ULTRAVIOLET OBSERVATIONS OF STELLAR CORONAE: EARLY RESULTS FROM HST

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ABSTRACT. I report on the first GHRS spectra of two very different late-type giant stars – Capella and γ Dra. Capella is a 104 day period binary system consisting of two stars (G9 III and G0 III) each of which shows bright emission lines formed in solar-like transition region and corona. By contrast, γ Dra is a hybrid-chromosphere star with very weak emission lines from high-temperature plasma. Low-dispersion spectra of these stars covering the 1160 to 1717 Å spectral range show unresolved emission lines from neutral species through N V. The very different surface fluxes detected in the spectra of these stars suggest different types of heating mechanisms. Moderate dispersion spectra of Capella show intersystem lines of C III, N III, O III, O IV, Si III, and S IV, which provide electron density diagnostics. Echelle spectra of hydrogen and deuterium Lyman-α, Fe II, and Mg II permit measurements of the cosmologically interesting D/H ratio and the properties of the interstellar medium on the 13 pc line of sight to Capella.

1. Observing stellar coronae in the ultraviolet

Although coronae of stars other than the Sun previously have been detected only in the X-ray and radio portions of the spectrum, the HST and future spacecraft sensitive to ultraviolet (UV) and extreme ultraviolet (EUV) light will have the spectral resolution to study the dynamics and spectroscopic diagnostics of hot coronal plasmas. In the UV region accessible to HST, forbidden lines of FeXII at 1242 and 1349Å, of FeXXI at 1354Å, and other species are seen in solar flares and are predicted to be present in the spectra of active stars. Upcoming observations with the Goddard High Resolution Spectrograph (GHRS) by S. Maran will search for these lines in the dM2e star AU Mic and other stars.

Stellar coronal studies with HST can, in principle, answer a number of questions that X-ray and radio studies cannot presently address. Among these questions are: (1) the nature of the systematic and stochastic mass motions of hot plasma in both quiet and flaring stars, (2) the importance of mass motions in the energy balance of the corona, (3) the existence of coronal plasma at 10⁵K and cooler temperatures in red giants and other stars, (4) coronal pressures from density-sensitive lines formed

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in the transition region, and (5) the location and size of active regions deduced by
“Doppler imaging” transition region lines.

I report here on observations of the active spectroscopic binary Capella
(G0 III + G9 III) and the inactive K5 III star γ Draconis, which is a member of
the class of hybrid-chromosphere stars (Hartmann, Dupree, & Raymond 1980) char-
acterized by high-velocity blue-shifted features due to a cool wind and faint emission
lines formed at temperatures up to 150,000K. The Capella UV emission line spectrum
is dominated by the more rapidly rotating G0 III star of the system (Ayres & Linsky
1980; Ayres 1988).

2. Capabilities of the Goddard High Resolution Spectrograph

The Goddard High Resolution Spectrograph on the HST places new observa-
tional capabilities in the hands of astronomers studying the atmospheres of stars and
the interstellar medium. Both IUE and Copernicus have obtained ultraviolet spectra
of bright sources in the 1170–3200 Å spectral region, but the GHRS will expand our
observational capabilities enormously in at least four ways:

• The higher throughput of the GHRS and the low background of its Digicon detec-
tors support photon-limited observations of much fainter sources than heretofore
feasible, and allow the measurement of weak emission and absorption lines which
are buried in the noise of existing ultraviolet spectra.

• The GHRS can obtain spectra with signal/noise well in excess of 100:1 (Car-
penter et al. 1991), a major improvement over IUE. High S/N is critical for
measuring line profiles, Doppler-imaging experiments, and for studying individ-
ual velocity components in interstellar absorption lines.

• Small science aperture (SSA) spectra are not noticeably degraded in spectral reso-
novation by the spherical aberration of the Hubble primary. Wahlgren et al. (1991)
determined that at 1940 Å moderate dispersion G160M spectra have a resolu-
tion of 28,000 and the echelle spectra have a resolution of 87,000. Large science
aperture (LSA) spectra are degraded in resolution by a factor of 2 compared to
prelaunch expectations, but spectral deconvolution techniques can recover much
of the lost resolution for point sources when the signal/noise is sufficiently large.
Aside from echelle spectra of a few very bright sources obtained with a rocket
instrument, the GHRS is the highest resolution and most sensitive ultraviolet
spectrograph in operation.

• The very low scattered light level of the GHRS gratings and the solar-blind
detectors make observations of the ultraviolet spectra of very red stars possible.
These properties are essential for studies of interstellar deuterium, for example.

In this paper I provide examples of these new capabilities, which will yield
major scientific benefits in the study of cool stars and the interstellar medium. At
the same time, one should recognize that IUE beautifully complements the strengths
of the GHRS by its broad spectral coverage in single exposures, its ability to monitor
sources over many time scales, and its continuing success in observing targets of
opportunity.
3. Low Dispersion Spectra of Cool Giants

On 15 April 1991 as part of a GTO program we obtained low dispersion G140L spectra of Capella, a 104 day spectroscopic binary system consisting of a slowly rotating G9 III primary (Capella Aa) and a more rapidly rotating G0 III secondary (Capella Ab). (See Batten, Hill, & Lu 1991 for a discussion of the system parameters.) On the basis of phase-resolved IUE spectra, Ayres and Linsky (1980) showed that the G0 III star dominates the ultraviolet emission line spectrum of the system. During SV, we obtained on 6 April 1991 low dispersion spectra of the K5 III star $\gamma$ Draconis, a member of the class of hybrid-chromosphere giants. The ultraviolet spectra of such stars are characterized by high-velocity blue-shifted absorption features due to a cool wind (75–200 km s$^{-1}$) and faint emission lines formed at temperatures up to 150,000K (Hartmann, Dupree, & Raymond 1980; Drake, Brown, & Linsky 1984).

Low dispersion spectra with the G140L grating provide a means of rapidly observing broad spectral regions (288 Å at one time) with enough spectral resolution (2,000 with the SSA and roughly 1,000 with the LSA) to measure the fluxes of most important emission lines, although higher resolution spectra are needed to separate close blends. Let us first inspect the low dispersion spectra to identify the major differences between an “active” star like Capella Ab and a very inactive star like $\gamma$ Dra.

Figures 1 and 3, which display the 1170–1710 Å region of Capella, should be compared with Figures 2 and 4, which display the 1260–1740 Å region of $\gamma$ Dra. One notes immediately that the spectrum of Capella is dominated by bright emissions, including the resonance lines of C II, Si IV, C IV, and N V formed at temperatures of 20,000–150,000K (see Table 1). The brightest feature is Lyman-\(\alpha\), despite strong interstellar hydrogen absorption in its core (see below). In the Sun the H I resonance line forms at 40,000K as a result of ambipolar diffusion (Fontenla, Avrett, & Loeser 1991), and we suspect that it arises at similar temperatures in Capella. Emission lines of other neutral species form in the chromosphere at $T \leq 8,000K$ and are very weak, except for the C I multiplet near 1657 Å.

### Table 1. Comparison of Emission Line Surface Fluxes (log units)

<table>
<thead>
<tr>
<th>Multiplet</th>
<th>log$T$</th>
<th>Sat. Limit</th>
<th>V711 Tau (RS CVn)</th>
<th>Capella (G0III)</th>
<th>Sun (G2V)</th>
<th>$\gamma$ Dra (K5III)</th>
<th>$\alpha$ Boo (K2III)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C IV 1549 Å</td>
<td>5.0</td>
<td>6.0</td>
<td>5.62</td>
<td>5.43</td>
<td>3.73</td>
<td>2.08</td>
<td>&lt;2.00</td>
</tr>
<tr>
<td>Si IV 1400 Å</td>
<td>4.8</td>
<td></td>
<td>5.05</td>
<td>4.88</td>
<td>3.37</td>
<td>1.60</td>
<td>&lt;2.00</td>
</tr>
<tr>
<td>Si III 1892 Å</td>
<td>4.6</td>
<td></td>
<td>4.68</td>
<td>5.26</td>
<td></td>
<td>1.82</td>
<td></td>
</tr>
<tr>
<td>C II 1334 Å</td>
<td>4.3</td>
<td></td>
<td>5.46</td>
<td>5.20</td>
<td>3.67</td>
<td>1.93</td>
<td>&lt;2.00</td>
</tr>
<tr>
<td>O I 1304 Å</td>
<td>3.9</td>
<td></td>
<td>5.24</td>
<td>4.85</td>
<td>3.62</td>
<td>3.70</td>
<td>3.75</td>
</tr>
<tr>
<td>C I 1657 Å</td>
<td>3.8</td>
<td></td>
<td>5.07</td>
<td>5.01</td>
<td></td>
<td>2.51</td>
<td>2.84</td>
</tr>
<tr>
<td>Mg II 2800 Å</td>
<td>3.8</td>
<td>7.2</td>
<td>6.82</td>
<td>6.92</td>
<td>6.07</td>
<td>4.73</td>
<td>5.25</td>
</tr>
</tbody>
</table>

The low dispersion ultraviolet spectrum of $\gamma$ Dra shows a very different appearance: both Lyman-\(\alpha\) and the O I 1304 Å multiplet dominate over the high-temperature lines. The conditions under which Lyman-\(\alpha\) forms in inactive K giants...
Figure 1.: The GHRS low dispersion spectrum of Capella obtained with the G140L grating. The 1170–1450 Å spectrum contains emission lines formed at 20,000–150,000K.

Figure 2.: The GHRS low dispersion spectrum of γ Draconis obtained with the G140L grating. The 1260–1550 Å spectrum contains the bright O I resonance line multiplet (1302, 1304, and 1306 Å) blended with S I lines. The high-temperature transition region lines are very weak compared to those in the Capella spectrum. The fourth positive bands of CO are indicated. There are many weak emission lines that are not identified here, but no evidence for photospheric or other continua.
Figure 3.: Same as Fig. 1 except for the 1425–1710 Å region. This spectrum is dominated by the C IV resonance lines formed at 100,000K. Note the HeII 1640 Å line and the intersystem O III] line at 1666 Å, which is a part of a density-sensitive multiplet. The underlying continuum is from the G0 III star in the system.

Figure 4.: Same as Fig. 2 except for the 1450–1740 Å region. Unlike the Capella spectra, low-temperature emission lines dominate over the high-temperature C IV lines. There is no evidence for a photospheric continuum in this spectrum or out to 1840 Å.
are not known, but the O I lines arise in the chromosphere as a result of pumping by Lyman-\(\beta\) (Haish et al. 1977). The other prominent emission lines are from neutral species and fourth positive bands of CO, all characteristic of temperatures below 8,000K. While the CO bands could be identified in IUE spectra of Arcturus (Ayres, Moos, & Linsky 1981; Ayres 1986), the GHR spectra are of much higher signal/noise and will permit more detailed analysis. The high temperature resonance lines of C II to N V all are present, but are very weak compared with the low-temperature emission lines.

The qualitative difference in the spectra of Capella and \(\gamma\) Dra can be made quantitative by converting the observed emission line fluxes to surface fluxes, by dividing by the square of the stellar angular radii. The latter may be inferred simply from the stellar visual magnitudes and colors (Linsky et al. 1979). The resulting surface fluxes are listed in Table 1, together with corresponding values for the more active RS CVn system, V711 Tau (Byrne et al. 1987), the quiet Sun (Ayres, Marstad, & Linsky 1981), and the slowly rotating K giant Arcturus (\(\alpha\) Boo; Ayres, Simon, & Linsky 1982). Mg II and other chromospheric line fluxes were obtained from Ayres et al. (1982) and Simon, Linsky, & Stencil (1982). I also list the maximum observed C IV and Mg II surface fluxes for the youngest and most rapidly rotating stars without obvious circumstellar disks. Vilhu (1987) calls these fluxes “saturated” in the sense that they represent the maximum radiative emission from a star completely covered with “active regions”, which undoubtedly are locations of strong magnetic fields.

Table 1 indicates that the surface fluxes of the high-temperature lines of Capella Ab lie about a factor of 3 below the saturated limit, and those for the short-period V711 Tau system lie even closer to that limit. A natural explanation for the behavior is that a large fraction of the surface area of these active stars is covered by “plages” where the magnetic fields are strong and the heating rate is at or near its maximum possible value. Indeed, large plages have been identified on the surface of AR Lac by Doppler imaging techniques (Neff et al. 1989), and Linsky (1990) has shown that the surface fluxes in the plages of the RS CVn systems AR Lac, II Peg, and V711 Tau are near the “saturated” limit.

On the other hand, the surface fluxes for the high temperatures lines for \(\gamma\) Dra lie nearly a factor of 10,000 below the “saturated” limit. They are, in fact, the smallest surface fluxes ever measured on a cool star. Previously, the smallest values were the uncertain upper limits for \(\alpha\) Boo listed in Table 1 obtained with IUE. One could interpret the very small surface fluxes of high-temperature lines on \(\gamma\) Dra as indicating that the fraction of the surface of such slowly rotating inactive stars which is covered by active regions is \(\sim 10^{-4}\), less than 10% of the plage coverage of the quiet Sun. The hypothesis is reasonable, but not easily tested observationally. Other possible heating mechanisms include acoustic waves generated by the known convective motions in the photosphere, or perhaps magnetoacoustic waves if weak magnetic fields are present. Cuntz (1987) and Cuntz & Luttermoser (1990) have computed models of the K giant star \(\alpha\) Boo in which a stochastic distribution of acoustic wave periods leads to the occasional coalescence of individual shocks into very strong fronts that produce high-temperature plasma. Our observations of \(\gamma\) Dra
and our proposed observations of α Boo and other stars will extend the measurement of surface fluxes to even smaller values to test these and other competing theories.

4. Moderate Dispersion Spectra of Cool Giants

Let us now inspect the moderate dispersion spectra of Capella obtained through the LSA during our GTO program. These spectra have a nominal resolving power of 10,000 or 30 km s\(^{-1}\). Figure 5 shows a spectrum containing the C IV resonance lines obtained with the G160M grating. These line profiles appear to be smooth Gaussians with no identifiable structure or splitting. Since the components of the Capella system have a radial velocity separation of 53.5 km s\(^{-1}\) at phase 0.26, the absence of splitting or line asymmetry confirms that one star, the G0 III component as determined in previous studies, contributes most of the flux. The absence of line structure indicates that no single bright plage was on the surface of the G0 III star, as is consistent with earlier studies. However, more active RS CVn systems like AR Lac show enhanced discrete features in their Mg II emissions, superimposed on otherwise smooth line profiles: these are thought to be produced by bright plages that are Doppler-shifted by stellar rotation. We will observe the C IV lines in AR Lac at many phases to map the location of bright plage regions using the Doppler imaging technique.

The FWHM of the C IV 1548 Å line is 217 km s\(^{-1}\), while for the 1550 Å line it is 186 km s\(^{-1}\). These widths are much larger than the predicted thermal width, \(\Delta \lambda_D = 14.4\) km s\(^{-1}\), and the instrumental width of 30 km s\(^{-1}\), but are consistent with IUE observations at quadrature (Ayres 1984). The line flux ratio \(f_{1548}/f_{1550} = 1.77\) is significantly smaller than the 2.0 ratio of \(gf\) values. These data indicate that both turbulence and opacity broaden these lines, and that the more opaque line is optically thick. Such data will provide new constraints on acceptable model atmospheres for Capella and other stars.

4.1 Density-sensitive Line Ratios

Figure 6 illustrates the Si III] and C III] intersystem lines in a moderate dispersion G200M spectrum. The line fluxes can be measured without too much confusion above the photospheric absorption line spectrum of the star. Intersystem lines of O III] at 1660 and 1660 Å are shown in Figure 7, and the intersystem lines of O IV] and S IV] are depicted in Figure 8. To our knowledge, the S IV] features have never been detected previously in a stellar spectrum, except for the Sun, while the other intersystem lines have been detected by IUE in the spectra of several stars but with poor signal/noise. Clearly the GHRS can measure accurate fluxes for these faint lines. Note that the FWHM = 124 km s\(^{-1}\) for the Si III] line, while the predicted thermal width is \(\Delta \lambda_D = 6.0\) km s\(^{-1}\), and the instrumental width is 30 km s\(^{-1}\). The narrower width of this line compared to the C IV 1550 Å line is consistent with Si III] being turbulent broadened with no opacity broadening, as is expected for optically thin intersystem lines.

Intersystem lines are important, because they provide independent measures of the electron density at the plasma temperatures where the ions are abundant. This
Figure 5. A GHRS moderate dispersion spectrum of Capella obtained with the G160M grating. The C IV resonance lines are well-resolved in this spectrum. The profiles are smooth with no evidence for isolated plage regions on the surface of the G0 III star.

Figure 6. A GHRS moderate dispersion spectrum of Capella obtained with the G200M grating. The intersystem lines of Si III and C III are in emission superimposed on the photospheric absorption line spectrum.
Figure 7.: A GHRS moderate dispersion spectrum of Capella obtained with the G160M grating. Note the intersystem lines of O III], which provide density diagnostics.

Figure 8.: A GHRS moderate dispersion spectrum of Capella obtained with the G160M grating. Note the intersystem lines of O IV] and S IV], which yield density diagnostics.
can be seen by considering a simple three-level atom in which level 1 is the ground state, transition 1-3 is allowed, and transition 1-2 is an intersystem transition. For example, in Si III the 1-3 transition would be the $3s^2 \, 1S - 3s3p \, ^1P$ resonance line at 1206 Å, and the 1-2 transition would be the $3s^2 \, 1S - 3s3p \, ^3P$ intersystem line at 1892 Å. The statistical equilibrium equations for this three-level atom, ignoring stimulated emission, are:

$$n_1 [n_e \Omega_{12} + B_{12} \bar{J}_{12}] = n_2 [n_e \Omega_{21} + A_{21}]$$

$$n_1 [n_e \Omega_{13} + B_{13} \bar{J}_{13}] = n_3 [n_e \Omega_{31} + A_{31}],$$

where $n_i$ is the population of level $i$, $n_e \Omega_{ij}$ is the collisional rate for the $i-j$ transition, $\bar{J}_{ij}$ is the mean radiation intensity over the $i-j$ line, and $A_{ij}$ and $B_{ij}$ are the Einstein coefficients. Since the observed flux $f_{ij} \propto n_j A_{ij}$ for optically thin lines, the flux ratio of the permitted to the intersystem line is

$$\frac{f_{31}}{f_{21}} \approx \frac{\nu_{31}}{\nu_{21}} \frac{\Omega_{13}}{\Omega_{12}} \left( \frac{n_e \Omega_{21}}{A_{21}} + 1 \right).$$

Here $\nu_{ij}$ is the transition frequency, and I have neglected the terms in $\bar{J}_{12}$ and $\bar{J}_{13}$ because I assume the lines are optically thin. I also neglect the $n_e \Omega_{31}$ term in comparison to $A_{31}$.

When the first term in the parentheses in the above equation becomes appreciable, i.e., when $n_e \geq 0.1A_{21}/\Omega_{21}$, then collisional de-excitation of the upper state of the intersystem line is important and the flux ratio depends explicitly on the electron density. At higher densities collisional de-excitation from the upper state of the allowed transition (not included in the above equation) also becomes important, and the flux ratio is no longer sensitive to density. Table 2 summarizes the density range over which the prominent ions with ultraviolet intersystem lines are density sensitive. Figures 6–9 demonstrate that the GHRS can record beautiful spectra of these lines, thus it can provide the observational basis for accurate numerical models of stellar chromospheres and transition regions for late-type stars. An example is the model of β Dra computed by Brown et al. (1984) on the basis of earlier IUE spectra.

Table 2. Density-sensitive Line Ratios in the 1170–2350 Å Region

<table>
<thead>
<tr>
<th>Ions</th>
<th>logT</th>
<th>Wavelengths (Å)</th>
<th>Range of log(N_e)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C II</td>
<td>4.0</td>
<td>2323.5, 2324.7, 2325.4, 2326.9, 2328.1</td>
<td>7–9</td>
</tr>
<tr>
<td>Si III</td>
<td>4.6</td>
<td>1294.5–1303.3 (6 lines), 1892.0</td>
<td>9–12</td>
</tr>
<tr>
<td>O III</td>
<td>4.6</td>
<td>1660.8, 1666.2</td>
<td>9–13</td>
</tr>
<tr>
<td>N III</td>
<td>4.8</td>
<td>1746.8, 1748.6, 1749.7, 1752.2, 1754.0</td>
<td>8–10</td>
</tr>
<tr>
<td>S IV</td>
<td>4.9</td>
<td>1404.8, 1406.0, 1416.9</td>
<td>10–13</td>
</tr>
<tr>
<td>O IV</td>
<td>5.1</td>
<td>1397.2, 1399.8, 1401.2, 1404.8, 1407.4</td>
<td>8–12</td>
</tr>
<tr>
<td>O V</td>
<td>5.4</td>
<td>1218.4</td>
<td>10–13</td>
</tr>
</tbody>
</table>

5. High Dispersion Spectra

I discuss finally our beautiful echelle spectra of Capella obtained through the SSA, which have a measured spectral resolution (Wahlgren et al. 1991) of 87,000,
Figure 9.: A GHRS moderate dispersion spectrum of Capella obtained with the G140M grating. The Si III lines yield density diagnostics.

Figure 10.: A GHRS high-dispersion spectrum of Capella obtained with the Ech-B grating. Each of the Mg II resonance lines (2796 and 2803 Å) shows the narrow interstellar absorption line and self-reversed emission from the G9 III star (to the right) and the G0 III star (to the left).
corresponding to 3.4 km s$^{-1}$. Our objective in obtaining these spectra was to determine the D/H ratio and the physical properties of the interstellar medium along the 13 pc line of sight towards Capella. For this purpose Capella is a bright emission line source against which one measures the opacity of resonance lines formed in the interstellar medium. These data also are useful for other purposes as we shall see.

Figure 10 illustrates spectra of the Mg II h (2803 Å) and k (2796 Å) resonance lines obtained with the Ech-B grating. These tracings show the narrow interstellar absorption lines, which are spectrally resolved and do not go to zero flux after correction for scattered light. The analysis of the line profiles provides information on both the line opacity and broadening. To the right of the interstellar lines one can see the self-reversal of the emission line from the G9 III star, and to the left one can see a portion of the self-reversal of the emission line from the G0 III star. These features are barely present in IUE spectra at this phase. The shape of the composite emission line will be useful in testing chromospheric models of these stars.

The Ech-A spectrum of the Lyman-α region is depicted in Figure 11. The broad stellar Lyman-α emission line is modulated by the interstellar hydrogen Lyman-α absorption feature and a narrow interstellar feature due to deuterium Lyman-α centered at -0.32 Å relative to the hydrogen absorption line. The deuterium line has been seen in Copernicus and IUE spectra of Capella (e.g. Murthy et al. 1990) and other stars, but this spectrum is the first in which the line has been spectrally resolved. The small amount of instrumental scattered light can be measured from the minimum flux seen in the saturated interstellar core of the hydrogen absorption line. The central depth of the deuterium feature is a measure of its optical depth.

Figure 11.: A GHRS high-dispersion spectrum of Capella obtained with the Ech-A grating. Superimposed on the stellar Lyman-α emission line is interstellar absorption due to hydrogen and deuterium.
while the shape of the hydrogen absorption feature can be used to measure the hydrogen optical depth. A detailed analysis of this spectrum, now under way, will provide a very accurate measurement of the D/H ratio along that line of sight: a key to inferring the primordial D/H ratio, a major constraint on models of the very early universe.

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6. References


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