STELLAR CORONAL ABUNDANCES AT HIGH ACTIVITY LEVELS: ER VUL AND UX ARI

B. Ball[1], Jeremy J. Drake[1], D. Garcia-Alvarez, L. Lin[1], V. Kashyap[1]

Smithsonian Astrophysical Observatory, MS-3, 60 Garden Street, Cambridge, MA 02138, USA

Abstract

We present an analysis of *Chandra* HETG (MEG) spectra of the coronae of the active binaries, ER Vul (L_x = 5 x 10^{30} ergs s^{-1}) and UX Ari (L_x = 1 x 10^{31} ergs s^{-1}). We used the Markov-Chain Monte Carlo (MCMC) method to reconstruct the coronal DEMs and estimate chemical abundances. The results are characterised by a general deficiency of metals compared to solar values, though the lack of reliable photospheric abundance estimates for these stars precludes judgement on whether this is in general a coronal anomaly. However, the trends of abundances with FIP show clear coronal signatures common in other active stars, with the low FIP elements Mg, Si and Fe being depleted relative to the high FIP Ar and Ne. Evidence is also present for enhancement of the very low FIP elements Al and Na compared with Mg, Si and Fe, as has been seen in other active coronae. Finally, the high FIP/low FIP contrast as represented by the Ne/Fe abundance ratio is larger for UX Ari, which contains a subgiant, than for ER Vul. This trend is also apparent in other results in the literature, and suggests that, either the lower surface gravity, or the structure of the subgiant astmospheres, leads to the more extreme Ne/Fe ratios.

Key words: Stars: coronae – abundances: stars: DEMS: Abundances: FIP effect: X-rays - stars

1. Introduction

Chandra and *XMM-Newton* are providing the latest chapter in the continuing story of coronal abundance anomalies. The first analyses of spectra from both satellites of the RS CVn system HR1099 revealed overabundances relative to Fe of higher FIP elements and especially large enhancements of Ne (Brinkman et al. 2001; Drake et al. 2001). Drake et al. (2001) showed that evidence for the high Ne abundances was present in earlier *ASCA* analyses of active stars but had been overlooked. This behaviour contrasts sharply with the solar FIP effect. Indeed, the trend of different abundance anomalies in stars with different activity level was pointed out by Drake 1996. Audard and co-workers (Audard et al. 2001), based on a more extensive analysis of *XMM-Newton* observations of stars of different activity level, confirm that there is in fact a continuum of behaviour from the FIP effect in relatively inactive stars like the Sun to the inverse FIP effect in the most active stars. A spectral analysis by Güdel et al. (2002) of four solar analogs also supports these conclusions.

However, the notion that there is a FIP effect operating in solar-like stars and an inverse FIP effect on the most active stars is proving to be overly simplistic. Significant deviations from a single-valued FIP-based formula are present in the data from analyses of the active binaries II Peg and AR Lac (higher abundance values for Al and Ca, compared to those of higher FIP elements Mg, Si, and Fe; Huenemoerder et al. 2003). This is distinctly opposite to what is expected for an inverse FIP effect.

It is worth noting here that most of these analyses were done comparing stellar abundances to solar photospheric values (including this analysis: there are no available photospheric abundances for UX Ari and ER Vul that form the subject of this paper). It is widely acknowledged, however, that in order to make a meaningful study of abundance anomalies in stellar coronae, one must compare *stellar* coronal to *stellar* photospheric values. For some stars, differences between coronal and photospheric abundances are quite different to those obtained assuming solar values for the stellar photosphere (e.g. Sanz-Forcada et al. 2004). Photospheric abundance studies for magnetically active stars are difficult to undertake because of, e.g., binarity, rapid rotation (causing broadening and blending). However, for young stars and stars in clusters, one can often assume the local cosmic composition or the composition of other cluster members whose abundances are known.

The nearby binary systems ER Vul and UX Ari provide an opportunity to compare coronal abundances in two similar RS CVn systems. They are at the same distance and have similar X-ray luminosities, but they have two important differences: their spectral types and rotation velocities are different. This enables a direct comparison of abundances at slightly different spectral types but similar activity levels.

2. Targets and Observations

ER Vul (HD 200391; G0V + G5 V) consists of two solar-like G stars in a short-period detached binary at a distance of 50 pc. The stellar surfaces are separated by only

Table 1. Summary of properties for the ER Vul and UX Ari systems.

Star	Spectral Type	P_{orb} (days)	Dist (pc)	M_p ($M_\odot$)	M_s ($M_\odot$)	R_p ($R_\odot$)	R_s ($R_\odot$)	i (^{o})	log L_X (ergs s^{-1})
ER Vul	GO V + G5 V	0.70	50.0	1.10	1.05	1.07	1	66.7	30.70
UX Ari	KO 1V + G5	6.4	50.2	2.2	0.9	5	0.95	60	31.08

Hipparcos distances are taken from Perryman et al. 1997.
X-ray luminosites are taken from the *ROSAT* All-Sky Survey (Dempsey et al. 1993).

2 $R_\odot$. Both stars are rapid rotators with rotational velocities 81 and 71 kms,$^{-1}$ respectively (Hill et al. 1990) and are tidally locked; consequently they exhibit strong stellar activity.

UX Ari (HD21242; K0 IV + G 5V) is a double-lined spectroscopic binary with a short period of 6.4 days (Strassmeier et al. 1993). It belongs to the group of RS CVn stars whose members are synchronously rotating, and the cooler, primary components (subgiants or giants) exhibit spot and chromospheric activity. With an X-ray luminosity of 1.2×10^{31} ergs s^{-1} (Dempsey et al. 1993) and a distance of 50.2 pc (Perryman et al. 1997), UX Ari is one of the brightest X-ray sources in the sky. The stellar parameters for the two systems are summarised in Table 1.

Chandra HETG (MEG) X-ray spectra for ER Vul were obtained on 2001 March 29-30 (Brown et al. 2001) and the exposure time of the observations was 113.45 ks. Only one small flare was detected: its duration was only $\approx$ 30 minutes. *Chandra* HETG (MEG) X-ray spectra for UX Ari were obtained on 2000 October 3-4th, with a duration of 49.09 ks: no obvious, large-scale flaring activity was evident. The full dispersal spectra for both stars in the range 0-25 Å can be seen in Fig..

3. Analysis and Results

In order to determine the abundances, we used the Markov-Chain Monte Carlo (MCMC) method (Kashyap & Drake 1998). The MCMC method gives the volume emission measure distribution DEM(T) defined over pre-selected temperature grids. The grids used in this case were ΔlogT = 0.1 with a range 6.5 < logT < 8. A subset of the identified lines was chosen such that they were (where possible) unblended, of a sufficiently high S/N ratio and were not density-sensitive. Our DEM analysis is based on the He-like and H-like resonance lines of the abundant elements O, Ne, Mg and Si, together with some prominent lines of Fe and 3 line-free continuum regions—see, e.g., Ball et al. 2004 for further details of the method. Line fluxes were found by fitting modified Lorentzian profiles to two line subsets and the MCMC algorithm performed on each separately. Fig. shows ER Vul data on the left-hand side, UX Ari on the right. The DEM reconstructions are shown for each star for two different line lists. Underneath each DEM is the ratio of observed and modelled fluxes for the analysed ions plus the three line-free continuum regions.

Table 2. Elemental coronal abundances for ER Vul (relative to solar photospheric) based on DEMs from two different line lists (allowing for blending). Uncertainties are based on statistics only, they are not the true uncertainties.

Element	FIP (eV)	Line list 1	Line list 2
Al	5.99	-0.03±0.15	0.04±0.13
Mg	7.64	-0.36±0.04	-0.34±0.03
Fe	7.90	-0.48±0.05	-0.50±0.05
Si	8.15	-0.49±0.04	-0.47±0.04
S	10.36	-0.78±0.16	-0.70±0.14
O	13.62	-0.61±0.06	-0.69±0.06
Ar	15.76	-0.07±0.23	0.10±0.18
Ne	21.56	-0.21±0.04	-0.27±0.04

FIP: First ionisation potential
Line list 1: O, Ne, Mg and Si
Line list 2: O, Ne, Mg, Si, Fe XVII, Fe XVIII, Fe XXI

Table 3. Elemental coronal abundances for UX Ari (relative to solar photospheric) based on DEMs from two different line lists (allowing for blending)

Element	FIP (eV)	Line list 1	Line list 2
Na	5.14	-0.61±0.49	-0.60±0.51
Al	5.99	-0.30±0.12	-0.28±0.13
Mg	7.64	-0.73±0.05	-0.69±0.05
Fe	7.90	-0.70±0.12	-0.69±0.07
Si	8.15	-0.77±0.05	-0.73±0.05
S	10.36	-0.78±0.17	-0.77±0.17
O	13.62	-0.32±0.05	-0.33±0.05
Ar	15.76	-0.38±1.83	-0.39±1.80
Ne	21.56	0.15±0.04	0.13±0.04

The ER Vul and UX Ari abundance ratios are plotted at the bottom of Fig. . It can be seen for ER Vul that there is a decrease in abundance going from Al to S, then an increase, with Ar being possibly the most abundant

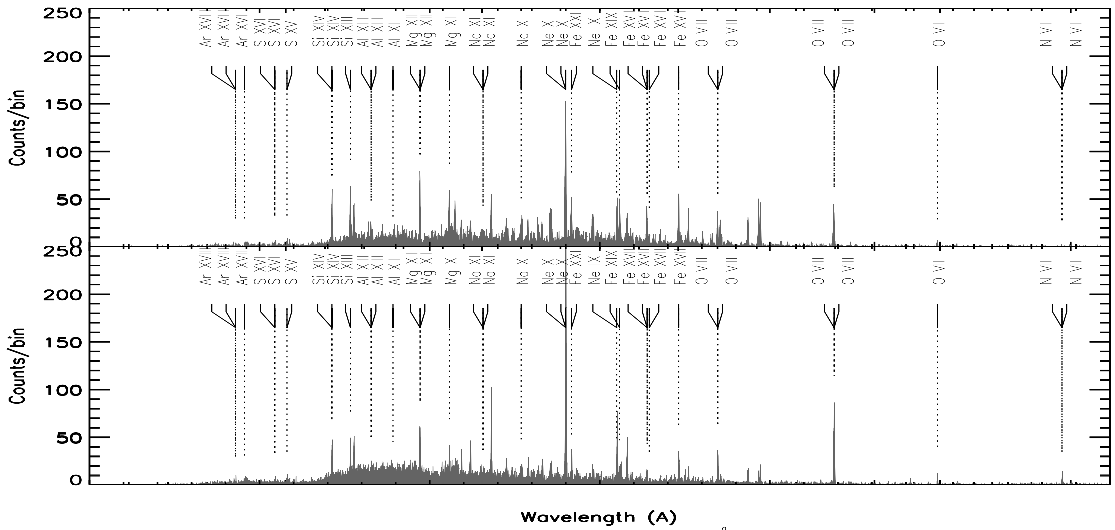

Figure 1. The MEG spectra of ER Vul (top) and UX Ari in the range 0-25Å, showing the identification of the prominent lines used in this analysis. The line subsets used were He-like and H-like lines of a) O, Ne, Mg and Si (line list 1) and b) O, Ne, Mg, Si, Fe XVII, Fe XVIII, Fe XXI (line list 2).

element. The low FIP elements Mg, Fe and Si are grouped together; Ne appears to be sub-solar. A similar pattern is seen for UX Ari: a gradual decrease to S, then a subsequent increase to Ne (slightly above solar). Whilst the overall pattern is similar in UX Ari, the abundance values for the low FIP (<10 keV) elements are lower. One can also see this by eye in the spectra in Figure 1. Sulphur is invariant at ≈ 0.2 solar for both stars. The large error bars on the Na abundance in UX Ari are due to the Na lines being very weak, and the fluxes were upper limits only.

4. Discussion

These ER Vul abundances reveal reasonable agreement with previous *ASCA* observations (Osten et al. 2002), except for oxygen whose abundance based on ASCA spectra is not reliable (see e.g., Osten et al. 2002). As noted in §1, *Chandra* and *XMM-Newton* investigations of the RS CVn binary V711 Tau (HR 1099) found abundance patterns similar to those found here (Drake et al. 2001; Brinkman et al. 2001). The pattern is characterised by a gradual decrease in abundance going from low to high FIP, a minimum close to S (FIP = 10 eV), followed by a gradual increase thereafter.

UX Ari has been observed recently by the *XMM-Newton* high-resolution RGS (Audard et al. 2003) as part of a study of several RS CVn binary systems (see also *ASCA* abundances, Güdel et al. 1999). The abundance patterns in all cases are very similar to the one shown here. Higher abundance values for low FIP elements (seen here in Al for both stars) compared to the higher FIP elements Mg, Fe and Si has also been seen before, e.g, on AR Lac for the elements Al and Ca (FIP=6.11 eV) (Huenemoerder et al. 2003).

Sulphur (FIP=10.36 eV), being at the transition stage between low FIP and high FIP elements, has a consistent abundance of ≈ 0.2 solar for both stars and line lists. It is unclear at present whether or not this value represents the underlying photospheric value, or whether these elements are in fact depleted in the corona.

There is, then, growing evidence for a more complicated scenario than just a simple FIP/inverse FIP effect (although the observed abundance patterns are certainly related to FIP). Abundances increase with increasing FIP (above $\sim$ 10 eV), except at very low FIP where an increase is also observed (see also the review by Audard in this volume).

Of note is that, while the abundances for the low FIP elements are lower for UX Ari than ER Vul, the abundance of Ne is higher. The contrast between the Ne/Fe abundances is therefore much greater for UX Ari than ER Vul. Indeed, there appears to be a trend of more extreme Ne/Fe ratios in the RS CVn systems with a subgiant component than is found in the most active dwarfs. This suggests that either surface gravity plays a rôle, or that the more extreme anomalies are related to the evolutionary state of the subgiants.

While the coronal abundance anomaly patterns in active stars show generally similar behaviour, these results need to be considered in the context of those for a much wider range of spectral type in order to begin to get a better global picture of abundance behaviour in stars and to understand the mechanisms of the underlying processes responsible.

Acknowledgements

BB and DGA were supported by *Chandra* grants GO1-2006X and GO1-2012X, and NASA Grant NAG5-9105. LL was sup-

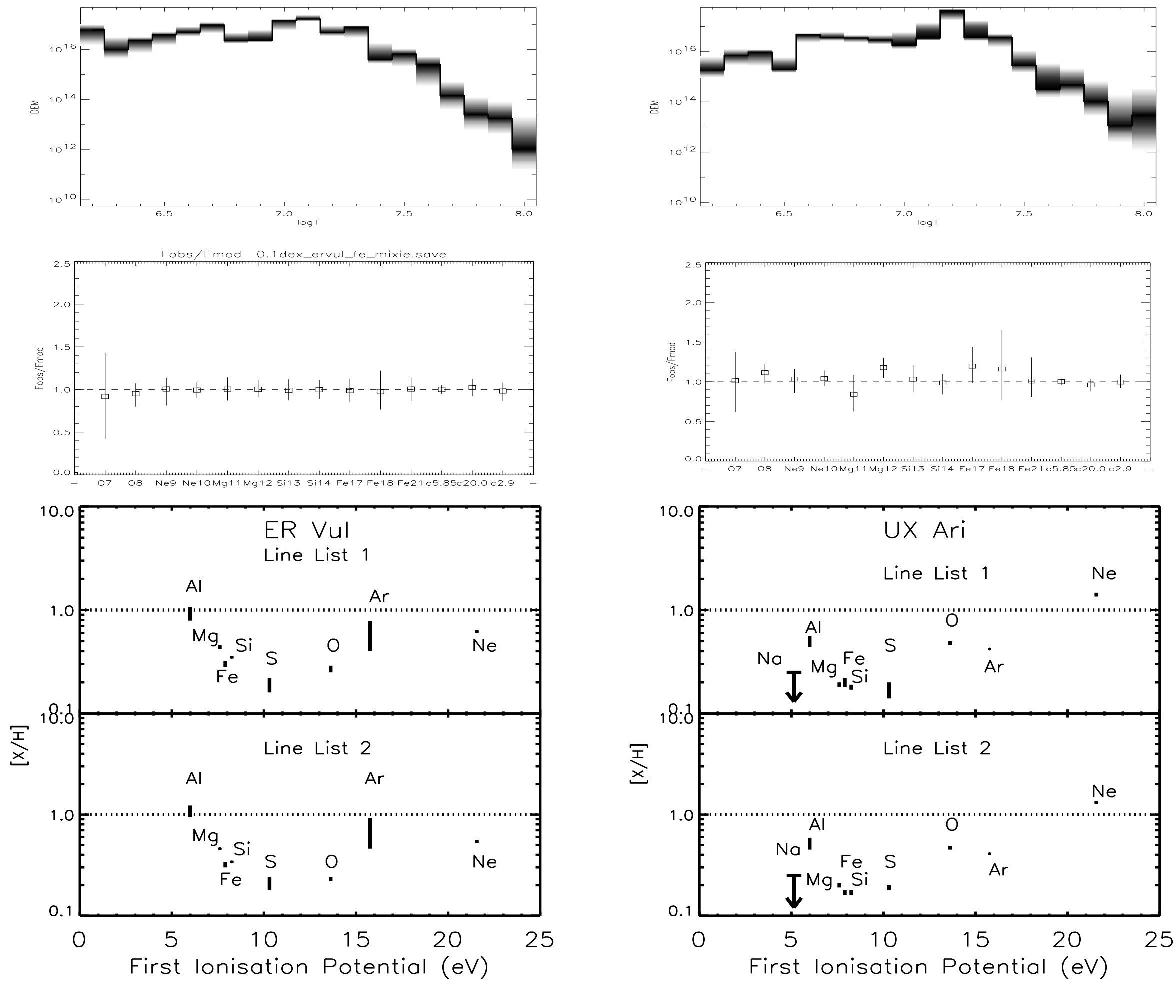

Figure 2. ER Vul data are in the left column, UX Ari on the right. Shown are the best DEM plots v. logT for line list 2. One sigma uncertanties are shown as a grey scale with a gradient determined by how the N simulated DEMs (which ordain the one sigma confidence intervals) are distributed about the best-fit DEM. Also shown are the Observed/Model fluxes plus the three continuum regions. The abundance ratios v. FIP are shown at the bottom.

ported by NASA AISRP contract NAG5-9322; we thank this program for providing financial assistance for the development of the PINTofALE package. JJD and VK were supported by NASA contract NAS8-39073 to the *Chandra* X-ray Center.

References

Audard, M., Güdel, M. and Mewe, R. 2001, A&A, 365, L318

Ball, B., Drake, J.J., Lin, L., Kashyap, V., Laming, J.M., Garcia-Alvarez, D., 2004, ApJ, in press

Brinkman, A.C. et al., 2001, A&A, 365, L324

Brown, A., Osten, R.A., Ayres, T.R., Harper, G. 2001, Two Years of Science with Chandra, Abstracts from the Symposium held in Washington, DC, 5-7 September, 2001

Dempsey, R., Linsky, J., Fleming, T., & Schmitt, J. 1993, ApJS, 86, 599

Drake, J.J., 1996, in "Magnetodynamic Phenomena in the Solar Atmosphere: Prototypes of Stellar Magnetic Activity", eds. Y. Uchida, T. Kosugi & H. Hudson, Kluwer:Dordrecht, p85

Drake, J.J. et al., 2001, ApJ, 548, L81

Güdel, M., Linsky, J.L. Brown, A., Nagase, F. 1999, ApJ, 511, 405-421

Güdel, M., Audard, M., Sres, A. Stellar Coronae in the *Chandra* and *XMM-NEWTON* Era, ASP Conf. Proc., Vol. 277. Ed. by Fabio Favata and Jeremy J. Drake, 497

Gunn, A.G., & Doyle, J.G. 1997, A&A, 318, 60

Hill, G., Fisher, W.A., & Holmgren, D. 1990, A&A, 238, 145

Huenemoerder, D.P., Canizares, C.R., Drake, J.J., & Sanz-Forcada, J. 2003, ApJ, 595, 1131

Katz, D., Favata, F., Aigrain, S., & Micela, G. 2003, A&A, 397, 747

Newmark, J.S. 1990, PhD. thesis, Pennsylvania State Univ.
Osten, R.A., Brown, A., Wood, B.E. & Brady, P. 2002, A&A, 138, 99-120
Perryman, M.A.C. et al. 1997, A&A, 323, L49
Sanz-Forcada, J., Favata, F., Micela, G. 2004, A&A, 416, 281
Strassmeier, K.G., Hall, D.S., Fekel, F.C., Scheck, M. 1993, A&AS, 100, #1, 173