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Doing Hot Cool Star Science with EUVE

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DOING HOT COOL STAR SCIENCE WITH EUVE

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ABSTRACT The Extreme Ultraviolet Explorer completed its all-sky survey in January 1993. Approximately half the detected sources are late-type stars. We present an overview of the coronal and flare physics problems that can be addressed using the new tool of EUV spectroscopy.

Keywords: EUVE; coronae; flares; spectroscopy

INTRODUCTION

How much poetry remains in the soul of the modern astronomer could be a topic of debate, and possible concern, but certainly little finds its way into the sober pages of the *Astrophysical Journal*. However if one digs deeply enough into any rule one can usually find the golden exception; and thus we find the musings of Milton adding a pensive mystique to the calculations of Cruddace et al. (1974) as they sought to uncloak the monarchs of skepticism. There is an extreme ultraviolet universe to behold! And since 1992 June 7, the Extreme Ultraviolet Explorer (*EUVE*) has been busy beholding it. Early scientific findings of the mission may be found in the 1993 September 10 *Ap. J. Letters*.

A brief history of EUV astronomy and extensive details of the EUVE may be found in the September 1993 issue of the *Journal of the British Interplanetary Society* dedicated to this mission. Up until 1990 only two dozen EUV sources had been detected. With the launch of ROSAT that year, the EUV window was partially opened by the British Wide Field Camera (WFC), a secondary instrument to the German soft X-ray (SXR) telescope, which surveyed the sky in two passbands (60–140 Å, 110–220 Å) straddling the EUV-SXR boundary (Pounds et al. 1993). EUVE, being the first mission actually dedicated to EUV astronomy, has broader spectral range (50–760 Å), deeper sensitivity; and, of most importance for the topic at hand—late-type stars—it has three moderate-resolution ($\lambda/\Delta\lambda \sim 200 - 250$) spectrographs to at last resolve individual spectral lines. The first EUVE catalog contains 410 objects (Bowyer et al. 1994).

Before we zero in on the rich new opportunities to address stellar coronal and flare physics, it is important to at least glance at the big picture. EUV astronomy now includes: (1) measurements of numerous new absorption features in white dwarf photospheres from which element stratification can be determined; (2) observations of photospheres of early-type stars giving new insights into non-LTE effects, and possibly giving us additional signatures of radiatively-driven winds; (3) light curves and spectra of cataclysmic variables; (4) images of the Vela supernova remnant and the Cygnus Loop; (5) new data on the structure and state of the ISM, including detection of cold, dark clouds;

(6) views of several AGN and BL Lac objects; and (7) at the opposite end, a unique new look at solar system objects, such as spatially resolved spectroscopy of the Io torus. We now know that there are tunnels in which the vista is clear to cosmological distances and many more directions in which there is very little absorption even out to 200 pc (see e.g. Vallerga et al. 1993).

KEY QUESTIONS IN CORONAL AND FLARE PHYSICS

Approximately half the EUV sources in the all-sky survey are late type stars (Malina et al. 1994; Bowyer et al. 1994). (The next largest group, approximately one-third, are white dwarfs.) New sources are being added to the list through the "right angle program" which obtains scanner and Deep Survey images during spectroscopic observations (McDonald et al. 1993). Since the sources of EUV emission from these stars are coronae and flares, we first consider some of the key questions that are being addressed by EUVE observations.

What is the size scale, filling factor and density of material in loop systems? On the Sun loops range in size from barely resolved (and presumably even unresolved) X-ray Bright Points ($L \sim 1000$ km) to individual structures that are a significant fraction of the solar radius (say, $L \sim 2 \times 10^5$ km). On the largest scale, it has been proposed that magnetic structures in RS CVn systems may reach from one star to the other, which would be $L \sim 10^7 - 10^8$ km, although a recent coronal eclipse observation of AR Lac does not support this concept of hot plasma pervading that binary system (see Ottmann, Schmitt and Kürster 1993). The size scale and surface distribution of coronal structures can be addressed in several ways by EUVE. Rotational modulation of EUV emission on the RS CVn V711 Tau has been observed by Drake et al. (1994) using both the scanning and Deep Survey telescopes. Using spectroscopy EUVE can provide the key combination of absolutely calibrated measurements of lines of known emissivity, density sensitive line ratios, and differential emission measures whereby the total amount of radiating material and spatial filling factor can be inferred.

Is there a universal shape for the differential emission measure (DEM)? As discussed in the next section, initial analysis of the Capella spectrum indicates that this may not be the case. On the Sun it is known that the DEM has rather similar shape, as a function of temperature, for a wide range of solar features (see Bruner and McWhirter 1988). This reflects both the intrinsic emissivity of plasma of solar abundance and the properties of heat conduction along magnetic field lines in coronal loops. EUVE filter photometry is now available for many late-type stars and this can be combined with X-ray and UV line data as was done for α Cen by Vedder et al. (1993) and two RS CVn's by Patterer et al. (1993) to provide new constraints on the DEM of numerous coronae. Again, the key to a detailed investigation of stellar DEM functions is spectroscopy. Combining EUVE-observed spectral lines with plasma emission codes will yield the best DEM estimates yet obtained.

What is the relation between coronal heating and flares? Three lines of evidence point to a close relation between flaring and coronal heating: (1) correlation between time-averaged flare energy release in dMe flare stars to coronal L_x; (2) high-T coronal components; and (3) short time scale variability suggestive of a continuous distribution of discrete energy inputs (see § 7 in Haisch, Strong and Rodono 1991, HSR). EUVE provides a simultaneous monitoring capability through the Deep Survey Lexan/B filter during acquisition of spectra allowing one to address the question of whether flare-like

lines persist even outside of obvious flares. EUV flares were seen during the all-sky survey on AU Mic (Cully et al. 1993, Landini and Monsignori-Fossi 1993), AT Mic, Prox Cen, YZ CMi and on II Peg (Patterer et al. 1993).

Are all coronae magnetic in origin? Three strong arguments converged over a decade ago to lay to rest the concept of acoustically heated coronae originally proposed by Biermann (1946) and Schwarzschild (1948). On the Sun, definitive upper limits were set on wave motions in the C IV line which restricted acoustic energy transport a factor of 1000 below the coronal energy requirements (Bruner 1981). On the stellar side observed coronal emissions bore no relation to the predicted T_{eff}, g dependence of acoustic heating, and, perhaps even more significant was the observation that at a given spectral type L_x could vary by orders of magnitude, whereas acoustic heating should be a unique function of spectral type. Magnetic heating has since been the reigning paradigm, with the question being whether continuous heating or variable heating due to flaring on all size scales was at work. However as summarized by Ulmschneider (1991), atmospheric heating by acoustic shock waves is both viable and prevalent in many types of stars. On the Sun and in other stars there is liable to be a basal level of acoustic heating (Schrijver 1987) which may actually dominate in certain types of stars and in certain regions on the Sun (Schrijver 1992). Are there stars in which coronae are predominantly acoustic, or in which there is at least an identifiable acoustic component? This could be the case in both M dwarfs and F dwarfs. Mullan and Cheng (1994) calculate that a surface flux as large as 10^5 ergs cm^{-2} s^{-1} could be provided by acoustic heating and that 20–30% of X-ray surveyed M dwarfs lie at or below this limit. For late A to mid-F stars on or near the main sequence, acoustic flux is expected to attain its maximum value while dynamo action is at a minimum since convection zones become extremely shallow (see Wolff, Boesgaard, and Simon 1986). Procyon (F5IV-V) was observed by Exosat (Lemen et al. 1989) to have a distinctly cool component ($T \sim 0.6$ MK) in addition to a hotter one ($T \sim 3$ MK); might this cool component be acoustically heated? An EUVE Procyon spectrum is now being analyzed. On the M dwarf end, Mathioudakis et al. (1993) are examining the possibility that HD 4628 may be an acoustically-heated coronal star since it was detected by EUVE but is not an X-ray source. Other F and M dwarf candidates for acoustically heated coronae are being observed by EUVE.

How do coronae change as stars evolve? It is now clear from the ROSAT all-sky survey that the Dividing Line (DL) proposed by Linsky and Haisch (1979) is real (Haisch, Schmitt, and Fabian 1992). As stars of less than $\sim 5\ M_\odot$ leave the main sequence and evolve horizontally across the H-R diagram coronal emission may be quite strong as they enter the stage of G giants, but once they evolve across the Dividing Line near spectral type early K, the coronae disappear from view. Several questions about coronal evolution arise. (1) G giants of $\geq 1.5\ M_\odot$ were F2V or earlier-type stars on the main sequence. Since they should not have had magnetic coronae on the MS, the switching on of coronae during this giant stage of evolution is an important clue regarding the dynamo. (2) The abrupt cessation of coronae and the apparently related onset of massive winds beyond the DL is a puzzle. (3) Since the more massive stars will actually loop back across the DL in the He-burning stage, do coronae turn back on again, and do the massive winds subside? Of particular interest is the status of the so-called hybrid stars, which now appear to have hot coronae and massive winds (see Haisch, Schmitt, and Rosso 1992; Reimers and Schmitt 1992). While most giants are heavily attenuated at EUV wavelengths, there are

Table 1. Trends from Einstein IPC 2-Temperature Fits

Stellar Type	Cool Component	Hot Component
M Dwarfs	3 MK	> 10 MK
FG Dwarfs	strong	weak/absent
Giants	weak/absent	strong
RS CVn's	weak/absent	> 30 MK

a sufficient number of relatively nearby giants to explore trends in coronal properties with EUVE as a function of proximity to the DL.

Do coronal abundances vary from photospheric? It appears to be the case that elements on the Sun with first ionization potentials less than $\sim$ 10.6 eV become overabundant in the corona, such overabundances becoming rather significant: factors of 10 or more (see Widing and Feldman 1993). Recognition of abundance variations is a relatively recent discovery which may prove to be quite important; again, an important key is EUV spectroscopy.

SPECTRA OF STELLAR CORONAE

The number of coronal spectra obtained prior to EUVE has been very small: three spectra of Capella, two spectra of σ^2 CrB (an RS CVn), and one spectrum of Procyon are the legacy of the Einstein focal plane crystal spectrometer and objective grating spectrometer and the Exosat transmission grating spectrometer. The Einstein solid state spectrometer observed seven RS CVn's, two dMe's and the active solar-like star π^1 UMa, but the spectral resolution of this instrument was only 160 eV over the 0.4 to 4.5 keV range. Most coronal information was gleaned from the even lower resolution Einstein imaging proportional counter (IPC) pulse height spectra. Looking for clues to fundamental differences between groups of stellar types, Schmitt et al. (1990) found the overall trend in the *DEM* of four categories of stars shown in Table 1.

The ability to do spectroscopy capable of measuring individual lines forming at a wide range of temperatures will take us a long way from such simple characterizations. An excellent overview of the potential for determining densities, temperatures, and abundances in this rich EUV spectral range has been presented by Feldman et al. (1992). Those are the three primary diagnostics of stellar coronal plasma available from EUV spectroscopy at the spectral resolution of EUVE. Determining excitation temperatures in individual ions from line ratios complements the *DEM* derivation involving numerous different ionization stages. The issue of differences between coronal and photospheric abundances is a potentially exciting area which has not even begun to be explored on other stars.

The ability to measure mass motions from Doppler shifts will have to await a higher resolution capability such as FUSE. A possible exception to this lies in very high outflows during flares. Bookbinder, Walter, and Brown (1992) found a redshift in the C IV line observed by HST during a flare on AD Leo indicating a peak velocity of 1800 km s^{-1},

Table 2. Prominent EUV Spectral Lines

λ_{lab}(Å)	Ion	log T_{max}	AR or Flare
91.02	Fe XIX	6.8	AR,FL
93.93	Fe XVIII	6.7	AR,FL
97.88	Fe XXI	7.0	FL
98.13	Ne VIII	5.8	AR
98.26	Ne VIII	5.8	AR
101.55	Fe XIX	6.8	FL
102.21	Fe XXI	7.0	FL
103.95	Fe XVIII	6.7	AR,FL
108.37	Fe XIX	6.8	AR,FL
109.97	Fe XIX	6.8	FL
111.70	Fe XIX	6.8	FL
114.39	Fe XXII	7.0	FL
117.17	Fe XXII	7.0	FL
117.51	Fe XXI	7.0	FL
118.66	Fe XX	6.9	FL
120.00	Fe XIX	6.8	FL
121.83	Fe XX	6.9	AR,FL
128.73	Fe XXI	7.0	FL
132.84	Fe XXIII	7.1	FL
135.78	Fe XXII	7.1	FL
142.16	Fe XXI	7.0	FL
148.37	Ni XI	6.2	AR
171.08	Fe IX	6.0	AR
172.17	O V	5.4	AR
173.08	O VI	5.5	AR
174.53	Fe X	6.0	AR
177.24	Fe X	6.0	AR
180.41	Fe XI	6.1	AR
182.17	Fe XI	6.1	AR
183.95	O VI	5.5	AR
184.54	Fe X	6.0	AR
185.23	Fe VIII	5.8	AR
187.45	Fe XI	6.1	AR
188.22	Fe XI	6.1	AR
192.03	Fe XXIV	7.2	FL
192.40	Fe XII	6.2	AR
193.52	Fe XII	6.2	AR
195.13	Fe XII	6.2	AR
202.04	Fe XIII	6.3	AR
211.32	Fe XIV	6.4	AR

Table 2. Prominent EUV Spectral Lines (*continued*)

λ_{lab}(Å)	Ion	log T_{max}	AR or Flare
220.09	Fe XIV	6.4	AR
220.35	O V	5.4	AR
224.74	S IX	6.0	AR
224.76	Fe XV	6.3	AR
225.03	Si IX	6.0	AR
233.87	Fe XV	6.4	AR
243.80	Fe XV	6.4	AR
256.32	He II	5.0	AR
256.68	S XIII	6.4	AR
257.38	Fe XIV	6.4	AR
264.80	Fe XIV	6.4	AR
270.51	Fe XIV	6.4	AR
274.22	Fe XIV	6.4	AR
284.15	Fe XV	6.4	AR
291.97	Ni XVIII	6.5	AR
303.30	Si XI	6.2	AR
303.78	He II	5.0	AR
335.41	Fe XVI	6.4	AR
360.80	Fe XVI	6.4	AR
368.07	Mg IX	6.1	AR

well within the resolution capability of the EUVE spectrographs, although probably too short-lived to yield many photons.

Two of the first coronal spectra taken by EUVE were those of Capella (G8III+G0III), obtained 1992 December 10–13 during the calibration phase (Dupree et al. 1993), and χ^1 Ori (G0V) acquired 1993 January 26–30 during the first month of the Guest Observer Program (Haisch, Drake, and Schmitt 1994, HDS). Ayres (1988) interprets the Capella pair as follows: Both are approximately 3 $M_\odot$ stars with an age of 250–300 Myr. The rapidly rotating (36 ± 3 km s^{-1}) secondary G0III star is evolving off the MS, while the slowly rotating (5 ± 2 km s^{-1}) G8III primary is already in a core helium burning blue-loop phase. It is the rapidly rotating G0III secondary that has the more intense chromospheric and transition region emission (by a factor of 5 to 10); this can be obtained from the radial velocity splitting of lines during the 104 day period, which cannot of course be done for coronal emission. By contrast, χ^1 Ori is a 1 $M_\odot$ MS star, a younger, more rapidly rotating (9 ± 0.2 km s^{-1}) twin of the Sun.

Figure 1 shows the short-wavelength spectra of Capella (from Dupree et al.; top) and χ^1 Ori (from HDS; bottom) along with a simulation (middle). The simulation was calculated to model χ^1 Ori using the Mewe, Gronenschild, and van den Oord (1985) plasma code together with a solar active region *DEM* from Dere (1982) extrapolated to zero above 10^7. The simulation was normalized to yield the correct number of counts for χ^1 Ori in the EUVE all-sky survey in the Lexan/B band. Several predicted lines,

especially in the medium-wavelength spectrum (see Figure 2 in HDS) match very well in terms of absolute predicted counts; others are conspicuously absent. However the (unplanned) match to the Capella spectrum is remarkable, giving us confidence in the accuracy of the plasma code. (The 171 Å line appears in the medium-wavelength Capella spectrum, see Figure 1 in Dupree et al.)

Based on these two stellar spectra, solar data, and the simulation, we list 40 of the strongest lines in Table 2. What can we learn from measurement of such lines? It is important, of course, to ascertain that we have the correct line identifications, and that line fluxes are not contaminated by blending with other, weaker lines. Theoretical branching ratios are known for a number of the line pairs originating in the same ion. Dupree et al. (1993), for example, cite the following: Fe XVI $\lambda335.41/\lambda360.80 = 2.18$; Fe XVIII $\lambda103.95/\lambda93.92 = 0.38$; Fe XIX $\lambda111.70/\lambda101.55 = 0.39$; Fe XIX $\lambda109.97/\lambda101.55 = 0.51$; and Fe XIX $\lambda120.00/\lambda108.37 = 0.27$.

The tool that has not heretofore been available for stellar coronal physics is the ability to determine electron densities from line ratios. Dupree et al. have used three pairs of line ratios, all of Fe XXI forming at 10^7, to estimate the electron density at that temperature in the spectrum of Capella. The range found from these three pairs has an uncomfortably large spread, $n_e \approx 4 \times 10^{11} - 10^{13}$ cm^{-3}. On the Sun, densities range from a few times 10^{10} to a maximum (measured) of 4×10^{12} cm^{-3} (see HSR). The filling factors of solar flares appear to be very small (< 0.01, see HSR). The conditions in the 10^7 K component of the Capella corona would thus appear to be similar to a solar flare. In the χ^1 Ori spectrum material also appears to be present at temperatures as hot as $\log T = 7.2$. Preliminary analysis of the EUV spectrum of the G0III Hertzsprung gap star 31 Com by Ayres (priv. comm.) indicates an extremely hot spectrum dominated by Fe XXIII with very high density inferred from Fe XXI, as in Capella. It is certainly interesting that these first EUVE coronal spectra indicate flare-like components in seemingly quiescent coronae.

Regarding the hypothesis of a universal shape for the DEM, Dupree et al. argue that this is not the case for Capella. They believe that the emission measure distribution has a minimum near 10^6 rather than near 10^5 as on the Sun. This would be a major finding.

FLARES AND VARIABILITY

Since the deep survey imaging telescope observes the brightness of the star whose spectrum is being obtained, one has a simultaneous $65 - 190$ Å light curve to monitor for flares. An example of such an event is the large flare on AU Mic on 1992 July 15 (Cully et al. 1993). More than one flare was observed, and other flare observations are discussed elsewhere in these proceedings (see for example the article by Vedder). The accompanying spectra can then be broken out into different flare and quiescent stages. Abbott, Cully, and Fisher (1993) derive time-dependent DEM during the evolution of the AU Mic flare. Cully et al. (1994) model this event as a Coronal Mass Ejection-like phenomenon involving 10^4 times as much mass and energy as the largest solar CME.

Yet another flare star was the subject of a successful coordinated observing campaign. From 1993 March 1–3 AD Leo was monitored by T. Simon. At least two EUV flares are evident, and a particularly exciting result is the observation of simultaneous dips in the optical flux (McDonald Obs. and Lick Obs.) lasting several minutes suggest-

ing prominence eruption or other mass ejection associated with the flares. Strong Fe lines appear in the $\lambda 170 - 190$ Å region of the flare spectrum (S. Cully, priv. comm.).

The largest stellar flares that we are aware of occur on RS CVn's (HSR). In fact, recently a new record may have been achieved with a 9-day long outburst involving more than 4.5×10^{36} ergs (see the article by Kürster, these proceedings). Even thought the RS CVn systems are much more distant on average than the flare active dMe stars, the enormous energies, frequent occurrence, and the fact that the $T \geq 10^7$ K emission lines fall primarily in the shorter wavelengths where the ISM attenuation is less important, make the observation of RS CVn flare lines quite likely during spectroscopy of these stars. The $t > 34$ ks EUV event on II Peg is a good example of what we might expect (Patterer et al. 1993). Simulations indicate that 4 ks events (not to mention 34 ks or 800 ks events!) on such objects as UX Ari and BH CVn should yield good short-wavelength flare spectra.

Looking to longer time scales of variability there are several possibilities to search for activity cycles analogous to the 11-year solar cycle. Drake et al. (1993) are comparing the EUVE all-sky survey fluxes to those from the WFC two years before. Pointings and flux measurements during the right angle program are providing new data points. The possibility of resurveying all or part of the sky to study variability is an option being explored.

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