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THE X-RAY SPECTRUM OF A METAL-POOR CORONA

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ABSTRACT

We present an ASCA SIS spectrum of the Population II binary star HD 89499. This is the most metal poor star ([Fe/H] = −2.1) known to have a corona. The *ASCA* data confirm initial results from *ROSAT* which suggested a very hot, single-component plasma temperature, with the temperature derived from the *ASCA* data being slightly higher (2.6×10^7 K) than the one determined by *ROSAT*. The *ASCA* spectrum clearly shows the absence of emission lines and can be best modeled as thermal bremsstrahlung, although strong absorption at photon energies less than 0.5 keV is indicated. We suggest that such an extremely high coronal temperature results from the lack of an efficient cooling mechanism due to the absence of metallic (mostly Fe) emission lines.

Subject headings: stars: coronae — stars: Population II — X-rays: stars

1. INTRODUCTION

According to the currently accepted paradigm for stellar activity, where chromospheres and coronae are heated by magnetic fields generated via dynamos whose efficiencies are a function of stellar rotation, coronal X-ray emission should decrease with age as the star undergoes magnetic braking (see the reviews by Pallavicini 1989; Rosner, Golub, & Vaiana 1985). Given this, it should be quite difficult to detect coronal X-ray emission from metal-poor, Population II stars because of their extreme age. However, it has been shown that activity timescales can be lengthened for stars which are in close binary systems, e.g., the BY Dra binaries (Young, Sadjadi, & Harlan 1987), the RS CVn binaries (Dempsey et al. 1993a), or the active binary stars detected in the old open cluster M67 with *ROSAT* (Belloni, Verbunt, & Schmitt 1993). In these cases, synchronous rotation allows for the transfer of orbital angular momentum to rotational angular momentum of the components, which prevents them from spinning down. So if one were looking to study a metal-poor (Population II) corona, one would stand a better chance of finding one among Population II close binary systems.

Radial velocity studies have been undertaken to find close binaries among known Population II stars (e.g., Carney & Latham 1987). Pasquini et al. (1991) were the first to show evidence of strong chromospheric and coronal activity in a few of these old binaries. The detection of 14 Population II binaries at X-ray wavelengths during the *ROSAT* all-sky survey (RASS; Ottmann, Fleming, & Pasquini 1996) confirms the fact that orbitally-enforced rotation can extend activity timescales to the age of halo stars and that Population II stars can indeed possess active coronae. These stars, therefore, make excellent laboratories for studying the effect of metallicity on coronal plasmas.

With this in mind, we chose the most extreme case for further observation. Of the 14 Population II binaries which were detected in the RASS, HD 89499 is the most metal-poor ([Fe/H] = −2.1; Spite, Pasquini, & Spite 1994). In fact it is the most metal-poor star known to have a corona. The spectral type of the primary is G3 VI with an effective temperature of 4850 K, it has space motions consistent with it being a member of the halo, and its orbital period is 5.6 days (Ardeberg & Lindgren 1991).

There is much ambiguity, however, over the distance to HD 89499. Three trigonometric parallaxes have been published for this star: $\pi = 0\farcs019 \pm 0\farcs013$ (52.6 pc; Jenkins 1952); $\pi = 0\farcs057 \pm 0\farcs013$ (17.5 pc; Gliese & Jahreiß 1991; Gliese 1969); and $\pi = 0\farcs025 \pm 0\farcs015$ (40 pc; van Altena, Lee, & Hoffleit 1996). Distances to HD 89499 have also been estimated using the spectroscopic parallax (45 pc; Hartmann & Gehren 1988) and photometric parallax (51–61 pc; Allen, Schuster, & Poveda 1991) methods. But photospheric line profile fits by Spite et al. (1994) indicate a much lower gravity ($\log g = 2.0$) than was found in previous studies. Their model results suggest a synthetic spectral type of K0 IV for HD 89499, which would place it more like 150–200 pc away. Given the poor quality of the trigonometric parallaxes, we tend to doubt their validity. The question of distance to HD 89499 will be discussed further in the next section, where the results of our X-ray data analysis support the larger distance to HD 89499.

In this Letter, we report the results of our observations of HD 89499 made with the *ROSAT* and *ASCA* satellites to follow-up the original RASS detection. Table 1 shows the basic X-ray data. The next two sections describe the *ROSAT* and *ASCA* observations and our attempts to fit spectral models to the two data sets simultaneously. Finally, we discuss the resulting spectrum of a metal-poor corona and attempt to interpret it.

2. *ROSAT* PSPC DATA

HD 89499 was observed in early 1992 March by *ROSAT* using the Position Sensitive Proportional Counter (PSPC; Pfeffermann et al. 1986) for a total exposure time of 4340 s. This observation was intended to achieve a higher SNR detection than that of the RASS. The count rate (0.233 ± 0.007 counts s^{-1}) was close to that measured in the

TABLE 1

BASIC X-RAY DATA ON HD 89499

Data	Sequence Number	Observation Date	Exposure (s)	Count Rate (count s^{-1})	HR	f_X (0.5–2.0 keV) (10^{-12} erg s^{-1} cm^{-2})
ROSAT Survey[a]	...	1990 Sep	391	0.181 ± 0.030	0.79 ± 0.10	1.72 ± 0.28
ROSAT PSPC	WG 200594	1992 Mar 1–9	4340	0.233 ± 0.007	0.55 ± 0.03	2.07 ± 0.06
ASCA SIS0	23032000	1995 Apr 4–5	30410	0.211 ± 0.003	[b]	2.96 ± 0.03
ASCA SIS1	23032000	1995 Apr 4–5	30410	0.162 ± 0.003	[b]	2.96 ± 0.03

[a] Ottmann et al. 1996.
[b] HR is not defined for *ASCA* data.

RASS and the hardness ratio of 0.55 confirmed that this star indeed had a very hard X-ray spectrum.

The PSPC pulse-height spectrum of HD 89499 is shown in Figure 1. Compared to the pulse-height spectra of other active stars (e.g., the RS CVn binaries, Dempsey et al. 1993b; dMe stars, Giampapa et al. 1996), this one looks quite different. A typical PSPC pulse-height spectrum for an active star has twice as many counts below the carbon edge (at 0.28 keV) as above, but the pulse-height spectrum for for HD 89499 has more than 3 times the number of counts above than below the carbon edge. This is indicative of an unusually hot coronal plasma and/or heavy absorption. The pulse-height spectrum is best fit with a thermal bremsstrahlung model of temperature 1.5×10^7 K and an interstellar H absorption component with a column density of 3.5×10^{20} cm^{-2}.

It is puzzling why the X-ray spectrum of HD 89499 should be so heavily absorbed, especially if the star is indeed nearby (<50 pc). The total amount of Galactic interstellar H column density in the direction of HD 89499 is 8.85×10^{20} cm^{-2} (Dickey & Lockman 1990). If we assume a scaleheight of 250 pc for H in the disk and that it is distributed uniformly (which, of course, it is not) and taking the Galactic latitude of HD 89499 ($b^{II} = -23\overset{\circ}{.}3$), then most of the interstellar H along this line of sight is distributed over a distance of 630 pc. If HD 89499 is, say, 200 pc away, then the interstellar column to the star would be roughly 2.8×10^{20} cm^{-2}, while at 50 pc it would be roughly 7.0×10^{19} cm^{-2}. The interstellar H maps of Frisch & York (1983) also indicate that column densities greater than 10^{20} cm^{-2} are rarely found within 50 pc. Furthermore, HD 89499 was detected by the *IRAS* survey in the 2.2 μm band only, thus providing no evidence for an infrared excess or possible circumstellar dust shell. We must, therefore, conclude that it is plausible for the amount of absorption measured by *ROSAT* to be interstellar in origin if HD 89499 is about 200 pc away and that, unless another origin for this absorption can be found, a distance of around 50 pc or less is highly unlikely.

In any event, the results of the PSPC observation were curious enough to warrant further X-ray observation at a higher spectral resolution. We, therefore, proposed to observe HD 89499 with *ASCA*.

3. *ASCA* SIS DATA

HD 89499 was observed in early 1995 April by the *Advanced Satellite for Cosmology and Astrophysics* (*ASCA*; Tanaka, Inoue, & Holt 1994) with both Solid State and Gas Imaging Spectrometers (SIS0, SIS1, GIS2, and GIS3, respectively). We concentrate on the SIS data since one can obtain higher spectral resolution ($\Delta E/E = 0.06$ at 1 keV) with the SIS. This is 7 times higher than the resolution achieved with the *ROSAT* PSPC ($\Delta E/E = 0.42$ at 1 keV). The star was observed for a total of 30,410 s and was detected at a count rate of 0.211 counts s^{-1} with SIS0 and 0.162 counts s^{-1} with SIS1 (see Fig. 1*b*). This yields a combined spectrum containing 11,300 counts. Although the SIS is sensitive from 0.3 to 10 keV, all of the photons from HD 89499 fall below 5 keV.

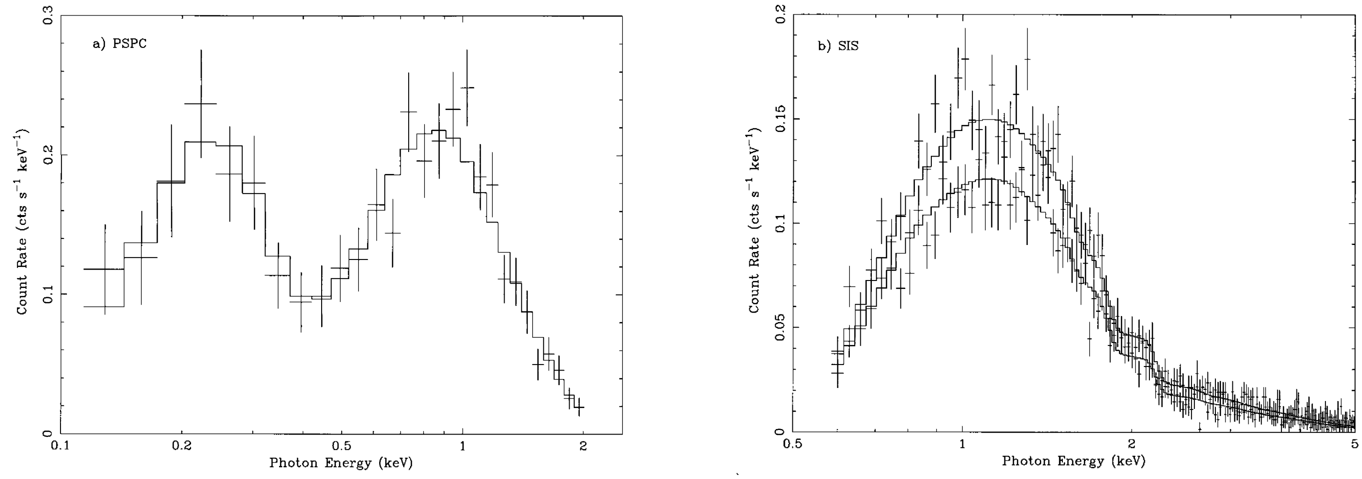
With the spectral resolution of the SIS, it is possible to partially resolve coronal emission lines of elements like Fe, Si, and Mg (see Singh, White, & Drake 1996; Drake et al. 1994). But such emission lines are notably absent from the SIS spectrum of HD 89499.

As was the case for the PSPC spectrum, the *ASCA* spectra[1] were best-fitted with a one-component, thermal bremsstrahlung model. The results are summarized in Table 2. Due to the currently poor calibration of the SIS detector response matrix below photon energies of 0.55 keV, we have chosen to exclude all energy channels less than 0.6 keV from our analysis. As can be seen from Table 2, the *ASCA* data indicate a higher coronal temperature than the *ROSAT* data but, like the *ROSAT* data, it too appears to be absorbed. Finally, we fitted both the *ROSAT* and *ASCA* spectra simultaneously for the most accurate results. Since the total X-ray flux appears to have increased by about 50% between the *ROSAT* and *ASCA* observations (see Table 1), we allowed separate normalizations for the PSPC and SIS data. The ratio between these two normalizations for the best fit was the same as the ratio between to two flux values (1.43). The harder spectral response of the *ASCA* spectrum allows us to constrain the high coronal temperature of HD 89499 more accurately, while the softer spectral response of the *ROSAT* PSPC gives us a more reliable value for the absorption.

We also fit Raymond-Smith and Mewe-Gronenschild plasma models to the *ASCA* + PSPC spectra and allowed the metallicity parameter, i.e., the relative abundance of elements heavier than He scaled to the Fe abundance relative to Solar values, to vary. For both models the metallicity parameter went to zero, in which case these models reduce to thermal bremsstrahlung. In order to quantify this result, we show in Figure 2 a confidence contour plot of T_c versus Abundance for the Raymond-Smith fit. For the best-fit coronal temperature, the abundance is 0.0 + 0.03 or, in other words, the metallicity of the corona is less than 3% of the solar metallicity value to 1 σ accuracy.

Thus, we obtain a single-component coronal temperature of 2.6×10^7 K for HD 89499. Such hot ($>2 \times 10^7$ K) coronal temperatures which have been measured in other active stars are always the hotter of two temperatures in a two-component fit (e.g., Swank et al. 1981; Schmitt et al. 1990; Dempsey et al. 1993b; see discussion below), and are usually more variable in nature than the "cool" components. However, the "cool"

[1] The SIS0 and SIS1 spectra were fitted simultaneously rather than being co-added since the two detectors have different response matrices.



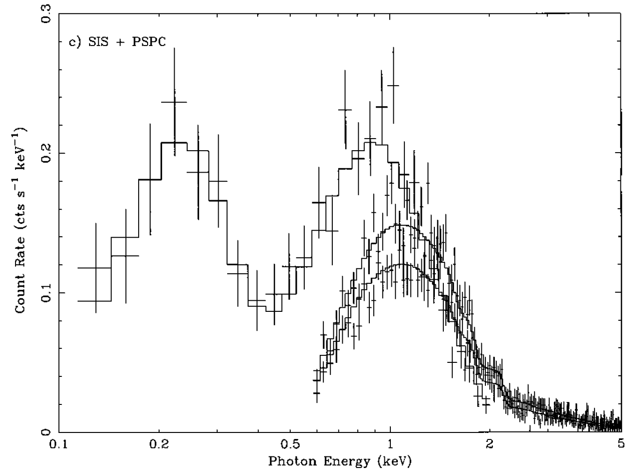


FIG. 1.—X-ray spectrum of HD 89499: (*a*) the *ROSAT* PSPC pulse-height distribution; (*b*) the *ASCA* SIS0 and SIS1 spectra; and (*c*) the *ROSAT* and *ASCA* data combined. The solid lines represent the best-fit model parameters as given in Table 2 for each data set.

component is always present in these other active stars; furthermore, in moderately active and inactive stars, it is only the "cool" component that is evident (Giampapa et al. 1996). Thus, its apparent absence from the corona of HD 89499 would make this star quite unique among stellar coronae.

However, given that the HD 89499 spectrum is heavily absorbed, is it possible that the star does indeed possess a "cool" component in its corona whose soft X-ray emission is mostly absorbed by (presumably) the interstellar medium? To answer this question, we have added a "cool" component to the best-fit bremstrahlung model. In our initial analysis, we did begin with two-component models; but for the minimum value of χ^2, the emission measure (EM) of the lower temperature component always went to zero. This time, we held the best-fit values of $N_{\rm H}$, T_c(hot), and EM(hot) fixed and evaluated χ^2 for a grid of T_c(cool) and EM(cool) values in order to estimate probabilities for the existence of a "cool" component. The resulting confidence contours are plotted in Figure 3 which, in essence, give upper limits on EM as a function of T_c for a possible "cool" coronal component.

The results of this analysis show that, for $T_c > 3 \times 10^6$ K, the 90%-confidence upper limit on EM(cool) is 1/7 the value of EM(hot). For plasma cooler than 3×10^6 K, the problem is not well constrained by our PSPC + SIS data. By comparison, the results of spectral analyses of the coronae of a large sample of RS CVn binaries made by Dempsey et al. (1993b) show that T_c(cool) $< 3 \times 10^6$ K for almost all of the stars studied and EM(hot) is typically 5–10 times larger than EM(cool). This would suggest that we can not rule out the existence of a "cool" component in the corona of HD 89499.

4. DISCUSSION

Previously published *ASCA* spectra of active stellar coronae (Singh et al. 1996; Drake et al. 1994; White et al. 1994) indicate that the corona is underabundant in metals with respect to the photosphere. Should this be generally true then, with a photospheric metallicity of [Fe/H] = −2.1, the corona of HD 89499 should be severely lacking in metals. This appears to be the case as evidenced by the complete absence of emission lines of elements such as Fe, Mg, Si, etc., from the X-ray spectrum of HD 89499. Its coronal emission is described simply by thermal bremsstrahlung.

However, the dominant temperature of this corona is higher than normal. Most active stars rarely exhibit coronal temperatures above 2×10^7 K. When they do, it is the hot temperature in a two-component model fit which is sometimes variable or of low filling factor (see Schmitt et al. 1990; Dempsey et al. 1993b; Giampapa et al. 1996). In the previous section, we concluded that it was possible for the corona of HD 89499 to

TABLE 2

BEST MODEL FIT PARAMETERS

Data Fit	$N_{\rm H}$ (cm^{-2})	T_c (K)	EM (cm^{-3})	χ^2_ν
PSPC only	$3.5 \times 10^{20} \pm 3.2 \times 10^{19}$	$1.5 \times 10^7 \pm 2.5 \times 10^6$	$1.8 \times 10^{53}(d/50\ {\rm pc})^2$	0.71
SIS only	$6.1 \times 10^{20} \pm 1.1 \times 10^{20}$	$2.4 \times 10^7 \pm 9.5 \times 10^5$	$2.2 \times 10^{53}(d/50\ {\rm pc})^2$	0.92
SIS + PSPC	$2.9 \times 10^{20} \pm 1.9 \times 10^{19}$	$2.6 \times 10^7 \pm 7.5 \times 10^5$	$2.0 \times 10^{53}(d/50\ {\rm pc})^2$	0.94

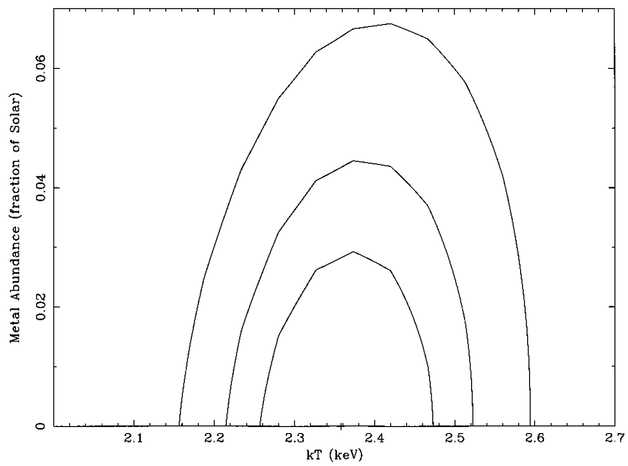


FIG. 2.—Confidence contours for coronal temperature and metal abundance which were obtained when fitting a Raymond-Smith plasma model to the combined PSPC + SIS spectra. The best-fit (i.e., minimum χ^2) values are indicated by the cross. The successive contours correspond to probabilities of 68%, 90%, and 99%.

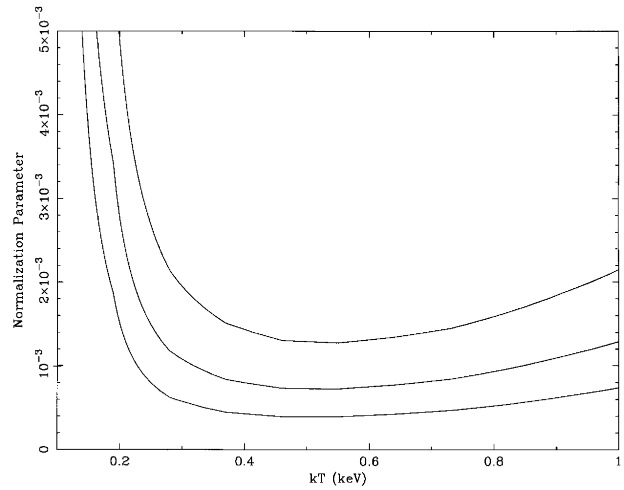


FIG. 3.—Confidence contours for coronal temperature and a normalization parameter which is linearly proportional to the emission measure of a second, "cool-temperature" component to the bremsstrahlung model. The contours are, in essence, 68%, 90%, and 99% (*bottom to top*) confidence upper limits on the emission measure of any cooler plasma that may exist in the corona of HD 89499. The value of the normalization parameter for the hotter plasma component that was fitted to the data is 6.44×10^{-3}.

have a hidden "cool" component. However, we must also point out that this conclusion is based on analogy to Population I RS CVn binaries whose photospheres and coronae are much more metal-rich than HD 89499. It could be unreasonable to assume the existence of a $1\text{–}2 \times 10^6$ K plasma in a completely metal-depleted corona.

And as for the "hot" (2.6×10^7 K) plasma, it does appear to have varied in emission flux at the 50% level, although one must caution against comparing flux measurements from separate detectors covering different wavelength bands. Please note that the errors in f_X listed in Table 1 reflect statistical errors only and not any systematic errors, e.g., a larger error in the RASS flux due to the fact that it was calculated using a conversion factor (see Fleming et al. 1995) instead of integrating the best model fit to the PSPC and SIS spectra. However, we still find no evidence for strong flarelike activity among the various X-ray data (i.e., clear variability on timescales of minutes to hours).

Therefore, it seems that the X-ray emission which we detect is coming from a relatively stable, quiescent plasma. Such a quiescent plasma in stellar coronae is usually a few million degrees (see Giampapa et al. 1996) while hotter plasma tends to be highly variable and exhibit flares. But given the lack of coronal emission lines in a metal-poor corona, the efficiency with which the corona can release energy (i.e., cool) is severely decreased, which would lead to higher temperatures for the stable, quiescent plasma.

Quantitative attempts to model coronal plasmas usually involve static loop models (see, e.g., Rosner, Tucker, & Vaiana 1978; Stern, Antiochos, & Harnden 1986) where the plasma heating rate, ϵ, must balance the radiative loss function, $\Lambda(T)$. Cook et al. (1989) have computed the contributions of individual elements to $\Lambda(T)$. At temperatures below 10^7 K, line emission dominates $\Lambda(T)$; even at 10^7 K, Fe line emission accounts for 60% of the total radiative losses. Thus, in the absence of line emission, $\Lambda(T)$, which is proportional to $T^{1/2}$ in the case of pure bremsstrahlung, is substantially less. So T must increase in order for $\Lambda(T)$ to balance ϵ. Therefore, the coronal temperature which we measure for HD 89499 is reasonable and could very well represent quiescent coronal plasma.

In summary, we have presented the X-ray spectrum of a stellar corona that is devoid of metals and shown that it is best-fitted by a single-component, thermal bremsstrahlung model at a temperature of 2.6×10^7 K. Such a coronal configuration is unusual and much hotter than most metal-rich coronae. It is also evident that the phenomenon of stellar activity can last on timescales approaching the age of the Galactic halo (upward of 12 billion years) for RS CVn-like binaries.

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