THE ASTROPHYSICAL JOURNAL, 436:L87–L90, 1994 November 20

ASCA X-RAY SPECTRA OF THE ACTIVE SINGLE STARS β CETI AND π^1 URSAE MAJORIS

S. A. DRAKE,[1,2] K. P. SINGH,[1,3] N. E. WHITE,[1] AND THEODORE SIMON[4]
Received 1994 June 3; accepted 1994 August 26

ABSTRACT

We present X-ray spectra obtained by *ASCA* of two single, active stars, the G dwarf π^1 UMa, and the G9/K0 giant β Cet. The spectra of both stars require the presence of at least two plasma components with different temperatures, 0.3–0.4 keV and ~0.7 keV, in order for acceptable fits to be obtained. The spectral resolving power and signal-to-noise ratio of the SIS spectra allow us to formally constrain the coronal abundances of a number of elements. In β Cet, we find Mg to be overabundant, while other elements such as O, Ne, and N are underabundant, relative to the solar photospheric values. From the lower signal-to-noise ratio SIS spectrum of π^1 UMa, we find evidence for underabundances of O, Ne, and Fe. These results are discussed in the context of the present understanding of elemental abundances in solar and stellar coronae.

Subject headings: stars: abundances — stars: coronae — stars: individual (π^1 Ursae Majoris, β Ceti) — X-rays: stars

1. INTRODUCTION

Previous X-ray spectral observations of coronal stars with the *Einstein*, *EXOSAT*, and *ROSAT* satellites have concentrated on the most X-ray luminous (log $L_X \sim 31.0$) nearby late-type stars (F–G–K) in close binary systems (RS CVn–type or Algol-type). The coronal activity in these systems is believed to be enhanced because the tidally induced rapid rotation of the two stars causes increased dynamo activity. No high-quality X-ray spectra with adequate signal-to-noise ratio of single G-type stars having log $L_X \sim 27.0$–30.0 were obtained with either the *Einstein* Solid State Spectrometer (SSS) or the *EXOSAT* Transmission Grating Spectrometer. With the launch of *ASCA* and its large-area X-ray telescopes, it is possible for the first time to perform moderate-resolution ($E/\Delta E \sim 15$–50) spectroscopy in the 0.5–10 keV range on *single* coronal-type stars (albeit stars that are still more active than the Sun at solar maximum) and to explore the temperature structure and patterns of elemental abundances in their coronae. With this purpose in mind, we observed π^1 UMa (G1.5 Vb; distance $D = 13.8$ pc) and β Cet (G9.5 III; $D = 18.3$ pc) with *ASCA*. These stars are among *the more active* single G-type stars in the solar neighborhood: log $L_X = 28.9$ for π^1 UMa (Schmitt et al. 1990b), compared to an average value of 27.4 for nearby late F and G dwarfs (Maggio et al. 1987), while log $L_X = 29.8$ for β Cet (Schmitt et al. 1990a), compared to an average value of 28.7 for single G giants (Maggio et al. 1990). We present here preliminary results from our *ASCA* observations.

2. OBSERVATIONS

The observation of β Cet was made on 1993 December 1/2 while π^1 UMa was observed on 1993 November 13/14. The *ASCA* observatory (Tanaka et al. 1994), contains four imaging thin-foil grazing incidence X-ray telescopes, two of which are equipped with solid state imaging spectrometers (SIS) and the other two with gas imaging spectrometers (GIS). In this *Letter*, we present the analysis of the data obtained by the SIS0 spectrometer; analysis of the data from the other *ASCA* detectors, however, yields results that are consistent within the uncertainties with those obtained using SIS0. Each SIS consists of four CCD chips; for these observations the SIS cameras were operated in the 2-CCD mode with a resultant field of view of 22.'2 × 11.'2. The energy resolution of both SIS cameras is energy dependent and about 2% (FWHM) at 5.9 keV, degrading to 6% at 1.0 keV. Since the SIS is sensitive to light leakage, the "good" data were selected by requiring a telescope viewing direction of >25° from the bright Earth limb or >10° from the dark Earth limb. These selections resulted in useful SIS exposure times of ~18,800 s and ~29,300 s for β Cet and π^1 UMa, respectively. Hot and flickering pixels in the CCDs were eliminated using the technique recommended by the *ASCA* Project (Day et al. 1994). The counts and pulse height spectra were accumulated from a source region of 4′ radius, while the background was taken from source-free regions. Typical SIS count rates were 0.8 counts s^{-1} for β Cet, and 0.1 counts s^{-1} for π^1 UMa.

3. ANALYSIS AND RESULTS

The X-ray flux observed by *ASCA* in the energy range of 0.4–2.4 keV was $(1.80 \pm 0.02) \times 10^{-11}$ ergs cm^{-2} s^{-1} for β Cet and $(2.43 \pm 0.06) \times 10^{-12}$ ergs cm^{-2} s^{-1} for π^1 UMa. No significant time variations were detected during the *ASCA* observation of either star. The corresponding X-ray luminosities are log $L_X = 29.86$ for β Cet and log $L_X = 28.74$ for π^1 UMa, respectively. A comparison of these values with previous X-ray measurements in the same approximate bandwidth (e.g., Ayres et al. 1994; Schmitt et al. 1990a) implies that neither star was flaring during the *ASCA* observations. The X-ray spectra for β Cet and π^1 UMa from the SIS0 detector are shown in Figures 1 and 2, respectively. Several features are clearly visible: e.g., the line near 1.84 keV in the spectrum of β Cet due to Si XIII, the line at 1.35 keV in the π^1 UMa spectrum due to

[1] Code 668, Laboratory for High Energy Astrophysics, NASA/GSFC, Greenbelt, MD 20771.
[2] Also USRA, Code 610.3, NASA/GSFC.
[3] NRC-NASA Senior Research Associate, on leave from Tata Institute of Fundamental Research, Bombay, India.
[4] Institute for Astronomy, University of Hawaii, Honolulu, HI 96822.

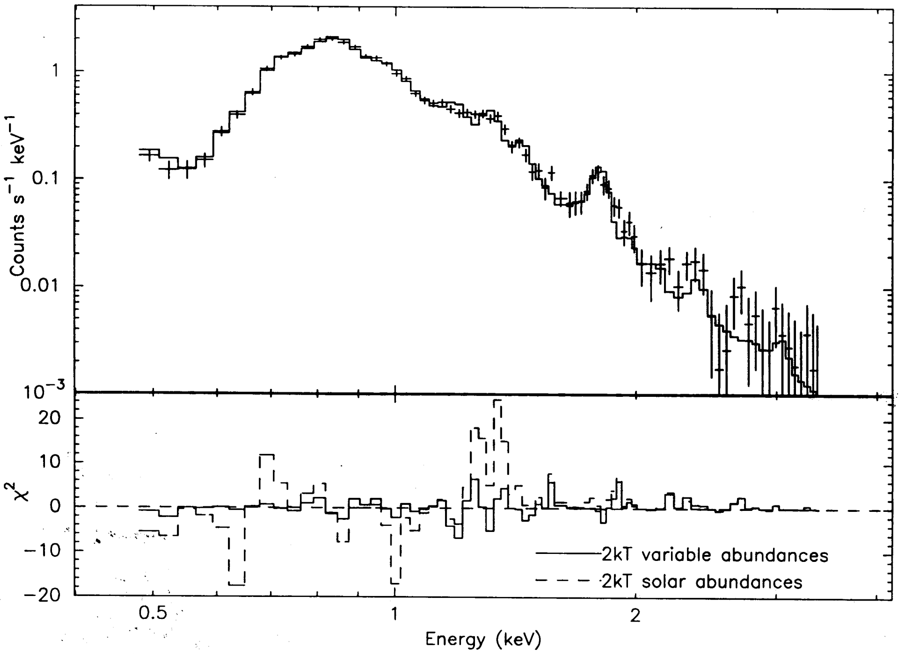

FIG. 1.—X-ray spectrum of β Cet as observed with the SIS0 detector aboard the *ASCA* satellite is shown in the top panel. The best-fit "MEKA" two-component plasma emission model folded through the detector response is shown as a histogram. The bottom panel shows the χ^2 for two cases—the solid line is for the best-fit model, and the dashed line is for a two-temperature model assuming solar abundances.

Mg XI, and the unresolved structure at lower energies due to line emission from the Fe L complex and from medium-z elements.

We have used the XSPEC (Version 8.34) spectral analysis package to fit the data for both stars with two different spectral models for thermal equilibrium plasmas, viz., the RS model (Raymond & Smith 1977; Raymond 1990), and the "MEKA" model (Mewe, Gronenschild, & van den Oord 1985; Kaastra 1992). We used the 1994 January 14 response matrix for the SIS. Interstellar column densities are low toward both stars: we adopted fixed values of 10^{19} cm^{-2} for our modeling. During the fitting it was found that the predominent lines of Si and Mg had their energy centroids slightly shifted from the expected values, thereby requiring a small (1.3%) reduction in the slope of the energy–to–pulse-height channel relation, or gain. This effect is consistent with the expected degradation of

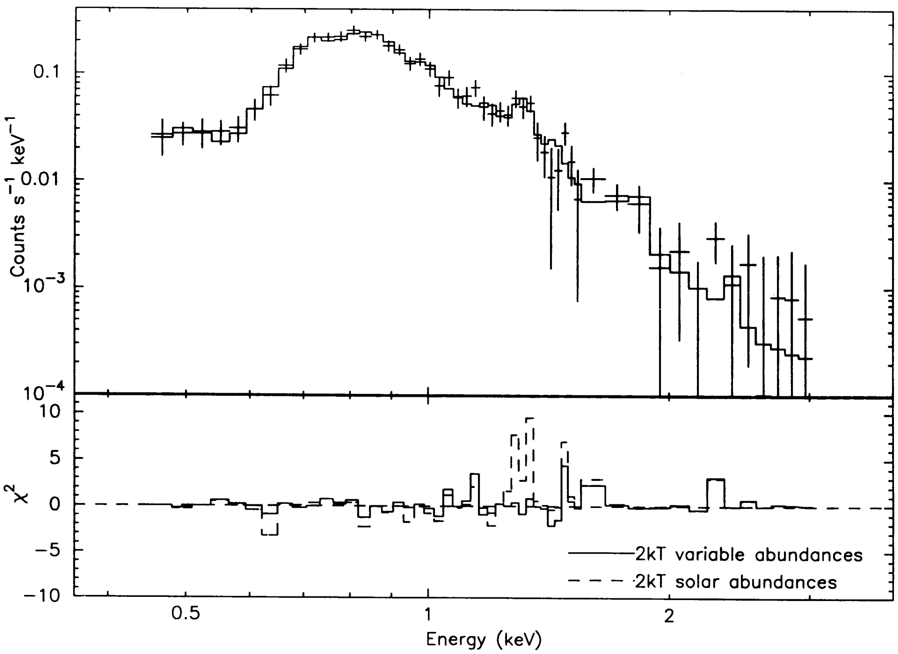

FIG. 2.—Same as Fig. 1 for π^1 UMa. Notice that the contrast of the Mg XI emission line at 1.35 keV relative to the neighboring "continuum" is primarily determined by the relative abundance of the Mg/Fe ratio: in π^1 UMa, this ratio is 2.7 times its solar value, compared to 1.9 times solar in β Cet, and hence this line appears more prominently in the π^1 UMa spectrum than in the latter, despite the lower value of Mg/H in π^1 UMa.

the CCD charge transfer efficiency in space (M. Bautz, private communication).

Our first finding is that no single-temperature RS or "MEKA" plasma model that assumes either solar photospheric (Anders & Grevesse 1989) or nonsolar abundances can fit the data, as unacceptably large values of χ^2_ν are obtained. In general, we find that "MEKA" models can fit the data better than the RS models, and henceforth we will concentrate on the results obtained using the former. The "MEKA" plasma models with two components at different temperatures and with solar photospheric abundances prove adequate for π^1 UMa ($\chi^2_\nu = 1.24$) but fail for β Cet ($\chi^2_\nu = 2.8$). Three-component solar abundance plasma models also cannot provide acceptable fits to the β Cet spectrum ($\chi^2_\nu = 2.5$).

The two-component "MEKA" model provides a very good fit for both stars ($\chi^2_\nu = 1.35$ for β Cet and 0.76 for π^1 UMa) when the abundances of the elements N, O, Ne, Mg, Si, S, and Fe are allowed to vary. Varying the abundances of the other elements, He, C, Na, Al, Ar, Ca, and Ni, produces essentially no improvement to the fit. The best-fit model is shown as a histogram in the top panels of Figures 1 and 2. In the bottom panels of the figures we compare the contributions of the residuals to the signed (observed − fitted) χ^2 for the best-fitting variable abundance model (*solid line*) as well as for a solar photospheric abundance model (*dashed line*). The comparison shows that the poor fit to a solar abundance model is caused by the model underpredicting the line strengths of Mg near 1.35 keV, and overpredicting the line strengths of Ne near 1.1 keV, of O near 0.65 keV, and of N near 0.52 keV, hence the improvement obtained by adjusting their abundances.

The best-fit values and 90% uncertainties of the parameters of the two-component "MEKA" models are listed in Table 1. In β Cet, the abundances of N, O, and Ne are $\leq 50\%$ of the solar photospheric values, whereas the abundance of Mg is $\sim 50\%$ higher. The rest of the elemental abundances are consistent with solar values (see Table 1). For π^1 UMa we find a similar pattern of elemental abundances, except that the Mg abundance is near-solar and the Fe abundance is 40% solar. Using the F-statistic test, we find that solar abundances for N, O, Ne, and Mg in the case of β Cet, and for O and Fe in the case of π^1 UMa, can be formally ruled out at the 99% confidence level. Finally, we have made three-component variable abundance "MEKA" fits to the β Cet spectrum and obtain essentially the same pattern of peculiar coronal abundances as for the two-component "MEKA" models, suggesting it is not an artifact of the admittedly simple thermal structure that we have adopted.

4. DISCUSSION

The SIS spectrum of β Cet cannot be fitted by models comprised of components of different temperatures, if the abundances are fixed at the solar photospheric values, nor, indeed, can it be fitted by models with abundances set equal to the photospheric abundances of this star (e.g., Gratton & Ortolani 1986). The spectrum can be well fitted, however, by a two- (or three-) component "MEKA" model in which the more abundant elements are allowed to vary. The fit to the SIS spectrum of π^1 UMa also significantly improves when the abundances of some of the elements, particularly O and Fe, are permitted to vary. The temperatures derived for the two plasma components in these two stars are 0.3–0.4 keV and 0.6–0.7 keV in both cases. These values are very similar to those obtained from analyses of *Einstein* IPC spectra of these and similar stars (Schmitt et al. 1990a, b) and from our unpublished analysis of a rather weakly exposed *Einstein* SSS spectrum of π^1 UMa.

The true uncertainties in the abundances that we have obtained for β Cet and π^1 UMa are likely larger than the formal statistical bounds listed in Table 1, due to inadequacies in the atomic physics incorporated in the plasma codes used in the present study (cf. Liedahl et al. 1994), the simplified coronal thermal structure we have adopted, and, perhaps, to residual instrumental effects. Nevertheless, we believe that the basic result that these spectra cannot be fitted by solar abundance plasma models is not in doubt. For example, the extreme N deficiency inferred for β Cet is driven by the absence of the predicted strong N VII feature (peak emissivity temperature 0.2

TABLE 1

RESULTS OF SPECTRAL MODELING WITH TWO-COMPONENT MEKA PLASMAS: BEST-FIT PARAMETER VALUES, ALLOWED RANGES, AND COMPARISON WITH SOLAR CORONAL ABUNDANCES

Parameter	β Ceti	π^1 UMa	Capella[a]	AR Lac[b]	Sun[c]
Emission Measures and Temperatures					
$EM_1(10^{52}\ cm^{-3})$	1.7(1.4, 2.1)	0.22(0.13, 0.38)	7.3(5.5, 9.6)	30	...
kT_1(keV)	0.43(0.40, 0.46)	0.34(0.20, 0.40)	0.41(0.38, 0.44)	0.58	...
$EM_2(10^{52}\ cm^{-3})$	2.5(2.0, 2.9)	0.22(0.12, 0.36)	6.8(5.1, 8.8)	49	...
kT_2(keV)	0.71(0.67, 0.73)	0.64(0.56, 0.78)	0.72(0.67, 0.78)	1.96	...
Elemental Abundances (relative to solar photospheric)					
N (FIP = 14.53 eV)	0.0(<0.17)	0.0(<1.0)	0.0(<0.77)	<0.1	1.0
O (FIP = 13.61 eV)	0.37(0.23, 0.56)	0.26(0.12, 0.76)	0.13(0.03, 0.27)	0.38	1.0
Ne (FIP = 21.56 eV)	0.36(<0.66)	0.31(<0.85)	0.15(<0.38)	1.63	1.0
Mg (FIP = 7.64 eV)	1.45(1.23, 1.93)	1.12(0.72, 1.75)	1.02(0.80, 1.32)	0.67	4.4
Si (FIP = 8.15 eV)	1.02(0.81, 1.40)	0.47(0.05, 1.05)	0.85(0.67, 1.07)	0.44	4.3
S (FIP = 10.36 eV)	0.43(<1.0)	0.04(<1.5)	0.73(0.39, 1.14)	0.26	2.3
Fe (FIP = 7.87 eV)	0.77(0.59, 1.01)	0.41(0.31, 0.65)	0.46(0.36, 0.61)	0.32	4.2
χ^2_{min}/dof	123.1/91	31.4/41	101.6/80	445.5/299	...

NOTE.—Allowed ranges are at 90% confidence level for a single-parameter ($\chi^2_{min} + 2.71$).

[a] From Drake et al. 1994.

[b] Best fit values from White et al. 1994.

[c] Typical pattern of solar coronal abundances from Anders & Grevesse 1989 assuming high FIP elemental abundances are at solar photospheric values.

keV) at 0.52 keV in the SIS spectrum. The uncertainty in the detector quantum efficiency in this region is quite small, ~5%–10% (G. Crew 1994, private communication), and there is no other known instrumental problem that could explain such a strong suppression of this predicted feature.

A strong justification for relaxing the standard assumption that the coronae of these stars have solar (photospheric) abundances comes from the known characteristic of the *solar* corona that its elemental abundances can deviate substantially from those of the underlying photospheric layers. Meyer (1985), Reames (1992), and Feldman (1992) have reviewed this subject and present evidence that the solar corona, solar wind, and solar energetic particles all generally exhibit an underabundance of elements with high first ionization potential (FIP) values (≥ 9 eV) relative to elements with lower FIP values by typical factors of ~4–6. It is now generally accepted (e.g., Feldman & Widing 1990; McKenzie & Feldman 1992) that it is the low-FIP elements whose coronal abundances are enhanced relative to their photospheric values rather than the high-FIP elements whose coronal abundances are depleted. A typical pattern of solar coronal abundances for the elements N, O, Ne, Mg, Si, S, and Fe is given in Table 1.

Other evidence for "peculiar" coronal abundances in late-type stars comes from a reanalysis of the SSS spectra of Capella (Drake et al. 1994) and from an analysis of the *ASCA* spectrum of the RS CVn system AR Lac (White et al. 1994). These results are summarized in Table 1. Capella shows a similar pattern of temperature structure and abundances to that reported here for β Cet, viz., the best-fit model has two components with temperatures of 0.4 and 0.7 keV and exhibits underabundances of O, Ne, N, and Fe, and close to solar photospheric abundance for Mg, Si, and S. The abundance pattern inferred for AR Lac is quite similar to that of the other stars in the table, despite its having a much hotter corona: most elements are 2–4 times underabundant as compared to their solar photospheric values. The most contrasting values are Ne and Mg: the low-FIP element Mg is either solar or slightly overabundant in β Cet, π^1 UMa, and Capella, but is underabundant in AR Lac, while the high-FIP element Ne is overabundant in AR Lac, but is underabundant in β Cet, π^1 UMa, and Capella.

If a low-FIP enhancement process similar to that inferred for the solar corona were operative in these stellar coronae, we might have anticipated that the absolute abundances of the low-FIP elements Fe, Mg, Si, and Ni would be elevated above solar photospheric values. On the contrary, only for Mg in β Cet do we find such evidence, while Fe appears to be slightly depleted relative to solar, and both Si and Ni appear close to their solar values. Instead, we find stronger evidence in our *ASCA* spectra that the abundances of the high-FIP elements N, O, and Ne are depressed below solar photospheric values, i.e., we find an actual depletion of the high-FIP elements. It should be noted, however, that the absolute normalization of the heavy element abundances relative to hydrogen in our model fits is not as well determined as are their relative abundances. Thus, if we fix the Fe abundance at the solar photospheric value, we can find poorer but still acceptable fits which have near-solar abundances for the high-FIP elements and enhanced abundances for the low-FIP elements Mg and Si. However, the higher signal-to-noise ratio *ASCA* spectrum of AR Lac analyzed by White et al. (1994) cannot be acceptably fitted by such a model.

Thus, though it is unclear whether it is exactly the same FIP-differentiating mechanism producing the abundance peculiarities in the coronae of β Cet and π^1 UMa (and of other active cool stars) that is operative in the Sun, the overall abundance pattern is fairly similar, at least in terms of the inferred *relative* abundances of the low- and high-FIP elements within their coronae. The most discrepant element is the low-FIP element Fe which, in contrast to the solar corona, appears to have an abundance behavior more like a high-FIP element than that of a low-FIP element.

We thank the entire *ASCA* operations and software teams for their invaluable assistance, Charles Day for a tutorial on the XSELECT package, and Don Reames for a useful discussion on the subject of solar coronal abundances.

REFERENCES

Anders, E., & Grevesse, N. 1989, Geochim. Cosmochim. Acta, 53, 197
Ayres, T. R., et al. 1994, ApJ, in press
Day, C. S. R., et al. 1994, The ABC Guide to *ASCA* Data Reduction, *ASCA* Guest Observer Facility (NASA/Goddard Space Flight Center)
Drake, S. A., White, N. E., Kaastra, J., & Mewe, R. 1994, in preparation
Feldman, U. 1992, Phys. Scripta, 46, 202
Feldman, U., & Widing, K. G. 1990, ApJ, 363, 292
Gratton, R. G., & Ortolani, S. 1986, A&A, 169, 201
Kaastra, J. S. 1992, An X-Ray Spectral Code for Optically Thin Plasmas (SRON-Leiden Report, updated version 2.0)
Liedahl, D. A., Osterheld, A. L., Mewe, R., & Kaastra, J. S. 1994, PASJ, in press
Maggio, A., Sciortino, S., Vaiana, G. S., Majer, P., Bookbinder, J. A., Golub, L., Harnden, F. R., Jr., & Rosner, R. 1987, ApJ, 315, 687
Maggio, A., Vaiana, G. S., Haisch, B. M., Stern, R. A., Bookbinder, J. A., Harnden, F. R., Jr., & Rosner, R. 1990, ApJ, 348, 253
McKenzie, D. L., & Feldman, U. 1992, ApJ, 389, 764
Mewe, R., Gronenschild, E. H. B. M., & van den Oord, G. H. J. 1985, A&A, 62, 197
Meyer, J.-P. 1985, ApJS, 57, 173
Raymond, J. C. 1990, private communication
Raymond, J. C., & Smith, B. W. 1977, ApJS, 35, 419
Reames, D. V. 1992, in Proc. of the First SOHO Workshop (ESA SP-348), ed. V. Domingo (Noordwijk: ESA Publ. Div., ESTEC), 315
Schmitt, J. H. M. M., Collura, A., Sciortino, S., Vaiana, G. S., Harnden, F. R. Jr., & Rosner, R. 1990a, ApJ, 365, 704
Schmitt, J. H. M. M., Micela, G., Sciortino, S., Vaiana, G. S., Harnden, F. R. Jr., & Rosner, R. 1990b, ApJ, 351, 492
Tanaka, Y., et al. 1994, PASJ, in press
White, N. E., et al. 1994, PASJ, in press