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COORDINATED *EINSTEIN* AND *IUE* OBSERVATIONS OF A *DISPARITIONS BRUSQUES* TYPE FLARE EVENT AND QUIESCENT EMISSION FROM PROXIMA CENTAURI

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ABSTRACT

We report on simultaneous *Einstein* and *IUE* observations of the dM5e flare star Proxima Centauri during a 5 hour period in 1980 August. A major X-ray flare was observed in its entirety with the *Einstein* IPC; the flare exhibited a peak luminosity, $L_x \sim 2 \times 10^{28}$ ergs s^{-1}, and a maximum temperature, $T \sim 27 \times 10^6$ K. We present a detailed X-ray light curve, temperature determinations during various intervals, and UV line fluxes before, during and after the flare. There is indirect evidence for a "two-ribbon flare"—like prominence eruption. The previous detection of quiescent coronal emission is also confirmed, but the coronal luminosity of 1980 August, $L_{\rm cor} \sim 5 \times 10^{26}$ ergs s^{-1}, is less than it was in 1979 March, $L_{\rm cor} \sim 2 \times 10^{27}$ ergs s^{-1}; the temperature remains the same, $T \sim 4 \times 10^6$ K. We calculate a ratio of coronal to bolometric luminosity, $L_{\rm cor}/L_{\rm bol} \sim 8 \times 10^{-5}$ to 3×10^{-4}, about 100 times the solar ratio. The corona of Proxima Cen is analyzed in the context of static loop models, from which we conclude that less than 6% of the stellar surface seems to be covered by X-ray emitting active regions.

Subject headings: stars: chromospheres — stars: coronae — stars: flare — stars: individual — ultraviolet: spectra — X-rays: sources

I. INTRODUCTION

Flares on dMe stars are extremely complex, energetic, and seemingly unpredictable phenomena but are thought to be manifestations of the same magnetic processes that are responsible for solar flares. On 1979 March 6 we were fortunate in witnessing a major X-ray flare on the dM5e star Proxima Centauri (= α Cen C = V645 Cen = Gliese 551) during a coordinated, simultaneous observing program involving both the *Einstein Observatory* (*HEAO 2*) and the *International Ultraviolet Explorer* (*IUE*) as well as optical and radio facilities (Haisch *et al.* 1980, 1981). Again on 1980 August 20 using both *Einstein* and *IUE*, we had the incredibly good fortune of observing another X-ray flare on Proxima Cen twice as intense as the previous one, resulting in excellent temporal resolution of the X-ray light curve, temperature determinations, and UV chromospheric and transition region (TR) line variation data. Flares have been observed previously in dMe stars either in X-rays (e.g., Heise *et al.* 1975; Kahn *et al.* 1979; Kahler *et al.* 1982), ultraviolet light (Butler *et al.* 1981), or at optical and radio wavelengths, but to our knowledge the 1980 August 20 flare on Proxima Cen is the only event for which both excellent quality X-ray and ultraviolet data are available, which permit a thorough discussion of the energy balance in the flare; a review of stellar X-ray flare observations is presented by Haisch (1983).

II. THE OBSERVATIONS

The *Einstein* observations were made with the Imaging Proportional Counter (IPC), which has a field of view of ∼1°, a spatial resolution of ∼1′, a spectral range of ∼0.2–4.0 keV, photon timing resolution of 63 μs, and 32 channel pulse height analysis energy resolution (cf. Giacconi *et al.* 1979 for details).

The instrument was pointed at Proxima Cen from 10:27–16:03 UT on 1980 August 20. Due to a fortuitous alignment of Proxima Cen with the south pole of the satellite's orbital plane on the date of the observation, there was no Earth occultation of the star. A periodic brightening of the background field is clearly

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visible in the data as the line of sight swings through the X-ray halo above the Earth's limb, but the star remained continuously in view well above the background. In addition to Proxima Cen, the nearby unknown source 2 was prominent at the same flux level as in 1979, but source 3 was not seen (cf. Haisch *et al.* 1980).

We show in Figure 1 the X-ray light curve, integrated over all energy channels. Using the Vaiana *et al.* (1981) conversion factor for IPC counts into X-ray flux, 1 IPC count s^{-1} corresponds to $f_x(0.2\text{–}4.0\ \mathrm{keV}) = 2.0 \times 10^{-11}$ ergs $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ at the Earth; we find that 1 IPC count s^{-1} corresponds to an X-ray luminosity of $L_x(0.2\text{–}4.0\ \mathrm{keV}) = 4.0 \times 10^{27}$ ergs s^{-1}, given the known distance of Proxima Cen of 1.31 pc (4×10^{18} cm).

a) *Measured X-Ray Parameters*

We have estimated coronal temperatures from the IPC X-ray data using programs developed at the Center for Astrophysics that account for both instrumental and statistical uncertainties. These programs employ the conventional technique of convolving model spectra with the instrument response. The best fit χ^2 using the thermal plasma model of J. C. Raymond (1979, private communication) was calculated, assuming cosmic abundances, as described in more detail by Golub *et al.* (1982). We note that the quoted temperature ranges in Table 1 represent 90% joint confidence intervals in T and N_{H} (the column absorption density along the line of sight) but do not include the effects of gain uncertainty in the IPC. The latter uncertainty is primarily a function of source position in the IPC, which showed very little variation during our observations. The *absolute* uncertainties are somewhat larger, of order 30%–50% and similar to those discussed in detail by Kahler *et al.* (1982) for a flare on YZ CMi.

The observation was divided into eleven segments, labeled A through K. Table 1 includes the results of a full temperature analysis for each segment. We chose variable time intervals so as to approximately equalize the number of detected photons per segment, as shown in Figure 1. Although Proxima Cen was continuously visible to *Einstein*, we omitted portions of the data outside of the flare during which the bright Earth halo entered the IPC field, in order to minimize systematic effects due to this background noise on the fairly sensitive spectral fitting procedure. The determination of the absolute flux level of Proxima Cen above the background is quite straightforward, however, owing to the clear periodicity of the background and the Proxima Cen flux being at least equal to the background in the detection cell[5] even at preflare minimum. The background has been subtracted from the X-ray light curve depicted in Figure 1.

During the low background, preflare interval A, the count rate from Proxima Cen was quite low, 0.1 IPC counts s^{-1}; we therefore used the totality of these data to determine the temperature of what we presume is quiescent coronal emission, although there is some indication of low level flaring activity in the first half of this interval. We derived a coronal luminosity during interval A of $L_x(0.2\text{–}4.0\ \mathrm{keV}) \approx 4 \times 10^{26}$ ergs s^{-1} and a temperature of $T \approx 5^{+2.5}_{-1} \times 10^6$ K. This temperature is higher, but probably not significantly so, than that measured in 1979 March, 3.5–4 × 10^6 K. However, the X-ray luminosity is significantly lower by a factor of 3–4 than the previous determination of $L_x(0.2\text{–}4.0\ \mathrm{keV}) \approx 15 \times 10^{26}$ ergs s^{-1} (Haisch and Linsky 1980; Haisch

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[5] Background measurements were made in all four quadrants surrounding the centered Proxima Cen image for each interval (100 s or 400 s) shown in Fig. 1; the range in the four background determinations is generally much less than the derived mean background.

TABLE 1

TEMPERATURES AND COLUMN DENSITIES DURING SELECTED INTERVALS

Interval	Time (s)	Time (UT)	Coronal Temperature[a] (10^6 K)	log N_{H}[b] (cm^{-2})	χ^2[c]
A	2380–5450	11:06:40–11:57:50	$5^{+2.5}_{-1}$	$18^{+2.3}$	6.2
B	7950–8450	12:39:30–12:47:50	$10^{+3.5}_{-4.5}$	18^{+2}	12.1
C	8450–8880	12:47:50–12:55:00	$20^{+5.5}_{-4.5}$	$19^{+1.5}$	5.6
D	8880–9150	12:55:00–12:59:30	$16^{+2.5}_{-2.5}$	$18^{+1.5}$	24.0
E	9150–9300	12:59:30–13:02:00	27^{+20}_{-6}	$19^{+0.5}$	10.1
F	9300–9450	13:02:00–13:04:30	$20^{+4.5}_{-4.5}$	$19^{+1.0}$	10.1
G	9450–9700	13:04:30–13:08:40	$15^{+2.5}_{-2}$	$20^{+0.3}_{-0.5}$	10.5
H	9700–10,000	13:08:40–13:13:40	$14^{+3}_{-2.5}$	$19^{+1.0}$	5.8
I	10,000–10,500	13:13:40–13:22:00	$17^{+3.5}_{-3}$	$18^{+1.3}$	10.7
J	14,050–17,170	14:21:10–15:13:10	10^{+2}_{-3}	$18^{+1.3}$	9.3
K	16,800–20,000	15:07:00–16:00:20	3–4?	18	12.5

[a] Temperatures are best fits for a J. C. Raymond (1979, private communication) thermal spectrum. Uncertainties are from all sources other than the IPC gain, which may extend the range of uncertainty considerably.

[b] Lower limit on N_{H} for 90% confidence is zero in all cases, except for interval G; thus only upper limits are indicated in those cases.

[c] All fits are for 10 degrees of freedom.

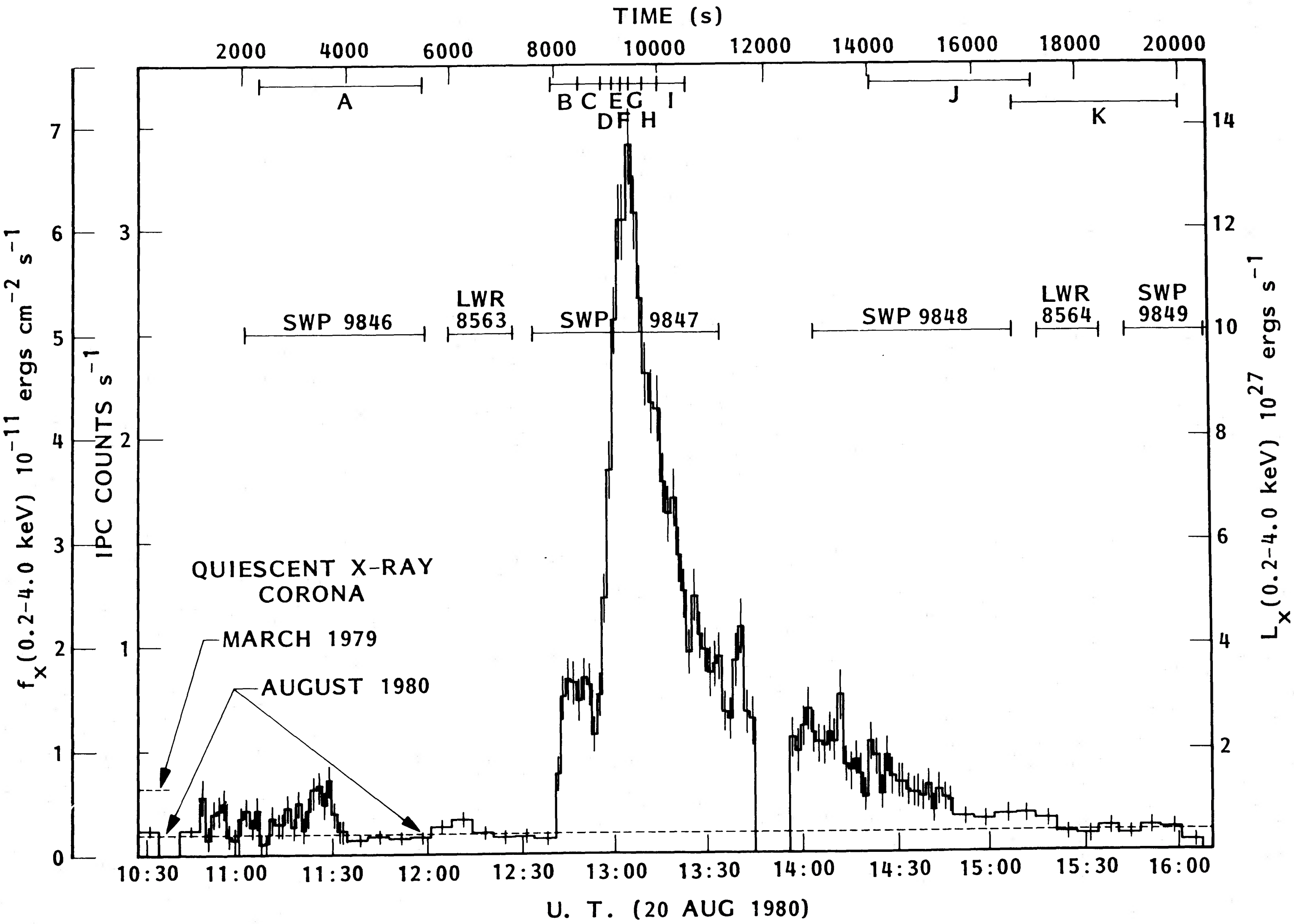

FIG. 1.—The X-ray flux, f_x(0.2–4.0 keV) of Proxima Centauri as observed by the *Einstein Observatory* IPC, binned in either 100 s or 400 s intervals. Error bars are $\pm 1\ \sigma$. The level of quiescent coronal emission during this observation is $L_x(0.2\text{–}4.0\ \text{keV}) \approx 4 \times 10^{26}$ ergs s^{-1}, a factor of 3–4 lower than that observed in 1979 March, and the peak flare luminosity is $L_x(0.2\text{–}4.0\ \text{keV}) \approx 1.4 \times 10^{28}$ ergs s^{-1}. Events of this size usually occur a few times per year on the Sun near solar maximum.

et al. 1980). This may be indicative of a secular change from 1979 March to 1980 August as a consequence of a "stellar cycle," but given order of magnitude changes in the solar flux below 10 Å on a daily and weekly basis (Kreplin *et al.* 1977), the change in L_x for Proxima Cen could be due to similar short term variability.

The next portion of low background data begins at 12:39:30 UT, at which time the count rate rises steeply, levels off for about 500 s, and possibly even drops briefly, and then increases suddenly with a $1/e$ rise time of ≈ 7 minutes. As is often the case with solar X-ray flares (cf. Doschek *et al.* 1981; McKenzie and Landecker 1981; Svestka 1976), the temperature peaked just before the luminosity does. Here the peak temperature of 27×10^6 K occurred during interval E ($L_x \approx 1.2 \times 10^{28}$ ergs s^{-1}), whereas the temperature dropped to 20×10^6 K by the time the emission peaked ($L_x \approx 1.4 \times 10^{28}$ ergs s^{-1}) 2 or 3 minutes later during the latter part of interval F and early part of G.

The flare decay proceeded more slowly than the rise, with an initial $1/e$ decay time of ≈ 20 minutes; but later in the flare the temperature and luminosity decayed more slowly such that at the end of interval J (15:13 UT) both were still substantially above their initial values. During the final half-hour of observation, the X-ray flux returned to the quiescent level, but the temperature (3–4×10^6 K) was rather uncertain because of the fairly high background.

The luminosity at the flare peak represents an increase by a factor of 34 over the quiescent coronal emission of Proxima Cen. Also, the spectral fitting program consistently found a decrease in the flux in the lowest energy channels that is simply interpreted as an increase in N_H during the brief period (interval G) immediately following flare maximum. The column absorption increased temporarily to a value of $N_H \approx 10^{20}$ cm^{-2}, and then returned to the preflare values of 10^{18}–10^{19} cm^{-2} which are consistent with no measurable absorption at these wavelengths within the uncertainties of our data.

As we discuss in § III, the characteristics of this event are remarkably similar to the class of solar flares variously known as *disparitions brusques*, gradual rise and fall, prominence eruptions, and two-ribbon flares.

b) Ultraviolet Spectra

Between 11:00 and 16:00 UT on 1980 August 20, we obtained six ultraviolet spectra of Proxima Cen using the *International Ultraviolet Explorer* (*IUE*) spacecraft (cf. Boggess *et al.* 1978). The time of the individual spectra are listed in Table 2 and are shown along with the X-ray light curve in Figure 1. The four low dispersion short wavelength spectra (1150–2000 Å) consist of image SWP 9846, which contains primarily quiescent transition region (TR) emission lines but may include weak flaring prior to the main flare event, image SWP 9847, which is centered on the peak X-ray flux, image SWP 9848, which includes the later decay phase, and image SWP 9849, which occurs at a time of return to quiescent X-ray emission. The two long wavelength (LWR) spectra (2000–3200 Å) occur at X-ray quiet times prior to and after the main flare.

The four SWP spectra are compared in Figure 2. The spectrum taken during X-ray maximum, image SWP 9847, clearly shows the bright emission lines of He II, C I–IV, N V, Al III, and Si II–IV. By comparison, the decay phase spectrum (SWP 9848) shows weak C I, C IV, and N V emission lines, and the preflare (SWP 9846) and postflare (SWP 9849) spectra show only weak C IV emission.

We have thus been fortunate in obtaining one of the first spectra of a stellar flare; to the best of our knowledge the only other ultraviolet flare spectrum was obtained by Butler *et al.* (1981) for the dM2e flare star Gl 867A.

TABLE 2

Proxima Centauri Ultraviolet Emission-Line Fluxes (10^{-14} ergs cm^{-2} s^{-1})

Line	log $T_{\max}$	SWP 9846	SWP 9847	SWP 9848	SWP 9849	LWR 8563	LWR 8564	Mean[a] Quiescent	Flare Only	E_{flare} (ergs)
N V λ1239	5.3	<4.3	38.4	11.6	<10.0	...	...	8.0	30.0	2.3(29)
C IV λ1550	5.1	36.3	109.0	36.1	18.0	...	...	16.0	93.0	7.2(29)
Si IV λ1400	4.9	...	33.4	...	...	...	...	...	...	...
He II λ1640	...	<3.6	17.5	<7.1	<6.0	...	...	5.0	12.5	9.6(28)
C III λ1175	4.7	...	32.0	4.0	...	...	...	...	...	...
Al III λ1860	...	...	10.9	...	...	...	...	...	5.9	4.5(28)
Si III λ1893	4.7	...	3.9	...	...	...	...	...	...	...
C II λ1335	4.3	<4.5	28.3	<7.5	<3.9	...	...	...	19.3	1.5(29)
Si II λλ1808, 1817	3.8	<7.0	~8.5	<4.3	<5.0	...	...	5.0	~3.5	2.7(28)
C I λ1561	3.7	...	9.7	...	...	...	...	3.0	6.7	5.1(28)
C I λ1657	3.7	12.4	24.1	<7.1	<6.0	...	...	...	...	...
Mg II λλ2795, 2803	3.8	...	...	...	...	46.5	54.2	86.0	...	...
Fe II λ2610	3.7	...	...	...	...	32.3	21.3	...	...	...
Exposure time (minutes)		58	60	64	26	20	20	395(SWP) 185(LWR)	...	...
Begin-end time (UT)		1101–1159	1233–1333	1403–1507	1542–1608	1207–1227	1515–1535	...	...	...

[a] From Linsky *et al.* 1982.

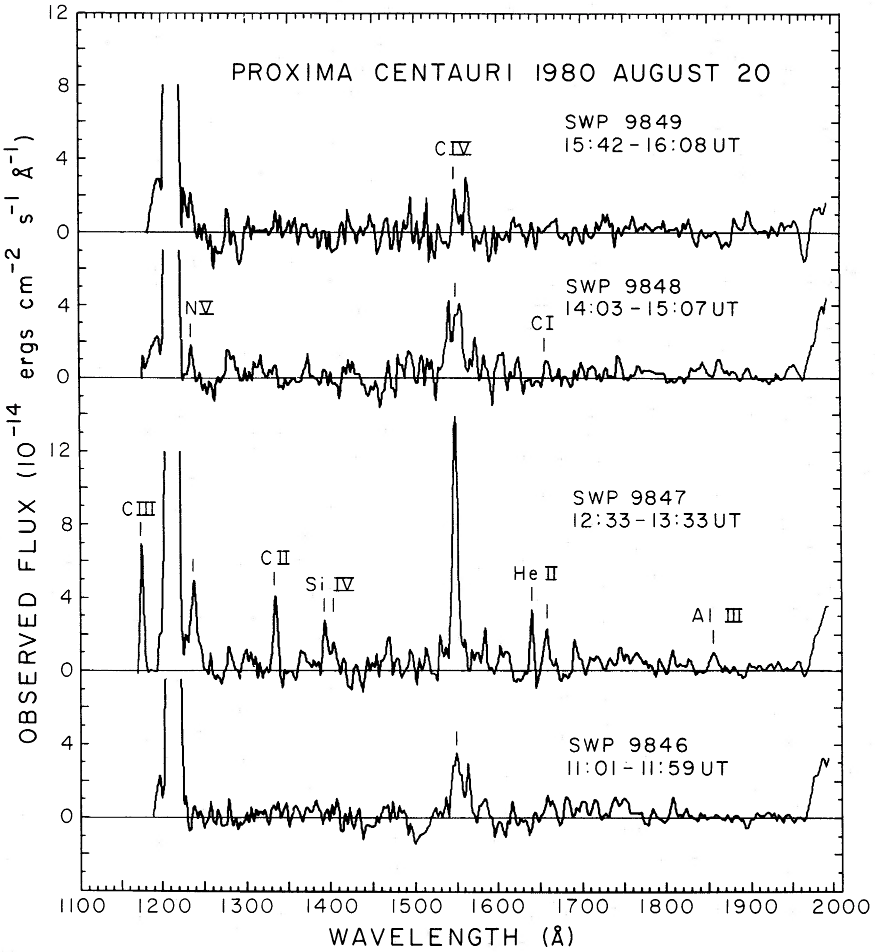

FIG. 2.—*IUE* spectra of Proxima Centauri before, during, and after the X-ray flare. SWP 9847 straddles the peak of the flare as seen in X-rays (cf. Fig. 1).

Our previous attempt to obtain an *IUE* spectrum of Proxima Cen during an X-ray flare did not result in an enhanced emission line spectrum (Haisch *et al.* 1981).

Listed in Table 2 are the integrated emission line fluxes obtained from the six *IUE* spectra. In addition to the ions previously mentioned, the LWR images contain an Fe II blend near 2610 Å and the Mg II resonance lines at 2796 Å and 2803 Å. Linsky *et al.* (1982) have published composite quiescent spectra of Proxima Cen summing together spectra of Carpenter and Wing (1979) and of Haisch and Linsky (1980) for total integration times of 395 minutes (SWP) and 185 minutes (LWR). The mean quiescent fluxes from these composite spectra are also presented in Table 2.

III. DISCUSSION

a) *The Quiescent Corona*

As discussed above, on 1979 March 6 we measured a quiescent coronal luminosity of L_x(0.2–4.0 keV) $\approx 1.5 \times 10^{27}$ ergs s^{-1}, corresponding to a ratio of $L_x/L_{\rm bol} \approx 2.2 \times 10^{-4}$, where $L_{\rm bol}$ is the bolometric luminosity of Proxima Cen ($L_{\rm bol} = 6.7 \times 10^{30}$ ergs s^{-1}; Frogel *et al.* 1972). The quiescent data for 1980 August 20 imply L_x(0.2–4.0 keV) $\approx 4 \times 10^{26}$ ergs s^{-1} corresponding to a ratio, $L_x/L_{\rm bol} \approx 6 \times 10^{-5}$. These ratios, however, measure only a portion of the total coronal radiation due to the limitations of the IPC passband. Since we are now confident of the quiescent coronal temperature, $\sim 4(\pm 1) \times 10^6$ K, we use the data in Haisch and Simon (1982) to estimate that $\sim 80\%$ of the flux from a thermal emission spectrum lies in the IPC passband at that temperature. Making this minor correction we determine that for Proxima Cen the fraction of the total luminosity radiated as coronal emission is $L_{\rm cor}/L_{\rm bol} \approx 8 \times 10^{-5}$ to 3×10^{-4}. Since there are presumably other energy losses associated with the existence of a hot corona, such as thermal conduction down to the chromosphere, possible downward enthalpy fluxes, stellar wind losses, downward X-ray irradiation (we are measuring only about half of the coronal emission), etc., we believe that as much as 0.1% of the energy generated by thermonuclear reactions in the stellar interior somehow heats the stellar corona.

Additional energy of course is needed to power the stellar flares; our limited observational data suggest that flares may consume at least as much power as the quiescent corona, perhaps substantially more.

The coronal energy requirements may also be expressed in terms of surface fluxes. The total coronal energy requirements of the Sun are $\pi F_{\rm cor} \approx 2\text{–}6 \times 10^5$ ergs cm^{-2} s^{-1} (Bruner 1981; Athay 1976) and the photospheric surface bolometric flux is $\pi F_{\rm bol} \approx \sigma T_{\rm eff}^4 = 6.4 \times 10^{10}$ ergs cm^{-2} s^{-1}. The solar ratio is $\pi F_{\rm cor}/\pi F_{\rm bol} \approx 3\text{–}9 \times 10^{-6}$, and thus

$$(\pi F_{\rm cor}/\pi F_{\rm bol})_{\rm Prox\ Cen} \approx 100(\pi F_{\rm cor}/\pi F_{\rm bol})_{\rm Sun} .$$

The theory that purely acoustic waves are responsible for heating the solar corona has encountered major refuting evidence in the last few years (cf. Linsky 1980, 1981), coming from two entirely different directions: direct measurements of wave propagation in the solar atmosphere, and detection of stellar coronae. On the one hand, the most recent analysis by Bruner (1981) of *OSO 8* measurements of time-resolved line profiles of the C IV λ1548 resonance line places an upper limit on the acoustic flux of $\pi F_{\rm ac} \leq 3 \times 10^2$ ergs cm^{-2} s^{-1}, approximately three orders of magnitude below the coronal requirements. And on the other hand, recent surveys of stellar X-ray emission with the *Einstein Observatory* (e.g., Haisch and Simon 1982; Helfand and Caillaut 1982; Vaiana *et al.* 1981; Johnson 1981; Ayres *et al.* 1981) show evidence of stellar coronae in virtually all classes of stars except luminous cool stars, and very wide ranges in coronal emission for stars of a given type, with no apparent agreement between predictions based on acoustic heating theories and the observations. The present data on the corona of Proxima Cen add further evidence to the deficiencies of the acoustic heating theory.

It now appears that heating by waves in magnetic fields, rather than purely acoustic waves, is a more likely explanation for the heating of stellar coronae. Belvedere, Chiuderi, and Paterno (1981, 1982), among others, have proposed models based on scaling properties developed by Golub *et al.* (1980) for the creation and conversion of magnetic energy into thermal energy based on dynamo theory for various stellar types. Stein (1981) and Ulmschneider and Bohn (1981) have proposed that slow mode magnetic waves are responsible for the heating of stellar chromospheres and coronae on the basis that calculations for these waves are consistent with the empirical evidence for the dependence of heating on stellar effective temperature and gravity and the fact that such waves can explain the large heating rates needed to account for the coronal radiative loss rates in some active stars.

For an M5 V star, Belvedere, Chiuderi, and Paterno (1981) predicted a coronal heating surface flux of $\pi F_{\rm cor} \approx 10^7$ ergs cm^{-2} s^{-1}, and the "magnetic enhancement" projections of Ulmschneider and Bohn (1981) predict about the same, $\pi F_{\rm cor} \approx 2 \times 10^7$ ergs cm^{-2} s^{-1}. In terms of a flux ratio, taking $\pi F = \sigma T_{\rm eff}^4 = 3 \times 10^9$ ergs cm^{-2} s^{-1} (for $T_{\rm eff} = 2700$ K; Frogel *et al.* 1972), we arrive at a predicted value of $\pi F_{\rm cor}/\pi F_{\rm bol} \approx 5 \times 10^{-3}$, about an order of magnitude or so higher than the observed ratio. We discuss coronal heating fluxes further in the following section.

b) Comparison with Solar Coronal Loop Models

Given the observed values of the coronal luminosity ($L_{\rm cor} = L_x/0.80 = 5.0 \times 10^{26}$ ergs s^{-1}), the mean quiescent C IV emission expressed as a luminosity ($L_{\rm C\,IV} = 4\pi d^2 f_{\rm C\,IV} = 6 \times 10^{25}$ ergs s^{-1}), and the coronal temperature ($T_{\rm cor} = 4 \times 10^6$ K), it is possible to test whether these values are compatible with static loop models analogous to those which have been proposed for the solar corona (e.g., Withbroe 1981; Rosner, Tucker, and Vaiana 1978; Craig, McClymont, and Underwood 1978; Vesecky, Antiochos, and Underwood 1979).

The differential emission measure has been defined in various, slightly different, ways. We take as our definition,

$$\xi(T)d(\ln T) = n_e^2 dV , \tag{1}$$

which may be expressed in terms of the temperature gradient along the loop (dT/ds) parallel to the magnetic field lines and loop cross sectional area (A), as

$$\xi(T) = A n_e^2 \left| \frac{1}{T} \frac{dT}{ds} \right|^{-1} . \tag{2}$$

We parameterize the dependence of ξ on T as $\xi(T) \sim T^\delta$ and compare the predictions of the static model with the observations.

In terms of a static model, for a single loop of constant cross section the prediction is that $\delta = 1$ (e.g., Raymond and Doyle 1981*b*); but in general we expect that there may be significant variation in the loop area between the apex and the base and furthermore that a collection of loops rather than a single loop is responsible for the observed emission. The effect of the area variation is to enhance the X-ray emission over the C IV and hence to *increase* δ (e.g., Vesecky, Antiochos, and Underwood 1979). On the other hand, the effect of a collection of loops rather than a single loop is to *decrease* δ, since no individual loop will have a δ larger than 1, and cool loops whose maximum temperature is less than 10^6 K will contribute only C IV emission. Therefore, the static model actually predicts a range of values about a mean $\delta \sim 1$.

Turning to the observations, using the observed values of the X-ray and C IV luminosities, we can determine the emission measure of Proxima Cen at the maximum temperature (4×10^6 K), and at the temperature at which the C IV line is formed ($\sim 10^5$ K; cf. Zolcinski *et al.* 1982). We find that:

$$\xi(T = 4 \times 10^6\ {\rm K}) = 8.3 \times 10^{48}\ ({\rm cm}^{-3}) ,$$

and

$$\xi(T = 10^5\ {\rm K}) = 1.3 \times 10^{47}\ ({\rm cm}^{-3}) ,$$

where we have used the X-ray emissivity given by

Raymond, Cox, and Smith (1976) and the C IV emissivity given by Raymond and Doyle (1981*a*). These emission measures yield a value, $\delta \approx 1.1$, which is certainly compatible with the range of values predicted by the static model.

If we now assume that the coronal emission from Proxima Cen originates from an ensemble of identical static loops distributed in some fashion over the stellar surface, we can calculate the fraction of the stellar surface, ϵ, covered by bright X-ray emitting loops. Ionson and Golub (1983) have shown that approximately one-fourth of the total conductive flux goes into maintaining the coronal radiative losses; the remainder of the conductive flux flows down into the transition region and chromospheric footpoints of a loop. Equating one-fourth of the conductive flux with the radiative losses we obtain,

$$L_{\text{cor}} \approx n_e^2 \Lambda(T) H 2\pi R^2 \epsilon \approx \tfrac{1}{4} \times 10^{-6} \frac{T^{7/2}}{H} 2\pi R^2 \epsilon \,, \quad (3)$$

where R is the stellar radius ($R = 1.0 \times 10^{10}$ cm; Pettersen 1976), H is the loop length, Λ is the radiative loss rate for optically thin coronal plasma ($\Lambda \approx 10^{-22}$ ergs s^{-1} cm^3; cf. Rosner, Tucker, and Vaiana 1978), and Spitzer's (1962) form for the thermal conductivity is assumed. From these relations two constraints can be obtained on the three unknown parameters, n, H, and ϵ:

$$nH = 1.8 \times 10^{19} \text{ cm}^{-2}$$

and

$$H/\epsilon = 4.0 \times 10^{10} \text{ cm} .$$

An additional constraint can be derived from the requirement that the height of the emitting regions, which we assume is approximately equal to the loop length H, must be of the order or less than the gravitational scale height, $H_g = 1.7 \times 10^8 T/g$, where $g = 2.8 \times 10^5$ cm s^{-2} is the surface gravity of Proxima Cen assuming $M = 0.2\, M_\odot$ (Allen 1973). For a coronal temperature of 4×10^6 K, the gravitational scale height is $H_g = 2.4 \times 10^9$ cm; and, hence, an upper limit on ϵ is obtained; $\epsilon \leq 6\%$, and a lower limit on the coronal density, $n \geq 7.5 \times 10^9$ cm^{-3}.

It appears, therefore, that the corona of Proxima Cen is very similar to the Sun's in that the bulk of the X-ray emission originates from active regions that cover only a small fraction of the stellar surface. A small area coverage implies that the value of 1.1 obtained for δ is actually only a lower limit to the true value in the active regions since a significant amount of C IV emission may originate from the quiet corona of Proxima Cen. In fact, the observed values for δ in solar active regions are quite large, $\delta \sim 2$, whereas $\delta \sim 1.5$ in quiet regions and $\delta \sim 1.0$ in coronal holes (Raymond and Doyle 1981*b*). We believe that this is probably also the case for Proxima Cen, but our observations are inadequate to resolve this issue.

With the limited data available, only an upper bound on the area of Proxima Cen's active regions can be determined: $2\pi R^2 \epsilon \lesssim 3.8 \times 10^{19}$ cm^2. Note that this implies a value for the upward energy flux at the photosphere in these regions of at least 1.3×10^7 ergs cm^{-2} s^{-1}, in good agreement with the magnetic heating models of Belvedere, Chiuderi, and Paterno (1981) and the "magnetic enhancement" projections of Ulmschneider and Bohn (1981). This result provides further evidence against the pure acoustic wave heating model since this theory would predict that a star as late-type as Proxima Cen would have an insignificant surface flux of acoustic waves (e.g., Mewe 1979).

We conclude that the observed UV and soft X-ray emission from Proxima Cen is compatible with a solar-like corona. Assuming a static model, constraints on the coronal parameters are derived which indicate that the emitting regions on Proxima Cen may be quite similar to very active regions on the Sun. An important quantity is the fraction of the stellar surface covered by these regions. We find that it must be less than ~6%, and therefore there should be rotational modulation of the emission. In fact, the large quiescent X-ray flux change observed between 1979 March and 1980 August might be the result of rotational modulation, as might the observed changes in the C IV flux levels. It should be possible to observe this modulation by monitoring the C IV emission from Proxima Cen over a period of days. These observations could also be used to obtain the rotational period of the star and thereby provide new information on the important question of the relationship between stellar coronae and stellar rotation.

c) The X-Ray Flare: Comparison with Solar Two-Ribbon Flare

As shown in Figure 1, the peak X-ray luminosity of the flare within the IPC passband was $L_x(0.2\text{–}4.0 \text{ keV}) \sim 1.3 \times 10^{28}$ ergs s^{-1}. For a thermal spectrum at a temperature, $T \sim 20\text{–}25 \times 10^6$ K, we estimate that approximately two-thirds of the total X-ray radiation lies within this passband (cf. Table 3 in Haisch and Simon 1982). We thus estimate that the total X-ray luminosity at flare maximum was $L_{x,\text{tot}} \sim 2 \times 10^{28}$ ergs s^{-1}.

In order to calculate the total energy of the flare, we have used the temperature determinations in Table 1 together with the data in Haisch and Simon (1982) to estimate the fraction of the X-ray flux detected by the IPC for various intervals spanning the flare event. Integrating these "bolometrically corrected" X-ray luminosities, less the quiescent coronal luminosity, from $t = 8000$ s to $t = 17{,}200$ s (see Fig. 1), we estimate for the total energy of the flare, $E_{\text{tot}} \sim 3.5 \times 10^{31}$ ergs.

The X-ray characteristics of this flare event are strongly suggestive of a solar analog: the two-ribbon flare. In the Sun two physically distinct classes of flare events are observed (Pallavicini, Serio, and Vaiana 1977; Kahler 1977). The more common class, typically occurring in the bright core area of an active region, consists of compact flares with rapid rise and fall times and high coronal energy densities. The less common flare class, the long decay X-ray events, are characterized by large and diffuse systems of X-ray loops and are associated with prominence eruptions generally away from active regions. The long decay time standards used by Kahler to separate the latter class of flare events would put the Proxima Cen flare into that category.

These events on the Sun are known to be closely linked to white-light coronal transients, to the acceleration of MeV protons, and to metric type II slow-drift radio bursts (Kahler, Hildner, and van Hollebeke 1978; Munro *et al.* 1979). Two-ribbon flares are generally modeled by the description of Kopp and Pneuman (1976), who assumed that the magnetic field lines which initially supported the cool prominence material are opened as a result of the prominence eruption, so that there is a high outward flux of energy and mass while the field lines are open. This initial phase is followed by reconnection of the magnetic field and the formation of a large system of hot loops high in the corona. The two ribbons observed as enhanced Hα emission are found at the footpoints of this loop system.

Direct observations of the X-ray and Hα configurations in two-ribbon flares were obtained during the *Skylab* mission. An example of such an event is shown in Figure 3, taken from Kahler (1977). It is possible in light of this picture to attribute the temporary increase in N_H observed in the Proxima Cen event to the passage of cool, dense prominence material across our line of sight, thus temporarily obscuring the X-ray event. This is admittedly a speculative interpretation; however, the main argument in its favor is that the 90% confidence intervals on N_H are quite narrow during the brief time interval in which the absorption is seen. At all other times during the flare, the allowable lower limit on N_H is consistent with zero absorption (Table 1). However, during the one time interval, the lower limit is 3×10^{19} cm^{-2}, lasting for about 4 minutes. A solar-type prominence contains enough material to cause 10^{20} or more of absorption, thus leading to our interpretation.

Another possibility is that the observation is due to material ejected from a prior flare elsewhere on the star (we have in mind the peculiar 12:45 UT "preflare") which happens to cross our line of sight during the main flare. But in either scenario the duration of the occultation ($\sim$4 minutes) and the typical expansion velocities of erupting prominences on the Sun ($\sim$300–500 km s^{-1}) allow us to derive a very crude size scale for a possible ejected magnetic loop on Proxima Cen, namely about 10^{10} cm, which is equal to the stellar radius.

Other solarlike explanations are possible, of course, such as occultation by infalling (rather than ejected) material analogous to "coronal rain." The point, however, is that all the evidence suggests a very solarlike event; we call attention to the fact that $T_{\max}$ precedes $L_{\max}$ consistent with solar flare observations and evaporative loop models such as those of Antiochos and Krall (1979), Krall and Antiochos (1980), and Moore *et al.* (1980).

The X-ray parameters of the Proxima Cen event are all within the range observed in similar solar events (Pallavicini, Serio, and Vaiana 1977). The X-ray luminosity in excess of 10^{28} erg s^{-1} is rather high by solar standards; events of this size usually occur a few times a year near solar maximum. However, the flare event on Proxima Cen previously reported by Haisch *et al.* (1980) reached a comparable peak emission, about half as large. Therefore, either our two Proxima Cen flare observations detected two rare large flares by chance, or the distribution of flare sizes on Proxima Cen is such that very large solar-type flares are fairly common. The latter case is more likely and is more consistent with the active nature of dMe stars in general.

d) *The Ultraviolet Flare*

We have previously noted that the quiescent X-ray flux level on 1980 August 20 was considerably below that of 1979 March 6–7. The quiescent ultraviolet line fluxes for C II, N V, Mg II, and Fe II and perhaps also He II and Si II are also smaller than in the mean quiescent spectrum. Thus there are some uncertainties in comparing the flare and quiescent spectra. The line fluxes in the column marked "flare only" in Table 2 are the differences between the fluxes in image SWP 9847 and those in the mean quiescent spectrum. They should therefore fairly represent the enhanced emission due to the flare itself during the time interval 1233–1333 UT, which includes the X-ray flare peak and most of the flare X-ray emission. We note that the C IV flux was somewhat enhanced in images SWP 9846 and 9848, when the X-ray flux was higher than quiescent, but was at the mean quiescent level in image SWP 9849, when the X-ray emission was at the quiescent level. Thus with the crude time resolution of the *IUE* data, typically 60 minutes, the ultraviolet line fluxes formed in the transition region and chromosphere rise and fall in step with the coronal X-ray flare emission.

The flare energies in the individual ultraviolet emission lines during image SWP 9847 are given in Table 2 as E_{flare} assuming a distance of 1.31 pc to Proxima Cen. The total flare energy in the lines of He II, C II, C IV, N V, Al III, and Si IV was 1.2×10^{30} ergs. Since these are typically the brightest transition region lines, 1.2×10^{30} ergs is probably a good approximation for E_{flare} (TR). By comparison, the observed total X-ray energy during image SWP 9847 was E_{flare} (X-ray) = 2.5×10^{31} ergs. Thus E_{flare} (TR)/E_{flare} (X-ray) $\sim$ 0.05 during SWP 9847.

We cannot determine directly the energy in the stellar Lyα line due to bright Lyα geocoronal emission and interstellar Lyα absorption. We can, however, estimate its strength by comparison with solar data. Canfield *et al.* (1980) have summarized the radiative energy output of the particularly well-studied solar flare of 1973 September 5. Throughout this flare the EUV spectroheliometer on *Skylab* obtained near simultaneous observations of the Lyα line and the C II λ1335 resonance line doublet. During the 4 minutes of peak X-ray flux, the mean Lyα/C II flux ratio was 4.7, but this ratio increased to 15 about 20 minutes after peak

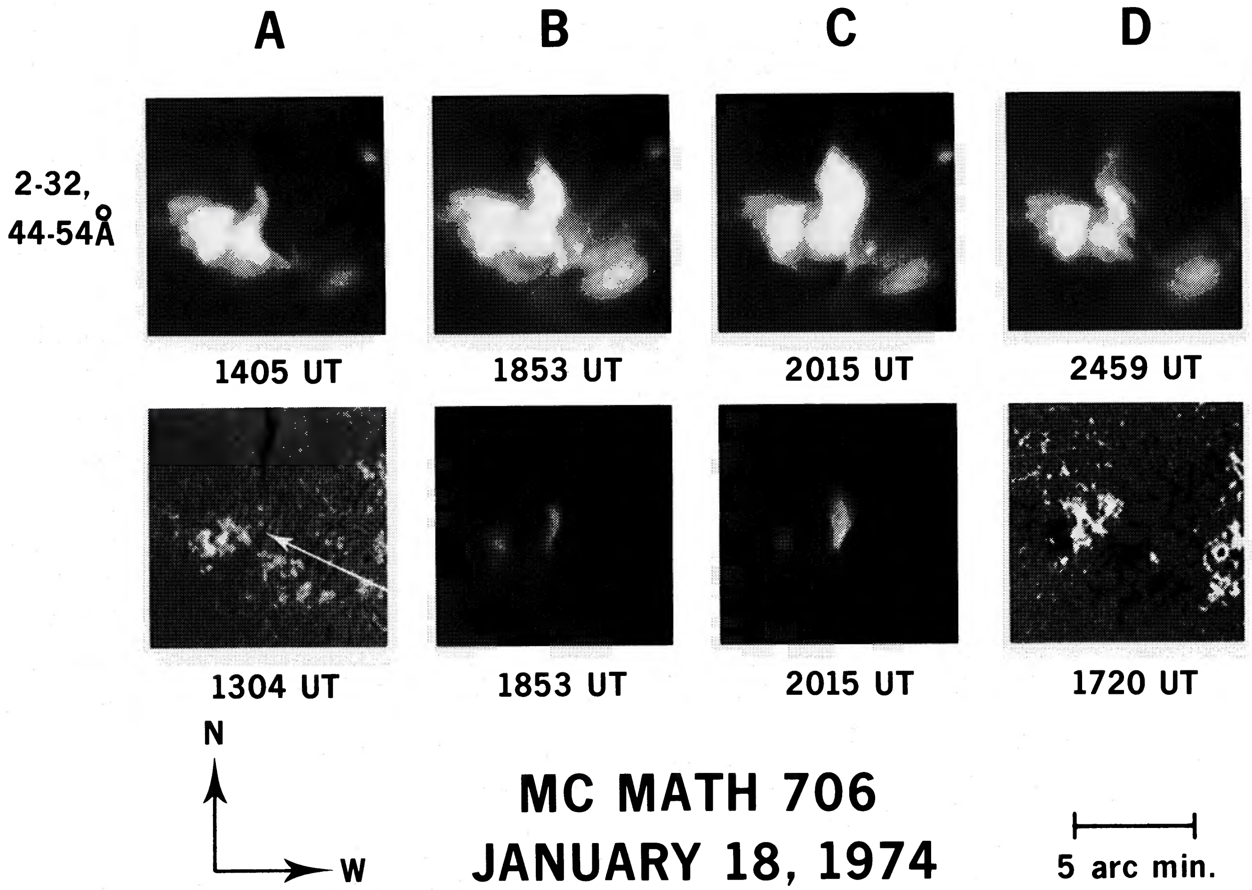

FIG. 3.—X-ray, Hα, and magnetogram images of a solar long-decay event associated with a prominence eruption. Top row shows broad-band short exposure X-ray images from the *Skylab* S-054 X-ray telescope. Column (A) is the preflare X-ray image with the Hα image underneath, showing a filament with a southern extension into an active region. Short exposure X-ray images in the bottom row show the development of the X-ray event and the magnetogram at lower right shows the magnetic field configuration. The top right X-ray image (col. [D]) shows the long-enduring system of X-ray loops following the prominence eruption (from Kahler 1977).

X-ray flux. By comparison the Lyα/C II ratio is 40 in a typical active region and 54 in the mean quiet Sun (Vernazza and Reeves 1978). Since the SWP 9847 spectrum is 60 minutes in duration and includes preflare and postflare emission where the flux levels are much lower than at flare maximum, we estimate that the Lyα/C II flux ratio is 10 ± 5 during this interval. Thus E_{flare} (Lyα) $\sim (1.5 \pm 0.75) \times 10^{30}$ ergs, comparable to E_{flare} (TR), and E_{flare} (Lyα)/E_{flare} (X-ray) $\sim 0.06 \pm 0.03$.

As discussed by Canfield *et al.* (1980), emission from the lower chromosphere and temperature minimum in the Mg II resonance lines, lines in the visible (esp. Ca II and Hα), and the EUV continuum (1400–1960 Å) exceeded the coronal and transition region line emission during the 1973 September 5 solar flare. We cannot comment on the chromospheric emission line energy because we have no visible data and our Mg II fluxes obtained before and after the flare are below the mean quiescent value. At maximum for the previously described solar flare the observed 1400–1960 Å power was 4.8 times that observed in all the emission lines between 1175 Å and 1863 Å, excluding Lyα. This continuum flux was roughly constant per angstrom between 1400 Å and 1700 Å and then increased to longer wavelengths. If we assume that the same 4.8 ratio applies to the Proxima Cen flare, then the continuum flux should have been roughly 1×10^{-14} ergs cm^{-2} s^{-1} Å^{-1}. There is no evidence, however, for a continuum this bright during image SWP 9847 (see Fig. 2), although Butler *et al.* (1981) did detect ultraviolet continuum emission during a flare on Gl 867A. The absence of an ultraviolet continuum in the Proxima Cen flare spectrum could be explained either by a much shorter duration of continuum emission compared to the ultraviolet line emission or a difference between the Proxima Cen flare and the specific solar flare cited.

A final point is the comparison between the flare soft X-ray (0.2–4.0 keV) and He II λ1640 line fluxes. The He II line is important because unlike typical transition region lines, it may be formed partly by recombination following photoionization by very soft X-rays ($\lambda < 227$ Å). Linsky *et al.* (1982) found that the $f_x/f_{1640\,\text{Å}}$ ratio is roughly 200 for quiescent Proxima Cen and other dMe stars, and on this basis argued that the He II line is probably formed by recombination. During the flare $f_x(0.2\text{–}4.0\ \text{keV})/f_{1640\,\text{Å}} \sim 230$, so that the He II line is likely formed by recombination also during the flare.

In conclusion, we find that the time behavior of the X-ray and ultraviolet emission line fluxes is similar during the Proxima Cen flare given the coarse time resolution of our *IUE* spectra. We also find that the soft X-ray energy emitted during the flare is much larger than either that observed in the transition region lines or that inferred for the Lyα line. By comparison with the well-studied 1973 September 5 solar flare, the ratio of the soft X-ray flux during the Proxima Cen flare to the Lyα and the transition region line flux was about 10 times larger, indicating that the radiative energy loss from the corona compared to the transition region was more important for the Proxima Cen flare than for the indicated solar flare. Since the observed transition region and chromospheric emission fluxes provide upper limits on the conductive heating of these layers from the flare itself, we conclude that the observed flare on Proxima Cen is not cooled significantly by conduction but rather by radiation and perhaps other processes like expansion.

IV. CONCLUSIONS

1. The quiescent coronal temperature of Proxima Cen has been measured now on two separate occasions, and we find that $T \sim 4(\pm 1) \times 10^6$ K; the coronal luminosity, corrected for the limitations of the IPC passband, is variable and lies in the range $L_{\text{cor}} \sim (5 \times 10^{26})$–$(2 \times 10^{27})$ ergs s^{-1}.

2. The fraction of the total stellar luminosity radiated as coronal emission is $L_{\text{cor}}/L_{\text{bol}} \sim (8 \times 10^{-5})$ to (3×10^{-4}), or about 100 times the solar ratio; allowing for additional energy losses associated with the presence of a hot corona, we estimate that as much as 0.1% of the thermonuclear energy generation may be channeled into the corona, and substantially more energy may be required to sustain the observed flare activity.

3. Based on a coronal loop model analysis, it appears that the corona of Proxima Cen is similar to the Sun's in that a few percent of the stellar surface ($\lesssim 6\%$) seems to be covered by X-ray emitting active regions; this requires an energy flux in these active regions of $\sim 1.3 \times 10^7$ ergs cm^{-2} s^{-1}, in agreement with magnetic heating models; however, the surface averaged heating flux requirements fall in between purely acoustic heating predictions and magnetic enhancement projections.

4. An X-ray flare was observed having a peak (bolometrically corrected) luminosity of $L_x \sim 2 \times 10^{28}$ ergs s^{-1} and a maximum temperature of $T \sim 27 \times 10^6$ K; the maximum temperature occurred 2 or 3 minutes prior to the emission peak. The total energy emitted by the flare in X-rays was $E_{\text{tot}} \sim 3.5 \times 10^{31}$ ergs. The duration of the flare event was over 2 hours.

5. The X-ray characteristics are strongly suggestive of a solar two-ribbon flare (disparitions brusques), since the spectral data imply a transient increase in column absorption, $N_{\text{H}} \sim 10^{20}$ cm^{-2}, suggesting passage of cool, dense material across the line of sight following an inferred prominence eruption. The X-ray luminosity is roughly equivalent to an X20 solar flare, rare events on the Sun, but consistent with the presumed active nature of dMe stars.

6. The UV line fluxes observed by *IUE* show enhancement of high temperature lines during the flare; we estimate that E_{flare} (TR)/E_{flare} (X-ray) ~ 0.05, and that E_{flare} (Lyα)/E_{flare} (X-ray) ~ 0.06, both ratios being about 10 times smaller than the well-studied 1973 September 5 solar flare observed by *Skylab*. This implies that radiative cooling of the hot X-ray emitting plasma was relatively more important during this event on Proxima Cen than in the solar event, which suggests that radiative cooling probably predominated over conductive cooling during this flare on Proxima Cen.

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