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ENHANCED NOBLE GASES IN THE CORONAE OF ACTIVE STARS

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ABSTRACT

We have analyzed *Chandra* High-Energy Transmission Grating spectra of the active RS CVn–type binary V711 Tauri (HR 1099; HD 22468) in order to examine the chemical composition of its coronae. Observed fluxes and flux upper limits for spectral lines from a range of charge states of iron, covering species Fe xvi–Fe xxv, have been used to determine the emission measure distribution as a function of temperature, while the observed Fe line-to-continuum ratio has been used to examine the absolute iron abundance, Fe/H. Abundances of elements O, Ne, Mg, Si, S, and Ar relative to both Fe and H have been estimated by comparison of observed line fluxes with predictions based on the emission measure distribution. We confirm results of earlier studies finding the coronae of V711 Tau to be metal-poor and derive an iron abundance of Fe/H $= 7.0 \pm 0.1$. We find the noble gas elements Ne and Ar to be enhanced relative to the local cosmic value and enhanced by an order of magnitude relative to Fe. Very mild enhancements of O and Mg relative to Fe are also discerned. By examination of coronal abundances of Ne relative to Fe culled from the literature, in addition to Ne lines seen in hitherto unpublished *Chandra* spectra, we conclude that large Ne abundance enhancements are a common feature of active stellar coronae.

Subject headings: stars: abundances — stars: activity — stars: coronae — stars: late-type — Sun: corona — X-rays: stars

1. INTRODUCTION

There now exists a substantial body of evidence demonstrating that the chemical compositions of solar and stellar coronae differ from those of their underlying photospheres. In the case of the solar corona, the differences appear to be related primarily to the element first ionization potentials (FIPs) in that the abundances of elements with FIP $\lesssim 10$ eV (e.g., Mg, Si, and Fe) are enhanced compared to abundances of high FIP ($\gtrsim$10 eV; e.g., O, Ne, and Ar) elements by an as yet unidentified mechanism that preferentially feeds the corona with ions from material at chromospheric temperatures. In other stars, examples of this "FIP effect" have been found in stellar coronae with solar-like and intermediate activity levels, based on analyses of *Extreme Ultraviolet Explorer* (*EUVE*) spectra. In contrast, analyses of *EUVE, Advanced Satellite for Cosmology and Astrophysics* (*ASCA*), and *BeppoSAX* spectra of more active stars have shown their coronae to be metal-poor, although in some cases it is possible that the metal paucity is also shared by the parent photospheres. These results are reviewed and discussed by, e.g., Feldman & Laming (2000), Drake (2001), Drake (1996), and references therein.

In the context of coronal abundance anomalies and their potential promise as diagnostics for processes occurring in stellar outer atmospheres, the detailed study of coronal compositions in stars with a wide range of parameters using high-resolution spectra from the recently launched *Chandra* and *XMM-Newton* observatories is highly motivated. We describe here an analysis of *Chandra* High-Energy Transmission Grating (HETG) observations of the well-known chromospherically and coronally active RS CVn system, V711 Tauri (HR 1099; K1 IV + G5 V), aimed at determining coronal abundances of elements O, Ne, Mg, Si, S, Ar, and Fe and at shedding more light on coronal abundance anomalies in active stars.

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2. OBSERVATIONS

V711 Tau was observed by the *Chandra* HETG and Advanced CCD Imaging Spectrometer-S (ACIS-S) detector (see, e.g., Canizares et al. 2000 and references therein for details) over the period UT 23:00 1999 September 14 to UT 20:00 1999 September 16 (ObsID 62538). These observations and data have also been described by Ayres et al. (2001), who in addition provide a summary of the characteristics of V711 Tau. Data were processed, and first-order High-Energy Grating (HEG) and Medium-Energy Grating (MEG) spectra were extracted using standard pipelines (CIAO 1.0) and techniques. Positive and negative first-order spectra were combined and corrected for small differences in their dispersion relations that could be attributed to small errors in the assumed locations of ACIS-S chip boundaries. The total exposure time for the final extracted spectra was 136 ks.

3. ANALYSIS

Spectra were analyzed with the PINTofALE interactive data language software suite (Kashyap & Drake 2000). Emissivities for both lines and continua were adopted from the SPEX plasma radiative loss model (Kaastra, Mewe, & Nieuwenhuijzen 1996b), in conjunction with the ion balance of Mazzotta et al. (1998).

Our analysis method can be summarized as follows: lines due to Fe ions with a wide range of charge states and minimally affected by line blends were used to derive the emission measure (EM) distribution as a function of temperature, EM(T); this EM distribution was then used to predict both the fluxes that should be observed from spectral lines due to different elements and also the continuum flux resulting from bound-

TABLE 1
IDENTIFICATIONS AND INTENSITIES FOR SPECTRAL LINES USED IN THIS ANALYSIS

λ_{obs} (Å)	Ion	Transition	log T_{max} (K)	Intensity (counts)	Notes
1.849	Fe XXV	$1s2p\ ^1P_1$–$1s^2\ ^1S_0$	7.80	50	H, U
10.624	Fe XXIV	$3p\ ^2P_{3/2}$–$2s\ ^2S_{1/2}$	7.30	312 ± 15	H
10.984	Fe XXIII	$2s3p\ ^1P_1$–$2s^2\ ^1S_0$	7.20	222 ± 14	H
11.177	Fe XXIV	$3d\ ^2D_{5/2}$–$2p\ ^2P_{3/2}$	7.30	327 ± 16	H
11.744	Fe XXIII	$2s3d\ ^1D_2$–$2s2p\ ^1P_1$	7.20	412 ± 18	H
11.777	Fe XXII	$2s^23d\ ^2D_{3/2}$–$2s^22p\ ^2P_{1/2}$	7.10	331 ± 16	H
12.292	Fe XXI	$2s^22p3d\ ^3D_1$–$2s^22p^2\ ^3P_0$	7.00	448 ± 18	H[a]
12.402	Fe XXI	$2s^22p3d\ ^3D_1$–$2s^22p^2\ ^3P_1$	7.00	95 ± 14	H
13.512	Fe XIX	$2s^22p^3(^2D)3d\ ^3D_3$–$2s^22p^4\ ^3P_2$	6.90	111 ± 10	H
15.263	Fe XVII	$2s^22p^53d\ ^3D_1$–$2s^22p^6\ ^1S_0$	6.75	727 ± 33	H
15.623	Fe XVIII	$2s^22p^4(^1D)3s\ ^2D_{5/2}$–$2s^22p^5\ ^2P_{3/2}$	6.90	321 ± 25	M
16.078	Fe XVIII	$2s^22p^4(^3P)3s\ ^4P_{5/2}$–$2s^22p^5\ ^2P_{3/2}$	6.90	633 ± 31	M
16.778	Fe XVII	$2s^22p^53s\ ^1P_1$–$2s^22p^6\ ^1S_0$	6.70	875 ± 35	M
17.058	Fe XVII	$2s^22p^53s\ ^3P_1$–$2s^22p^6\ ^1S_0$	6.70	1086 ± 38	M
17.098	Fe XVII	$2s^22p^53s\ ^3P_2$–$2s^22p^6\ ^1S_0$	6.70	1084 ± 39	M
17.503	Fe XVI	$2s^22p^53s3p\ ^4P_{3/2,\,5/2},\ ^2D_{3/2}$–$2s^22p^63p\ ^2P_{1/2,\,3/2}$	6.60	75	M, U
3.946	Ar XVII	$1s2p\ ^1P_1$–$1s^2\ ^1S_0$	7.10	150 ± 41	H
4.729	S XVI	$2p\ ^2P_{1/2}$–$1s\ ^2S_{1/2}$	7.40	80 ± 26	H
	S XVI	$2p\ ^2P_{3/2}$–$1s\ ^2S_{1/2}$	7.40	40 ± 13	H
5.037	S XV	$1s2p\ ^1P_1$–$1s^2\ ^1S_0$	7.20	114 ± 33	H
9.172	Mg XI	$1s2p\ ^1P_1$–$1s^2\ ^1S_0$	6.80	520 ± 35	H
6.649	Si XIII	$1s2p\ ^1P_1$ –$1s^2\ ^1S_0$	7.00	598 ± 35	H
10.244	Ne X	$3p\ ^2P_{1/2}$–$1s\ ^2S_{1/2}$	6.80	945 ± 30	H
	Ne X	$3p\ ^2P_{3/2}$–$1s\ ^2S_{1/2}$	6.80	945 ± 30	H
12.139	Ne X	$2p\ ^2P_{1/2}$–$1s\ ^2S_{1/2}$	6.80	1345 ± 50	H
	Ne X	$2p\ ^2P_{3/2}$–$1s\ ^2S_{1/2}$	6.80	2691 ± 50	H
13.449	Ne IX	$1s2p\ ^1P_1$–$1s^2\ ^1S_0$	6.60	659 ± 31	H
18.973	O VIII	$2p\ ^2P_{1/2}$–$1s\ ^2S_{1/2}$	6.50	1362 ± 19	M
	O VIII	$2p\ ^2P_{3/2}$–$1s\ ^2S_{1/2}$	6.50	2725 ± 39	M

NOTE.—H = HEG; M = MEG; U indicates value treated as an upper limit.
[a] Resolved from Fe XVII λ12.27.

free, free-free, and two-photon processes. Under the assumptions of the analysis—that the observed coronal emission arises from an optically thin, collision-dominated plasma—the ratio between predicted and observed line fluxes from a given element X yields the abundance of that element relative to that of iron, X/Fe. Similarly, because the soft X-ray continuum at the temperatures that characterize active coronae, such as those of the RS CVn–type active binaries, is predominantly due to bound-free and free-free emission from hydrogen, the ratio between predicted and observed continuum levels yields the abundance of iron relative to hydrogen, Fe/H.

Spectral line intensities were measured from both HEG and MEG spectra. HEG spectra were adopted when photometric accuracy was sufficient (of order 10% or better based on Poisson statistics); this generally corresponded to wavelengths $\lambda < 15$ Å. Consistency of HEG and MEG fluxes was verified by comparison of lines measured in both spectra and that appeared unblended at HEG resolution. Lines used in the analysis are listed in Table 1, together with their observed fluxes and their peak temperatures of formation under the assumption of thermal equilibrium in the absence of weighting by the EM distribution. Iron is represented in ions Fe XVI–XXV. The lowest charge state corresponds to Fe XVI λ17.50, which is not detected but which provides a useful upper limit with which to constrain the "lowest" temperatures we are able to investigate by means of Fe lines in HETG spectra.

We have determined the EM distribution based on Fe lines using the Markov Chain Monte Carlo method described in detail by Kashyap & Drake (1998). The resulting EM(T), illustrated in Figure 1, was then used to determine the ratio of predicted to observed fluxes of lines due to other elements. It is only within the temperature range log T = 6.5–7.7, dictated by the upper limit on the flux from Fe XVI λ17.50 and by the information from the Fe λ1.87 He-like resonance line, that we have sufficient information on the EM distribution to estimate the relative abundance of an element X/Fe. Within this temperature range, we can find lines from O VIII, Ne IX, Ne X, Mg XI, Si XIII, S XV, and Ar XVII in our HETG spectra. Measured fluxes and temperatures of peak formation are listed for lines from these species in Table 1.

An illustration of the derivation of the iron abundance by comparison of predicted and observed continua is presented in Figure 2. The resulting Fe abundance Fe/H = 7.0 ± 0.1, corresponding to a fractional abundance of 0.3 ± 0.05 of the solar photospheric Fe abundance, or [Fe/H] = −0.51, where the solar photospheric abundance is Fe/H = 7.51 (Biémont et al. 1991; Holweger et al. 1991). The uncertainty is dictated by the subjective judgement of the best match of observed and predicted continua and by other hidden uncertainties, such as uncertainties in the atomic data and instrument calibrations. Other uncertainties in the computation of the continua based on the EM distribution itself are small since they are only weakly dependent on the exact details of the EM distribution and more strongly dependent on the measured line fluxes. However, the uncertainties in the atomic data entering the analysis are difficult to assess, and our 0.1 dex uncertainty should be treated

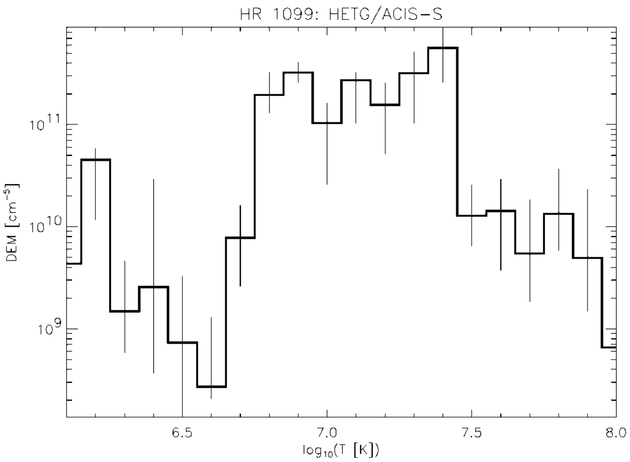

FIG. 1.—Differential EM distribution for the coronae of V711 Tau derived from lines of various charge states of Fe and without correction for stellar distance. The error bars are 1 σ values but are usually larger than the absolute EM uncertainty owing to the general lack of constraint on EM distribution variations at temperature scales $\Delta \log T \lesssim 0.2$.

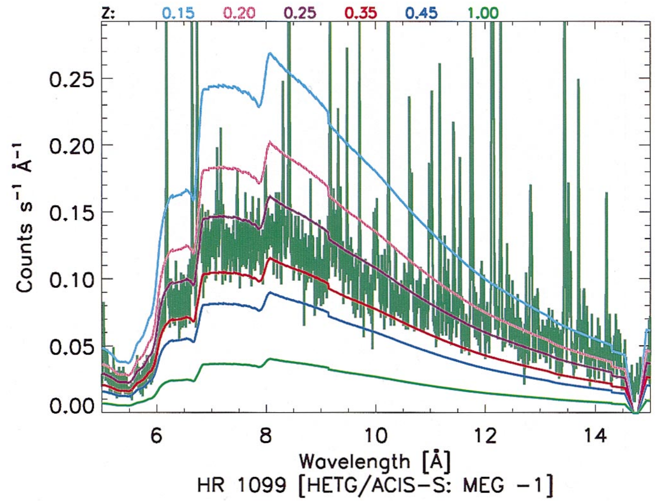

FIG. 2.—Illustration of the determination of the abundance of iron relative to hydrogen, Fe/H. The spectrum shown is that of the negative first-order MEG. The curves are continua simulated for values of the fractional solar photospheric iron abundance of, from top to bottom, 0.15, 0.2, 0.25, 0.35, 0.45, and 1.0. The adopted iron abundance corresponds to 0.3 of the solar value, or Fe/H = 7.0 ([Fe/H] = −0.51 for a solar photospheric abundance Fe/H = 7.51; see text), with a formal uncertainty of about 0.1 dex.

as only a very rough estimate. The abundance of Fe together with abundances of O, Ne, Mg, Si, S, and Ar obtained using predicted and observed line fluxes are listed in Table 2. The errors listed for these other abundances include a quadrature addition of 30% to allow for atomic data uncertainties (see Drake, Laming, & Widing 1995).

4. DISCUSSION AND CONCLUSIONS

The striking features of the abundance results (Table 2) are a deficit of Fe with respect to the solar photospheric abundance by a factor of about 3, strongly enhanced abundances of Ne and Ar compared to that of Fe, and mild enhancements of O and Mg compared to Fe, all relative to the solar photospheric mixture. We find the S/Fe abundance ratio to be essentially solar, while Si might just be very mildly enhanced. The Fe abundance derived here is similar to the value [Fe/H] ~ −0.4, derived by Drake & Kashyap (1998) based on *EUVE* spectra, and to the general metal paucity first found for V711 Tau in different low-resolution soft X-ray spectra by Drake, Singh, & White (1996). We also note that our relative abundances are fairly similar to the very recent results of Brinkman et al. (2001), who estimated coronal abundances relative to O based on *XMM-Newton* spectra of V711 Tau.

Regarding Fe, an interesting question is whether or not the low observed abundance is different than the underlying photospheric value, indicating that some fractionation in the Fe abundance has taken place in the outer atmospheres of these stars. Photospheric abundance estimates are often lacking for active stars that are the subject of coronal abundance studies. However, there are at least two examples of active stars whose photospheric abundances are well known and do appear significantly higher than the reported coronal values (discussed by J. J. Drake in Jordan et al. 1998; see also the more recent work of Ottman, Pfeiffer, & Gehren 1998); these are the young star AB Doradus (Mewe et al. 1996) and the RS CVn–type binary II Pegasi (Covino et al. 2000; Mewe et al. 1997).

The case of V711 Tau is less clear. The coronal iron abundance we have derived here is consistent within reasonable experimental uncertainties with the Fe abundance, [Fe/H] = −0.6, estimated by Randich, Giampapa, & Pallavicini (1994) for the primary K1 IV component that is known to dominate the X-ray emission (e.g., Ayres et al. 2001 and references therein). However, the Fe abundances for some stars from the Randich et al. (1994) study appear to be underestimated (e.g., Ottmann et al. 1998), and the abundance derived for the G5 V component was also much higher at [Fe/H] = 0, indicating that the coronal abundance derived here may actually be significantly lower than the true photospheric abundance and thus might represent an abundance anomaly. We defer firm conclusions to future work.

Neon and argon are observationally inaccessible in late-type stars at optical wavelengths, and the results presented here probably represent the first definitive absolute Ne and Ar abundance measurements in late stellar types. A literature search has also revealed some evidence for enhancements of Ne relative to Fe by factors of 2–6 or so in other active stars based on multiparameter isothermal and two-temperature plasma model fits to low-resolution soft X-ray pulse-height spectra obtained by *ASCA* (e.g., λ And: Ortolani et al. 1997; AR Lac: Kaastra et al. 1996a; Singh, White, & Drake 1996; II Peg: Mewe et al. 1997; UX Ari: Güdel et al. 1999; β Per: Antune, Nagase, & White 1994; AB Dor: Mewe et al. 1996). The high Ne/Fe ratios attracted little comment other than a rightful state-

TABLE 2
ABUNDANCES OF ELEMENTS IN THE CORONAE OF V711 TAU DERIVED IN THIS STUDY[a]

[O/Fe]	[Ne/Fe]	[Mg/Fe]	[Si/Fe]	[S/Fe]	[Ar/Fe]	Fe/H
0.48 ± 0.11	0.99 ± 0.11	0.40 ± 0.12	0.28 ± 0.11	0.17 ± 0.16	1.39 ± 0.15	7.00 ± 0.10

[a] Values expressed relative to the solar photospheric mixture of Anders & Grevesse 1989, except for Fe (see text), in conventional logarithmic spectroscopic bracket notation with a hydrogen abundance of H/H = 12.

ment of caution regarding the low-resolution results due to severe blending of Ne with lines of Fe with $n = 2$ ground states (e.g., Singh et al. 1996; Güdel et al. 1999). In contrast, little evidence for strong Ar enhancements as found here is present in the *ASCA* results, although this could be due in part to difficulties in obtaining sufficient signal at shorter wavelengths in *ASCA* spectra. In the case of II Peg, a recent high-resolution *Chandra* HETG spectrum exhibits a very strong Ne x Lyα doublet (D. P. Huenemoerder et al. 2001, in preparation), while Ne x Lyα is also the strongest line in a Low-Energy Transmission Grating + ACIS-S observation of σ Gem (J. J. Drake et al. 2001, in preparation), providing strong evidence that Ne is enhanced relative to Fe in both these stars and reinforcing our conclusion that strong Ne/Fe enhancements are common in active stellar coronae.

Based on nucleosynthesis arguments, enhanced photospheric abundances of Ne and Ar relative to O appear unlikely. These strong enhancements also argue against simple gravitational settling as an explanation for the apparent metal depletion relative to photospheric values in RS CVn corona proposed by Mewe et al. (1997) since such a mechanism is dependent on particle mass. Such a mechanism also seems unlikely in RS CVn coronae that are probably comprised of compact and quite high-density ($N_e \gtrsim 10^{12}$ cm^{-2}) loops that are smaller than the typical pressure scale height (e.g., Drake 2001). If gravity does play a significant role, the observed anomalies imply that other effects must also be at work. Indeed, Ne and Ar enhancements suggest that FIP could be relevant, although in a fractionation process that results in larger coronal abundances of very high FIP species (the FIPs of Ne and Ar are 21.6 and 15.8 eV, respectively)—quite opposite to the solar FIP effect. Indeed, Brinkman et al. (2001) suggest that the logarithmic abundance enhancement factors relative to O found in their *XMM-Newton* analysis is proportional to FIP, although this relationship is not well-supported by our study.

High Ne/O abundance ratios during long-duration γ-ray flare events observed on the Sun (Shemi 1991 and references therein; see also Share & Murphy 1995) may be relevant to the intense X-ray luminosity and frequent large flares seen on an active binary like V711 Tau. Shemi (1991) has interpreted the high Ne/O ratio in the FIP framework, arguing that the penetration depth of soft X-ray photoionizing radiation generated in a flare event is sufficient to reach chromospheric layers where high-FIP species are otherwise still neutral. By virtue of a higher photoionization cross section in the relevant soft X-ray range, a larger population of Ne^+ ions than, e.g., C^+ or O^+ ions is produced, and these are preferentially swept into the corona along with ions of low-FIP elements. Such a mechanism might be plausible for the enhancements of Ne relative to H but does not explain the enhancement relative to Fe. Nevertheless, photoionization in chromospheric layers by X-ray irradiation from the corona could be significant for ion-neutral fractionation mechanisms based in the chromospheres of active stars.

Models of quiescent solar coronal loops have uncovered conditions where the abundance of He may be enhanced relative to H (Hansteen, Leer, & Holzer 1994, 1997; Lenz 1999). While this putative He abundance enhancement has so far not been detected in the solar corona (see Laming & Feldman 2001), our abundances for V711 Tau are reminiscent of the idea discussed by Drake (1998) that a stellar corona strongly enhanced in He would emit significantly more thermal bremsstrahlung and thus give rise to an apparent metal paucity if H is assumed to be the dominant background plasma constituent; we note that an increase by about an order of magnitude in the coronal abundances of the noble gases He, Ne, and Ar would reproduce not only our observed (apparent) value of [Fe/H], but also [Ne/Fe] and [Ar/Fe]. To the contrary, Covino et al. (2000) noted that an enhanced He abundance could not explain the low Fe abundances they deduced in the *BeppoSAX* spectrum of II Peg, although no details of the problem with the He explanation were given.

Finally, determining whether or not Fe is depleted in the corona relative to the photosphere would be an important step toward understanding the derived abundances, since it could be possible that at least some of the observed Ne and Ar excesses relative to Fe are simply reflections of their photospheric abundances and it is Fe and other species that are depleted rather than Ne and Ar being enhanced. Once this step is achieved, the challenge will be for theoretical models to account for the emerging gamut of abundance anomalies in stellar coronae in addition to the FIP effect.

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