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A SEARCH FOR CORONAL SOFT X-RAY EMISSION FROM COOL STARS WITH *HEAO 1*

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ABSTRACT

We summarize a search of the *HEAO 1* A-2 experiment all-sky survey for coronal soft X-ray emission from a sample of active chromosphere G–M stars including six dwarfs, eight giants, four supergiants, and 10 dMe flare stars. Point sources were detected near the positions of several of the stars on our list. However, of these, only the flare stars BY Draconis (dM0e) and AD Leonis (dM3.5e) appear to be likely candidates for the detected X-rays.
Subject headings: stars: coronae — stars: late-type — X-rays: sources

I. INTRODUCTION

This *Letter* reports on a search of the *HEAO 1* A-2 soft X-ray survey data for point sources of emission near the positions of a selected sample of late-type stars, excluding RS Canum Venaticorum–type systems which have been discussed in detail elsewhere (Walter, Charles, and Bowyer 1978). Our hope was to identify stellar analogs of the solar corona in an effort to better understand the dependence of coronal properties on fundamental stellar parameters. Out of the nearly 30 cool stars in our list, we found weak soft X-ray sources near the positions of only four.

II. SOFT X-RAY DETECTIONS

a) The A-2 Experiment

The A-2 experiment[3] soft X-ray detectors on *HEAO 1* have been described in detail elsewhere (Rothschild *et al.* 1978). The data described here are based on 1 day superpositions of scans from the left field of view of low energy detector 1 (LED 1). Source positions and amplitudes were determined from the full energy range of LED 1, layer 1 (0.15–3 keV).

b) Target Stars

We chose target stars on the basis of optical brightness and enhanced chromospheric activity indicators for their spectral classes, for example, Ca II K emission (Wilson 1976; Warner 1969) and He I λ10830 equivalent widths (Zirin 1976).

c) Source Positions

An examination of the A-2 survey data revealed weak sources near the positions of four of the target stars. Error boxes were derived from the source intensity profiles, using the approach outlined by Nugent and Garmire (1978).

d) Source Candidates

The error boxes in Figure 1 generally contain other possible candidates for the X-ray emission in addition to the original target stars. A useful way of discriminating among possible source candidates is the apparent X-ray-to-optical luminosity ratio. In particular, L_x (0.15–3 keV)/$L_{\rm opt}$ is roughly 1×10^{-6} for the Sun (Vaiana and Rosner 1978) and α Centauri (Nugent and Garmire 1978) and, with the possible exception of RW UMa, is less than 10^{-2} for the very active short-period RS Canum Venaticorum–type systems (see Walter *et al.*).

To convert measured count rates into apparent source fluxes, we convolved theoretical X-ray spectra of hot plasmas (Raymond and Smith 1977) with the A-2 detector responses (Rothschild *et al.* 1978), taking into account the distortion of the initial energy distribution by interstellar absorption (see Ayres *et al.* 1978). We estimated source temperatures based on ratios of the "$\frac{1}{4}$ keV" broad-band channel (scaler 5) to the full energy range of layer 1 (scaler 1).

Results are listed in Table 1 for the most promising source candidates. The tabulated soft X-ray magnitudes are defined as

$$m_x \equiv -2.5 \log l_x - 11.51 , \qquad (1)$$

where l_x is the apparent luminosity of the source in the 0.15–3 keV band (ergs $\rm cm^{-2}\,s^{-1}$ at the Earth). The constant on the right side of equation (1) normalizes m_x to the bolometric magnitude scale (e.g., Allen 1973). The ratio of X-ray to total stellar "optical" luminosity is then simply

$$L_x/L_{\rm opt} \approx {\rm dex}\,[-(m_x - m_{\rm bol})/2.5] . \qquad (2)$$

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[3] The A-2 experiment on *HEAO 1* is a collaborative effort led by E. Boldt of GSFC and G. Garmire of CIT with collaborators at CIT, JPL, UCB, and GSFC.

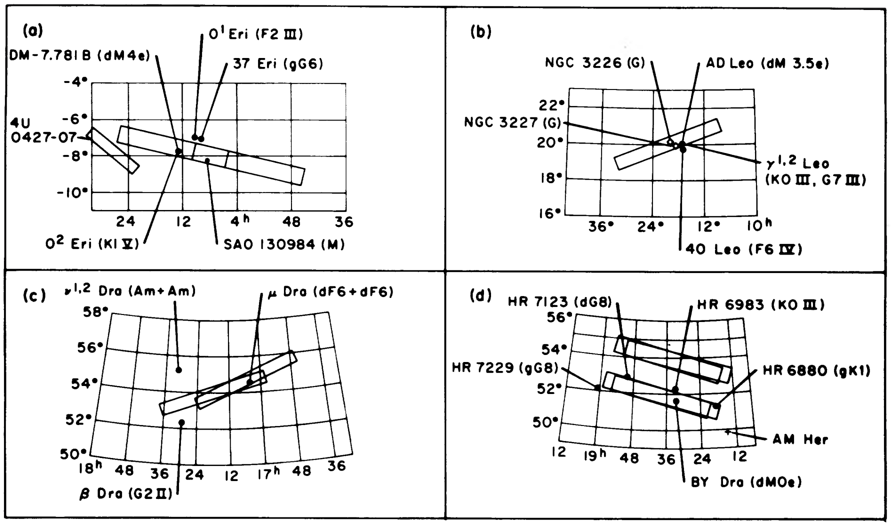

FIG. 1.—Error boxes for *HEAO 1* soft X-ray detections. Positions of bright cool stars in the neighborhood of each source are designated by name and spectral type. Prominent NGC objects are also indicated: G = galaxy. The error box for the 4U hard source near H0405−08 was taken from the catalog of Forman *et al.* (1978).

The bolometric magnitude $m_{\rm bol}$ can be estimated from the apparent visual magnitude of the star, m_v, and a $(B - V)$ color-dependent bolometric correction (e.g., Allen 1973).

$L_x/L_{\rm opt}$ ratios are listed in Table 1 for each of the candidate coronal sources. These ratios are more meaningful than absolute X-ray luminosities for comparisons with the Sun and other X-ray stars, because differences in source sizes (i.e., stellar surface areas) are automatically taken into account.

Descriptions of the individual source detections and possible source candidates are given below.

1) H0405−08.—This weak point source appears against a broad feature in the soft X-ray background (the "Eridanus hot spot"). The centroid of the overlap between the two extreme error boxes lies within 2° of the K dwarf o^2 Eri (40 Eri A). Although o^2 Eri itself is not particularly remarkable—it was the least active K dwarf in our sample—the 40 Eri system also contains a dMe flare star (DM−7.781B; 40 Eri C; see Kunkel 1975) and a compact object (the DA white dwarf 40 Eri B; see Allen 1973). As a consequence, the 40 Eri system must be considered a good candidate for H0405−08. However, the large $L_x/L_{\rm opt}$ ratios for 40 Eri A and C (Table 1), and the high emission temperature, present a serious dilemma in assigning which component or combination of components in the system might be responsible for the detected emission. This question has been pursued in greater detail than space permits here by Cash *et al.* (1979).

A light curve (see Nugent and Garmire 1978) was constructed for this source using 1 day superpositions from day 230.6 to day 237.6 (of 1977). If the source is assumed to be at the position of 40 Eri, the light curve is variable and sharply peaked at day 233.6. Alternatively, if the source is assumed to be at the overlap box centroid, the apparent X-ray output is relatively constant during the several days of observation. Other possible candidates for H0405−08 include the F2 giant o^1 Eri (38 Eri) and the G6 giant 36 Eri, both of which lie just outside of the error box overlap region. However, the $L_x/L_{\rm opt}$ ratios for these giants would be an order of magnitude larger than that of the RS Canum Venaticorum system Capella, whereas neither of the stars has an active chromosphere, at least as measured by the Ca II K line index.

Finally, the brightest cool star in the error box overlap region is SAO 130984 (M type). $L_x/L_{\rm opt}$ would be of order 6×10^{-4} for this star, which is comparable to a flare star (see below). However, SAO 130984 is not known to be a prominent flare star.

2) H1021+20.—This source was detected within 1 day of the transit of the well-known UV Ceti–type flare star AD Leo. Since $L_x/L_{\rm opt} = 10^{-3}$ is comparable to that of the most active RS Canum Venaticorum–type systems, we suggest AD Leo as the source of the X-ray emission. A light curve constructed for this source from three 1 day superpositions (centered on days 326.6, 327.6, and 328.4 of 1977) is consistent with a steady X-ray output.

Other possible candidates within or near the derived error box include the bright binary $\gamma^{1,2}$ Leo (41 Leo; K0 III + G7 III) and the F6 subgiant 40 Leo. However, the $L_x/L_{\rm opt}$ ratios for these two systems would be comparable to or larger than that of Capella, whereas neither of the systems shows a particularly remarkable K index or λ10830 equivalent width. Finally, two bright galaxies, NGC 3226 and NGC 3227, lie near the center of the error box. However, neither of these galaxies appears to be particularly unusual.

3) H1712+54.—This is the softest of the detected sources. The overlap of the extreme error boxes lies near the position of the active chromosphere G2 giant β Dra. However, β Dra is sufficiently far from the centroid of H1712+54 that this bright giant is an unlikely candidate. The brightest object within the error box overlap is the μ Dra binary, which consists of a pair of F6 dwarfs. The $L_x/L_{\rm opt}$ ratio for this system,

TABLE 1

COUNT RATES, X-RAY MAGNITUDES, BROAD-BAND FLUX RATIOS, AND SOURCE CANDIDATES

Source	$C_{\text{sca'er 1}}$ (counts cm^{-2} s^{-1})	m_x	$C_{\text{sca'er 5}}/C_{\text{sca'er 1}}$	log T_x(K)	Possible Candidates	Spectral Type	m_{bol}	L_x/L_{opt}[a]
H0405−08....	$1.7\pm0.4\times10^{-2}$	15.1	0.5	6.6	o^1 Eri (38 Eri)	F2 III	4.0	4×10^{-5}
					o^2 Eri A (40 Eri A)	K1 V	4.3	5×10^{-5}
					DM−7.781B[b] (40 Eri C)	dM4e	9.7	7×10^{-3}
					SAO 130984	M	7	6×10^{-4}
H1021+20....	$2.7\pm0.4\times10^{-2}$	14.6	0.6	6.5	AD Leo[b,c]	dM3.5e	7.4	1×10^{-3}
					$\gamma^{1,2}$ Leo (41 Leo)	K0 III+G7 III	1.8	8×10^{-6}
					40 Leo	F6 IV	4.7	1×10^{-4}
H1712+54....	$6.5\pm0.9\times10^{-3}$	16.2	1.0	6.0	β Dra (23 Dra)	G2 II	2.9	5×10^{-6}
					μ Dra (21 Dra)	dF6+dF6	5.1	4×10^{-5}
H1834+54....	$1.8\pm0.3\times10^{-2}$	15.1	0.8	6.4	No candidates	...	...	...
H1837+52....	$2.1\pm0.3\times10^{-2}$	14.9	0.6	6.5	BY Dra[b,c]	dM0e	7.1	8×10^{-4}

[a] $(L_x/L_{\text{opt}})_\odot = 1 \times 10^{-6}$; $(L_x/L_{\text{opt}})_{\text{Capella}} = 6 \times 10^{-6}$; $(L_x/L_{\text{opt}})_{\odot\ \text{flare}} = 5 \times 10^{-2}$ (Vaiana and Rosner 1978).

[b] Flare stars (Kunkel 1975).

[c] Likely candidates.

4×10^{-5}, would be an order of magnitude larger than that of Capella. A light curve based on 1 day superpositions from day 229.6 to day 238.6, and assuming a source position coincident with μ Dra, produced a remarkably constant X-ray output in both scaler 1 and scaler 5. If μ Dra is indeed the source of soft X-rays, it would add support for a rotation-activity connection among late-type stars (Kraft 1967; Skumanich 1972), since F6 dwarfs are rapid rotators compared with G dwarfs like the Sun (see Allen 1973).

4) H1834+54, H1837+52.—This pair of partially blended sources appears close to the scan angle of the strong X-ray accretion source AM Her, but well after the latter's transit. One of the brightest late-type stars within the H1837+52 error box is the well-known "spotted" flare star BY Dra (Kunkel 1975). The L_x/L_{opt} ratio for BY Dra, 8×10^{-4}, would be comparable to that of AD Leo. We conclude that BY Dra is the most promising candidate for H1837+52.

However, we could not find any reasonable late-type stars as candidates for the companion source H1834+54.

Light curves constructed for both sources (days 284.7–295.0) exhibit day-to-day fluctuations, although the scaler 5/scaler 1 softness indices appear to be relatively steady.

III. DISCUSSION

The sources we have described above are weak ($m_x \approx 15$ mag). We were therefore unable to determine reliable source spectra. In addition, the source identifications are by no means certain, owing to the coarse spatial discrimination of the A-2 survey experiment. Nevertheless, we wish to make the following suggestions.

1) Out of the nearly 30 active cool stars in our sample, we detected soft X-ray sources near the positions of only four. For two of the detections, 40 Eri and β Dra, the initial target star is not coincident with the derived source position. We had expected to detect bright cool stars such as α Boo (K2 III) and α Tau (K5 III) if their L_x/L_{opt} ratios were comparable to those of the Sun and α Centauri. We also expected to detect very active dwarf stars such as ϵ Eri (K2 V) and 61 Cyg (K5 V + K7 V) if their L_x/L_{opt} ratios were 3×10^{-5} or larger. However, the bright giants and active dwarfs were not obvious sources in the 1 day superposition data. We conclude that K-type giants (outside of close binaries) probably have weak coronae compared with the Sun. This conclusion is in accord with the small $L_{\text{Mg II}}/L_{\text{opt}}$ ratios for K and cooler giants (Linsky and Ayres 1978) and the lack of high excitation emission lines in the *IUE* ultraviolet spectra of such stars (Linsky and Haisch 1979). The active chromosphere dwarfs probably have much brighter coronae than quiet stars such as the Sun and α Centauri, but the X-ray emission levels are apparently below the *HEAO 1* A-2 detection limits. However, the active dwarf stars should be detectable by *HEAO 2*, if their L_x/L_{opt} ratios are solar or larger.

2) Two, and possibly three, of the detections may be flare stars. From simultaneous observations of optical and X-ray flares on UV Ceti and YZ CMi, it has been estimated that stellar flares typically have L_x/L_{opt} ratios of order 0.05 (see, e.g., Haisch *et al.* 1977). Cristaldi and Rodono (1975) have shown that, on a time-averaged basis, flares provide roughly 10^{-3} of the optical luminosity of a typical flare star. Therefore, one might expect a time-averaged level of $L_x/L_{\text{opt}} \approx 5 \times 10^{-5}$ for flare stars, which increases to as much as 5×10^{-2} during major flare outbursts. The L_x/L_{opt} ratios we have estimated for the candidate flare stars, if they are indeed the sources of the detected X-rays, are of order 10^{-3}, which fits comfortably between the two extremes.

3) We have not yet found any evidence for the existence of stellar coronal sources that are quantitatively different from the range of coronal phenomena observed on the Sun (i.e., no $L_x/L_{\text{opt}} \gg 10^{-2}$). The lack of large L_x/L_{opt} ratios suggests that coronae in stars, as in the Sun, represent only a small perturbation on the overall stellar energy budget.

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