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A SENSITIVE SEARCH FOR SOFT X-RAYS FROM ARCTURUS AND PROCYON

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ABSTRACT

Sensitive soft X-ray observations have been obtained of α Boo and α CMi using rocket-borne large area proportional counters. No flux was detected from either star, yielding limits on intrinsic luminosity in the 75–2000 eV band (6–165 Å) as stringent as 10^{28} ergs s^{-1} depending upon assumed coronal temperature. These are at least an order of magnitude better limits than previously reported values. Upper limits are also set on a mass loss rate of 3×10^{-9} $M_\odot$ yr^{-1} and on an emission measure of less than 3×10^{53} cm^{-3}. If these stars are typical, then giants and subgiants cannot be responsible for a significant fraction of the soft component of the diffuse X-ray background.

Subject headings: coronae, stellar — mass loss — stellar winds — X-ray sources

I. INTRODUCTION

A growing body of observations and theoretical analysis points to the existence of extensive coronae around subgiant and giant stars. Statistical arguments, based on the lifetime and rate of hydrogen burning of stars in the red giant phase, have been advanced for an appreciable loss of mass after a star leaves the main sequence (Salpeter 1958; Weymann 1963). These suspicions were given weight by observations of doubly reversed Ca II H and K emission lines in M giant and supergiant spectra (Deutsch 1956; Weymann 1962), revealing the presence of a chromosphere, and particularly by observations of the H and K absorption cores in the spectrum of the visual companion to α^1 Her (Deutsch 1956), indicating an extensive corona. The mass loss rate from M giants has been estimated to increase from about $10^{-11} M_\odot$ yr^{-1} to $10^{-8} M_\odot$ yr^{-1} at M5 (Deutsch 1960). The violet-shift of the absorption core yields expansion velocities of 10–20 km s^{-1}, implying a corona far cooler than that of the Sun. Centrally reversed H and K lines have been observed in the more numerous G and K giants also (Liller 1968). The absorption cores are broad and shallow, and may be chromospheric, quite unlike the deep narrow cores in M giant spectra, which probably are produced by circumstellar absorption. Assuming the ejection velocity to be 10 km s^{-1} and the calcium to be singly ionized, Wilson (1960) placed an upper limit of $10^{-10} M_\odot$ yr^{-1} on the mass loss rate from K giants, based on the equivalent width of the M_3 and K_3 lines. However, this limit may be exceeded if the corona is hot enough to doubly ionize the calcium, as in the case of the Sun.

Although a clear picture of solar coronal heating mechanisms has not emerged yet, a number of processes have been studied. Two important heating agents appear to be acoustic waves emitted from the solar convective layer which develop into shock waves as they propagate outward, and magnetic field annihilation resulting from plasma instabilities above the solar surface. Considering only the former, a number of authors (Kuperus 1965; Ulmschneider 1967; De Loore 1970; Landini and Fossi 1973) have predicted the characteristics of the coronae of a variety of stars. Ulmschneider's (1967) predictions exclude active coronae for late supergiants and stars earlier than about B5 due to the absence of a convective layer, and predict maximum acoustic energy production and hence higher coronal temperatures and radiative flux, in a region extending from the F supergiants to G giants. Landini and Fossi's (1973) results eliminate stars earlier than about A5, and also predict a rise in coronal temperature and radiation flux as a star evolves off the main sequence. However, they eliminate the whole giant and supergiant region, in which it is claimed that acoustically energized coronae will not form, because acoustic energy will be dissipated totally in the chromosphere and appear directly as radiation. Landini and Fossi (1973) also predict the X-ray and radio luminosities of stellar coronae.

More recently, observations have been reported which set limits to the emission measure of selected subgiant and giant stars near the Sun. Margon *et al.* (1974) searched for soft X-ray emission from the K giants ϵ Sco, γ Dra, and α Boo, and from the K subgiant θ Cen. They placed limits of $6–26 \times 10^{31}$ ergs s^{-1} upon the soft X-ray luminosity and $2.7–9.0 \times 10^{-9}$ $M_\odot$ yr^{-1} upon the mass loss rate of any coronae around these stars. This sets a limit of between 10^{55} and 10^{56} cm^{-3} to their coronal emission measure (the emission measure for the quiet sun is $\sim 4 \times 10^{49}$ cm^{-3}). Similar observational limits on soft X-ray emission from giants and subgiants have been given by Vanderhill *et al.* (1975). Recently Mewe *et al.* (1975) have reported more stringent upper limits on objects of this class; their level of sensitivity is similar to that reported here.

More stringent limits upon the emission measure of

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the coronae of nearby stars have been established by analysis of the chromospheric Ca II (λλ3934, 3968) and Mg II (λλ2796, 2803) line profiles in spectra of the F5 subgiant α CMi (Ayres *et al.* 1974), and the K giants β Gem (K0), α Boo (K2) and α Tau (K5) (McClintock *et al.* 1975; Ayres and Linsky 1975). The upper limits fall in the range 10^{49}–10^{52} cm^{-3}. In the case of β Gem a spectral feature was found between 1218 and 1219 Å and identified with the O V λ1218.4 line (Gerola *et al.* 1974). The intensity was found to be too great for the line to originate in the chromosphere-corona transition region, under the restrictions imposed by analyses of the Ca and Mg resonance lines, but was explained satisfactorily if the line were assumed to be coronal. The best match of the emission measures obtained from the chromospheric lines and the coronal 1218.4 Å line was obtained for a coronal temperature of 260,000 K.

This *Letter* describes attempts to detect soft X-ray emission from α Boo and α CMi, using a detector of substantially greater sensitivity than previous observations. Neither star was detected as an X-ray source. We have used the results to improve significantly the luminosity and mass loss-rate limits set by Margon *et al.* (1974) for α Boo, and to establish limits for α CMi. The values obtained for α Boo set an upper bound of about 5 percent to the contribution of red giant coronae to the diffuse soft X-ray background (Hills 1973). Upper limits have been obtained also for the emission measures of coronae around α Boo and α CMi.

II. OBSERVATIONS AND DISCUSSION

The results to be described were obtained by a propane-filled, soft X-ray proportional counter equipped with a thin (0.8 μ) polypropylene window. The instrument was launched twice by Black Brant VC rockets from White Sands Missile Range, at 5^h15^m UT on 1974 June 15, and at 8^h10^m UT on 1974 November 25. The detector was equipped with two circular fields of view 3° (FWHM) in diameter and offset from each other by 5°. During the first flight one of these fields, having an effective area of 260 cm^2, was pointed steadily at α Boo for 20 s, and during the second flight it was pointed at α CMi for 10 s. The efficiencies of the detector at 44, 68 and 115 Å were respectively 0.71, 0.61, and 0.22 on the first flight, and 0.78, 0.56, and 0.13 on the second flight.

We consider only data obtained above an altitude of 150 km, so that absorption of long-wavelength X-rays was small (<10 percent at 100 Å). Comparison of the average count rates with count rates measured immediately preceding and following the observations yielded no significant difference attributable to α Boo or α CMi. The 3 σ upper limits for count rates produced by these stars were:

α Boo: 4.4 cts s^{-1} (75–300 eV);
5.6 cts s^{-1} (75–2000 eV).
α CMi: 13.1 cts s^{-1} (75–300 eV);
15.5 cts s^{-1} (75–2000 eV).

The weaker limits for α CMi are due to the enhanced intensity of the soft component of the diffuse X-ray background in this region, which has been noted by several observers.

The detector count rate produced by a stellar corona is given approximately by

$$\int n_e^2 dV \int \epsilon(\lambda, T) t_{\rm ISM}(\lambda) t_{\rm ATM}(\lambda) \eta_{\rm DET}(\lambda) d\lambda \,, \quad (1)$$

where $\int n_e^2 dV$ is the emission measure of the corona, $t_{\rm ISM}(\lambda)$ and $t_{\rm ATM}(\lambda)$ give the transmission of the interstellar medium and atmosphere respectively, $\eta_{\rm DET}(\lambda)$ is the detector efficiency, and $\epsilon(\lambda, T)$ is the plasma emissivity. Upper limits for the emission measure, mass loss rate, and X-ray luminosity may be derived if assumptions are made regarding the emissivity of the coronal plasma and the opacity of the interstellar medium. The line contribution to the emissivity has been obtained from Mewe's calculations (1972, 1975), which assume solar abundances of the elements and cover the temperature range 1×10^5 to 1×10^8 K, and the wavelength band 1.46–220 Å. The additional contribution from continuum radiation (free-bound and free-free), which is small compared to the line contribution, has been obtained between 10^6 and 10^7 K from Landini and Fossi's (1970) calculations, and between 10^5 and 10^6 K by multiplying the bremsstrahlung flux by a factor 10. Table 3 of the paper by Tucker and Koren (1971) suggests that this factor yields a reasonable lower limit for the wavelength range 44–140 Å.

The distances of α Boo and α CMi have been taken as 11.1 pc (Hoffleit 1964) and 3.5 pc (Jenkins 1963), respectively. The transmission of the Earth's atmosphere has been calculated as a function of wavelength for the zenith angle and mean altitude of the appropriate observation. We have assumed a mean density of 0.1 cm^{-3} for the interstellar medium in the vicinity of the Sun. This is not a critical assumption for such nearby stars, and is based on estimates of interstellar Lα absorption in the spectra of these objects (Moos *et al.* 1974; Evans *et al.* 1975) and on a review of observational evidence bearing on the opacity of the local interstellar medium (Cruddace *et al.* 1974). The Lα observations permit values as low as 0.01 cm^{-3}. The greatest effect of such a density upon our calculations, in an extreme case, would be to raise the estimated detector count-rate by 30 percent.

In Figure 1 we show the upper limits which we have established for the emission measures of coronae around α Boo and α CMi. The lines join points calculated using equation (1) and our 3 σ limits for the soft X-ray count rate. The dotted lines are the values obtained from analyses of Ca and Mg resonance lines in the spectra of α Boo (Ayres and Linsky 1975) and α CMi (Ayres *et al.* 1974), which yield the pressure p at the chromosphere-corona transition region. This is related to the emission measure by an expression of the form

$$\int n_e^2 dV \approx n_e^2 \times 4\pi R_*^2 H = \pi \frac{p^2}{g} \frac{R_*^2}{m_H k T} \,,$$

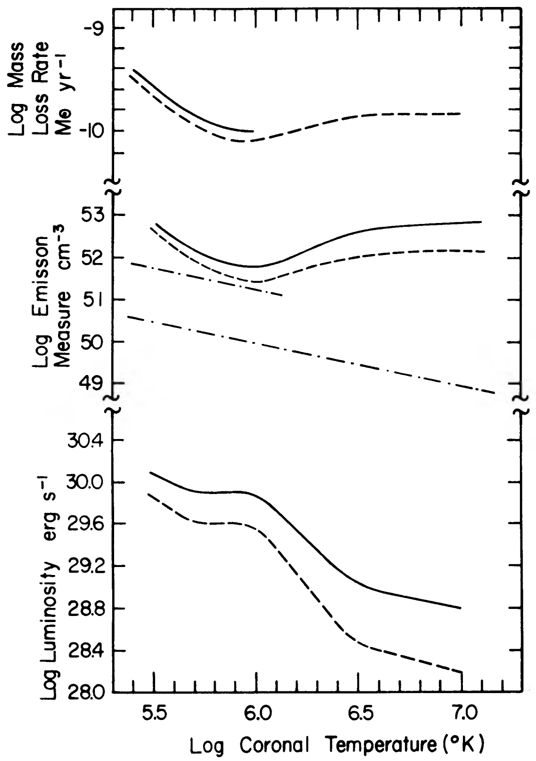

FIG. 1.—Upper limits on soft X-ray luminosity (75–2000 eV), coronal emission measure, and mass loss rate for α Boo (*solid lines*) and α CMi (*broken lines*). The dotted lines in the center panel are values obtained from analysis of Ca and Mg resonance lines (Ayres and Linsky 1975; Ayres *et al.* 1974).

where $H = kT/m_{\rm H}g$ is the coronal scale height, g is the gravitational acceleration, R_* is the stellar radius, $m_{\rm H}$ is the proton mass, and T is the temperature. This approximation assumes that the scale height is small compared to R_*, and in the case of giant stars becomes unreasonable for temperatures above 10^6 K. Our limits lie slightly above the values allowed by the chromospheric resonance lines.

We have set limits to the mass loss rate, $\dot{m}$, using the following approximation:

$$\int n_e^2 dV \approx \dot{m}^2 H/(4\pi R_*^2 m_H^2 V^2) \ ,$$

where we have assumed an upper limit of $(kT/m_{\rm H})^{1/2}$ for the radial flow velocity. The latter is a safe assumption, as the major contribution to $\int n_e^2\, dV$ is at the base of the corona, where densities are high and radial flow velocities subsonic. The upper limits for $\dot{m}$ are also shown in Figure 1. The limits for α Boo are significantly lower than those established by Margon *et al.* (1974), and are similar to the limit of $10^{-10}\ M_\odot\ {\rm yr}^{-1}$ established by Wilson (1960) on the assumption that G and K giant coronae possess cool, low-velocity flows like the M giants. There is yet no evidence that G and K giants, which constitute the bulk of the giant population, lose a substantial fraction of their mass by means of a steady coronal outflow.

Upper limits to the soft X-ray (70–300 eV) luminosity of α Boo and α CMi have been obtained by integrating with respect to wavelength the product of the plasma emissivity and the emission measure upper limit. The results are also given in Figure 1 as functions of the assumed coronal temperature. The upper limit for α Boo, $\sim 10^{30}$ ergs s^{-1}, is about 50 times less than the limit set by Margon *et al.* (1974), and about an order of magnitude less than the luminosity required by Hills's (1973) model of the soft X-ray background, in which the diffuse flux is attributed to red giant coronae. If α Boo is a typical red giant, then such coronae contribute no more than about 5 photons cm^{-2} s^{-1} keV^{-1} to the diffuse background. This calculation assumes a space density of 6×10^{-4} pc^{-3} (Allen 1973).

For an F5 subgiant, Landini and Fossi (1973) predict a coronal temperature of about 2×10^6 K and a luminosity of 2×10^{30} ergs s^{-1} in the 200–280 eV energy band. After making a correction for the different energy band used by our detector, we find our upper limit for the soft X-ray luminosity of α CMi to be 70 times less than the predicted value.

Zirin (1975) has recently suggested that the soft X-ray flux of nearby stars may be computed by scaling the He I λ10830 equivalent widths and stellar surface areas against solar values. If we adopt for Procyon $R_* = 2.2\ R_\odot$ (Hanbury Brown *et al.* 1967) and EW (λ10830) = 160 mÅ (Vaughan and Zirin 1968), we find the soft X-ray flux of α CMi should exceed the solar value by a factor of 80. In our bandpass the solar flux is of order 0.3 ergs cm^{-2} s^{-1} at Earth (e.g., Malinovsky and Heroux 1973), indicating an expected soft X-ray luminosity of α CMi of about 7×10^{28} ergs s^{-1}. Our data already eliminate this possibility for a large range of coronal temperatures (cf. Fig. 1).

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