OBSERVING STELLAR CORONAE WITH THE GODDARD HIGH RESOLUTION SPECTROGRAPH. II. THE RS CVn BINARY SYSTEM HR 1099

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ABSTRACT

We report time series observations of the RS CVn star HR 1099 taken with the Goddard High Resolution Spectrograph onboard the Hubble Space Telescope. The data cover a wavelength range from 1342 to 1375 Å and show a measurable continuum, as well as emission lines of O i, C i, Cl i, Fe ii, O vi, and Fe xxi. The chromospheric and transition region features are seen only in the active K1 IV component of the binary system, while the Fe xxi (10^7 K) flux may come from both components, with the active component having the stronger flux. There is no indication of Fe xii emission, formed at 1.3 × 10^6 K. The width of the Fe xxi profile indicates that the corona of the primary is unlikely to extend to heights greater than 2.3R*, while other indicators suggest that the average loops are really much smaller, having a length of ~3 × 10^10 cm with an electron density on the order of 10^10 cm^-3. Some evidence for atmospheric turbulence is detected in all of the observed emission lines. This turbulence initially increases with height, going from less than 30 km s^-1 in the chromosphere to as much as 150 km s^-1 in the transition region. The turbulence then decreases in the corona, where velocities of less than 65 km s^-1 are indicated. Theoretical fits to the O vi profile also suggest that this turbulence is anisotropically distributed, with motions directed primarily along or perpendicular to the radial direction. While admitting that the atmosphere is heated by micro flare events, we examine an alternative heating process that involves the damping of MHD turbulence, which might be generated by nonlinear Alfvén waves or by shocks. Simple calculations indicate that the observed turbulence is sufficient to account for the transition region and coronal heating.

Subject headings: stars: chromospheres — stars: coronae — stars: individual (HR 1099) — ultraviolet: stars

1. INTRODUCTION

HR 1099 (= HD 22468, V711 Tau) is one of the most thoroughly studied of all RS CVn binary systems. It is composed of an active K0 IV star and a much less active G0 IV star in a 2.84 day orbit (Fekel 1983), and it has numerous examples of magnetically related activity. Photometric variability and Doppler imaging techniques have indicated the presence of variable dark spots on the surface of the K1 component. Strong quiescent emission has been observed in chromospheric, transition region, and coronal lines, as well as in radio and soft X-ray continuum. This radiation varies on timescales of hours to years (e.g., Dorren & Guinan 1990). Occasionally, extremely powerful flare events are observed, lasting for up to 1 hr and having energies of up to 10^38 ergs, more than 10^6 times the energy in the largest solar flare (Foing et al. 1984).

To study this system in more detail, we undertook an observing program that used the Goddard High Resolution Spectrograph onboard the Hubble Space Telescope (HST), in order to examine the spectral region centered at 1360 Å at moderate spectral resolution. As discussed by Maran et al. (1994, hereafter Paper I), this wavelength region is unique in that it contains spectral lines formed at a wide range of temperatures, including the following: Cl i, O i, and C i lines formed near 10^4 K; O vi λ1371 formed near 2.5 × 10^5 K; Fe xii λ1349 formed at 1.3 × 10^6 K; and Fe xxi λ1354 formed at 10^7 K. This is the only spectral region available to the HST that contains spectral lines formed at coronal temperatures.

The primary objective of the program was to look for short-term transient activity and the temporal relation between the plasma at different temperatures during these transients. We also planned to search for nonthermal line broadening in the coronal plasma, which might be related to the broadening of transition region lines, recently reported by Linsky & Wood (1994) for the dMe flare star AU Mic and by Wood et al. (1996, hereafter WHLD) for HR 1099. This broadening is thought to be closely related to the processes heating the stellar atmosphere.

In § 2, we describe the data and the reduction processes. Section 3 describes the observational results regarding both time variability and the analysis of the spectral lines in a time-integrated spectrum. Section 4 uses the observations to place constraints on the density, extent, and magnetic structure of the corona. We also discuss the possible atmospheric heating mechanisms, with particular emphasis on heating by MHD turbulence.

2. OBSERVATIONS AND DATA ANALYSIS

The observations were obtained on 1994 March 24, using the Goddard High Resolution Spectrograph onboard the Hubble Space Telescope, and are nearly identical to data
taken earlier of the dMe star AU Mic (Paper I). The data
consist of time sequences of spectra taken with the rapid
readout mode of operation, with one time sequence
acquired during each of eight consecutive HST orbits. Each
time sequence was 27 minutes long and contained approxi-
ately 4100 spectra (often referred to as readouts), with
diurnal exposure times of 0.4 s. The star was observed
through the 2" square Large Science Aperture (LSA) using
the G160M grating. The resultant spectra cover a 36 A
wavelength range, extending from 1342 to 1378 Å with a
sample spacing of 0.0715 Å diode⁻¹ (16 km s⁻¹ diode⁻¹).
The instrumental profile for LSA observations has improved
considerably since the installation of HST corrector
optics (COSTAR) and now has a FWHM ~ 1.6 diodes,
compared with the pre-COSTAR profiles, which had wings
extending out to ± 4 diodes. To ensure maximum wave-
lengt accuracy, each time sequence was bracketed by
observations of an onboard Pt wavelength calibration
lamp.

During the course of an orbit, the wavelengths observed
by the GHRS are subject to various drifts caused by vari-
tions in the instrumental temperature and the interaction of
the detector with Earth's magnetic field. The magnitude of
these variations was determined from models derived by the
GHRS instrument team, as well as by comparing the wave-
lenght calibration exposures taken before and after the time
sequence. The drifts were found to be smaller than one
diode width in all of the data sets and were therefore
neglected in the analysis. The wavelength scale for each
time sequence was determined from the average of the two
associated wavelength calibration exposures.

The total number of counts in an individual 0.4 s readout
are highly dependent upon the level of the background radia-
tion, which is caused primarily by Cerenkov radiation from
cosmic rays passing through the window of the detector (e.g., Beaver et al. 1991). Normally, an individual
space ray event will result in only one or two photons and
cannot be easily differentiated from simple statistical fluc-
tuations in the stellar flux, which averaged about four photons for every readout in this data set. Occasionally,
however, an extremely energetic particle will create a burst
of up to several hundred photons. To eliminate these events,
we assumed that the data could be described by Poisson
statistics. We then selected all readouts in which the total
number of counts detected, C, was more than three stan-
dard deviations greater than the average count for that time
period 〈C〉, i.e., C > 〈C〉 + 3〈C〉 ⅓. If these were isolated


3. RESULTS
3.1. Radial Velocity Variations

Integrating each of the time sequences over its entire
duration results in spectra having a S/N of up to 15 in the
emission lines. Examination of these spectra show a persist-
ent drift in the central wavelengths of the lines, caused by
the orbital motion of the stars. To quantify these motions,
we start by cross-correlating each spectrum against the first
and then shifting and adding the spectra to generate a final
spectrum with an S/N of up to 40:1 in the emission lines and
a wavelength scale appropriate to the first orbit. This is
shown in Figure 1. The radial velocities of the strong emis-
sion lines of CI and O I were then determined using a
Gaussian fitting routine. These resulted in a average radial
velocity of 29 ± 2 km s⁻¹. The shifts found in the cross
correlations then allowed an accurate determination of the
average radial velocity of the other orbits (see Table 1). The
results are presented in Figure 2, which also shows the

<table>
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* The sum of all photons detected over the entire 27 minute time sequence.
* Data taken on 1994 March 23.
* Data taken on 1994 March 24.
3.2. Integrated Profiles

The spectrum in Figure 1 represents an effective 3.5 hr integration and has a total of 1700 counts at the peak of the strongest emission line. As will be discussed in § 3.3, there is no indication of strong flare activity during the observations, so the integrated spectrum essentially represents the quiescent state of the star. In Figure 3, we show the quiescent spectrum of the dMe flare star AU Mic, taken with the same experimental setup and a similar total integration time. The maximum number of counts for each diode for this spectrum is 250. Note the much weaker CI lines in HR 1099 and the presence of a continuum. Overall, though, the two spectra have a very similar appearance, with pronounced CI, O I, Fe xxii, and O V emission, but no indication of the Fe xii line at 1350 Å.

The emission lines were analyzed by fitting the observations with a Gaussian profile of adjustable width, strength, and central wavelength. The results of the analysis for HR 1099 are presented in Table 2, while the results of a similar analysis of AU Mic are presented in Paper I. The absolute radial velocity of the lines in HR 1099 are somewhat uncertain. However, it is important to notice that there is no evidence for significantly different values of radial velocity, as measured by lines formed at different temperatures. The most obvious difference between the spectra of the two stars is in the line widths, which are much more pronounced in HR 1099, even after removing a rotational broadening with

![Fig. 1. Calibrated spectrum of HR 1099 derived by summing data taken during more than 3.5 hr of observations (during eight spacecraft orbits). Data have been corrected for radial velocities of the star, the effects of bad diodes, and vignetting, and the background noise has been subtracted, as explained in the text. Peak emission line has an integrated count of 1700 above a background of 100 counts.](image1)

![Fig. 2. Measured radial velocity of spectra taken during each of eight consecutive HST orbits (crosses) as a function of orbital phase. The expected radial velocity for each component of the system, taken from the ephemeris of Fekel (1983), is shown for comparison.](image2)

![Fig. 3. Calibrated spectrum of the dMe star AU Mic, taken with the same experimental setup as used for the HR 1099 observations. Peak emission line has 250 counts above a background of 60 counts.](image3)

<table>
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<tr>
<th>Measured Wavelength (Å)</th>
<th>Laboratory Wavelength (Å)</th>
<th>Flux (× 10⁻¹⁴ ergs cm⁻² s⁻¹)</th>
<th>FWHM (km s⁻¹)</th>
<th>Radial Velocity (km s⁻¹)</th>
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<td>O V No. 2</td>
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<td>200 ± 12</td>
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</table>

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$V \sin i = 38 \text{ km s}^{-1}$ (Fekel 1983). In Figure 4, we present expanded plots of the isolated Cl I and O I lines for HR 1099. The lines were not resolved in the AU Mic observations but are fully resolved in HR 1099. There is no indication of any emission from the G5 IV star, which should appear at a radial velocity of about $-75 \text{ km s}^{-1}$.

Figure 5 shows the O V line, which is also fully resolved. This line is much broader than the cooler Cl I and O I lines and has wings that are substantially wider than expected from a purely Gaussian profile. This behavior is similar to that previously reported by WHLD for other transition region lines on HR 1099.

Following WHLD, we can accurately fit the line using the superposition of two Gaussian profiles, one representing the core and the other the wings. The fit is shown in Figure 5a, and the properties of the fit are presented in Table 2. The broad component, with a FWHM of 200 km s$^{-1}$, represents 74% of the line flux and is not significantly displaced from the narrow component. The narrow component, on the other hand, is considerably narrower than any described by WHLD, with a width only slightly larger than that expected from a rotationally broadened thermal profile.

Figure 6 shows a detailed view of the Fe XXI line. Note that HR 1099 shows no indication of the C II blend, which is prominent in the AU Mic data. The main part of the profile in HR 1099 is consistent with a thermally broadened Gaussian at a temperature of $2.2 \times 10^7$ K, which is slightly hotter than the temperature of $2 \times 10^7$ K derived from...
X-ray observations (e.g., Dempsey et al. 1993) and located at the expected radial velocity of the primary. An excess emission on the blue wing of the line is consistent with a second Gaussian centered at the expected radial velocity of the secondary and having a width compatible with a temperature of $10^7$ K. This suggests that the secondary is also surrounded by a hot coronal plasma, although a final proof of this hypothesis will require a second observation taken when the secondary is at the opposite conjunction, so that emission from it shows up in the red wing of the profile. The profile also shows excess emission at a radial velocity of more than $-200$ km s$^{-1}$. Although this emission is very weak, it can be shown to be statistically significant and, therefore, is probably real.

Finally, inspection of Figure 1 shows no indication of emission in the Fe xii line at 1349.37 Å. This line was also absent from the AU Mic data. Assuming that any emission in this line must be spread over at least three diodes by the rotational and thermal broadening, we can use the statistical properties of the data to estimate an upper limit to the possible Fe xii flux. The integrated spectrum near 1350 Å had an average of 210 counts diode$^{-1}$ and a measured variance of 15.5 counts, which is near the value expected from Poisson statistics. The sum of three diodes will have 3 times the average and $3^{1/2}$ times the variance of a single diode. Thus, if we require a 3 $σ$ deviation to make a positive detection, then the integrated counts in the line (above the continuum) must be less than 80, corresponding to a flux of $2.8 \times 10^{-15}$ ergs cm$^{-2}$ s$^{-1}$.

### 3.3. Temporal Variations

In Figure 7, we examine the time variations for the continuum and prominent emission lines, as obtained from spectra integrated over each of the eight separate time sequences. Small but statistically significant variations occur in all of the plots, having a timescale that is too short to be caused by rotational modulation by stellar surface features. In most cases, the flux variations in the continuum are not related to the spectral line variations. In one case, however, near phase 0.375, a continuum increase of 50% is accompanied by enhancements in the O V and O I λ1355 lines. That increase is substantially larger than expected from uncertainties in the background and it probably represents a flarelike event. Overall, however, the amount of flare activity is small, so that the integrated spectrum presented in Figure 1 represents the quiescent state of the star.

To search for the presence of shorter duration variations we examined each of the eight time sequences individually. After eliminating the background contaminated readouts, as described in § 2, we binned the time sequences into 20 s intervals (summing 50 readouts) and plotted selected fluxes as a function of orbital phase. The results for both the continuum and the Fe xii line are shown in Figure 8. Most of the long-term variations are caused by fluctuations in the background radiation as the satellite moves in geomagnetic latitude during its orbit (Heap et al. 1995), as indicated by the dashed line. In all of the orbits, the continuum flux is greater than the expected background, suggesting that a true quiescent continuum is present. However, since the background is derived from a statistical model rather than measured directly, it is not possible to accurately define the magnitude of this continuum.

To search for flarelike transients lasting less than a few minutes, we fit a smooth curve through the binned time sequence and searched for times at which the integrated counts exceeded the local average by three standard deviations or more. The technique is similar to that described by Robinson et al. (1995). A total of 12 possible events were detected in the continuum flux (see Fig. 8). In most cases, these lasted for less than 10 s and only marginally exceeded the 3 $σ$ detection criterion; thus, they may simply be the result of counting statistics or background noise. In no case were these continuum variations accompanied by a statistically significant increase in the flux of any emission line. If some of these increases do represent actual flarelike events, we must conclude that they are relatively rare and
should contain substantially less energy than the larger flare event seem near phase 0.38.

4. DISCUSSION

4.1. Emission Measure

For an optically thin medium, the integrated flux at Earth from a given emission line, $j$, can be estimated from the expression

$$I_j = \frac{1}{4\pi d^2} \int_{\nu} P_j(N_e, T_e) N_e^2 dV \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1},$$

(1)

where $P_j$ is the integrated line emissivity (in ergs cm$^3$ s$^{-1}$) and $d$ is the distance to the star. For an isothermal plasma, this can be written in terms of the volumetric emission measure, $\text{VEM} = \int_{\nu} N_e^2 dV$, as

$$I_j = \frac{1}{4\pi d^2} P_j(N_e, T_e) \text{ VEM}.$$  

(2)

From the observed line fluxes presented in Table 2, we can estimate the emission measure for the O vi, Fe xii, and Fe xxi lines. The results are presented in Figure 9. In these calculations, we have used line emissivity values tabulated by Monsignori-Fossi & Landini (1995), and we assume a distance of 31 pc (Hoffleit & Jaschek 1982). The most probable emission measure for the Fe xxi emitting plasma, formed at $10^7$ K, is $\sim 10^{53}$ cm$^{-3}$. This is somewhat smaller...
than has been deduced from X-ray observations, which also tend to derive a higher temperature. Barstow (1988) deduced a quiescent temperature of $3.5 \pm 0.3 \times 10^7$ K and an emission measure of $1.4 \times 10^{54}$ cm$^{-3}$ from EXOSAT emission measure observations of HR 1099, while Dempsey et al. (1993) derive an emission measure of $1.2 \times 10^{54}$ cm$^{-3}$ and a temperature of $2 \times 10^7$ K from ROSAT data.

4.2. Line Broadening

If we assume that the observed emission lines are optically thin, then we can write the line profile as the convolution (e.g., Gray 1992):

$$ F(\Delta \lambda) \sim G(\Delta \lambda) \Phi(\Delta \lambda) \exp \left[-\frac{(\Delta \lambda/\Delta \lambda_0)^2}{2}\right], $$

where $\Delta \lambda$ is the wavelength shift, $G(\Delta \lambda)$ is the rotational broadening, $I(\Delta \lambda)$ is the instrumental broadening (a Gaussian with $\sigma = 16$ km s$^{-1}$), and $\Delta \lambda_0$ is the Doppler broadening. $\Delta \lambda_0 = \lambda_0 V_0/c$. Here $V_0$ has contributions from both thermal motions and turbulence, $V_{turb}$:

$$ V_0^2 = \frac{2kT_f}{M_f} + (V_{turb})^2, $$

where $T_f$ and $M_f$ are the temperature and mass of the relevant ion. The chromospheric and transition region lines (i.e., O I, C I, Cl I, and O V) should all be formed near the surface of the star, and they are, therefore, subject to normal rotational broadening, with $V \sin i = 38$ km s$^{-1}$. Assuming that the limb darkening for these lines is negligible and the temperature is optimum for the particular ionization state (e.g., Landini & Monsignori Fossi 1990), we can use the observations to calculate $V_{turb}$. The results are presented in Table 3.

As mentioned in § 3.2, the shape of the O V line can be accurately reproduced using a superposition of two Gaussian profiles. These two components could be attributed to nonhomogeneous surface features, as suggested byWHLD. However, as pointed out by Gray (1992), a non-Gaussian shape can also be explained by the presence of anisotropic macroturbulence. According to this theory, the turbulent velocity, $V_{turb}$, in equation (4) can be expressed in terms of a microturbulent component, $\xi$ (which is assumed to be isotropically distributed), and a macroturbulent component, $V_{mac}$—which is directed along (or perpendicular to) the stellar radius, as might be the case if the motions were restricted by radially directed magnetic fields within a flux tube. Thus,

$$ V_{turb}^2 = \xi^2 + V_{mac}^2 \cos^2 \theta, $$

where $\theta$ is the angle between the macroturbulent motions and the line of sight. If the motions are along the radial direction, then the line widths from a small surface element at the limb will be determined only by the thermal motions and the isotropic microturbulence, since the macroscopic motions are primarily directed perpendicular to the line of sight. The full width of the profiles is only seen from disk center. The narrow contributions from near the limb enhances the line center relative to the wings and results in a cuplike shape when the light is integrated over the entire stellar surface (Gray 1992). Similar results are expected if the motions are primarily directed perpendicular to the radial direction.

The results of applying this theory to the O V data are shown in Figure 5b. As seen in Figure 5b, the profile can be accurately represented assuming a temperature of $2.5 \times 10^5$ K, a microturbulence of $5$ km s$^{-1}$, and a macroturbulent velocity ($V_{mac}$) of $130$ km s$^{-1}$. The close agreement between observations and theory suggests that the turbulence is indeed anisotropically distributed and can be characterized by a single velocity distribution.

In all cases, the turbulence seen in the chromospheric and transition region lines from HR 1099 is substantially greater than that found in the AU Mic spectrum, where it was essentially unresolved. Note that the deduced turbulence increases dramatically from the chromosphere to the transition region, as expected from the earlier results of WHLD. The calculated values are really upper limits, since no opacity broadening has been assumed in the calculations.

**TABLE 3**

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<th>$\Delta \lambda_0$ (Å)</th>
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* Properties derived from a two-component Gaussian fit to the profile.

* Properties deduced from a single-component fit, assuming an anisotropic macroturbulent velocity distribution.
While a low opacity may be expected for the O v line, it is not necessarily the case for the chromospheric lines; thus, the differences between the chromospheric and transition region may be even larger than indicated in Table 3.

Since protons at 10^5 K have a thermal velocity of ~400 km s^{-1}, which is substantially greater than the escape velocity of ~180 km s^{-1} for HR 1099, we expect that the Fe ii line is formed within closed magnetic fields, which, presumably, corotate with the stellar surface. If we assume that these are very low-lying loops, then the rotational broadening will be characterized by a normal photospheric broadening function. Assuming low-lying loops and a temperature that is nominal for that ionization state (~10^7 K), the excess line width can be accounted for by a turbulence in the corona of 65 km s^{-1}, which is somewhat larger than the value deduced by Saba & Strong (1991) for the solar corona. This is the maximum value consistent with the observations, and it is considerably smaller than the turbulence indicated for the transition region.

On the other hand, the Fe xxiii line may be formed in an extended region, well above the surface of the star. To estimate the rotational broadening from an extended atmosphere, we set up a coordinate system that has the z-axis along the direction of observation and the axis of rotation in the y-z plane. In this coordinate system, the velocity along the line of sight, v_z, is simply given by

\[ v_z = c \Delta \lambda / \lambda_0 = \omega \sin \theta, \]

where \( \Omega \) is the rotational velocity and \( \theta \) is the angle of inclination. Thus, all plasma within a cross-sectional slab in the y-z plane will have the same value of \( v_z \) and, consequently, the same Doppler shift. The Fe xxiii line comes from an intercombination transition, and it is therefore expected to be optically thin. The broadening profile should, therefore, be directly related to the volume of the corona having a given value of \( x \). For simplicity, we assume that the corona is spherically symmetric, homogeneous, and that it extends from the photosphere, \( R_* \), to a maximum radius of \( R \). For \( |\Delta \lambda| < \Delta \lambda_L = R_* \lambda_c / \Omega \sin \theta / c \), the broadening function \( G(\Delta \lambda) \) is relatively flat, with a slight amount of limb brightening. For \( \Delta \lambda_L < \Delta \lambda < (R/R_*) \Delta \lambda_L \), the function is given by

\[ G(\Delta \lambda) = C[1 - (R_* \Delta \lambda / R \Delta \lambda_L)^2], \]

where \( C \) is a normalization constant.

To estimate the maximum radial extent of the atmosphere, we assumed that there was no turbulent broadening, and we convolved a thermally broadened Gaussian at a temperature of 10^7 K with a variety of rotational broadening functions, each calculated using a different value of \( \theta \). The resultant profile was then compared with the observations. The maximum allowable line width is consistent with an atmosphere with \( R = 2.3 R_* \sim 6 \times 10^{11} \) cm, where we use the value of \( R_* \sim 3.9 R_\odot \) given by Fekel (1983).

4.3. Coronal Structure

Donati et al. (1990) have used a Doppler imaging type of technique to directly measure the magnetic fields on the surface of HR 1099. This study detected nearly unipolar fields within a localized region covering approximately 18% of the stellar surface and having a “filling factor” of 14% within that region. The field strength was approximately 1000 G, which is near the equipartition value at which the magnetic pressure equals the photospheric gas pressure (as deduced from a Kurucz atmospheric model with \( \log g = 3.5 \) and \( T_{eff} = 5000 \) K). The technique is insensitive to small-scale, mixed-polarity field configurations, however, allowing the possibility that a substantial fraction of the surface fields may have been missed. Further, magnetic field measurements using separate techniques on more slowly rotating active stars (e.g., Saar 1991; Basri & Marcy 1994) have detected fields of similar strength and with fractional coverage of as much as 50% of the stellar surface. Therefore, we conservatively assume that the photospheric field strength is 1000 G and the fractional coverage is 10% in the photosphere. These fields expand considerably in the chromosphere and transition region (e.g., Rabin 1991) and can easily reach a unity filling factor in the lower corona, where they form the magnetic canopy (Gabriel 1976). The average coronal field strength is determined by the crowding of the flux tubes. Thus, assuming an average photospheric coverage of 10% indicates an average field strength at the base of the corona of approximately 100 G.

The scale height (\( \lambda = k T / g M_\odot \)) for the 10^7 K plasma responsible for the Fe xxiii emission is about 5 \times 10^{11} cm \sim 2R_\odot. This is comparable to the maximum extent of the corona as deduced from the Fe xxiii line profile (§ 4.2). The density is therefore expected to be reasonably constant along a coronal loop. If we assume that the corona is filled with magnetic loops extending to radius \( R \), all of which contain hot plasma, then we can express the emitting volume, \( V \), as the volume of a spherical shell extending from radius \( R_* \) to \( R \) minus that portion of the shell that is occulted by the star. The emission measure then becomes

\[ \text{VEM} \sim N_e^2 V \sim f N_e^2 [\pi (R^3 - R_*^3) / 3 - \pi R_*^2 (R - R_*^3)], \]

where \( f \) is the magnetic filling factor. The maximum emitting volume can be calculated assuming \( f = 1 \) and \( R = 2.3 R_* \), which is the maximum radial extent allowed by the Fe xxiii profile. This turns out to be \sim 9.2 \times 10^{33} \) cm^3. Using the calculated emission measure of 10^{43} cm^{-3} (§ 4.1), we estimate that the minimum average coronal electron density is 3.3 \times 10^8 cm^{-3}.

Further restrictions on the loop properties can be obtained from loop-scaling laws, similar to those calculated by Rosner, Tucker, & Vaiana (1978). These provide relations between the loop temperature, length, and electron density under the assumption of quasi-static equilibrium. The most current scaling law has been calculated by Klimchuk & Gary (1995), which is based on unpublished calculations of the radiative loss function by Raymond. For \( \log T > 6.55 \), this takes the form

\[ N_e L = 9.12 \times 10^8 T^{1/9/2}, \]

where the constant was determined from hydrostatic loop modeling, under the assumption that the heating is uniformly distributed along the loop.

Using equations (8) and (9), and assuming that the individual loops are semicircular—so that \( L \sim \pi (R - R_*) \)—we can determine the loop lengths and densities, which are consistent with both the emission measure and the observed temperature. For \( T = 10^7 \) K, \( f = 1 \), and \( \text{VEM} = 10^{43} \) cm^{-3}, we find \( L \sim 2.8 \times 10^{10} \) cm and \( N_e \sim 4.0 \times 10^9 \) cm^{-3}. For comparison, the results obtained using the standard RTV relationship (e.g., Sylwester & Sylwester 1993)

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are \( L \sim 4.6 \times 10^{10} \) cm and \( N_e \sim 3.0 \times 10^9 \) cm\(^{-3}\). In reality, electric currents initiated by convective flows beneath the photosphere (e.g., twists and shears) and directed along the fields will introduce an azimuthal component to the field, and it will form well-defined loops. Furthermore, observational tests of the RTV relation have shown that it can underestimate the electron density by as much as an order of magnitude (e.g., Haisch et al. 1988). Thus, we expect that coronal densities may be as high as \( 10^{11} \) cm\(^{-3}\).

### 4.4. Atmospheric Heating

In most of the currently proposed nonradiative heating processes, the ultimate source of the energy is the gas motions within the stellar convection zone. For magnetically related processes, the type of heating depends upon the timescale of these gas motions with respect to the Alfvén transit time across the magnetic loops; thus, \( \tau_A = 2L/V_A \), where \( V_A = B/(4\pi \rho)^{1/2} \) is the Alfvén velocity, \( L \) is the loop length, \( B \) is the magnetic field strength, and \( \rho \) is the gas density. If the gas motions are slow, for example those related to large-scale subsurface flows and differential rotation, then the magnetic configuration will evolve through a series of quasi-static equilibrium states, gradually storing free magnetic energy until it is released by the onset of magnetic instabilities. The classic example of this process is the work of Parker (1988), who showed that the shuffling and braiding of the footpoints of coronal loops can produce current sheets in the solar corona, which then lead to impulsive energy releases termed nanoflares. Alternatively, if the gas motions vary on a timescale shorter than or equal to \( \tau_A \), then it is possible for the flows to resonate with the loop and generate MHD waves, which then propagate upward along the magnetic field lines and may heat the plasma by a resonant absorption process (e.g., Ionson 1978; Davila 1987; Hollweg & Yang 1988). In reality, the convective motions possess a wide range of timescales, and the type of heating that dominates in any given star will depend upon the detailed distribution of these motions, as well as the magnetic topology present.

Recently Cargill (1994) examined the expected observational signatures for a variety of proposed solar heating mechanisms, with particular emphasis on the nanoflare theory. A nanoflare event is initiated within a narrow current sheet and should generate a pair of plasma jets directed along the magnetic fields, and away from the site of reconnection, with speeds that are on the order of the Alfvén velocity. The jets rapidly heat the plasma, which then expands along the fields at near the sound velocity. Cargill modeled the effects of thousands of such reconnections occurring randomly throughout multiple loop systems spread uniformly across the surface of the star. Considering only the plasma associated with the jets, Cargill predicted a symmetrically broadened profile with a width of as much as 150 km s\(^{-1}\), which is similar to the broadening in transition region lines reported in WHLD and in the present study. Line broadening of up to 200 km s\(^{-1}\) has been reported for both the solar transition region (e.g., Cheng 1990) and corona (Fludra et al. 1989) during solar flares, while a substantial broadening of transition region lines during flares on dMe stars has been reported by Bookbinder, Walter, & Brown (1992) and Linsky & Wood (1994). Thus, it is possible that microflares may be the source of nonthermal broadening in the transition region lines of HR 1099. If this is the case, however, it is difficult to understand the relatively small amount of nonthermal broadening that we see in the Fe XXI line profile. We also note that microflares are the low-energy end of a distribution of flare energies in which the occurrence rate, \( \nu \), of a flare with energy \( E \) is proportional to \( E^{-\beta} \), where \( \beta \sim 1 \) (e.g., Gershberg & Shakhovskaya 1983). If large numbers of microflare events are heating the atmosphere and causing the observed line broadening, then we would expect to see larger, less frequent flares. While very large, long lasting flares are indeed observed (Foing et al. 1984), there is very little evidence for smaller, short-duration flare activity in HR 1099, in either radio (Lefevre, Klein, & Lestrade 1994; Umana et al. 1995), X-rays (Brown et al. 1994), or UV (§ 3.3). In contrast, UV observations of dMe stars (Robinson et al. 1995) detected microflares at a rate of more than 15 events hr\(^{-1}\), while Yokoh X-ray observations of the Sun detected flares at a rate of more than 20 hr\(^{-1}\) (Shimizu et al. 1994).

A second possibility, closely related to flares, is a stellar analog to the "transition region explosive events" observed on the Sun. As reported by Dere, Bartoe, & Brueckner (1989), these events are characterized by transition region lines with widths of \( \sim 100 \) km s\(^{-1}\), a spatial extent of about 2\( \varnothing \), an average duration of 60 s, and a flux enhancement of about a factor of 5. They occur in both active regions and within the network, at any given time covering about 1% of the solar surface, and they are associated with the emergence of magnetic flux. WHLD have suggested that the transition region line broadening in HR 1099 may be caused by these events. While this is possible, the physics behind these events and their role in atmospheric heating is far from clear. Dere et al. (1989), for example, suggest that the occurrence rate (about 600 s\(^{-1}\)) is not sufficiently large to account for the solar coronal heating. Dere et al. (1991) also point out that the events typically occur near the edges of magnetic regions, rather than near the brightest regions, where most of the heating presumably occurs.

As an alternative to the flaring or explosive event hypothesis, we now examine the possibility that nonradiative heating on HR 1099 is caused by the resonance absorption of magnetohydrodynamic (MHD) surface waves, which was first discussed by Ionson (1978) in order to explain solar coronal heating. In this theory, the ultimate source of the Alfvén waves is the interaction of the stellar convective turbulence with the footpoints of localized magnetic flux tubes. According to Ionson (1984), the efficiency \( \epsilon \) by which convective energy having a turnover frequency, \( \nu_c \), can be converted into wave energy in a magnetic loop is given by

\[
\epsilon = \frac{\nu_A}{\nu_c} \left[ 1 + \left( \frac{\nu_A - \nu_c}{\nu_c} \right)^2 \right]^{-1},
\]

where \( \nu_A = V_A/2L \) is the resonant Alfvén frequency for the loop. The value of \( \epsilon \) is a sharply peaked function that reaches a maximum value when \( \nu_A/\nu_c \approx 1 \). If we take the presence of nonthermal turbulence as evidence for the dominance of the Alfvén wave heating mechanism, then the requirement that \( \nu_A/\nu_c \sim 1 \) places additional constraints on the physical properties of the loops; i.e.,

\[
L \nu_c^{1/2} \approx 10^{11} \frac{B}{\nu_c}.
\]

It is expected that the convective turbulence will have the most energy at a turnover frequency \( \nu_c = V_c/L_y \), where \( V_c \) is
the characteristic velocity of the granular motion and \( L_p \) is the height of a granule, which is approximately 5 times the pressure scale height in the photosphere (Mullan 1984). The active K1 IV primary in the HR 1099 system has an effective temperature of 4623 K (Zhai et al. 1994) and \( \log_{10} (g) \) of 3.4 (Fekel 1983), which implies a photospheric scale height of approximately 1500 km. Theoretical models of convection on cool giants (e.g., Gustaffson et al. 1975) also suggest that the convective velocities are slightly larger than for the Sun, with values of 2–4 km s\(^{-1}\). This implies that the convective frequency is on the order of 0.2–0.5 mHz. If we take values of \( L \sim 3 \times 10^{10} \) cm and \( N_\phi \sim 10^{19} \) cm, as deduced in § 4.3, then the resonance condition presented in equation (11) implies that the coronal loops should have an average field strength of \( \sim 15 \) G, which is quite realistic.

One of the greatest difficulties with the linear Alfvén wave heating theories has been the difficulty in dissipating the wave energy. However, it has been pointed out by a number of authors (e.g., Heyvaerts & Priest 1983; Hollweg 1987, 1991; Hollweg & Yang 1988) that nonlinear effects associated with the Alfvén surface waves can dramatically increase the effectiveness of the wave dissipation. Briefly, Alfvén surface waves generated in a magnetic loop have characteristic velocity fluctuations, \( \delta V \), which are maximum at the surface of the tube, and which decrease rapidly toward the center, forming a velocity shear. Energy flux conservation implies that \( \delta V \) will be proportional to \( B^{-1/2} \) (e.g., Hollweg 1990) and will rapidly increase as the waves travel from the photosphere, through the chromosphere, and into the transition region (as we see in our observations). Eventually, if the velocity shear associated with the Alfvén wave becomes sufficiently large, then a Kelvin-Helmholz instability will be initiated, which rapidly converts the wave energy into MHD turbulence having a size scale comparable to that of the original velocity shear. The details of this process are still largely uncertain. The large-scale turbulence is then expected to cascade to smaller sizes, which are efficiently damped through viscous and ohmic dissipation processes. Since the fluid motions are primarily directed perpendicular to the magnetic field, the theory also accounts for the anisotropic turbulent velocity distribution deduced from the O\( \iota \) profile (§ 4.2).

Support for this theory was recently supplied by Olman & Davila (1994, 1996), who used numerical three-dimensional MHD simulations to study the nonlinear propagation of Alfvén waves in an inhomogeneous plasma. These simulations showed the development of highly sheared velocities and an associated Kelvin-Helmholz instability, which resulted in the formation of compact vortices in both the velocity and magnetic field. The theory predicts that the turbulence is generated primarily in the outer layers of the loop.

The damping rate for MHD turbulence, \( \gamma \), is directly proportional to the velocity shear \( \sim \delta V/\Delta y \), where \( \Delta y \) is the original size scale of the turbulent eddy before the cascade. The heating rate from Alfvén surface wave-induced turbulence is then equal to the damping rate times the kinetic energy density of the turbulent motions, \( M_\beta N_\phi \delta V^2 \). A formal solution for the heating rate, \( Q \), is given by Hollweg & Yang (1988) as

\[
Q = \frac{\pi M_\beta N_\phi \delta V^2}{4} \frac{3/2}{\Delta y}.
\]

The factor of 2 in this expression takes into account the two polarization states of the wave.

Since the waves are effectively dissipated during the formation of the MHD turbulence, most of the wave energy will be deposited in the transition region. This would explain the relatively small amount of turbulence that we see in the corona. The hot coronal gas can then be explained by (1) a heating of the gas by the small amount of wave and turbulent energy reaching the corona, or (2) the velocity filtration process discussed in detail by Scudder (1992a, 1992b). Velocity filtration basically assumes the existence of particles in the transition region with a \( "Kappa\) velocity distribution. This distribution has a considerably higher number of energetic particles than a normal Maxwellian, and it is expected to be formed in the presence of MHD turbulence. The high-energy tail has sufficient energy to escape from the gravitational well of the star and, thereby, it forms the hot coronal plasma.

First, we examine the possibility that the corona is locally heated. Here we adopt an average loop length of \( 3 \times 10^{10} \) cm and a coronal electron density of \( 10^{10} \) cm\(^{-3}\). MHD turbulence formed within the corona will exist over a wide range of sizes. Since the smallest scale turbulence will damp the most rapidly, the actual value of \( \Delta y \) should reflect the smallest scale turbulence present. However, to be conservative, we adopt the largest turbulence size, which is comparable to the cross-sectional radius of the loop, \( R_L \). Assuming an aspect ratio, \( L/R_\phi \sim 10 \), which is typical for solar coronal loops (Golub 1990), we have \( \Delta y < R_L \sim 3 \times 10^9 \) cm. The total radiative losses from an optically thin plasma at a temperature of \( 10^{7} \) K and electron density of \( 10^{10} \) cm\(^{-3}\) are \( 7.45 \times 10^{-3} \) ergs cm\(^{-3}\) s\(^{-1}\) (Klimchuk & Gary 1995), and conductive losses would be of comparable magnitude. From equation (12), we see that these losses can be balanced by heating, provided the turbulence has a velocity of about \( 60 \) km s\(^{-1}\), approximately the same as the maximum turbulence deduced for the coronal plasma.

If the coronal energy arises in the transition region, as suggested by the velocity filtration mechanism, then the transition region heating should be able to account for the observed coronal losses. Adopting a transition region electron density of \( 10^{10} \) cm\(^{-3}\) (WHLD), \( \delta V \sim 100 \) km s\(^{-1}\) from the O\( \iota \) profile, and \( \Delta y \leq 10^9 \), as for the coronal loop, we obtain a value of \( Q \sim 10^{-2} \) ergs cm\(^{-3}\) s\(^{-1}\) from equation (12). The VEM of O\( \iota \) is \( \sim 10^{52} \) cm\(^3\), which implies a transition region volume of \( 10^{32} \) cm\(^3\) and a consequent volumetric heating rate, \( Q/V \), of \( \lesssim 10^{30} \) ergs s\(^{-1}\). This is well above the energy required to heat the transition region and is about 10% of the observed emission in soft X-rays (Dempsey et al. 1993). However, the agreement is acceptable considering that the assumed size of the turbulent eddies may be considerably overestimated.

4.5. A Fly in the Ointment

In the above section, we assumed that the transition region (O\( \iota \) and coronal (Fe xxi) radiation come from the same ensemble of loops. However, recent evidence from the Extreme Ultraviolet Explorer (EUV) satellite suggest that this may not necessarily be the case. According to Brown (1994), the intensities of density sensitive lines of Fe xxi \( \lambda 102.35/\lambda 128.73 \) and Fe xxi \( \lambda 114.4/\lambda 117.2 \) both imply a coronal electron density of \( \sim 10^{14} \) cm\(^{-3}\) on HR 1099. Such densities have also been deduced by Dupree et al. (1993) for Capella. This implies a coronal pressure of nearly \( 3 \times 10^4 \)
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dynes cm$^2$ and would require magnetic fields of nearly $10^5$ G in order to confine the plasma. On the other hand, WHLD have used density sensitive line ratios to deduce a transition region electron density of $\sim 10^{10}$ cm$^{-3}$ in HR 1099. This is comparable to transition region densities found in Capella, Procyon, and the quiet Sun (e.g., Linsky et al. 1995; WHLD; Dere & Mason 1993), and it implies a transition region pressure of $\sim 0.35$ dynes cm$^{-2}$. If the coronal density measurements are valid, then this would imply that the X-ray and EUV emission from these dense coronal loops completely dominates that from lower density loops, which are presumably associated with the transition region emission. The existence of such high-density structures in an atmosphere that is normally characterized by much lower densities implies highly unstable structures and might be evidence for microflare activity.

While these coronal density measurements are highly suggestive, they do suffer from several sources of uncertainty. First, all of the density sensitive lines are extremely weak and are measured against a very noisy background, in such a way that their flux is uncertain. Second, the lines are probably formed in a region of extreme turbulence, in such a way that ionization equilibrium may not be in effect (see Noci et al. 1989). Finally, the theoretical analysis assumes a Maxwellian velocity distribution for the electrons. However, as shown by Anderson, Raymond, & Van Balle-gooijen (1996), emission line strengths can change dramatically if non-Maxwellian velocity distributions are assumed, as would be the case if the velocity filtration mechanism were operating. A dramatic example of the uncertainty involved in the density measurements was presented by Monsignor Fossi et al. (1994), who analyzed EUV spectra obtained during a flare on AU Mic. During this flare, a density of $10^{13}$ cm$^{-3}$ was deduced from the lines. However, an analysis of the flare decay rate using data from the broadband Lexan/B detector (Cully et al. 1993) gave densities of $5 \times 10^{11}$ cm$^{-3}$, while a more detailed model (Cully et al. 1994) suggests an electron density of only $10^9$ cm$^{-3}$. These models involve a number of fundamental assumptions and certainly do not disprove the existence of high coronal densities during the flare. However, they do suggest that the densities might be smaller than implied by the standard line ratio analysis.

5. CONCLUSIONS

We report the detection of the Fe XXI coronal emission line from the active RS CVn binary system HR 1099. The observations were obtained near quadrature at a time of minimal stellar flare activity and are unique in that they fully resolve the spectral line. This gives us the first opportunity for directly measuring the turbulence and mass flows of the coronal plasma in an RS CVn system.

The maximum acceptable width of the Fe XXI emission line component originating from the primary is compatible with a thermal plasma at a temperature of $2.2 \times 10^7$ K, considerably larger than the temperature ($10^6$ K) at which this ion is formed. The additional width can be accounted for in two ways, turbulence or rotational broadening from an extended atmosphere. In practice, the broadening is probably a combination of these two processes, with the turbulence being restricted to values less than $65$ km s$^{-1}$ and the height of the atmosphere having an upper limit of $2.3R_\star$. Using the emission measure and the RTV relation indicates that the loops are probably dense, low-lying structures with lengths of $\sim 3 \times 10^{10}$ cm and electron densities $\sim 10^{10}$ cm$^{-3}$. The small height of the loops implies that the total width of the X-ray emitting region is only slightly larger than the diameter of the star, $\sim 5 \times 10^{11}$ cm, assuming that the loops are uniformly distributed across the stellar surface. This is substantially smaller than the lateral size of $\sim 10^{12}$ cm deduced for the quiescent 5 GHz radio source (Mutel et al. 1985), and it suggests that the X-ray and radio sources are not coplateral. Other evidence for the separation of the X-ray and radio sources was provided by Falla et al. (1994), who estimated that the maximum thermal electron density in the region producing the quiescent radio emission from HR 1099 should be $10^7$ cm$^{-3}$.

The strong transition region turbulence previously reported by WHLD for HR 1099 was confirmed in our analysis of the O V line at 1372 Å. WHLD suggest that this turbulence is the result of microflaring activity, and they point to the lack of such turbulence in the relatively inactive star Procyon as proof of this assertion. However, while we admit that flares may play a role, we examine a second possible heating process that involves the dissipation of MHD turbulence, possibly generated by nonlinear Alfvén waves. Linear Alfvén wave formalism is often used to explain atmospheric heating, and it does imply that a strong coupling can exist between the convective motions and the magnetic loops in HR 1099. However, that theory fails to predict the strong turbulence that we see in the transition region and the relative lack of turbulent broadening in the corona. The linear Alfvén waves also have extremely long damping lengths in the corona (e.g., Hollweg 1990). On the other hand, nonlinear Alfvén waves have been shown under certain circumstances to generate MHD turbulence by initiating a Kelvin-Helmholtz instability. The observations suggest that most of this turbulence is generated within the transition region, although there is a possibility that some waves do leak into the corona. In either case, simple calculations suggest that the observed turbulence can supply enough heat to account for the coronal energy losses.

If the large measured pressure differences between the transition region and corona are simply the result of a non-Maxwellian electron energy distribution, then we feel that the most consistent model would involve atmospheric heating in the transition region and the injection of hot plasma into the coronal loops via the velocity filtration process proposed by Scudder (1992b). This model is consistent with the large transition region turbulence (as opposed to the very marginal detection of turbulence in the corona), and it also has the possibility of explaining the measured coronal pressures. If the pressure difference is real, however, then it implies the presence of two distinct types of magnetic structures. The loops responsible for the transition region radiation are probably heated by the MHD turbulence, while the large coronal densities imply the presence of non-equilibrium structures, probably resulting from numerous flarelike events. More analysis and observations will be required before this question is resolved.

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