Enhanced Noble Gases in the Coronae of V711 Tau

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1. Coronal Abundance Anomalies

Chemical compositions of solar and stellar coronae differ to those of their underlying photospheres.

FIP In the case of the solar corona and coronae of moderately active stars, 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, Fe) are enhanced compared to abundances of high FIP ($\gtrsim 10$ eV; e.g. O, Ne, Ar) elements by an as yet unidentified mechanism that preferentially feeds the corona with ions from material at chromospheric temperatures.

MAD In the case of very active stars—RS CVn-type, BY Dra-type binaries, rapidly rotating single stars—some coronae appear to be *depleted* in metals relative to their underlying photospheres: the coronal MAD (metal abundance deficiency) syndrome. The MAD effect is not understood; suggested mechanisms include gravitational settling, diffusion, or greatly enhanced coronal Ne abundances.

The FIP and MAD abundance anomalies promise potentially powerful clues and insights to processes occuring in and sustaining stellar coronae. However, the observed abundance anomalies are not yet understood. The way forward is observational: to investigate and map out coronal abundances over the range of spectral types and activity levels.

2. Observations and Analysis

1. V711 Tau was observed by the Chandra HETG and ACIS-S detector over the period UT 23:00 1999 September 14 to UT 20:00 1999 September 16 (ObsID 02538). The total exposure time for extracted and reduced spectra was 136 ks. The MEG -1 order spectrum is illustrated in Figure 1, together with labels identifying the spectal lines used in this analysis.
2. Spectra were analysed with the PINTofALE IDL software package (Kashyap & Drake 2000). Observed fluxes and flux upper limits for spectral lines from a range of charge states of iron (Table 1), 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 iron abundance, Fe/H.
3. Abundances of elements O, Ne, Mg, Si, S and Ar have been estimated by comparison of observed line fluxes (Table 1) with predictions based on the emission measure distribution derived from Fe lines. Abundance results are presented in Table 2.

ABSTRACT

We have analysed *Chandra* HETG spectra of the active RS CVn-type binary V711 Tau (HR 1099; HD 22468; K1IV+G5V; P_{rot} = 2.84*d*) in order to examine the chemical composition of its coronae. Abundances of elements O, Ne, Mg, Si, S, and Fe have been investigated. 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±0.1. Strikingly high abundances of Ne and Ar are found, indicating these elements to be 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 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.

3. Results

- We confirm results of earlier studies based on EUVE and ASCA observations finding the coronae of V711 Tau to be metal poor (Drake & Kashyap 1998; S.A. Drake, Singh & White 1996), and derive an iron abundance of Fe/H= 7.0 ± 0.1 ([Fe/H] = −0.5). At face value, this Fe abundance is compatible with the photospheric abundance [Fe/H]= −0.6, estimated by Randich et al. (1994) for the *primary* K1 IV component that is known to dominate the X-ray emission (e.g. Ayres et al. 2000 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 photospheric abundance derived for the G5V component was also much higher at [Fe/H] = 0.
- In what is likely the first definitive absolute abundance study of Ne and Ar based on high resolution spectra of a late-type star other than the Sun, we find both of these elements to be enhanced by an order of magnitude relative to Fe. Very mild enhancements of O and Mg relative to Fe are also discerned (Table 2).

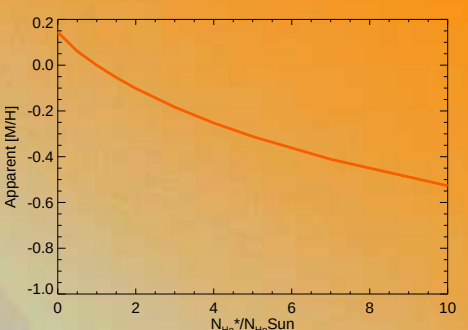

Fig. 4.— The relationship between the overabundance of He relative to H in an otherwise solar composition plasma and the perceived plasma metallicity in the EUV–X-ray spectral range. The perceived metal abundance, relative to that of the Sun in the usual spectroscopic notation, is plotted as a function of the ratio of solar and stellar coronal number densities of He nuclei relative to H nuclei (from Drake 1998).

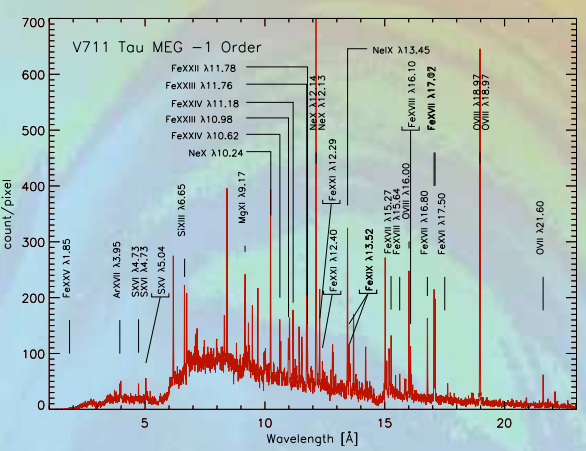

Fig. 1.— The MEG -1 order spectrum of V711 Tau shown with identifications for the spectral lines used in this analysis. Indentification labels were applied in only 20 minutes using a preliminary version of the PINTofALE routine PLOTID.

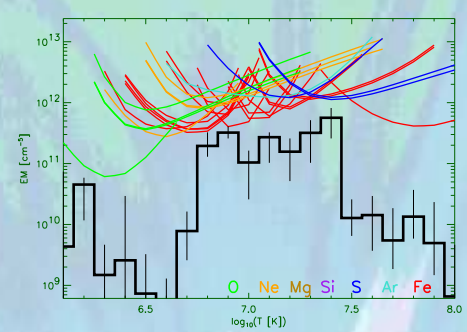

Fig. 2.— The differential emission measure distribution (black histogram) for the coronae of V711 Tau derived from lines of various charge states of Fe, and without correction for stellar distance. The error bars are 1σ values but are usually larger than the absolute EM uncertainty owing to the general lack of constraint on EM distribution variations at temperature scales $\Delta \log T \lesssim 0.2$. We used the Markov-Chain Monte Carlo method of Kashyap & Drake (1998), which avoids adoption of arbitrary smoothness either through parameterization or, eg, by forcing smooth second derivatives. The coloured curves are the *isothermal emission measure loci* corresponding to the individual spectral lines used in the analysis.

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	$3p\ ^1P_{1/2} - 2s\ ^2S_{1/2}$	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	$3d\ ^2D_{3/2} - 2p\ ^2P_{1/2}$	7.30	327 ± 16	H
11.744	Fe XXIII	$2s3d\ ^1D_2 - 2s2p\ ^1P_1$	7.20	412 ± 18	H
11.777	Fe XXII	$2s^23d\ ^2D_{3/2} - 2s^22p\ ^2P_{3/2}$	7.30	331 ± 16	H
12.292	Fe XXI	$2s^22p3d\ ^3D_1 - 2s^22p^2\ ^3P_1$	7.00	448 ± 18	H,:[1]
12.402	Fe XXI	$2s^22p3d\ ^3D_1 - 2s^22p^2\ ^3P_1$	7.00	95 ± 14	H
13.512	Fe XIX	$2s^22p^3\ [^2D]3d\ ^3D_1 - 2s^22p^3\ ^3P_1$	6.90	111 ± 10	H,:[2]
15.263	Fe XVII	$2s^22p^33d\ ^1D_1 - 2s^22p^4\ ^1S_0$	6.75	727 ± 33	H
15.823	Fe XVIII	$2s^22p^3\ [2]3s\ ^2D_{3/2} - 2s^22p^3\ ^2P_{3/2}$	6.90	321 ± 25	M
16.078	Fe XVIII	$2s^22p^3\ [^2P]3s\ ^2P_{1/2} - 2s^22p^3\ ^2P_{3/2}$	6.90	633 ± 31	M
16.778	Fe XVII	$2s^22p^33s\ ^1P_1 - 2s^22p^4\ ^1S_0$	6.70	875 ± 35	M
17.058	Fe XVII	$2s^22p^33s\ ^1P_1 - 2s^22p^4\ ^1S_0$	6.70	1086 ± 38	M
17.098	Fe XVII	$2s^22p^33s\ ^3P_1 - 2s^22p^4\ ^1S_0$	6.70	1084 ± 39	M
17.563	Fe XVI	$2s^22p^33s3p\ ^1P_{1,2,3/2} - 2s^22p^33p\ ^1P_{1,2,3/2}$	6.60	75	M,U
3.946	Ar XVII	$1s2p\ ^1P_1 - 1s^2\ ^1S_0$	7.30	150 ± 41	H
4.729	S XVI	$2p\ ^1P_{1/2} - 1s\ ^2S_{1/2}$	7.40	80 ± 26	H
···	S XVI	$2p\ ^1P_{3/2} - 1s\ ^2S_{1/2}$	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	$3p\ ^2P_{3/2} - 1s\ ^2S_{1/2}$	6.80	945 ± 30	H
···	Ne X	$3p\ ^2P_{1/2} - 1s\ ^2S_{1/2}$	6.80	945 ± 30	H
12.139	Ne X	$2p\ ^2P_{3/2} - 1s\ ^2S_{1/2}$	6.80	1345 ± 50	H
···	Ne X	$2p\ ^2P_{1/2} - 1s\ ^2S_{1/2}$	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	$2p\ ^2P_{3/2} - 1s\ ^2S_{1/2}$	6.50	1362 ± 19	M
···	O VIII	$2p\ ^2P_{1/2} - 1s\ ^2S_{1/2}$	6.50	2725 ± 39	M

NOTES –
H– HEG ; M– MEG
1. Resolved from Fe XVII 12.27
U Treated as an upper limit

Table 2. Abundances of Elements in the Coronae of V711 Tau Derived in this Study

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

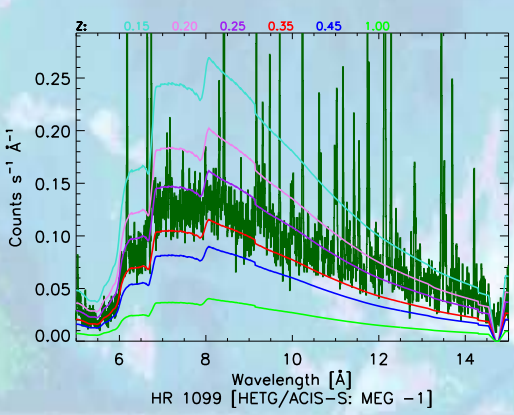

Fig. 3.— Illustration of the determination of the abundance of iron relative to hydrogen, Fe/H. The spectrum shown is that of the negative first order MEG. The curves are continuum simulated for values of the fractional solar photospheric iron abundance of, from top to bottom, 0.15, 0.2, 0.25, 0.35, 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), with a formal uncertainty of about 0.1 dex.

4. Discussion and Conclusions

Large Ne abundance enhancements are a common feature of active stellar coronae. A literature search has revealed evidence for enhancements by factors of 2-6 of Ne relative to Fe in other active stars based on low resolution ASCA spectra (e.g. λ And, Ortolani et al. 1997; AR Lac, Kaastra et al. 1996, Singh et al. 1996; II Peg, Mewe et al. 1997; UX Ari, Güdel et al. 1999; β Per, Antunes et al. 1994; AB Dor, Mewe et al. 1996). The Chandra HETG spectrum of II Peg exhibits a very strong Ne X Ly α doublet (Huenemoerder et al., 2001) indicative of Ne enhancements relative to Fe by as much as an order of magnitude. A similarly strong Ne X Ly α doublet is also seen in an LETG+ACIS-S observation of σ Gem (Drake et al., in preparation).

These abundance anomalies are currently not understood.

Fractionation Mechanisms Based on nucleosynthesis arguments, enhanced photospheric abundances of Ne and Ar relative to O are unlikely. Gravitational settling proposed by Mewe et al. (1997) is also unlikely because of mass dependency, though 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, though in a fractionation process that results in larger coronal abundances of very high FIP species (the FIP's of Ne and Ar are 21.6 and 15.8 eV, respectively)—quite opposite to the solar FIP effect.

Solar Connection? High Ne/O abundance ratios have been observed on the Sun during long duration γ-ray flare events. Shemi (1991) interpretted this in the FIP framework, whereby Ne is photoionised in the chromosphere by the flare and behaves as a low FIP element. If relevant to V711 Tau, such a mechanism does not explain the enhancement relative to Fe.

Enhanced He? Enhanced noble gas abundances 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 (Figure 4). If the coronae of active stars are very rich in He as well as Ne (and perhaps Ar), all metals except for these would appear depleted relative to the solar mixture.

Fe Depleted or Photospheric? Conclusions as to whether Fe is depleted relative to photospheric values must await more refined photospheric abundance studies. This would be an important step toward understanding the derived abundances—are metals like Fe depleted and then are Ne and Ar excesses relative to Fe simply reflections of their photospheric abundances?

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