HEAO 1 OBSERVATIONS OF ACTIVE CORONAE IN MAIN-SEQUENCE AND SUBGIANT STARS

Frederick M. Walter
Space Sciences Laboratory and Department of Astronomy, University of California, Berkeley

Jeffrey L. Linsky
JILA, National Bureau of Standards, University of Colorado

Stuart Bowyer
Space Sciences Laboratory and Department of Astronomy, University of California, Berkeley

Gordon Garmire
California Institute of Technology

Received 1979 August 7; accepted 1979 December 19

ABSTRACT

We have searched the HEAO 1 data for evidence of X-ray emission from 105 bright late-type stars of luminosity class IV and V, selected on the basis of indirect optical evidence of the presence of a hot corona. Six of the target stars were detected at the 3σ level and 15 were coincident with 2σ X-ray sources. On a statistical basis no more than 5 of these 21 sources are spurious, and the probability that the identification with the class of active chromosphere stars is spurious is < 10^-5.

The sources lie near a line of $L_{\text{X}} / L_{\text{bol}} = 10^{-4}$, similar to a solar plage, and we conclude that we are observing the most active coronae of late-type stars which are not members of close binary systems. The RS CVn systems discovered to date seem to form a distinct class of coronal X-ray sources, but the lowest X-ray luminosity members of the group, of which Capella may be the prototype, appear to overlap the domain of these single stars with active coronae. The data do not fit the coronal model of Gorenstein and Tucker (1976), but they are consistent with the coronal loop model of Rosner et al. as extended by Walter et al.

Subject headings: stars: coronae — X-rays: sources

I. INTRODUCTION

The study of stellar coronae has only recently become possible. Stars which have been detected in X-rays and which may be emitting via a coronal-type mechanism include Capella (Catura, Acton, and Johnston 1975; Cash et al. 1978), Sirius (Mewe et al. 1975), Vega, and η Boo (Topka et al. 1979). With the launch of HEAO 1 many new soft X-ray sources have been identified as stellar coronae, notably the class of RS CVn stars (Walter, Charles, and Bowyer 1978a, b; Walter et al. 1980), α Cen (Nugent and Garmire 1978), 40 Eri (Cash et al. 1979), η Boo (Walter, Charles, and Bowyer 1978b), and Ap stars (Cash, Snow, and Charles 1979). The soft X-ray luminosities of these sources range from $\sim 10^{32}$ to $\sim 10^{34}$ ergs s^-1, and the coronal temperatures range from $\sim 10^6$ to $10^7$ K.

We report here on a search for coronal X-ray emission from bright F-K dwarfs and subgiants using the HEAO 1 A-2 low-energy sky survey experiment. In selecting late-type stars to be searched for coronal X-ray emission, we were guided by two indirect coronal indicators. (1) Zirin (1975) has argued that He I λ10830 absorption in late-type stars indicates coronae. The most likely mechanism for populating the 2p S lower state of this transition lying 19 eV above the ground state is by recombination following photoionization of He I by coronal and transition region photons at λ < 504 Å. (2) In the large-scale structures on the Sun and in RS CVn systems, active chromospheres, indicated by bright emission in the Ca II resonance lines, are well correlated with bright coronal X-ray emission.

Most of the targets were taken from Wilson's (1978) list of stars with strong Ca II emission as evidence for chromospheric activity. We also observed those dwarfs and subgiants with He I λ10830 Å in absorption (Zirin 1976), and the dwarfs studied by Linsky and Haisch (1979) and by Linsky et al. (1979a, b). A total of 105 targets were searched, of which 80 possess one or more coronal indicators and the rest are stars used by the above authors as comparison stars.

II. OBSERVATIONS

The data presented here were obtained by the low-energy detectors of the HEAO 1 cosmic X-ray experiment, a complete description of which is given by Rothchild (1979). We used only that detector most sensitive to point sources (LED 1) which has a field of view...
view of 1.5 \times 3.0 \text{ (FWHM)}. The detectors are propane-filled proportional counters with polypropylene windows with a nominal energy range of 0.15–2.8 keV. The data are taken with the spacecraft scanning in ecliptic latitude at a rate of 0.2 s\(^{-1}\). Count rates are internally binned every 1.28 s. Sky coverage was not uniform due to operational difficulties during the mission.

The X-ray data for each target consists of a 3 day sum of scanning data, in 0.5° bins, centered at the time of target transit. These data were then fitted with a second-order polynomial approximating the background, plus a triangular collimator response. The region of the background fitted is generally 10° in extent, and was chosen to avoid other sources or poor data. The source significance was computed by forcing the amplitude of the triangle to zero and examining the change in \(x^2\) from that of the best fit (see discussion in Cash, Snow, and Charles 1979). This technique somewhat overestimates the uncertainties. Sources detected at the 2 \(\sigma\) level in either the 0.15–0.4 keV energy band or the 0.15–3 keV energy band were noted and checked for coincidences with identified X-ray sources.

At the 105 target positions, we observed 21 X-ray sources at the 2 \(\sigma\) or greater level of significance. Six of these, three of which have been previously reported, were detected at the 3 \(\sigma\) level (see Table 1). Of the six 3 \(\sigma\) detections, two are single dwarf stars, and three consist of a pair of dwarfs in a wide binary orbit. Only in 40 Eri is there the possibility that the emission does not arise in a fairly normal main-sequence star. However, Cash et al. (1979) examined this system in detail and concluded that the most likely source of the X-rays is coronal emission from the K1 V.

All told, 20% of the targets were detected at or above the 2 \(\sigma\) significance level. On the assumption that Gaussian statistics are appropriate here, one would expect to observe \(\sim 5\%\) of the targets at a 2 \(\sigma\) level due to the uncertainties.

### TABLE 1

<table>
<thead>
<tr>
<th>Star</th>
<th>Spectral Type</th>
<th>(d_{\text{pc}})</th>
<th>(L_x) ((10^{33}\text{ ergs s}^{-1}))</th>
<th>(I_{\text{CaII}})</th>
<th>(W_{\text{HeI}10830}) (b)</th>
<th>Mean H-K Flux (c)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>40 Eri</td>
<td>K1 V+dMe+DA</td>
<td>5.0</td>
<td>1.0±0.15</td>
<td>2</td>
<td>0.2</td>
<td>0.202</td>
<td>Cash et al. 1979a</td>
</tr>
<tr>
<td>(\eta) Ori</td>
<td>G0 V</td>
<td>9.9</td>
<td>3.6±1.3</td>
<td>2</td>
<td>0</td>
<td>0.03</td>
<td>Topka et al. 1979</td>
</tr>
<tr>
<td>((\eta) Boo)(d)</td>
<td>G0 IV+</td>
<td>9.8</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0.289</td>
<td>Topka et al. 1979</td>
</tr>
<tr>
<td>(\xi) Cen</td>
<td>G2 V+K1 V</td>
<td>1.33</td>
<td>0.03</td>
<td>0.2</td>
<td>0</td>
<td>0.03</td>
<td>Nugent and Garmire 1978</td>
</tr>
<tr>
<td>(\xi) Boo</td>
<td>G8 V+K5 V</td>
<td>6.9</td>
<td>1.6±0.46</td>
<td>5</td>
<td>0.26A</td>
<td>0.411, 1.009</td>
<td>Walter et al. 1978b</td>
</tr>
<tr>
<td>70 Oph</td>
<td>K0 V+K5 V</td>
<td>5.3</td>
<td>1.1±0.3</td>
<td>3</td>
<td>0.3A</td>
<td>0.372, 0.795</td>
<td>Walter et al. 1978b</td>
</tr>
<tr>
<td>HR 6806</td>
<td>K2 V</td>
<td>10</td>
<td>2.9±0.8</td>
<td></td>
<td></td>
<td>0.188</td>
<td>Walter et al. 1978b</td>
</tr>
</tbody>
</table>

#### 2 \(\sigma\) Sources\(a\)

<table>
<thead>
<tr>
<th>Star</th>
<th>Spectral Type</th>
<th>(d_{\text{pc}})</th>
<th>(L_x) ((10^{33}\text{ ergs s}^{-1}))</th>
<th>(I_{\text{CaII}})</th>
<th>(W_{\text{HeI}10830}) (b)</th>
<th>Mean H-K Flux (c)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\eta) Cas</td>
<td>G0 V</td>
<td>5.5</td>
<td>(0.53±0.38)</td>
<td>0</td>
<td>0</td>
<td>0.209</td>
<td>Wilson-Bappu</td>
</tr>
<tr>
<td>107 Psc</td>
<td>K1 V</td>
<td>7.5</td>
<td>(1.1±0.57)</td>
<td>3</td>
<td>0.3A</td>
<td>0.168</td>
<td>Wilson-Bappu</td>
</tr>
<tr>
<td>112 Psc</td>
<td>dG1</td>
<td>29</td>
<td>(21±9.7)</td>
<td>0</td>
<td>0.3A</td>
<td>0.168</td>
<td>Wilson-Bappu</td>
</tr>
<tr>
<td>e Eri</td>
<td>K2 V</td>
<td>3.3</td>
<td>(0.38±0.17)</td>
<td>1.3</td>
<td>0.3A</td>
<td>0.168</td>
<td>Wilson-Bappu</td>
</tr>
<tr>
<td>50 Per</td>
<td>dF7</td>
<td>22</td>
<td>(6.7±2.3)</td>
<td>1</td>
<td>0</td>
<td>0.281</td>
<td>Wilson-Bappu</td>
</tr>
<tr>
<td>HR 1321/2</td>
<td>G0 V+G5 V</td>
<td>30/28</td>
<td>(13±6)</td>
<td>0.365</td>
<td>0.270</td>
<td></td>
<td>Wilson-Bappu</td>
</tr>
<tr>
<td>HR 5384</td>
<td>dG3</td>
<td>16</td>
<td>(4.9±2.4)</td>
<td>0</td>
<td>0</td>
<td>0.166</td>
<td>Wilson-Bappu</td>
</tr>
<tr>
<td>HR 5568</td>
<td>K5 V+dM2</td>
<td>5.8</td>
<td>(0.5±0.4)</td>
<td>5</td>
<td>0.26A</td>
<td>0.166</td>
<td>Wilson-Bappu</td>
</tr>
<tr>
<td>(\mu) Her</td>
<td>G5 IV</td>
<td>9.3</td>
<td>(1.7±0.8)</td>
<td>0</td>
<td>0.26A</td>
<td>0.166</td>
<td>Wilson-Bappu</td>
</tr>
<tr>
<td>HR 7163</td>
<td>F5</td>
<td>38</td>
<td>(24±15)</td>
<td>0</td>
<td>0</td>
<td>0.190</td>
<td>Wilson-Bappu</td>
</tr>
<tr>
<td>HR 7354</td>
<td>F6 V</td>
<td>34</td>
<td>(36±13)</td>
<td>0</td>
<td>0</td>
<td>0.203</td>
<td>Wilson-Bappu</td>
</tr>
</tbody>
</table>

#### Sun\(f\)

| Coronal holes                                      | \(-0.005\) | 0 | \(-0.03A\) | 0.171 |
| Quiet Sun (Flare)                                   | \(-0.05\)  | 0 | \(-0.03A\) | 0.171 |
| Active Sun (Flare)                                  | \(-2\)     | 0 | \(-2\)     | 0     |
| Flaring Sun (Flare)                                 | \(-200-2000\) | 0 | \(-2\)     | 0     |

\(a\) Wilson-Bappu Ca II K line intensities (Wilson and Bappu 1957).

\(b\) \(\text{He I} \lambda 10830\) equivalent widths in Angstroms (Zirin 1976); \(E = \text{emission}, A = \text{absorption}\).

\(c\) Mean H-K flux (Wilson 1978).

\(d\) Not detected by HEAO 1.

\(e\) As many as five of the 2 \(\sigma\) X-ray sources may be spurious; see discussion in § III.

\(f\) Estimated soft X-ray luminosities if the entire solar disk were covered by these features (Vaiana and Rosner 1978).
A search of 1000 random positions for X-ray sources yielded 4.2% at the 2σ or greater significance level, ruling out the hypothesis that our observed success rate is a statistical fluctuation at greater than the 99.999% confidence level. Thus our detection of 20% of the searched targets at this level indicates that most of the 21 X-ray sources are probably real.

On the basis of the error boxes alone, which typically cover 2–3 square degrees because of the low significance of sources above background, it is not possible to conclude that any particular one of the target stars is the optical counterpart of the X-ray source. However, the target stars all lie within ~0.25 of and are all consistent with the center of the error box in the best defined direction. Hence it is reasonably straightforward on a statistical basis that in the majority of cases the active chromosphere stars in each error box are responsible for the observed X-ray emission. In the second half of Table 1 we present the stars which may be identified with the 2σ X-ray sources. We caution the reader that while 10 of the 15 targets are probably real X-ray sources, it is impossible to state which are real and which are not.

We examined a subset of the data consisting of the 18 standard stars used by Wilson (1978) as a check on the rest of the data. Since these standards show no evidence of strong chromospheric activity, they might well be expected not to have bright coronae. Only one X-ray source was observed at the 2σ level in this sample, which is consistent with the number expected from random fluctuations in the data. This strengthens our claim that stars with active chromospheres have bright coronae, and hence are seen as X-ray sources, while less active stars are not detectable at our level of sensitivity.

Because of the low fluxes, detailed X-ray spectral parameters are unattainable for the sources we have examined. We can determine, however, that the sources are soft (T ≤ 10^7 K). Spectra have been previously published for α Cen (Nugent and Garmire 1978), ξ Boo (Walter, Charles, and Bowyer 1978b), and 40 Eri (Cash et al. 1978a).

III. DISCUSSION

In Table 1 we present the target stars associated with the X-ray sources, their derived 0.15–3 keV luminosities, and the values of three of the indirect coronal indicators for these stars. The mean H-K flux values obtained by Wilson (1978) are a quantitative measure of the Ca II emission normalized to the continuum on either side of the line. The least active stars have values of 0.13–0.15, independent of spectral type; those stars with mean fluxes ≥0.2 can probably be called active chromosphere stars. The Wilson-Bappu K line index, I(Ca II), is a crude measure, such that F stars with I(Ca II) ≥1, G stars ≥2, and K stars ≥4 are probably active-chromosphere stars. Most of the stars in Table 1 satisfy one or more of these coronal indicators. The only clear exceptions are η Boo, α Cen, and the 2σ sources η Cas, 112 Psc, HR 4067 and HR 5384.

The Wilson-Bappu K line index, I(Ca II), is a cruder measure, such that F stars with I(Ca II) ≥1, G stars ≥2, and K stars ≥4 are probably active-chromosphere stars. The mean fluxes ≥0.2 can probably be called active chromosphere stars. The Wilson-Bappu K line index, I(Ca II), is a cruder measure, such that F stars with I(Ca II) ≥1, G stars ≥2, and K stars ≥4 are probably active-chromosphere stars. Most of the stars in Table 1 satisfy one or more of these coronal indicators. The only clear exceptions are η Boo, α Cen, and the 2σ sources η Cas, 112 Psc, HR 4067 and HR 5384. These latter four sources, on a statistical basis, may not be real detections.

The two lines in Figure 1 are the locus of constant surface flux at 10^7 ergs cm^-2 s^-1 and the locus of constant Lx/Lbol = 10^-4 for stars of luminosity class V. The data do not fit the constant surface flux line, indicating that the change in radius with spectral type along the main sequence is not the dominant effect in relative coronal intensities, but they are consistent with the Lx/Lbol = 10^-4 locus. Although no individual 2σ observation can be considered real, 80% are real on a statistical basis. Thus the trend of most of our detected stars lying near the locus of Lx/Lbol = 10^-4 for main-sequence stars must be real. The lack of detections much above this locus is also real, but below this locus our data are very incomplete because of selection effects. The quiet Sun (Vaiana and Rosner 1978) and α Cen lie far below the Lx/Lbol = 10^-4 locus, and both stars would not have been detected by HEAO 1 if located even at 2 pc.

Vaiana and Rosner (1978) have estimated that the soft X-ray luminosity of the Sun, if covered entirely by active regions, would be Lx ~ 2 x 10^30 ergs s^-1 (Lx/Lbol = 5 x 10^-6). We therefore believe that we are detecting the most active coronae of single stars or widely separated binaries, and that they are similar to the active regions seen on the solar disk. These stars populate the upper end of the Lx/Lbol distribution function, and we hypothesize that the range of stellar coronal luminosity extends downward to at least Lx/Lbol = 10^-4 where the quiet Sun and α Cen are located. We note that Vaiana et al. (1979) have reported preliminary HEAO 2 results that random F stars show Lx ~ 10^30 ergs s^-1, which is below our detection limits even for the nearest F stars.

The RS CVn systems form a distinct group well above the Lx/Lbol = 10^-4 locus with Lx in several cases as large as would be observed on the Sun were it covered with flares. However, taking into account the greater surface area of the active components in RS CVn systems, the surface fluxes of the less luminous RS CVn systems are similar to those of the active stars. Ayres and Linsky (1979) claim that the coronal emission from Capella, a long-period RS CVn system, arises on the B component (F9 III). Since Capella B is a giant and is only slightly brighter than the active-corona F stars, the surface flux of Capella B is actually smaller than that of the active-corona F stars. The arguments suggest that the mechanism responsible for the RS CVn characteristics, seen at low level in the Capella system, is not qualitatively different from but is an extreme case...
of stellar activity in a single late-type star as suggested by Walter et al. (1980). We expect that HEAO 2 observations of less extreme RS CVn systems than were observable with HEAO 1 will show these systems to have coronal X-ray luminosities similar to active-corona single stars.

Ayres (1979) has proposed that rapid rotation, which is produced by tidal synchronism of rotation and revolution, enhances dynamo processes and leads to large magnetic fields and strong coronal X-ray emission. This is consistent with these data, since the RS CVn's, which rotate synchronously, are rapid rotators, and the active chromosphere stars, which we have shown to have strong coronae, tend to be rapid rotators as compared to stars of similar spectral type which do not possess active chromospheres (Kraft 1967).

Our detected X-ray luminosities from active-chromosphere single stars are about two orders of magnitude larger than luminosities predicted on the basis of coronal heating by the dissipation of acoustic waves generated in stellar convection zones (e.g., Gorenstein and Tucker 1976), but are consistent with measured fluxes from solar active regions. Since active regions on the Sun differ from quiet regions as a result of enhanced magnetic fields, we conclude that magnetic fields play an essential role in the coronal energy balance of active corona stars.

Walter et al. (1980) have applied the coronal loop

![Figure 1](https://example.com/figure1.png)

**Fig. 1.—** A coronal H-R diagram for stars with active chromospheres. Here coronal X-ray luminosity is plotted versus spectral type. The RS CVn systems are marked by crosses and subgiants are marked by open circles. The quiet Sun, active Sun, and flaring Sun are indicated, and $\alpha$ Cen, $\eta$ Boo, $\eta$ Cas, and Capella are labeled by name. Error bars are $\pm 1 \sigma$; upper limits are $2 \sigma$. The lines drawn are loci of constant coronal surface flux of $10^7$ ergs cm$^{-2}$ s$^{-1}$ and of constant X-ray luminosity to total stellar luminosity of $L_x/L_{bol} = 10^{-4}$. Both lines are valid only for stars of luminosity class V. The $L_x/L_{bol} = 10^{-4}$ line appears to delineate the maximum $L_x$ for stars not subject to forced rapid rotation.
model of Rosner, Tucker, and Vaiana (1978, hereafter RTV), which accounts for soft X-ray emission from solar coronal loops, to explain emission from RS CVn systems. We assume that this model also applies to these active stars, and take as parameters loop lengths $L = 10^{10}$ cm (typical for solar active-region loops) and $T = 10^7$ K (the estimated value for 40 Eri and η Boo).

Using equation (4.3) in RTV, these parameters predict $P = 36$ dynes cm$^{-2}$, a value of the pressure which is typical for flare loops on the Sun, but is an order of magnitude larger than for solar active-region loops (cf. RTV). Assuming these parameters, the relation between X-ray luminosity and emission measure in RTV, and equation (3) in Walter et al. (1980), we estimate that along the $L_x/L_{bol} = 10^{-4}$ locus about 50% of the surface of an F5 dwarf and about 10% of the surface of a K5 dwarf are covered with X-ray emitting loops. This rough calculation shows that this model with reasonable input parameters is consistent with the observed emission from these active stars.

We conclude that we have observed the upper extent of coronal activity in late-type dwarfs and subgiants which are single stars or members of widely separated binaries. These active-corona stars typically exhibit one or more coronal indicators. The RS CVn systems form a distinct group with X-ray luminosity greater than that of the active corona stars. The upper limit of X-ray emission from late-type “single” stars lies near $L_x \sim 10^{-4}L_{bol}$, and $L_x$ extends downward more than two orders of magnitude for quiet-corona stars like the Sun and α Cen.

We thank the referee for very useful comments. This work has been supported by NASA grants NAS8-33084 at the University of Colorado and CIT44-466866 at the University of California. S. B. acknowledges the support of a Miller Professorship.

REFERENCES

Ayres, T., and Linsky, J. 1979, Bull. AAS, 11, 472.


Stuart Bowyer and Frederick M. Walter: Space Sciences Laboratory, University of California, Berkeley, CA 94720
Gordon Garmire: Downs Laboratory of Physics, 320-47, California Institute of Technology, Pasadena, CA 91125
Jeffrey L. Linsky: JILA, University of Colorado, Boulder, CO 80309

© American Astronomical Society • Provided by the NASA Astrophysics Data System
Fig. 3.—The 38 s pulsar finding charts enlarged from an ESO quick blue survey plate, showing the 90% confidence error parallelograms numbered 1–4 in Table 1 and Fig. 2. North is up and east is to the left. Twenty-five stars listed in Table 2 have been investigated spectroscopically. Star 8 shows spectral variability. The position of star 38, a very red object not visible on this plate, is indicated.

Armstrong et al. (see page L133)