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Astro-D Observations of Flares: Detecting the Impulsive Phase

Period of Performance: April 20, 1994 to October 15, 1995

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As stated in the proposal, the objective of this program was to carry out and analyze observations of X-ray flares using the Astro-D (ASCA) satellite on the dMe star Proxima Centauri. This was successfully accomplished.

The results of this investigation were reported to the scientific community in the following oral presentations:

(1) ASCA OBSERATIONS OF PROXIMA CENTAURI, B. Haisch, J.H.M.M. Schmitt, J. Lemen and A. Antunes, AAS High Energy Astrophysics Division Meeting "The Multi-Mission Perspective", Napa Valley, CA, November 2–5, (1994).
(2) ASCA OBSERVATIONS OF SOLAR-LIKE M-FLARES ON PROXIMA CENTAURI, B. Haisch, A. Antunes and J.H.M.M. Schmitt, 185th AAS Meeting, Tucson, AZ, BAAS, 26, 1380, (1995).
(3) STELLAR X-RAY FLARES, B. Haisch, IAU Colloquium No. 153: Magnetodynamic Phenomena in the Solar Atmosphere, Makuhari, Japan, May 22-26, (1995).
(4) ASCA OBSERVATIONS OF X-RAY FLARES ON PROXIMA CENTAURI, A. Antunes, B. Haisch and J.H.M.M. Schmitt, 186th AAS Meeting, Pittsburgh, PA. June 11–15, (1995).
(5) X-RAY OBSERVATIONS OF STELLAR FLARES, B. Haisch, Röntgenstrahlung from the Universe, Würzburg, Germany, Sept. 25–29, (1995).

The primary research article that resulted from this work appeared in *Science*:

SOLAR-LIKE M-CLASS X-RAY FLARES ON PROXIMA CENTAURI OBSERVED BY THE ASCA SATELLITE, B. Haisch, A. Antunes, and J.H.M.M. Schmitt, Science, 268, 1327, (1995).

This article is attached as Appendix A:

These observations were also mentioned in the following two articles now in press:

ADVANCES IN SOLAR-STELLAR ASTROPHYSICS, B. Haisch & J.H.M.M. Schmitt, invited review for P.A.S.P., in press, (1995).

STELLAR X-RAY FLARES, B. Haisch, Invited Review for *IAU Colloquium No. 153: Magnetohydrodynamic Phenomena in the Solar Atmosphere*, Y. Uchida, T. Kosugi and H.S. Hudson (eds.), Kluwer, in press, (1995).

The latter article is attached as Appendix B.

Bernhard Haisch
Palo Alto, California
October 10, 1995

APPENDIX A

SOLAR-LIKE M-CLASS X-RAY FLARES ON PROXIMA CENTAURI OBSERVED BY THE ASCA SATELLITE

B. Haisch, A. Antunes, and J.H.M.M. Schmitt, Science, 268, 1327, (1995)

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Solar-Like M-Class X-ray Flares on Proxima Centauri Observed by the ASCA Satellite

Bernhard Haisch, A. Antunes, and J. H. M. M. Schmitt

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Solar-Like M-Class X-ray Flares on Proxima Centauri Observed by the ASCA Satellite

Bernhard Haisch, A. Antunes, J. H. M. M. Schmitt

Because of instrumental sensitivity limits and stellar distances, the types of x-ray flares observable on stars have been intrinsically much more energetic than those on the sun. Such enormous events are a useful extrapolation of the solar phenomenon if the underlying assumption is correct that they form a continuous sequence involving similar physical processes as on the sun. The Advanced Satellite for Cosmology and Astrophysics (ASCA), with its greater sensitivity and high-energy response, is now able to test this hypothesis. Direct comparison with solar flares measured by the x-ray–monitoring Geostationary Operational Environmental Satellites (GOES) is possible. The detection of flares on Proxima Centauri that correspond to GOES M-class events on the sun are reported.

Geomagnetic storms associated with the largest solar flares can cause communications disruptions and even power outages. For example, the event associated with the X-class flare of 10 March 1989 blacked out the Hydro-Quebec power system (*1*). Non-negligible radiation exposure of passengers on long commercial flights can result during major events, especially in the auroral latitude zones. Understanding solar flares is therefore of some importance, and the monitoring of solar activity and the development of flare forecasting ability have been long-standing programs in both the U.S. Department of Commerce and Department of Defense (*2*). Since 1969, the key observational component in this system has been the GOES series of the National Oceanic and Atmospheric Agency (NOAA), which continuously monitor the solar x-ray flux.

Stellar flares have been observed for 20 years to emit x-rays, but the events must be much larger—by as much as a factor of 10^4—than even the most energetic on the sun in order to be detected across the enormous distances. While stellar "superflares" are of considerable interest, it is equally important to ascertain whether and with what frequency commonplace solar-like events occur on stars. Being able to observe such events is an important test of the working hypothesis that we are dealing with scaled-up versions of the same physical phenomenon. The Japanese ASCA satellite (*3*) has now succeeded in such a detection, observing very typical M-class solar-like flares on the next nearest star, Proxima Centauri.

The GOES classification for solar x-ray flares is a linear function of the flux in the ~1 to 8 Å band by which criterion flares are assigned a class of C, M, or X. The satellite also measures a harder spectral component (~0.5 to 4 Å) in which the flux is typically 10 to 100 times weaker. This weakness is a result of the steeply falling thermal emissivity of plasma at flaring temperatures $T > 10^7$ K for wavelengths $\lambda < 2$ Å (Fig. 1). The plotted spectrum is a simulation based on the plasma emissivity model of Mewe *et al.* (*4*) applied to a flare differential emission measure, which represents the amount of radiating material at the distribution of temperatures typical for flares (*5, 6*). For this spectral distribution, the GOES band measures 63% of the actual flux in an ideal 1 to 8 Å band because the

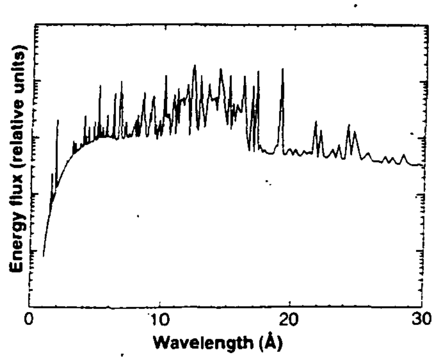

Fig. 1. Spectrum synthesized with the use of a solar flare differential emission measure and a plasma emission code accounting for both lines and continuum radiation in the 1 to 30 Å region.

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GOES response is not flat in this interval and tails off above and below the nominal limits (7, 8). To differentiate the GOES band from an ideal flat-response one, we hereafter refer to the measured (soft) band as the "GOES-S" band.

A flare of class M1 has a peak power of $L_x = 2.8 \times 10^{25}$ ergs s^{-1} in the GOES-S band, where L_x is the x-ray analog of the astronomical quantity of luminosity. An M2 flare is twice as energetic, and so on. The X class similarly covers the next higher decade; for example, $L_x(X2) = 5.6 \times 10^{26}$ ergs s^{-1}. The degree of solar flaring follows the solar cycle (Table 1) (9). The only cycle for which complete coverage is available is cycle 21, which lasted from June 1976 through August 1986, during which there were 2632 M flares and 172 X flares. Figure 2 shows, as an example, the monthly GOES plot from October 1991, a period of intense solar activity; M and X flares were numerous.

The first detections of stellar x-ray and extreme ultraviolet flares took place in the mid-1970s, although with very poor sensitivity (10, 11). Shortly thereafter, the High-Energy Astronomy Observatory 1 (HEAO-1) satellite succeeded in detecting several flares (12). It was the Einstein Observatory that opened the window on x-ray flares, and one of the most detailed light curves of such an event was observed on 20 August 1980 on Proxima Centauri as part of a coordinated program with the International Ultraviolet Explorer (13). The most detailed view of a nonsolar flare can be had from the nearest nonsolar site of such activity, which turns out to be Proxima Centauri, at a distance of 1.3 pc. This star is an extremely faint dM5.5e companion to the first-magnitude α Cen binary. Proxima is at such an extreme distance from its companions α Cen A and B that it is not certain whether it is actually bound to the system; its separation in the sky is >2° (14).

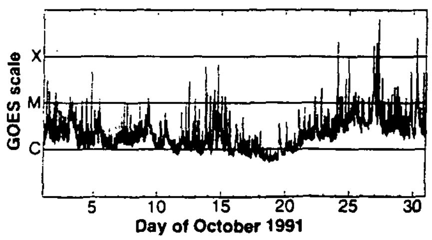

Fig. 2. The monthly GOES plot from October 1991, a period of intense solar activity showing numerous M and X flares.

Further flare observations of Proxima Centauri were made by the Exosat Observatory (15). Then in 1990, with the launch of ROSAT, a new opportunity arose for such measurements (16). However, the passbands of all these observatories differ significantly from that of GOES-S: ~3 to 60 Å for the Einstein Observatory Imaging Proportional Counter; ~6 to 300 Å for the Exosat Low Energy Telescope; and ~6 to 120 Å for the ROSAT Position Sensitive Proportional Counter. The ASCA observatory, launched 20 February 1993, is sensitive to more energetic x-rays (~1 to 24 Å) and, even at overlapping wavelengths, has significantly more effective area than the previous telescopes [see figure 2 in (3)]. The lower detection threshold and the fact that the ASCA band overlaps entirely with the GOES-S band thus afford a direct comparison between commonplace flares on Proxima Centauri and on the sun.

Proxima Centauri was the target of a National Aeronautics and Space Administration (NASA) Guest Observation with ASCA on 18 to 20 March 1994 that lasted for 23 satellite orbits and yielded about 50,000 s of good data. Observations were carried out with four identical grazing-incidence x-ray telescopes and two different pairs of detectors: two charge-coupled device (CCD)–camera solid-state imaging spectrometers (SIS) and two gas scintillation imaging proportional counters (GIS) (3). The data (Fig. 3) were divided into quiescent and flare intervals, and spectral analysis was carried out according to standard plasma emission models tailored to the ASCA instruments. It is customary to attempt a two-temperature (2T) fit: Generally, a low-T component is interpreted as the average (that is, the most common) temperature, and a high-T component indicates the approximate peak temperature. The statistically best 2T fit for the aggregate of the flare emission was $T_1 \sim 7.3$ MK and $T_2 \sim 44$ MK. A formal 2T fit for the quiescent interval was attempted as well, but only the cooler component appears credible. We take the obtained $T_1 \sim 6.1$ MK as representative of the nonflaring coronal emission (17).

We have calibrated the flares relative to the GOES-S band using the solar flare differential emission measure (5, 6) that yields the spectrum in Fig. 1 (18). Calibrated to the SIS response, an M1 flare having solar differential emission measure at the distance of Proxima Centauri would yield 0.1 count s^{-1} in each SIS telescope-detector system. From spectral simulation, it is expected that the GIS would be about half as sensitive to flare radiation. This is indeed the case: During this observation, the average count rates during flare-enhanced intervals showed an SIS to GIS ratio of 1.94 (19). Thus, for the total summed flare signal in all four instruments, an enhancement of 0.3 count s^{-1} would correspond to an M1 flare.

The summed quiescent background was 0.23 count s^{-1} (Fig. 3, lower line). The top line in Fig. 3 indicates an M1 event level above quiescence. It is possible that the

Fig. 3. ASCA x-ray light curve for Proxima Centauri summed over all four detectors. The lower line shows the average quiescent summed count rate; the top line indicates the M1 flare level above the quiescent emission.

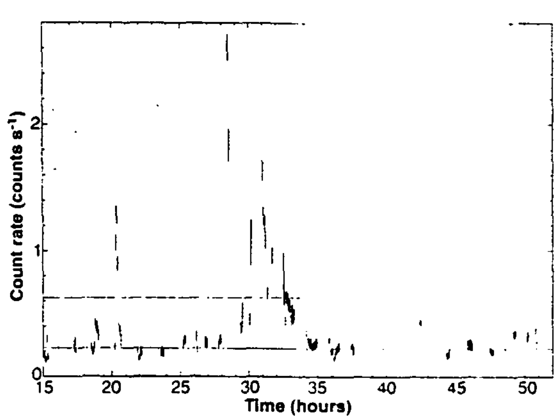

Table 1. Yearly rate of solar M and X flares. The peaks in 13-month averaged, smoothed sunspot number were in November 1968, December 1979, and July 1989 (solar cycles 20, 21, and 22, respectively). These correlate well but not precisely with the flare rate maxima.

Year	M flares	X flares
1969	352	41
1970	534	53
1971	120	6
1972	146	15
1973	80	8
1974	77	15
1975	18	1
1976	14	3
1977	48	4
1978	264	21
1979	452	29
1980	496	21
1981	506	38
1982	606	42
1983	105	6
1984	114	7
1985	17	2
1986	23	2
1987	29	0
1988	193	21
1989	618	59
1990	273	17
1991	590	54
1992	206	10
1993	75	0
1994	25	0

quiescent emission was the cumulative result of many ongoing events of class C or even lesser energy, but this issue of whether coronal heating is entirely the result of flare-like activity or has any steady component is an open issue even for the sun (*20*)

During solar maximum, the number of M flares per month is ~50, that is, ~1.7 per day. During this observation, Proxima Centauri was at least as active as the sun at maximum. It is important to put this in perspective for such a faint dwarf M star: The bolometric luminosity (mainly in the optical and infrared) of Proxima Centauri is only 6.7×10^{30} ergs s^{-1} (*21*), less than 1/500 that of the sun. The total x-ray luminosity at all wavelengths for the most energetic events on Proxima Centauri observed by ASCA and ROSAT is $L_x \sim 3 \times 10^{27}$ to 6×10^{27} ergs s^{-1}. This amounts to an instantaneous perturbation on the order of 0.1% of the total thermonuclear power of the star.

Observation of ordinary M-class flare events on Proxima Centauri indicates that the assumption that flares on the sun and on other stars are scaled versions of the same process is fundamentally sound. It remains a challenge to understand both how flares can, in an absolute sense, exceed those on the sun by up to four orders of magnitude on such extremely active stars as T Tauris (*22*) and RS CVn systems (*23*), and in a relative sense on such faint dwarf M stars as Proxima Centauri.

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17. The formal fits for the flare are $kT_1 = 0.63 \pm 0.01$ keV (k is Boltzmann's constant) with an emission measure $EM_1 = 5 \times 10^{49}$ cm^{-3} and $kT_2 = 3.83 \pm 0.67$ keV with $EM_2 = 3 \times 10^{49}$ cm^{-3}. These fits were calculated assuming a column density of hydrogen N_H conservatively fixed at 3×10^{19} cm^{-2}, resulting in a reduced $\chi^2 = 2.3$. For the quiescent intervals, $kT_1 = 0.53$ keV with $EM_1 = 10^{49}$ cm^{-3} and $kT_2 > 4$ keV with $EM_2 = 9 \times 10^{48}$ cm^{-3} (reduced $\chi^2 = 2.9$). In both cases, fitting was hindered by low count rates above 6 keV, and in particular, we do not consider the quiescent kT_2 fit to be credible. These temperatures are marginally statistically hotter than the Einstein Observatory determinations in (*13*).
18. A continuous distribution of temperature for the flaring plasma is likely to be more realistic than the two isolated temperatures T_1 and T_2. Moreover, the temperature of the DEM (differential emission measure) maximum and the highest temperature of the DEM are similar to T_1 and T_2 of the flare.
19. The average count rates for the flare intervals are $SIS_a = 0.331$, $SIS_b = 0.258$, $GIS_a = 0.136$, and $GIS_b = 0.168$ counts s^{-1}. The absolute values are quite dependent on the choice of flare interval; it is the ratio of 1.94 that is important. For the quiescent intervals, they are $SIS_a = 0.071$, $SIS_b = 0.063$, $GIS_a = 0.048$, and $GIS_b = 0.050$ counts s^{-1}.
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24. We wish to acknowledge the support of the NASA ASCA Guest Observer Program (contract S-14646-F, B.H. was principal investigator) and the Institute of Space and Astronautical Sciences ASCA Guest Observer Program under whose auspices these observations were carried out. We thank D. Speich of NOAA for providing solar flare data and G. Linford of Lockheed for GOES data plots.

21 November 1994; accepted 24 March 1995

APPENDIX B

STELLAR X-RAY FLARES
B. Haisch, Invited Review for
IAU Colloquium No. 153: Magnetohydrodynamic Phenomena in the Solar Atmosphere
Y. Uchida, T. Kosugi and H.S. Hudson (eds.), Kluwer, in press, (1995)

STELLAR X-RAY FLARES

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1. Introduction and Historical Overview

What is the importance of stellar X-ray flares to astrophysics, or even more, to the world at large? In the case of the Sun, changes in solar activity at the two temporal extremes can have quite significant consequences. Long-term changes in solar activity, such as the Maunder Minimum, can apparently lead to non-negligible alterations of the earth's climate. The extreme short term changes are solar flares, the most energetic of which can cause communications disruptions, power outages and ionizing radiation levels amounting to medical X-ray dosages on long commercial flights and even potentially lethal exposures for unshielded astronauts (Haisch, Strong and Rodonò 1991). Why does the Sun exhibit such behaviour? Even if we had a detailed knowledge of the relevant physical processes on the Sun — which we may be on the way to having in hand as evidenced by these *Proceedings* — our understanding would remain incomplete in regard to fundamental causation so long as we could not say whether the Sun is, in this respect, unique among the stars.

Since the 1970's we know that the Sun is not unique: Stars emit X-ray flares and this opens the opportunity to test for relationships between flaring and such stellar conditions as mass, age, rotation and the like.

The first stellar X-ray flare detections were the 1974 October 19 event on YZ CMi and the 1975 January 8 one on UV Ceti, both observed by the Dutch ANS satellite (Heise et al. 1975). This was followed by the 1975 July 22 EUV flare on Proxima Centauri detected by an astronaut-deployed telescope during the Apollo-Soyuz mission (Haisch et al. 1977). Two attempts were made to observe flares (on YZ CMi and Prox Cen) with the SAS-

C satellite in 1975 and 1977, but without success (see Haisch 1983). The HEAO-1 satellite in its 1977 all sky survey detected X-ray enhancements on AT Mic and AD Leo (Kahn et al. 1979). The *Ariel V* X-ray survey (2–18 keV) from 1974–1980 detected a number of transients which were later associated with flares (Pye and McHardy 1983). Substantial progress began to be made with the the capabilities of the *Einstein Observatory* (1978-1981); much more has followed via *Exosat*, *Ginga*, ROSAT, EUVE, ASCA and now XTE. The *Exosat* flare results have been nicely summarize by Pallavicini, Tagliaferri and Stella (1990). A review of ROSAT flare observations has been published by Schmitt (1994). The *Annual Reviews* article by Haisch, Strong and Rodonò (1991) is still reasonably current.

2. Observations of Hot Thermal Emission

The original "flare stars" were the dKe/dMe UV Ceti-type known since 1948 to undergo visual flaring episodes best observed in the Johnson $U-$ and $B-$bands where a 10000 to 20000 K optical flare spectrum has the advantage of enormous contrast over cool photospheric radiation. Flares in various wavelength regimes have now been observed on many different types of stars (see Pettersen 1989) and in particular it now appears that X-ray flares can be found "on all types of late-type stars" (Schmitt 1994). This conclusion is drawn from the ROSAT all-sky survey, carried out in 1990–91. During the survey, any individual star transited the X-ray telescope (XRT), Position Sensitive Proportional Counter (PSPC), 2-deg field-of-view once per satellite orbit for several days, depending upon the star's ecliptic latitude. The effective exposure time per orbit reached a maximum of 32 seconds. Some stars showed large enhancements during a given scan, interpretable as flares which could have started anytime after the previous scan and could have lasted up to the next scan. Examples of such X-ray flare snapshots are the two isolated single-scan outbursts on the F5 V star 36 Dra shown in Figure 1 of Schmitt (1994). Other flares are so long-lived that they are rather well-resolved even at this coarse resolution: for example the event on the G5 III star HR 3922 shown in Figure 2 of Haisch and Schmitt (1994). The all-sky survey provided a coarse but unbiased sampling of flare activity.

The benchmark for stellar X-ray flares is the Sun. Solar X-ray monitoring has been carried out since 1969 using the Geostationary Operational Environmental Satellites (GOES) series of the U. S. National Oceanic and Atmospheric Agency (NOAA). The flux at the earth in a $\sim$ 1 to 8 Å band is used to classify flares as type C, M or X. A flare of class M1 would have a corresponding peak luminosity of $L_x = 2.8 \times 10^{25}$ ergs s^{-1} in that GOES band (the luminosity in a ROSAT-PSPC-like band would be about

16 times larger); a flare of class M2 would be twice as energetic; a flare of class X1 would have ten times the power, etc. (Sawyer, Warwick and Dennett 1986). At solar maximum the Sun undergoes $\sim$ 600 M-flares and $\sim$ 40 to 60 X-flares per year; at solar minimum there are typically one to two dozen M-flares per year with X-flares being quite unlikely to occur at all (see Table 1 in Haisch, Antunes and Schmitt 1995 for a summary over the past 25 years). How do stars compare to this?

Most flares have naturally been considerably more energetic: Owing to stellar distances and instrumental detection limitations, the most intrinsically powerful events are the ones observed. Moreover, while we can with considerable confidence extrapolate from the generally softer energy regimes of *Einstein*, *Exosat* and ROSAT to the GOES band, it is desireable to actually have overlapping measurements. The ASCA satellite, whose wavelength regime is $\sim$ 1 to 24 Å, has done this, monitoring Prox Cen over 23 satellite orbits in March 1994 and succeeding in detecting a number of low-level flares that correspond to solar M-flares (Haisch, Antunes and Schmitt 1995) at a rate that appears to be somewhat in excess of the Sun at maximum ($\sim$ factor of two). A two-temperature fit to the summed flare data using the Mewe-Kaastra (MEKA) plasma code yielded 0.63 ± 0.01 and 3.83 ± 0.67 keV, i.e. 7.3 and 44 MK. This average over several events would appear to be significantly higher than even the peak of the 1980 *Einstein* flare: 27 MK (Haisch et al. 1983). While a few rare solar flares have been observed with temperatures as high as 50 MK (Garcia and McIntosh 1992), what we would expect to measure if the Sun were observed by ASCA (or *Einstein*) would be a maximum temperature during the event of 25 MK or less (Doschek and Feldman 1987, Doschek and Tanaka 1987). These ASCA observations constitute the lowest level of credible stellar X-ray flare detection and, overall, provide a reassuring indication that solar and stellar flares are fundamentally the same phenomenon.

At the other extreme are such superflares as those on the RS CVn stars UX Ari observed by *Ginga* (Tsuru et al. 1989) and AR Lac detected by ROSAT (Ottmann and Schmitt 1994), both with $L_x \sim 2 \times 10^{32}$ ergs s^{-1}. A flare on the RS CVn star CF Tuc lasted 9 days and released $E_x \sim 5 \times 10^{36}$ ergs (Kürster 1994). Although less energetic in an absolute sense, X-ray flares on the dM6e star AZ Cnc and on the K0 V star 197890 ("Speedy Mic") attained X-ray to bolometric luminosity ratios, $L_x/L_{bol} \sim 0.08$ (Schmitt 1994), constituting significant perturbations on the total power output of these stars.

The most energetic flares in terms of spectral distribution are those observed by the Japanese *Ginga* satellite in the 1.5–37 keV range. These include the observations of the RS CVn binary systems II Peg (6.7-d period) by Doyle et al. (1991) and UX Ari (6.4-d) by Tsuru et el. (1989), and of the eclipsing binary Algol (2.87-d) by Stern et al. (1992). The large flares that were observed have peak luminosities in the range $L_x \sim 10^{31}$ to 2×10^{32} ergs s^{-1} and peak temperatures of $T \sim 65$ to 80 MK. The highest temperature measured during any flare is $T \sim 100$ MK, both on the dMe star EQ 1839.6+8002 (Pan et al. 1995) and possibly during one of the UX Ari flares (Tsuru et al. 1989).

At such high temperatures lines of highly ionized iron, primarily Fe XXV at 6.7 keV, are a detectable feature in *Ginga* spectra, and the behaviour of these lines is interesting. In the II Peg, UX Ari and Algol flares, the equivalent width of this feature, actually a composite of several lines, is significantly less than calculated from models assuming solar abundance and an optically thin emitting plasma. A depression due to opacity is certainly possible but cannot explain reductions of up to a factor of 5; the most likely explanation is that the flaring plasma has a different and sometimes measurably variable abundance (cf. Stern, these proceedings). Moreover such an abundance deficiency cannot be explained by the first ionization potential (FIP) effect, since at 7.9 eV Fe is an easily ionized element and would thus, if anything, be overabundant (see Drake, Laming and Widing 1995 for entry into the FIP literature).

3. Searching for Impulsive Emission

There is no indication of any impulsive, non-thermal emission in the *Ginga* flares. When higher spectral resolution becomes available, with the AXAF transmission grating spectrometers for example, it will be possible to separate such prominent high-temperature lines as Fe XXV (6.7 keV) from low ionization Kα lines, such as Fe II at 6.4 keV. Photoionization by X-rays above 7.11 keV or collisional ionization by particle beams of the ground-state electron result in an inner-shell transition of this sort. It is well known from solar flares that inner-shell ionization of neutral or near-neutral Fe occurs (see Bai 1979) and that such a Kα line originating in cool gas subject to photoionizing flux or a particle beam often tracks the hard X-ray flux (see Figure 4 of Emslie, Phillips and Dennis 1986). The model of Bai (1979) is one assuming photoionization as the mechanism and the process is termed Kα-fluorescence. His calculations suggested a ~ 1 to 3 percent efficiency for conversion of continuum hard X-rays into Kα-fluorescence during the impulsive phase of a solar flare.

We applied this model in a very rough way to a stellar situation by equating the peak L_x for an observed flare on Prox Cen with a presumed impulsive HXR burst, a simple (if not simplistic) application of the "Neupert effect" (Neupert 1969, Dennis and Zarro 1993). This then allowed us to predict how many ASCA counts there would be during an impulsive event on Prox Cen at the onset of a flare equivalent to the 4 ct s^{-1} ROSAT PSPC event measured during the all sky survey (see Figure 4 of Schmitt 1991). This admittedly optimistic model predicted about 100 to 300 counts for the ASCA detectors during an impulse $K\alpha$-fluorescence burst. None of the flares observed by ASCA during its monitoring of Prox Cen were as energetic in soft X-ray as assumed in the model (Haisch, Antunes and Schmitt 1995). Nonetheless, there was no indication of any impulsive $K\alpha$ emission.

Theoretical calculations of the relationship between hard and soft X-rays do indicate that there should be a Neupert effect-like correlation between the hard X-ray time profile and the derivative of the soft X-ray light curve in the beam heating model but not in the superthermal model (Li, Emslie and Mariska 1993). Forthcoming observations of flares using XTE will search for rapid variations in the soft X-ray flux on Prox Cen, AR Lac and other stars. Another way to express the Neupert relationship is to equate the time integral of hard X-ray emission up to some point with the current value of the thermal soft X-ray emission. Hawley et al. (1995) have recently interpreted comparison of the time integral of $U-$band with EUV luminosity during a flare on AD Leo in this way.

With a single possible exception all X-ray emissions detected to date appear to originate in the thermal phase; X-ray impulsive emission has not yet been observed in stellar flares. The single exception is intriguing and owes its discovery to the availability of simultaneous optical photometry. UV Ceti was monitored by a high-speed multisource, multicolor photometer, specifically designed for stellar flare observations, operating at the Wendelstein Observatory in Bavaria in January 1992 during a ROSAT PSPC pointing. Two optical spikes were detected in the $U-$ and $B-$bands. The normally processed X-ray light curve showed a typical gradual event following the second optical burst. However, alerted to the presence of two optical bursts, a search was done for clustering of X-ray photons by examining the behaviour of a constant-count binned light curve. This is possible to do since every photon is time-tagged to $\sim$millisecond accuracy. The result was the presence of X-ray bursts with durations of $\sim$12 s. With this resolution the gradual phase event appears to consist of a dozen or so bursts, but more mysterious is the fact that both optical spikes are followed by X-ray bursts with a time delay of $\sim$30 s. The statistics of this, including the sticky issue of how to allow for the degrees of freedom permitted by varying the search windows, are presented in Schmitt, Haisch and Barwig (1993). While it is possible that these soft X-ray bursts could be the low energy tails of hard X-ray emission from particle beams, the time delay does not yet have a plausible explanation.

4. Discussion

Turning briefly to analytical tools, there are basically two models that have been applied to the thermal or decay phase of the X-ray light curves of stellar flares. The quasi-static cooling loop model has been developed most by van den Oord, Mewe and Brinkman (1988); the two-ribbon flaring model has been developed by Kopp and Poletto (1984). They make fundamentally different assumptions: the first model assumes that changing plasma conditions within a single loop give rise to the observed flare characteristics; the second assumes that over the course of the event *different* loops become activated. Both analyses have been applied to the same flare: viz. the Poletto et al. (1988) and the Reale et al. (1988) analyses of Prox Cen; also the Schmitt (1994) analyses of EV Lac. The bottom line, unfortunately, is that it does not yet appear to be possible to differentiate between low density, large structures and high density, compact ones on the basis of these models and the existing flare light curves. (Flare light curves are of course complicated by the situation that, without spatial resolution, one cannot separate out the combined signature of multiple, overlapping flares.)

Attempts to understand flares by studying ratios of emission in disparate wavelength regimes has a long history. Twenty years ago Mullan (1976) proposed a theory predicting ratios of X-ray to optical luminosity during flares. This was a laudable attempt to develop a quantitative relation between high temperature coronal plasma properties and the response of a heated chromosphere, but it was quickly found to be at variance with new flare observations (Haisch et al. 1977). Indeed, the ratio L_x/L_{opt} varies between zero and infinity over the course of a flare. Nevertheless, could such a type of ratio still have significance as an average over a flare? Butler et al. (1988) found what appeared to be a striking correlation between a chromospheric line (Hγ) and L_x applicable over four orders of magnitude to both solar and stellar flares, and this relationship was found to extend another two orders of magnitude recently (Butler 1993). This would be quite a significant result, however on looking at 370 solar flares in detail, classified simultaneously in Hα and as GOES-events, it became clear that while the proposed relationship is true on average over many flares, for any given flare the deviation from the relationship can be very large: a spread of up to three orders of magnitude in L_x for a given Hα emission (Haisch 1989). The conclusion is that ratios of coronal to chromospheric emission vary substantially both during a flare and from flare to flare; only the time- and event-averaged ratios show a credible correlation.

Flares and coronae are thought to go hand in hand, and indeed the concept that coronal heating is really a flare-like process is still a debated but viable concept. (The issue of coronal heating is so vast a topic that the place to enter the literature might be Zirker's 1993 "review of reviews"; also the Ulmschneider, Priest and Rosner 1991 volume; and recently Cargill 1994). The most current discovery on the stellar side relevant to this is the finding of a uniform soft X-ray to microwave relation ranging from solar microflares to stellar coronae, suggesting that "the heating mechanism of active stellar coronae is a flare-like process" (Benz and Güdel 1994).

This is relevant to the proposal of Kashyap et al. (1994) that the hybrid star α Trianguli Australis is an X-ray source on the basis of flaring, not steady emission. This late-type star (K4 II), and the other dozen or so luminosity class II or III K giants defining the hybrid star category appear to manifest both massive cool wind signatures and X-ray emission. It is thought that in most stars these two characteristics are mutually exclusive, owing to a phase transition across a dividing line in which coronae disappear (see Haisch, Schmitt and Fabian 1992 and references therein for entry into the stellar dividing line issues). The proposal that Kashyap et al. and Rosner et al. (1994) make is that X-rays from hybrid stars are solely due to flares, and that this is an indicator that large-scale magnetic dynamo activity is being replaced by much smaller scale magnetic structures. This would be an important discovery about stellar evolution, but it is not clear how to interpret the significance of their observation if all coronal heating is flare-like.

Although the majority of flare observations have come from such prolific sources as dKe/dMe stars and RS CVn binaries, it would not be surprising to detected a flare on any type of star that shows coronal emission. But what is one to make of a flaring Be star? A 30 ks ROSAT PSPC observation of λ Eri (B2e) shows a normal level of X-ray emission for a hot star presumably with a radiatively-driven wind. A substantial flare then takes place with flux levels enhanced by a factor of 6 and a duration of $\sim$50000 s. The following day the X-ray luminosity has returned to the preflare level and remains constant for the remainder of the observation, approximately half a day (Smith et al. 1993). The analysis of the event yields a peak luminosity, $L_x \sim 4 \times 10^{31}$ ergs s^{-1} and a temperature of 14 MK. IUE and optical spectra do not support any binary explanation, and Smith et al. argue for "violent magnetic activity on some B-type stars."

The possibility of having flares on Be stars, or in accretion disks, or in magnetic structures connecting two stars, all of which have been proposed, certainly make X-ray flare studies a challenging field.

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16. Abstract

The flare star Proxima Centauri was observed by the satellite for approximately 50 ks and a number of flares were successfully detected. The scientific results were presented at several meetings and were discussed in articles, primarily in "Solar-like M-Class X-ray Flares on Proxima Centauri Observed by the ASCA Satellite" by Haisch, Antunes and Schmitt, Science, Vol. 268, pp. 1327-1329, attached to the report.

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