OBSERVATIONS OF THE QUIESCENT CORONA, TRANSITION REGION, AND CHROMOSPHERE IN THE dMe FLARE STAR PROXIMA CENTAURI

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ABSTRACT

We present X-ray fluxes and ultraviolet spectra (1175–3200 Å) of the dM5e flare star Proxima obtained with the imaging proportional counter on HEAO 2 and the ultraviolet spectrographs on IUE. The quiescent, soft X-ray emission outside of flares is characterized by Lx = 1.5 × 1037 ergs s⁻¹, Lx/Lbol = 2.2 × 10⁻⁴, and a coronal temperature of ~3.5 × 10⁶ K. The ultraviolet spectra include emission lines of C iv, N v, and Si iv, indicative of a transition region between the chromosphere and corona. These observations are the first concrete evidence for a quiescent corona in an M dwarf outside of flares. We show that our measured coronal properties are consistent with the coronal loop model of Rosner, Tucker, and Vaiana.

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

I. INTRODUCTION

Proxima Centauri (α Cen C) is a well known dM5e flare star whose optical flare characteristics have been studied by Kunkel (1970, 1973, 1975). Haisch et al. (1977) detected a possible extreme-ultraviolet flare with the Apollo-Soyuz satellite and several optical and radio telescopes, Haisch et al. (1978) detected 30 optical flares and 12 possible radio bursts but no X-ray flares. We have set up a second coordinated observing program consisting of observations by HEAO 2, the International Ultraviolet Explorer (IUE) satellite, the Parkes radiotelescope, and several optical telescopes on 1979 March 6 and 7. Our results on flare emission will be described in a forthcoming paper by Haisch et al. (1980b). We report here on the unexpected detection of quiescent coronal X-ray emission, the first detection of a corona in an M dwarf outside of a flare, as well as the observation of many chromospheric and transition-region ultraviolet emission lines.

II. X-RAY OBSERVATIONS

We obtained observations in the direction of Proxima Cen with the imaging proportional counter (IPC) on HEAO 2 from 1424 to 1651 UT on 1979 March 6 and from 1410 to 1636 UT on 1979 March 7. The design and operation of the IPC are described by Giacconi et al. (1979). The field of view of the IPC is about 1° with a spatial resolution element of 1', and the instrument is sensitive to X-rays in the energy range 0.2–4.0 keV with low spectral resolution and a peak effective area of ~100 cm².

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We observed a strong, variable source located within ±0.6 of the expected position of Proxima Cen. In a companion paper by Haisch et al. (1980a) the bright flare and decay phase of a second event seen in these data are discussed, as well as the statistically significant X-ray fluctuations and details of the spectral fitting. Here we note that the flare events are superposed on quiescent X-ray emission of about 7 × 10⁻¹² ergs cm⁻² s⁻¹ in the 0.2–4.0 keV bandpass, corresponding to an X-ray luminosity of approximately Lx = 1.5 × 10³⁷ ergs s⁻¹ at the 1.31 pc distance of Proxima Cen. The low spectral resolution IPC data are best fitted by thermal emission from an optically thin plasma of cosmic abundance at a temperature of T ~ 3.5 × 10⁶ K (Haisch et al. 1980a). We attribute this emission to a quiescent corona.

III. ULTRAVIOLET OBSERVATIONS

On 1979 March 6 and 7 we obtained a sequence of 10 low-dispersion spectra of Proxima Cen using the long (2000–3400 Å) and short wavelength (1150–2000 Å) spectrographs on board IUE (cf. Boggsess et al. 1978; Linsky et al. 1978). Since we were attempting to obtain time-resolved flare spectra, we trailed the stellar image along the length of the large aperture as described by Haisch et al. (1980b). No evidence for flare enhancement is apparent in these spectra, however, and we present in Figures 1 and 2 summed spectra for each exposure (duration 20–76 minutes) and the composite of all spectra representing a total of 206 minutes for the SWP (short wavelength) and 135 min for the LWR (long wavelength) cameras.

a) Short-Wavelength Spectra

The four summed SWP spectra in Figure 1 were obtained by collapsing the individual trailed spectra perpendicular to the dispersion, subtracting a smoothed
background, and multiplying by the absolute flux calibration factors of Bohlin (1978)\(^3\) to obtain absolute fluxes at Earth. We have identified eight stellar emission features in the composite SWP spectrum. These are summarized in Table 1, together with the most likely line identifications and the integrated fluxes. The identifications are based on previous IUE SWP observations of cool stars by Linsky et al. (1978) and Linsky and Haisch (1979) and on the observed solar limb emission of Burton and Ridgeley (1970). We consider a feature likely to be real if it is clearly present in the composite spectrum and at least three of the four individual spectra.

Bright geocoronal La is the most prominent feature seen in the SWP exposures. The time-trailing technique used makes it difficult to disentangle geocoronal from stellar La with any degree of certainty, but stellar La flux in the composite spectrum is given in Table 1.

The next strongest features due to C \(\text{IV} \lambda 1550\), C \(\text{I} \lambda 1657\), C \(\text{II} \lambda 1335\), and N \(\text{V} \lambda 1240\) are definitely real. Weaker features identified as the Si \(\text{IV} - \text{O} \text{IV}\) blend (1399 Å) and He \(\text{II} - \text{Fe} \text{II}\) blend (1637 Å) are probably real. We note that the O \(\text{I}\) resonance lines near 1304 Å and Si \(\text{II}\) lines at 1808 and 1817 Å, which are generally very strong in hotter dwarfs and giants and in \(\alpha\) Ori (M2 Iab) (cf. Linsky and Haisch 1979), are not apparent in our data. Identification of lines due to C \(\text{IV}\), N \(\text{V}\), and Si \(\text{IV}\) is indicative of plasma at 100,000–200,000 K, which in analogy with the Sun is probably located in a transition region between the chromosphere and the \(3.5 \times 10^6\) K corona.

Also listed in Table 1 are the stellar surface fluxes derived from the stellar radius determination of Frogel et al. (1972), \(r_\star = 1.3 \times 10^6\) cm. The ratios of stellar to solar surface fluxes for these lines are presented in the last column of Table 1. The solar fluxes are the Rottman values as cited in Linsky et al. (1978) except for Mg \(\text{II}\), which is taken from Basri and Linsky (1980).

In our composite SWP spectrum, the emission lines stand up more clearly above the noise than in the single 4 hour exposure of Proxima Cen by Carpenter and Wing (1979), where only the La and C \(\text{IV}\) lines are definitely present. Our Proxima Cen spectrum is qualitatively similar to that of YZ CMi (M4e V), obtained by Carpenter and Wing (1979), and that of EQ Peg (M3.5e V + M4.5e V), obtained by Hartmann et al. (1979). In particular, the relative weakness of the O \(\text{I}\) and Si \(\text{II}\) lines and the strength of the N \(\text{V}\) line, compared to the relative strength of emission lines in the quiet Sun, appears to be a common property of dMe stars.

b) Long-Wavelength Spectra

Plotted in Figure 2 are spectra for the five individual LWR exposures and the total composite spectrum. The most prominent feature is the blend of the Mg \(\text{II} \ h\) and \(k\) resonance lines at 2795.52 and 2802.70 Å, which are unresolved at the 6 Å resolution of the low-dispersion
OBSERVATIONS OF PROXIMA CEN

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WAVELENGTH (Å)

Fig. 2.—IUE long-wavelength, low-dispersion spectra of Proxima Centauri. The lower five LWR spectra are sums of spectra trailed perpendicular to the dispersion with no background subtraction or absolute calibration applied. On top is a composite of the five LWR spectra, corrected for background noise, in absolute flux units, showing identification of emission features. The difference in the count rates among these five spectra is consistent with noise in the vidicon readout process and variations in the particle-induced background events.

The other emission features identified in Figure 2 are in many cases not much stronger than the noise level, and their identification must be considered tentative. We have not included broad features, such as that at 2670 Å, as they are more likely to be low-frequency changes in vidicon sensitivity. The majority of the tentatively identified lines are due to Fe II, although Cr II and Mn II appear to be present as well. In Table 2 we list the measured wavelengths of the emission features and probable identifications. The identifications, listed in order of decreasing probability as contributors, are based on the solar-limb spectrum identifications of Doschek, Feldman, and Cohen (1977), Burton and Ridgeley (1970), and Moore (1962). These lines are probably all formed in the chromosphere and photosphere of the star, probably at temperatures near 5000 K, and appear in emission due to the weak photospheric continuum in the ultraviolet.

IV. DISCUSSION

The identification of quiescent emission from Proxima Cen formed at temperatures \( \sim 3.5 \times 10^5 \) K, 100,000-200,000 K, and near 5000 K is highly suggestive of a quiescent outer atmosphere similar to the Sun, consisting of a hot corona, a cool chromosphere, and a transition region in between. These observations are, in fact, the first concrete evidence for a quiescent corona in an M dwarf at times other than during flares, although Hartmann et al. (1979) inferred the existence of a corona in EQ Peg from He \( \alpha \) emission. While the absolute fluxes cited are preliminary and future observations with longer exposure times and higher spectral resolutions are needed, we estimate properties for these atmospheric layers in Proxima Cen and compare these to the range of properties seen in the Sun and late-type dwarfs.

Several dMe flare stars have been observed during flares with values of \( L_x \) \( \sim 3-4 \) orders of magnitude larger than the quiescent value of \( L_x \sim 1.5 \times 10^{27} \) ergs s\(^{-1}\) for Proxima Cen. Kahn et al. (1979) using HEAO 1 obtained \( L_x \sim 1.6 \times 10^{30} \) and \( 4.6 \times 10^{30} \) ergs s\(^{-1}\) for two flares on AT Mic and \( L_x \sim 1.3 \times 10^{30} \) and \( 1.6 \times 10^{30} \) ergs s\(^{-1}\) for two flares on AD Leo. Haisch et al. (1978) also estimated values of \( L_x \sim 2 \times 10^{30} \) ergs s\(^{-1}\) for a flare on UV Ceti, \( 8 \times 10^{30} \) ergs s\(^{-1}\) for a flare on YZ CMi, and \( 1 \times 10^{30} \) ergs s\(^{-1}\) for a flare on Proxima Cen seen in the extreme ultraviolet. For comparison with other types of stars we compare the ratio \( L_x/L_{bol} \). The bolometric luminosity of Proxima Cen is \( 6.7 \times 10^{29} \) ergs s\(^{-1}\) (Frogel et al. 1972). The ratio of \( L_x/L_{bol} \) is therefore \( 2.2 \times 10^{-4} \) for the quiescent emission from Proxima Cen. By comparison, the quiet Sun typically has the value \( 1.5 \times 10^{-6} \), and the Sun, if it were entirely covered with active regions, would have the ratio \( L_x/L_{bol} \sim 5 \times 10^{-4} \) (Vaiana and Rosner 1978). Walter et al. (1979) find that \( L_x/L_{bol} \) for the F5-K5 single dwarfs with the strongest X-ray emission (active corona stars) is typically \( 10^{-4} \). The nonflaring corona of Proxima Cen is therefore comparable to or somewhat larger in \( L_x/L_{bol} \) than solar active regions and the single dwarf stars which are the strongest X-ray emitters. On the other hand, the soft X-ray flux per unit area on Proxima Cen is only about 0.22 that of a solar active region.

The rate of coronal heating must be at least \( 2.2 \times 10^{-4} L_{bol} \) to balance radiative, conductive, and wind losses. This coronal heating rate is far larger than expected on the basis of acoustic wave heating. For example, Schmitz and Ulmschneider (1980) find that their calculations for the dK5e star EQ Vir show only \( 2 \times 10^{-6} L_{bol} \) of wave energy available to heat both the chromosphere and the corona. This suggests that magnetic fields play an important role in heating the quiescent corona of Proxima Cen and in determining a
loop-type basic structure as is true for solar active regions (Rosner, Tucker, and Vaiana 1978, hereafter RTV).

The RTV coronal loop model can be used to predict coronal properties. On the Sun active-region loops have lengths $L$ between $10^9$ and $10^{10}$ cm. Assuming similar values of $L$ and $T = 3.5 \times 10^6$ K for Proxima Cen, we obtain the pressures listed in Table 3 by using equation (4.3) in RTV. Also listed are comparison values of $P$ and $T$ for the quiet Sun (Vaiana and Rosner 1978). The emission measures (EM) cited are obtained from $L_x$ and the radiative loss relation given in RTV. Finally, we estimate the fractional area of the stellar disk covered by coronal loops, $f$, using equation (5) in Walter et al. (1979), which was derived from the coronal loop model. The data are thus consistent with the picture of the quiescent corona of Proxima Cen filled entirely of loops with lengths slightly larger than $10^{10}$ cm and with plasma pressures $P \sim 0.8$ dynes cm$^{-2}$, or partly filled with smaller loops at higher pressures.

Comparison of chromosphere and transition-region line surface fluxes with quiet-Sun values is a means of

### Table 1
Emission Features in the SWP Exposures

<table>
<thead>
<tr>
<th>IUE Wavelength (Å)</th>
<th>Identification</th>
<th>Flux at Earth (ergs cm$^{-2}$ s$^{-1}$)</th>
<th>Stellar Surface Flux (ergs cm$^{-2}$ s$^{-1}$)</th>
<th>$F_\lambda/F_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(0.2-4.0 keV)$^a$</td>
<td>soft X-ray emission</td>
<td>$7 \times 10^{-12}$</td>
<td>$7 \times 10^9$</td>
<td>9</td>
</tr>
<tr>
<td>1215</td>
<td>Fe ix 1215.7</td>
<td>$2 \times 10^{-12}$</td>
<td>$1.9 \times 10^6$</td>
<td>&gt;0.9</td>
</tr>
<tr>
<td>1249$^b$</td>
<td>N v (1) $\lambda$1238.8, 1242.8</td>
<td>$1 \times 10^{-13}$</td>
<td>$9.5 \times 10^4$</td>
<td>11</td>
</tr>
<tr>
<td>1336</td>
<td>C ii (4); Si ii (1); C t blend</td>
<td>$1.5 \times 10^{-13}$</td>
<td>$1.4 \times 10^4$</td>
<td>3</td>
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<tr>
<td>1396</td>
<td>Si iv blend; O iv blend</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1548</td>
<td>C iv (1) $\lambda$1548.2, 1550.8</td>
<td>$1.5 \times 10^{-13}$</td>
<td>$1.4 \times 10^4$</td>
<td>2.4</td>
</tr>
<tr>
<td>1634</td>
<td>Fe t blend; He t (12)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1657</td>
<td>C t (2); Fe t</td>
<td>$1.6 \times 10^{-13}$</td>
<td>$1.5 \times 10^4$</td>
<td>2.8</td>
</tr>
<tr>
<td>(1812)$^c$</td>
<td>Si ii (1) $\lambda$1808.0, 1816.9, 1817.4</td>
<td>$5 \times 10^{-14}$</td>
<td>$4.7 \times 10^4$</td>
<td>&lt;0.3</td>
</tr>
<tr>
<td>(2798)$^d$</td>
<td>Mg ii (1) $\lambda$2797 5, 2802.7</td>
<td>$8 \times 10^{-13}$</td>
<td>$8.1 \times 10^4$</td>
<td>0.06</td>
</tr>
</tbody>
</table>

$^a$ HEAO 2 IPC observation.
$^b$ Lower limit because no correction applied for interstellar absorption.
$^c$ N v fluxes may be somewhat larger than measured due to excess background subtraction resulting from geo-coronal Lo emission filling the large aperture.
$^d$ Line probably present but we cannot measure its flux reliably.
$^e$ No emission detected. Flux given is an upper limit.
$^f$ LWR observation.

### Table 2
Emission Features in the LWR Exposures

<table>
<thead>
<tr>
<th>IUE Wavelength (Å)</th>
<th>Identification</th>
</tr>
</thead>
<tbody>
<tr>
<td>2503</td>
<td>Fe ii (1) $\lambda$2598.37, 2599.40, 2607.08</td>
</tr>
<tr>
<td>2506</td>
<td>Fe ii (1) $\lambda$2598.37, 2599.40, 2607.08</td>
</tr>
<tr>
<td>2604</td>
<td>Fe ii (1) $\lambda$2625.66, 2628.29</td>
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<tr>
<td>2634</td>
<td>Fe ii (1) $\lambda$2631.05, 2631.32</td>
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<tr>
<td>2726</td>
<td>Fe ii (63) $\lambda$2727.54; Fe ii (62) $\lambda$2730.74</td>
</tr>
<tr>
<td>2779$^a$</td>
<td>Fe ii (234) $\lambda$2779.30, 2783.69</td>
</tr>
<tr>
<td>2798</td>
<td>Mg ii (1) $\lambda$2798 52, 2802.70</td>
</tr>
<tr>
<td>2851</td>
<td>Cr ii (5) $\lambda$2849.83, 2855.47</td>
</tr>
<tr>
<td>2859</td>
<td>Cr ii (5) $\lambda$2858.91, 2860.92, 2862.57, 2865.10, 2866.72, 2867.65; Fe ii (195,279)</td>
</tr>
<tr>
<td>2908</td>
<td>Fe t, ti blend$^b$</td>
</tr>
<tr>
<td>2917</td>
<td>Fe t blend$^b$</td>
</tr>
<tr>
<td>2931</td>
<td>Mn ii (5) $\lambda$2933.05, 2939.30; Mg ii (2) $\lambda$2936.50; Fe ii (60) $\lambda$2926.58</td>
</tr>
<tr>
<td>2939$^a$</td>
<td>Mn ii (5) $\lambda$2949.20; Fe ii (78) $\lambda$2944.40, 2947.66</td>
</tr>
<tr>
<td>2979$^a$</td>
<td>Fe ii (78) $\lambda$3002.65</td>
</tr>
<tr>
<td>3010</td>
<td>Fe ii (276) $\lambda$3012.59; Mn t (3) $\lambda$3008.82, 3012.85$^b$</td>
</tr>
<tr>
<td>3019</td>
<td>Fe ii (251) $\lambda$3021.41$^b$; Cu t (45) $\lambda$3021.54$^b$</td>
</tr>
<tr>
<td>3022$^a$</td>
<td>Fe t (131) $\lambda$3033.10$^b$; Cr ii (94) $\lambda$3034.54$^b$; N t (74) 3029.29$^b$</td>
</tr>
<tr>
<td>3041</td>
<td>Cu t (45) $\lambda$3044.03$^b$</td>
</tr>
<tr>
<td>3050$^a$</td>
<td>Fe t (131) $\lambda$3053.07$^b$; Cr ii (94) $\lambda$3055.44$^b$; Cu t$^b$; Ni t$^b$</td>
</tr>
<tr>
<td>3086$^a$</td>
<td>Ti ii (5) $\lambda$3088.03</td>
</tr>
</tbody>
</table>

$^a$ Identification less certain.
$^b$ Not seen in solar limb spectrum; identification from Moore (1962).
determining whether the relative distribution of material as a function of temperature is very different from or similar to that in the Sun. The transition-region lines (N v, C iv, and C ii) have surface flux ratios compared with the quiet Sun of 2.8–11, similar to a weak plage on the Sun or a surface partially covered with plage regions. It is interesting that the multiplet formed at the highest temperature in the transition region, N v formed at 200,000 K, has the largest surface flux ratio, which is similar to the soft X-ray flux value. The chromosphere lines show no definite trend. The Lα line, taking into account perhaps a factor of 2–3 loss due to interstellar absorption, and the C I line are about twice as bright as in the Sun, whereas the Si and Mg II resonance lines are significantly fainter than for the Sun.

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