}$ ergs s^{-1}) but at lower energies. After compensating for passband differences the RXTE-PCA mean level of activity is found to be similarly enhanced with respect to these observations. The star appears to be in a higher activity state, but no major flares were detected. Owing to the high RXTE background we cannot address the issue of solar-like, M-class flaring previously measured on Proxima by ASCA. Searches were carried out for short-duration bursts – as on the Sun during the flare impulsive phase – at all PCA energies (1.75–65 keV) using statistical tests for any significant clustering of 15, 25, 50 or 100 photons. Such events would be relatively insensitive to fluctuations and modeling limitations of the background. The number of photon clusters found was consistent with statistical fluctuations.

Key words: stars: coronae – stars: individual (Proxima Centauri) – X-rays: stars – stars: flare

1. Introduction

The dM5e flare star Proxima Centauri (= α Cen C; = V645 Cen; = Gliese 551) has been monitored for X-ray flare activity numerous times since the discovery of one of the first such high energy events by an extreme-ultraviolet telescope during the 1975 *Apollo-Soyuz* mission (Haisch et al. 1977). A two-hour flare observed by the *Einstein Observatory* in 1980 remains one of the best examples of a time-resolved solar-like flare on another star (Haisch et al. 1983). The peak power of that outburst and of several others observed by the *Einstein Observatory* and EXOSAT are in the range of $L_x = 2-3\,10^{27}$ ergs s^{-1} in a typical low energy band of $\sim 0.1-2$ keV. Such activity would be classified as major X-class flares on the Sun. Although large in comparison to the meagre optical output of this faint M-dwarf ($L_{bol} = 6.7\,10^{30}$ ergs s^{-1}; Frogel et al. 1972), such X-ray flares are small in comparison to the $10^{31}-10^{33}$ ergs s^{-1} "superflares" on RS CVn and T Tauri stars (e.g. Skinner et al. 1997).

Proxima is the nearest (1.295 pc) star to the Sun, slightly closer than the α Cen AB binary. It has an inferred semi-major axis (13000 AU) and period ($\geq 10^6$ yrs) but it is not certain that it is actually bound to α Cen AB (Matthews & Gilmore 1993). Indeed, its angular separation is over two degrees in the sky. This bears on the question of age vs. activity: if Proxima is not bound to the AB-pair whose evolutionary status ($\sim$ 6 Gyr) has been determined (Ayres & Flannery 1978), its age becomes unknown. Nonetheless we can capitalize on Proxima's status as the nearest extra-solar flare site to test the hypothesis that solar and stellar flares form a continuous sequence involving similar physical processes. To this end, the *ASCA* satellite succeeded in detecting the faintest bona-fide non-solar flares: several M-class events were observed during a 50 ks pointing in March 1994 (Haisch et al. 1995).

The range of X-flares on the Sun per year has ranged from 0 to 59 as a function of the solar cycle from 1969 on, while the number of M-flares has ranged from 14 to 618. With the caveat that the sampling over the past two decades has been sparse, the average activity on Proxima has appeared to be comparable to that of the Sun near maximu. We thus estimated that during a 50 ks *RXTE* pointing we would witness several events. Moreover all previous X-ray observations were of the "thermal phase" of a flare, reflecting the gradual cooling of $> 10^7$ K plasma on 1000 to 10000 s time scales (and in rare cases up to 10^5 s). It was our expectation that the short-lived impulsive events (1–100 s bursts) usually attributed to particle beam heating might be observed directly in the higher energies to which *RXTE* is sensitive or indirectly by rapid changes in the slope of the thermal X-ray emission at the lowest energies based on the Neupert effect (Hudson 1991, Dennis & Zarro 1993). There

Send offprint requests to: B. Haisch (e-mail: haisch@starspot.com)

was also the possibility of discovering even shorter bursts owing to the μs timing capability of RXTE.

2. Observations

Launched December 30, 1995, *RXTE* is geared to high-time resolution observations as short as microseconds, but with only moderate spatial resolution in the 2–250 keV regime. For stellar observations, only the lower energies are relevant for which the Proportional Counter Array (PCA) covering the 1.75–64 keV range is the appropriate instrument. Proxima was observed on three separate occasions in February 1996 (in gain 1) for a total of 50.87 ks as listed in Table 1.

In our analysis we have only used data collected in the top layer of Xe-filled anodes in each of the 5 identical proportional counters in the PCA. Given the low count rate and relatively soft spectrum of Proxima, almost all the counts in the lower layers are expected to be due to the background, and we have used this fact as a check on the validity of our spectral analysis. Indeed, it is crucial that the background be properly accounted for because of the relatively low signal compared to the estimated background ($\leq 50\%$) as well as the uncertainty in the magnitude of the diffuse cosmic X-ray component.

The PCA background consists of 3 components: (1) the astrophysical background, which is modeled as being isotropic; (2) the cosmic ray particle background determined by the anticoincidence or the large event discriminators; and (3) "activation", a post-SAA phenomenon which is only phenomologically understood. A strong stellar contribution to the diffuse X-ray background is expected close to the galactic plane (Kashyap et al. 1992). We have used the best available models for the background, but because Proxima is close to the Galactic plane ($l_{\rm II} = 314$, $b_{\rm II} = -1.88$), the magnitude of the diffuse cosmic X-ray component is relatively uncertain. We have estimated this uncertainty by comparing the observed count spectrum obtained in the top and bottom layers of a PCA scanning observation of the galactic plane (Valinia 1998, private communication; also Valinia & Marshall 1997) near the latitude of Proxima with model predictions. Assuming that the activation and particle background components are well determined, we find that for this scanning observation the observed cosmic X-ray component is 50% higher than predicted, at a latitude only 0.4 deg closer to the plane than Proxima. We have therefore, first added an extra component to the background predicted for Proxima with magnitude 0.5 times the predicted cosmic background, and later allowed the magnitude of this component to vary such that the counts at high energies are all attributable to background. In the latter case the magnitude of this extra component (essentially a correction to the value of the predicted cosmic background) is ~ 0.3 times the cosmic background. We attribute this difference to the slightly different latitudes as well as X-ray source structures between the two observations. We have elected to report the conservative estimate in most cases.

Fig. 1 shows the top layer spectrum of Proxima. The thin solid stepped line shows the background-subtracted spectrum along with 2σ error-bars. The thick stepped line is an "excess" cosmic background model component, scaled down to match the high-energy tail of the spectrum. The dashed line is an estimate of the actual cosmic background, obtained by subtracting the activation and particle components from a Galactic Ridge scan, and scaling the remainder to match the high-energy tail of the Proxima spectrum. Proxima would be detected at high significance even if we were to adopt a model for the cosmic background scaled from the Ridge scan observations. For comparison, we would expect no signal from the star at the level of layer 3, and this is shown in Fig. 2. Note that the cosmic background excess is set at the same level as with layer 1 data: the good match between the background-subtracted spectrum and the estimated excess for both layers shows that our method of background subtraction is adequate.

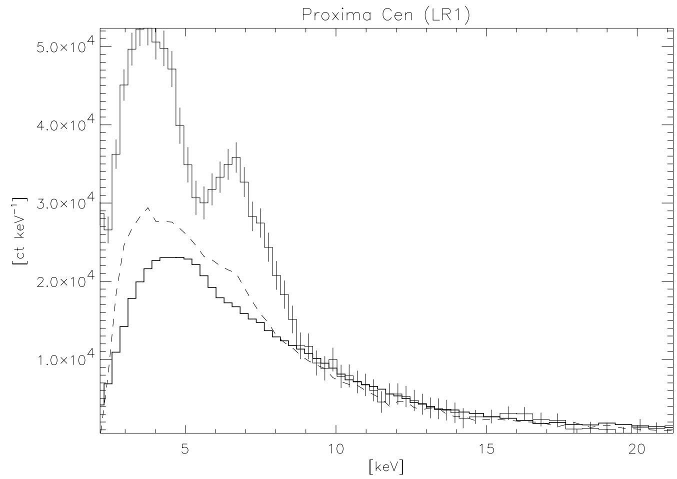

Fig. 1. XTE/PCA layer 1 spectrum of Proxima. The top line shows the background-subtracted spectrum with 2σ error-bars. The bottom line is an "excess" cosmic background model component, scaled down to match the high-energy tail of the spectrum. The dashed line is an estimate of the actual cosmic background, obtained by subtracting the activation and particle components from a Galactic Ridge scan, and scaling the remainder to match the high-energy tail of the Proxima spectrum.

The results of our analyses of the observed data are reported in Table 1. The quoted uncertainties are statistical, and are quite insignificant compared to the systematic errors inherent in background modeling. Our comparison of the observed and predicted counts at high energies in the scan observation of the galactic ridge (cf. Valinia & Marshall 1997) suggests that the maximum systematic error in the predicted background is 50% in the sense that it could be overestimated in our analysis.

Given the ~ 30 arcmin HWHM of the RXTE collimator we consider the possibility that a nearby source may have been the one detected rather than Proxima. Using the Einstein Imaging Proportional Counter (IPC) Haisch et al. (1980) found two unidentified sources that are 14.5 arcmin and 19.5 arcmin from the position of Proxima at the time of the observation. (The proper motion of Proxima is 3.839 arcsec per year.) The IPC fluxes of these sources were only 4 percent and 7 percent of the Proxima flux. Thus unless they are extremely hard and/or

Table 1. Observation log and spectral fit

OBI	Exposure [ksec]	Count Rate (2–5 keV) [ph s^{-1}]	Temperature [keV]	Luminosity (2–10 keV) [ergs s^{-1}]
Feb 20, 1996	19.936	1.15 ± 0.02	0.3-0.6[a]	$1.4\ 10^{27}$
Feb 23, 1996	11.328	0.41 ± 0.03	0.5-1.0[a]	$5.3\ 10^{26}$
Feb 25, 1996	19.600	0.31 ± 0.02	0.4-0.7[a]	$4.1\ 10^{26}$
Total	50.864	0.71 ± 0.02	0.6-1.1[a]	$7.0\ 10^{26}$
		1.63 ± 0.02	0.7-2.2[b]	$1.4\ 10^{27}$

[a] 50% excess cosmic background (see text)
[b] 30% excess cosmic background (see text)

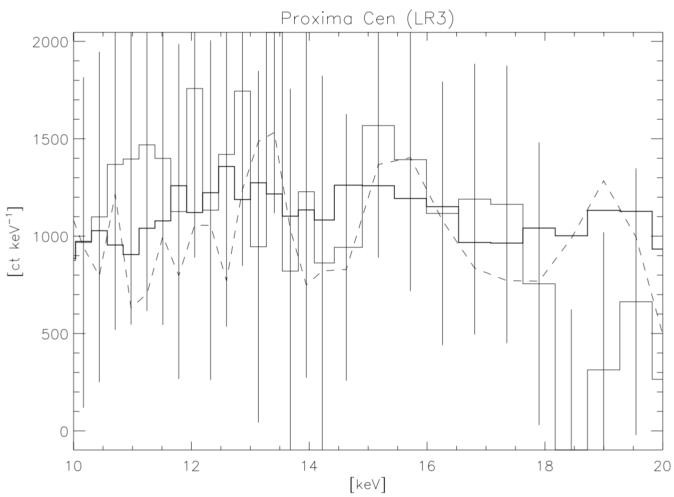

Fig. 2. Same as Fig. 1 but for layer 3 where no source counts are expected from the star. Note that the cosmic background excess is set at the same level as with layer 1 data.

variable they cannot be the source of our RXTE detection. We also searched the RASSBSC (Voges et al. 1996) and WGACAT (White, Giommi & Angelini 1994) catalogs and found no other plausible source.

We are thus able to claim the detection as well as a lower limit on the RXTE luminosity of Proxima. Further note that based on our conservative estimates of the systematic uncertainties, the observed fluxes and count rates are consistent with there being no change in the X-ray emission on Proxima during the observation (see also §4).This is also of relevance to the determination of the activity level of Proxima (see below). The higher temperature components are generally unconstrained, but are quite weak in emission measure (< 0.1).

3. Level of activity

Solar-like M-flares were detected on Proxima by ASCA (Haisch et al. 1995). M-flares are defined as solar events having peak luminosities in a $\sim 1 - 8$ Å passband of the GOES soft-energy X-ray detector of $2.8\ 10^{25}$ ergs s^{-1} for an M1 event, double that for M2, triple for M3, etc. Such events occur on average once or twice per day on the Sun near solar maximum. The three lowest energy PCA channels cover a similar passband ($\sim 1.4 - 6.9$ Å). A rate approximately one count per second in each of the three lowest PCA channels would yield a luminosity of $\sim 1.2\ 10^{27}$, 40 times more intense than an M1 flare. Such a level would correspond to an X4 flare.

We note fluctuations at this level in the background-subtracted signal from Proxima, but since this involves subtracting one large number from another, we refrain from interpreting this as individual flares. While we do not argue for the reality of individual fluctuations as flares, we do argue for the reality of a mean level of activity significantly enhanced over previous measurements. The mean quiescent level detected by ASCA in March 1994 was 0.23 cts s^{-1} corresponding to $\sim 8\ 10^{25}$ ergs s^{-1} in a passband similar to the PCA. The best-fit temperature for ASCA was 6.1 MK (reduced $\chi^2 = 2.9$), marginally higher than the previous *Einstein* IPC fits of ~ 4 MK.

The *Einstein*, EXOSAT and ROSAT observations generally indicated non-flaring emission with $L_x \sim 0.5 - 2\ 10^{27}$ ergs s^{-1} and a temperature similar (~ 4 MK) to the ASCA determination. These measurements were made in soft X-ray bands whereas the ASCA and RXTE measurements involve energies above 2 keV, comparable to solar GOES measurements. Since the ASCA and RXTE luminosities reflect emission in similar bands, their ratio indicates that Proxima was approximately an order of magnitude more active during the RXTE observations than during the ASCA ones.

The ASCA luminosity and temperature are consistent with emission by a corona in a state similar to that observed by *Einstein*, EXOSAT, EUVE and ROSAT. Taking into account the differences in passband, the RXTE-PCA mean level of activity is found to be similarly enhanced with respect to these observations. Proxima thus appears to be in an unusually high activity state in comparison to the many previous observations going back to 1979. A saturation effect is suggest by the fact that there were no individual flares detected that exceeded previous flares scaled by the same factor that characterizes the enhanced activity level.

We can put our RXTE observation in the context of previous observations by comparing the *emission measure loci* predicted by the various previously published broad-band EUV and X-ray count rates. For a given plasma radiative loss model, an observed broad-band count rate corresponds to a plasma emission measure, EM, for any given *isothermal* plasma temperature, T. Each filter count rate, then, when combined with a plasma

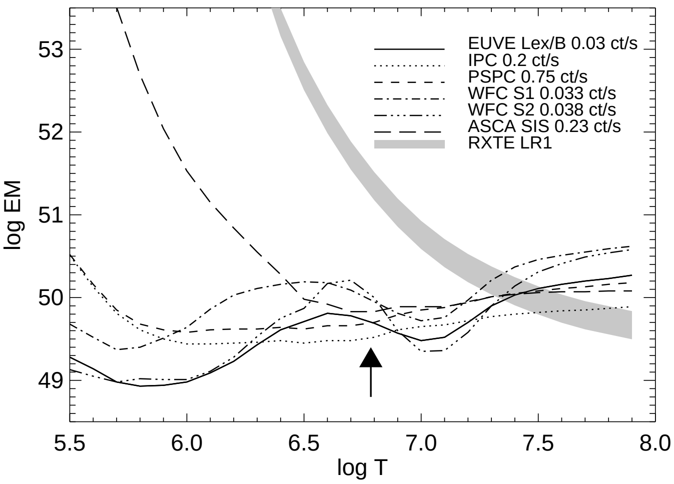

Fig. 3. Emission measure vs. temperature for different instrument count rates reported for Proxima for observations between 1979 and 1996. The shaded region denoting the RXTE observations lies significantly above the other loci.

radiative loss model, defines a locus in the emission measure-temperature plane.

In the case of stellar coronae, the plasma is not likely to be isothermal and the individual loci then represent the *upper limit* to the plasma EM at any given T. However, if the true EM distribution is relatively sharply peaked, and the bandpasses in question are largely dominated by lines formed at this peak temperature, then the isothermal approximation can be reasonable. Similar methods were applied to EXOSAT broad-band observations in different filters by Pallavicini et al. (1988) to estimate cornal temperatures; this approach has also been discussed in detail in the context of the EUVE filters by Drake (1998).

We have plotted the EM-T loci for different instrument count rates reported for Proxima in Fig. 3. The different observations, starting with the *Einstein Observatory* IPC in 1979, span a total of 17 years. The coronal temperature of $6.1\ 10^6$ K derived from the ASCA spectrum by Haisch, Antunes & Schmitt (1995) is marked on the plot by the arrow. We draw special attention to the emission measures indicated by the various observations at this temperature: excluding our RXTE observation, the different loci indicate the *same coronal emission measures to within a factor of about 3*. The RXTE observation is indicated by the shaded region. This region is bounded by the two loci corresponding to the source count rates found for the two different background models described, and represents a reasonable estimate of the uncertainty in the actual source count rate. This shaded region lies significantly above the other loci at the coronal temperature of Proxima. This result suggests that, at the time of the RXTE observation, Proxima was substantially more active than during the earlier observations–by up to an order of magnitude in coronal emission measure.

4. Search for impulsive bursts

During a 1992 simultaneous observation of the flare star UV Ceti by a ground-based observatory measuring U- and B-band flaring and the ROSAT IPC, several soft X-ray bursts were discovered trailing optical spikes by approximately 30 s (Schmitt et al. 1993). The origin of these bursts remains a mystery, but it was suggested that they could be the low energy tails of hard X-ray emission from particle beams. This prompted the inclusion of a search for similar bursts in the RXTE proposal to observe Proxima.

Solar X-rays in the $\sim 10-30$ keV range exhibit bursts near the onset of a flare together with the usual long-lived (minutes to hours) emission characterizing the thermal evolution of $T > 10^7$ K plasma. Above ~ 30 keV only the bursts are seen (cf. Golub & Pasachoff 1997). It is widely assumed that these bursts represent individual heating events that originate in particle beams striking the lower atmosphere and emitting thick-target bremsstrahlung. HXR fluctuations have been observed having timescales of a few milliseconds (cf. Golub & Pasachoff 1997, p. 292). Observations of 2830 solar flares by the SMM-HXRBS ($\sim 29-500$ keV) have shown hundreds of spikes with rise and decay times as short as 20 ms and widths as short as 45 ms (Kiplinger et al. 1983). Aschwanden et al. (1996) have measured time delays in the hard X-ray ($\sim 30-120$ keV) emission and find that the lower-energy bursts trail the higher ones by 40 to 220 ms. This is interpreted as due to shorter time-of-flight of more energetic, hence faster, electrons.

While impulsive HXR emission generally appears only above ~ 10 keV, it has been detected as low as ~ 3 keV (Golub & Pasachoff 1997, p. 292; Kahler & Kreplin 1971).

We analyze photon arrival time data, which are tagged with μs accuracy, using a variant of the photon clustering method applied by Schmitt et al. (1993) to the data of UV Ceti. This method is largely insensitive to details of the underlying model which describes the sum of source and background counts as a function of time. (We considered a method based on that of Gregory & Loredo (1992) which utilizes model comparison; it was not applied, in part, because of as-yet-unexplained systematic uncertainties in the RXTE PCA background model.) In this method, we determine the time interval $\Delta t = t_{i+n+1} - t_i$ over which the PCA detects a group of n counts, where t_i is the time tag of the first photon in the group. If the mean count-rate is A, the significance of a given group is:

$$S = \sum_{m=n}^{\infty} \frac{[A\Delta t]^m}{m!} e^{-A\Delta t}. \quad (1)$$

S represents the probability that n *or more* photons would be detected in time period Δt.

In our analysis, we use n = [15, 25, 50, 100], and determine A by averaging the source plus background amplitude in nine consecutive 16 s bins centered on the time period of interest. Because of this averaging, our method yields accurate estimates of S only when the counts data are constant or vary linearly as a function of time. (For instance, the method provides less reliable results near data gaps or when the count data show sharp peaks.)

We exercise caution when interpreting the significance, since very small values of S are to be expected if we examine a sufficiently large number of clusters. For instance, for a time series with 200,000 photons, we would expect at least one false burst detection unless we set our significance criterion below 10^{-5}. Thus for each observation of Proxima, and in each energy band, we compute the product of S and the "number of trials" T, which we conservatively estimate as the number of examined clusters. A burst is considered detected if $S \times T \leq 1$, and if it appears in two or more adjacent bands at times separated by less than one second (e.g. Aschwanden et al. 1996). By this criterion, we find no statistically significant bursts.

5. Summary

The X-ray emission of the dM5e flare star Proxima has been observed half a dozen times between 1979 and 1994 by the *Einstein Observatory*, EXOSAT, ROSAT (PSPC and Wide Field Camera), EUVE and ASCA. Its activity state has been consistently similar to that of the Sun near solar maximum. The 1996 RXTE-PCA observations show a much enhanced state with a mean X-ray luminosity approximately an order of magnitude higher than that determined by ASCA in a similar, GOES-like 1–8 Å passband in 1994. We also searched for short-duration impulsive burst which would be indicative of particle beam heating. None were found.

Acknowledgements. We are very grateful to Azita Valinia for allowing us access to the XTE scan data of the Galactic Ridge. VK thanks the personnel at XTEGOF for assistance during reduction and background estimation. VK was supported by NASA grants NAG5-3173, NAG5-3189 and NAG5-3195 during the course of this research. JJD was supported by the AXAF Science Center NASA contract NAS8-39073. BH acknowledges support by NASA contract S-73117-Z.

References

Aschwanden, M.J., Hudson, H.S., Kosugi, T., Schwartz, R.A., 1996, ApJ, 464, 985
Ayres, T.R., Flannery, 1978, ApJ, 221, 175
Dennis, B.R., Zarro, D.M., 1993, Solar Phys., 146, 177
Drake, J.J., 1998, ApJS, submitted
Frogel, J.A., Kleinmann, D.E., Kunkel, W., Ney, E.P., Strecker, D.W., 1972, PASP, 84, 581
Golub, L., Pasachoff, J.M., 1997, *The Solar Corona*, Cambridge Univ. Press.
Gregory, P.C., Loredo, T.J., 1992, ApJ, 398, 146
Haisch, B., Linsky, J.L., Lampton, M., Paresce, F., Margon, B., Stern, R., 1977, ApJ, 213, L119
Haisch, B.M., Linsky, J.L., Harnden, F.R. Jr., Rosner, R., Seward, F.D., Vaiana, G.S., 1980, ApJ, 242, L99
Haisch, B., Linsky, J.L., Bornmann, P.L., Stencel, R.E., Antiochos, S.K., Golub, L., Vaiana, G.S., 1983, ApJ, 267, 280
Haisch, B.M., Butler, C.J., Foing, B., Rodono, M., Giampapa, M.S., 1990, A&A, 232, 387
Haisch, B., Antunes, A., Schmitt, J.H.M.M., 1995, Science, 268, 1327
Hudson, H., 1991, Solar Phys., 133, 357
Kahler, S.W., Kreplin, R.W., 1971, ApJ, 168, 531
Kashyap, V., Rosner, R., Micela, G., Sciortino, S., Vaiana, G.S., Harnden, F.R., Jr., 1992, ApJ, 391, 684
Kiplinger, A.L., Dennis, B.R., Emslie, A.G., Frost, K.J., Orwig, L.F., 1983, ApJ, 265, L99.
Matthews, R., Gilmore, G., 1993, MNRAS, 261, L5
Pallavicini, R., Monsignori-Fossi, B.C., Landini, M., Schmitt, J.H.M.M., 1988, A&A, 191, 109
Schmitt, J.H.M.M., 1992, Seventh Cambridge Workshop on Cool Stars, Stellar Systems and the Sun, (M.S. Giampapa, J.A. Bookbinder, eds.), ASP Conf. Series, Vol 26, p. 83.
Schmitt, J.H.M.M., Haisch, B., Barwig, H., 1993, ApJ, 419, L81
Schmitt, J.H.M.M., Collura, A., Sciortino, S., Vaiana, G.S., Harnden, F.R., Jr., Rosner, R., 1990, ApJ, 365, 704
Skinner, S.L., Güdel, M., Koyama, K., Yamauchi, S., 1997, ApJ, 486, 886
Valinia, A., Marshall, F., 1997, presented at High-Energy Astrophy. Div. mtg of the AAS, Estes Park, CO.
Voges, W. et al., 1996, IAU Circ. 6420.
White, N.E., Giommi, P., Angelini, L., 1994, IAU Circ. 6100.