FROM THE HEART OF THE GHOUL: C AND N ABUNDANCES IN THE CORONA OF ALGOL B

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ABSTRACT

*Chandra* Low Energy Transmission Grating Spectrograph observations of Algol have been used to determine the abundances of C and N in the secondary star for the first time. In order to minimise errors arising from an uncertain coronal differential emission measure as a function of temperature, the analysis was performed relative to similar observations of an adopted “standard” star HR 1099. It is demonstrated HR 1099 and Algol are coronal twins in many respects and that their X-ray spectra are very similar in nearly all details, except for the observed strengths of C and N lines. The H-like $2p^5 3d^2 3p^3 {^1}P_1 \rightarrow 2s^2 1S_0$ transitions of C and N in the coronae of Algol and HR 1099 demonstrate that the surface abundances of Algol B have been strongly modified by CN-processing, as demonstrated earlier by Schmitt & Ness (2002). It is found that N is enhanced in Algol B by a factor of 3 compared to HR 1099. No C lines are detected in the Algol spectrum, indicating a C depletion relative to HR 1099 by a factor of 10 or more. These C and N abundances indicate that Algol B must have lost at least half of its initial mass, and are consistent with predictions of evolutionary models that include non-conservative mass transfer and angular momentum loss through magnetic activity. Based on H-like and He-like transitions in O and Ne, it is estimated that Algol is slightly metal-poor by 0.2 dex in terms of the coronal abundances of light elements relative to HR 1099, while the Fe XVII $2p^5 3d^2 3p^3 {^1}P_1 \rightarrow 2p^6 1S_0$ transition indicates a very similar Fe abundance. In reviewing coronal abundance results for active stars in the literature, and drawing on an earlier *Chandra* study of the coronal abundances of HR 1099, it is concluded that Fe is very likely depleted in the coronae of both Algol and HR 1099 by 0.5 dex relative to their photospheric compositions, but that Ne is enhanced by a similar magnitude. Light elements such as C, N and O are likely depleted in both stars by of order 0.3 dex. The similarities in these large abundance anomalies in HR 1099 and Algol is notable. Despite such compositional fractionation in these coronae, the relative C and N abundances in HR 1099, determined by comparing observed line strengths to theoretical C/N line ratios, are consistent with recent solar values, indicating that differential fractionation between these elements is not significant and that little or no dredge-up of material subjected to CN-processing has occurred on the subgiant component.

Subject headings: stars: abundances — stars: activity — stars: coronae — stars: late-type — Sun: corona — X-rays: stars

1. INTRODUCTION

Algol, whose name derives from Arabic for “the ghoul”, is the brightest eclipsing binary system in the sky and the prototype of its class. Algol-type binaries provide laboratories for studying close-binary evolution, Roche lobe overflow and mass transfer, and the extremes of stellar magnetic activity. They are comprised of an early-type main-sequence primary and a less massive late-type subgiant secondary that fills its Roche lobe and loses mass to the primary. The secondary can be stripped down to layers whose composition has been partially processed by nuclear burning but that is depth to which its outer layers have been altered by core hydrogen burning (e.g. Sarna & De Greve 1996).

The late-type secondaries of Algol systems are strongly magnetically active. Tidal forces synchronise rotational and orbital periods of these close binaries, and consequent rapid rotation excites dynamo action in the convection zone of the evolved star that is manifest at the surface in the form of chromospheric and coronal emission (e.g. S.A. Drake, Simon & Linsky 1989; Singh, S.A. Drake & White 1995). Radio and X-ray activity levels of Algol systems are similar to, but slightly lower than, those of their close relatives the short-period RS CVn-type binaries, in which both members are late-type stars (Singh et al. 1996; Sarna, Yerli & Muslimov 1998).

Eclipsing Algol-type binaries provide very accurate stellar masses and radii with which to confront sophisticated models that follow the evolution of the component stars, including Roche lobe overflow and mass transfer (e.g. Sarna 1992,1993; Nelson & Eggleton 2001). Quantitative determination of element abundances modified by nuclear processing in stellar interiors can provide critical tests of these evolutionary models. In particular, the degree of C depletion and N enhancement through CN-cycle processing in the secondary can provide a measure of the depth to which its outer layers have been stripped. In turn, the primary receives mass that might have been partially processed by nuclear burning but that is then diluted by rotationally-induced and thermohaline mixing with its pristine envelope. Measurements of C and N in the primary can then help constrain these mixing processes and the initial stellar mass of unprocessed material.

Based on high-resolution optical spectra, Parthasarathy, Lambert & Tomkin (1983) showed that the secondaries of the

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1 I adopt the common convention in which the primary component refers to the currently more massive star of an Algol-type binary, and the hotter (and usually less massive) star of an RS CVn-type binary.
Algol binaries U Cep and U Sge were depleted in C and enhanced in N by significantly greater amounts than field giants of similar spectral type. The more pronounced abundance changes are the result of the CN-processed material being mixed with a less massive outer envelope, confirming that these stars lost a significant amount of mass prior to the onset of deep convection. Cugier & Hardorp (1988), Cugier (1989), Dobias & Plavec (1985) and Polidan & Wade (1992) also found C depletions in the primaries and secondaries of several systems based on International Ultraviolet Explorer (IUE) observations of C II and C IV absorption and emission lines. Peters & Polidan (1984) found evidence for C depletion in circumstellar matter in several systems, and an extreme C depletion was found in AU Mon. Further studies of C and N abundances based on optical spectra of several Algol systems undertaken by Tomkin & Lambert (1989), Yoon & Honeycutt (1992), Tomkin, Lambert & Lemke (1993) and Tomkin & Lambert (1994) confirmed the general pattern of moderate to strong C and N abundance changes in secondary stars and less extreme changes in the primaries. The general picture of the chemical evolution of Algols and observational results supporting it has been summarised and explained in the review of Sarna & DeGreve (1996).

Algol primaries dominate the UV and optical spectra of these systems and are generally accessible for abundance studies. However, the comparatively faint secondaries can only be studied reliably during total eclipse. Moreover, the rapid rotation of these stars smears out spectral lines rendering high resolution spectroscopic studies more uncertain. In the case of Algol itself, no C and N abundances results exist for the secondary star.

In contrast to UV-optical wavelengths, at X-ray wavelengths Algol systems with primaries of spectral type mid-B to late-A are entirely dominated by the magnetically active secondary. Primaries in this spectral type range do not have either an outer convective envelope thought to be required to sustain strong coronal activity, or a strong, shocked stellar wind thought to be responsible for X-ray emission from O and early B stars.

In this paper, using Chandra Low Energy Transmission Grating spectograph (LETGS) X-ray spectra of Ly$\alpha$ resonance transitions in C and N H-like ions ($\S$2), I determine for the first time C and N abundances in the secondary of Algol ($\S$3). This study is performed relative to a “standard” star, the RS CVn system HR 1099. As this work was nearing completion, Schmitt & Ness (2002) presented an analysis of C and N lines in several different stars, including Algol. Though they did not derive formal values for C and N abundances, their work demonstrated that the surface abundances of the secondary of Algol have indeed been strongly modified through CN-processing. Ness et al. (2002) have also recently presented an analysis of other aspects of the Chandra LETG spectrum, including electron densities and temperature diagnostics.

In $\S$4, I compare the abundances derived here with theoretical predictions and show that these are consistent with current evolutionary models for Algol. Uncertainties and possible complications for this analysis are discussed in $\S$5. The X-ray deficiencies of Algol systems compared to RS CVn-type binaries are discussed briefly in $\S$6, and a summary of this paper is presented in $\S$7.

2. OBSERVATIONS AND ANALYSIS

Chandra LETGS spectra of Algol and HR 1099 where obtained in 2000 March and 2001 January, respectively, using the LETG and High Resolution Camera spectroscopic (HRC-S) detector in its standard instrument configuration. The observations are summarised in Table 1. Observational data were obtained from the public Chandra Data Archive\(^2\). Pipeline-processed (CXC software version 6.3.1) photon event lists were reduced using the CIAO software package version 2.2, and were analysed using the PINTofALE IDL\(^3\) software suite (Kashyap & Drake 2000). Processing included filtering of events based on observed signal pulse-heights to reduce background (Wargelin et al., in preparation). The spectra of the two stars are compared throughout the wavelength range of the LETG+HRC-S in Figure 2, and in the limited wavelength range 20-38 $\AA$ in Figure 3; identifications for prominent spectral lines are also indicated.

I first examined each data set in order to determine the extent to which HR 1099 and Algol might have varied during the observations. This is important because it is suspected that large flares are accompanied in some cases by detectable changes in the coronal abundances of the plasma that dominates disk-averaged spectra (see, eg, Drake 2002 for a recent review). Light curves for both observations were derived using the 0th order events extracted in a circular aperture that were then binned at 100s intervals. These light curves are illustrated in Figure 1. Both are smooth and devoid of obvious flare activity. I therefore conclude that these observations are representative of HR 1099 and Algol during times of quiescence, and are thus well-suited to comparing the coronal abundances of these stars. It is also worth noting the orbital phase during the observations: according to the ephemeris of Kim (1989), the observation started at phase $\phi = 0.74$ and ended at $\phi = 0.07$, where $\phi = 0$ when Algol B star is nearest the observer. No significant spectral evolution was seen during this period, consistent with an earlier HETG observation analysed by Chung et al. (in preparation). Irradiation by the strong UV flux of the primary does not then have a significant influence on the gross features of the spectrum, though radiative excitation of transitions from the metastable levels in He-like ions has been observed (eg. Ness et al. 2002).

I restrict the following spectral analysis to the wavelength range 15-35 $\AA$, which contains the prominent lines of C, N and O, and also includes the prominent 2p$^3$3d $^1$P$\text{f}$ $\rightarrow$ 2p$^1$1S$\text{o}$ resonance transition of Fe XVII at 15.01 $\AA$ and H-like Ne Ly$\alpha$ seen in second and third orders. Spectral line fluxes were measured by fitting “modified Lorentzian” functions of the form $F(\lambda) = a/(1 + 2\Gamma^2(\lambda - \lambda_0)^2)$, where $a$ is the amplitude and $\Gamma$ a characteristic line width. For a value of $\beta = 2.4$, it has been found that this function represents the line response function of the LETG+HRC-S instrument to the photometric accuracy of lines with of order a few 1000 counts or less (Drake et al., in preparation). The apparent continuum level in the spectral region 25.5-28.0 A, judged by both visual inspection and examination of radiative loss model spectral line lists to be “line-free”, was also determined in order to obtain a relative measure of continuum flux intensity.

The flux, $F_\nu$, from a collisionally-excited transition $j \rightarrow i$ in an ion of an element with abundance $A$ in an optically-thin
collision-dominated plasma can be written as

\[ F_{ji} = AK_{ji} \int_{\Delta T_{ji}} G_{ji}(T)\Phi[N_{i}(T),V(T)] \, dT \text{ erg cm}^{-2} \text{ s}^{-1} \]  

(1)

where \( K_{ji} \) is a known constant which includes the frequency of the transition and the stellar distance, and \( G_{ji}(T) \) is the “contribution” function of the line that describes the temperature dependence of the line emissivity. This quantity defines the temperature interval, \( \Delta T_{ji} \), over which the line is formed, and is dependent on the atomic physics of the particular transition. The kernel \( \Phi[N_{i}(T),V(T)] \) is commonly known as the differential emission measure (DEM)

\[ \Phi[N_{i}(T),V(T)] = N_{i}^2(T) \frac{dV(T)}{dT} \]  

(2)

and describes the temperature structure of the excitation power of the plasma, which is proportional to the mean of the square of the electron density, \( N_e \), and the emitting volume \( V \).

If one makes the assumption that the DEMs of the coronae of Algol and HR 1099 are very similar in terms of temperature dependence, then the expression for the ratio of fluxes in a given transition observed from the two stars reduces to the product of the ratio of abundances, \( A \), and the ratio of the emission measures of the two stars,

\[ \frac{F_A}{F_H} = \frac{\Phi[N_{i}(T),V(T)]_A}{\Phi[N_{i}(T),V(T)]_H} \frac{A_A}{A_H} \]  

(3)

where the subscripts \( A \) and \( H \) denote Algol and HR 1099, respectively, and \( Q \) represents the ratio of source DEMs. I adopt that assumption for the analysis here; I will further attempt to justify this in §3 and comment on its propriety in §5.

The ratio \( Q \) can be determined from the source continua. The continuum flux density \( F_c(\lambda) \) per unit wavelength interval can be approximated by the integral over temperature of the product of the DEM kernel and the expression for the emissivity of continuum processes (e.g. Mewe, Lemen & van den Oord 1986)

\[ F_c(\lambda) = K_c \int_{\lambda} \frac{G}{T \lambda^2 V^2} \exp \left( \frac{-143.9}{T} \right) \Phi[N_{e}(T),V(T)] \, dT \text{ erg cm}^{-2} \text{ s}^{-1} \]  

(4)

where \( K_c \) is again a constant involving the stellar distance, and \( G \) is the total Gaunt factor representing the sum of the Gaunt factors for the free-free, free-bound and two-photon processes for all elements in the source plasma. In practice, the total Gaunt factor is dominated by that of He, and to a lesser extent, H. Provided the temperature dependence of the DEM is approximately the same in both stars, the ratio of DEMs, \( Q \), reduces simply to the integrated continuum flux ratios within an arbitrary wavelength interval:

\[ Q = \frac{F_{cA}}{F_{cH}} \]  

(5)

Observed intensities (total counts) and their ratios, \( F_{A}/F_{H} \), for the features of interest here are listed in Table 2. Note that no lines of C were detected in the Algol spectrum, and only an upper limit could be obtained for H-like Ly\( \alpha \) 33.74 Å. This is dramatically illustrated in Figure 3 in which C VI is clearly detected in HR 1099 in 2\( p \rightarrow 1s \) and 3\( p \rightarrow 1s \) transitions.

### 3. ABUNDANCE RATIOS

#### 3.1. Formal Results

I first draw particular attention to the remarkable similarity of the spectra of Algol and HR1099 illustrated in Figure 2. The spectra show strong resemblance to one another in both the distribution of lines due to ions of different elements and formed at different coronal temperatures, and in the relative strengths of these lines, throughout the LETG range. It is clear from this comparison that the X-ray emitting coronae of Algol and HR1099 essentially share the same gross characteristics of temperature structure and relative element abundances. As I show below, Carbon and Nitrogen abundances are conspicuous exceptions.

A further test that the temperature structures of the DEMs of Algol and HR 1099 are very similar, at least in the temperature range that concerns us for the elements C and N, can be found in the temperature-sensitive ratios of H-like to He-like transitions among the CNO trio. While the He-like complexes of both N and C are both very weak and blended in Algol and HR 1099 spectra, the He-like O VII resonance line 1s2p \( ^1P_1 \rightarrow 1s^2 \) \( ^1S_0 \) is well-observed and can be compared with the H-like \( 2p^2 F_{3/2} / 2 \rightarrow 1s^2 \) \( ^1S_1/2 \). The observed photon counts in each line are listed for the two stars in Table 2 and their ratios \( F_{OVII}/F_{OVIII} \) are 9.9 ± 1.2 and 10.1 ± 1.0 for Algol and HR 1099, respectively—identical to within experimental uncertainties.

Turning now to C and N, a qualitative sense of the abundances of these elements in Algol relative to HR 1099 is immediately apparent on inspection of Figure 3. Lines of H-like N are stronger by more than a factor of two in Algol, whereas C is strong in HR 1099 yet undetected in Algol. Similar results were presented by Schmitt & Ness (2002).

Relative element abundances were derived from the observed line and continuum fluxes using Equations 1-4 in §2. I express abundances in Algol relative to those in HR 1099, thereby using the latter as the “standard” star. In the conventional spectroscopic bracket notation, the logarithmic relative abundance of element X, \([X/H]_{1099}\), is given by the logarithmic difference between line and continuum flux ratios:

\[ [X/H]_{1099} = \log_{10} \frac{F_{XA}}{F_{XH}} - \log_{10} \frac{F_{cA}}{F_{cH}} \]  

(6)

The resulting abundances for Fe, O and Ne are listed in Table 3. The corresponding numbers for C and N are \([C/H]_{1099} < -1.13 (3\sigma) \) and \([N/H]_{1099} = 0.31 \). The formal uncertainty on the N abundance based on the line intensity measurements is only 0.02 dex, though a more realistic uncertainty is of order 0.1 dex (§5). These C and N abundances demonstrate formally the severe depletion of C and enhancement of N in the corona of Algol B. Expressed as an abundance ratio, I obtain \([C/N]_{1099} < -1.44 \), which is a factor of 100 lower than the solar photospheric value of C/N = 0.47 (Allende Prieto et al. 2002; Grevesse & Sauval 1998).

I do not quote the values \([C/H]_{1099}\) and \([N/H]_{1099}\) in Table 3 because these quantities do not tell us directly what the changes in C and N abundances resulting from nuclear processing are. To determine these changes, we need to ascertain the values of the original C and N abundances in the unprocessed envelope of Algol B. There are two complications to this. Firstly, as noted in §1, coronal abundances in at least some stars appear not to reflect the values in the underlying stellar photosphere. Secondly, and again as noted in §1, both Algol and HR 1099 are “metal-deficient” in their coronae with respect to the solar photosphere. I address this latter point first.
3.2. Establishing the Photospheric Baseline

Transitions involving electrons with ground states in the Fe

\( n = 2 \) shell tend to dominate soft X-ray spectra of hot coronal plasmas, and for this reason Fe is often used as a proxy for the global plasma metallicity. The coronal Fe abundances for Algol and HR 1099 are identical to within observational

uncertainty. A recent measurement of the absolute Fe abundance in the corona of HR 1099, Fe/H= 7.0 ± 0.1 (corresponding to [Fe/H]= −0.5 relative to the solar photospheric abundance; e.g. Grevesse & Sauval 1998) was recently presented by Drake et al. (2001). Earlier estimates of the coronal Fe abundance of Algol have been made based on ASCA ([Fe/H]= −0.32 ± 0.01, with the error based on statistical uncertainty only; Antunes, Nagase & White 1994; see also Singh, Drake & White 1996) EUVE ([Fe/H]= −0.23 to −0.66; Stern et al. 1995), while Favata & Schmitt (1999) obtained a global metallicity of [M/H]≃ −0.35 during quiescence in an observation by BeppoSAX that captured a very large flare (the metallicity was interpreted as undergoing strong variations correlated with the flare rise and decay).

The determination of the coronal Fe abundance of Algol, "bootstrapped" from the earlier Drake et al. (2001) absolute Fe abundance of HR 1099, is in fairly good agreement with these values, and I consider this result quite robust. In quoting these other abundance results, I note that the works cited all adopted the solar abundance compilation of Anders & Grevesse (1989), which employed an iron abundance Fe/H= 7.67. I have accordingly adjusted the relative abundances to a solar iron abundance of Fe/H= 7.50 (see Drake, Laming & Widing 1995 for further details) used by Drake et al. (2001).

Having established the Fe abundance in both Algol and HR 1099, the next question is whether or not the value obtained is representative of their photospheric Fe abundances, or whether the coronal abundances have been altered by fractionation processes. To my knowledge, no detailed photospheric abundance analyses of either Algol A or B have been published and so a definitive answer to this question will have to wait. In either case, we have to consider what the initial C and N abundances, prior to mixing of the envelope and nuclear-processed core, would have been.

The elements C and N do not share the same nucleosynthetic origins: the dominant isotope C\(_{12}\) is produced mostly by He-burning, while the dominant N isotope N\(_{14}\) is produced mainly by H-burning. Studies of C and N photospheric abundances in stars of different metallicity (as represented by Fe) show different trends. The abundance of C exhibits moderate enrichment relative to Fe with decreasing [Fe/H], amounting to [C/Fe]≃ +0.2 at [Fe/H]≃ −0.7 (e.g. Tomkin, Woelfl & Lambert 1995, Gustafsson et al. 1999; Shi, Zhao & Chen 2002). In contrast, the abundance of N appears to follow that of Fe over a range of [Fe/H] from −0.8 to +0.1 (e.g. Shi et al. 2002). If Algol and HR 1099 were mildly metal-deficient, and this reflected the actual stellar compositions and was not the result of coronal compositional fractionation, then we might therefore expect original C and N abundances of [C/H]≃ −0.35 and [N/H]≃ −0.5. We can use these values, together with the C and N solar photospheric abundances C/H=8.39 (Allende Prieto et al. 2002), N/H=7.92 (Grevesse & Sauval 1998) to estimate projected changes in the number of C and N atoms in the envelope of Algol B. In the usual logarithmic notation for the number density relative to hydrogen, these are ∆C/H≃ −8.0 and ∆N/H≃ +7.4. These values pose an immediate problem: in

the CN-cycle, N is produced at the expense of a commensurate depletion in C, and the total number of C and N nuclei is expected to be conserved. That we do not arrive at equal changes in C and N implies that the initial unprocessed abundances assumed here are incorrect. This conclusion is not changed significantly because of the adoption of a slightly non-solar initial C/N abundance ratio expected in a disk star with [Fe/H]= −0.5; the difference only amounts to C/N being larger by 0.15 dex.

An alternative approach is to determine what initial absolute abundances of C and N would match the observed C depletion and N enhancement in Algol relative to HR 1099. Or, put another way, what value of metallicity, [M/H], would be required for the total number of C and N nuclei to be conserved. The number density of an element (n) is given by our observed fluxes and by Equations 3 and 5. We write the observed ratios of C and N in Algol and HR 1099 as

\[
\frac{n(C)}{n(H)} = \delta C \quad \text{and} \quad \frac{n(N)}{n(H)} = \delta N
\]

(7)

We now assume, firstly, that the total number density of C and N nuclei in the processed envelope of Algol remains unchanged compared to the initial pristine value, and, secondly, that this total number density is the same in HR 1099, except for a scaling factor allowing for different global metallicities between the two stars,

\[
\frac{n(C)}{n(H)} = m \frac{n(C)}{n(H)}_A = m \frac{n(N)}{n(H)}_A = m \frac{n(N)}{n(H)}_A
\]

(8)

where \( m = n(M)_A / n(M)_H \) is ratio of metallicities by number. The C/N abundance ratios by number for Algol and HR 1099 can then be written

\[
\left( \frac{n(C)}{n(N)} \right)_A = \frac{m \delta C - \delta N}{m \delta C - m} \quad \text{and} \quad \left( \frac{n(C)}{n(N)} \right)_H = \frac{m \delta C - m}{m \delta C - m}
\]

(9)

I illustrate these C/N abundance ratios as a function of the logarithm of the metallicity parameter \( m \) in Figure 4, adopting the derived C abundance upper limit for Algol as a proxy for use in the value \( \delta C \). Also indicated on this figure are the C/N abundance ratios from three sources: the solar ratio derived from the C abundance of Allende Prieto et al. (2002) and the N abundance of Grevesse & Sauval (1998) that I adopt as “reference” solar values; the ratio from the still commonly used solar abundance compilation of Anders & Grevesse (1989); and the ratio from the abundance values derived relative to that of O for the coronae of HR 1099 itself based on XMM-Newton observations by Brinkman et al. (2001). The intersection of these C/N ratios with the HR 1099 C/N locus indicates the metallicity of Algol relative to HR 1099 needed in order that the number density of C and N abundances be conserved. For the solar C/N ratios, we need a metallicity [M/H]$_{1099}$ ~ −0.25, whereas for the Brinkman et al. (2001) C/N ratio, the metallicity is −0.1 dex. The uncertainties of the values are of order 0.1 dex or so. Note that the metallicity derived in this way is not sensitive to the fact that I have used the upper limit to the C ratio, \( \delta C \), nearly all (over 90%) of the C in Algol has already been converted into N, and so the N abundance remains essentially the same regardless of the exact C abundance adopted.

I have already established above that the Fe abundances in the coronae of Algol and HR 1099 are essentially the same. The “metallicity” values indicated by the C/N ratios suggest slightly lower abundances in Algol than HR 1099, and possibly significantly so. This “metallicity” is of course just a number representing C and N. However, I note that the abundances for O and Ne are similar to this in being slightly lower in Algol than in HR 1099; the error-weighted mean of the Ne and O
abundances (Table 3) yields a “metallicity” \[[\text{M/H}]_{099} = -0.20\], a value consistent, within errors of 0.1 dex or so, with the C/N result. I take this agreement as indicating that indeed the light element abundances in Algol are lower by order of 0.2 dex than those in HR 1099.

By assuming an initial C/N ratio and that this ratio is represented by the current C/N ratio in HR 1099, we arrive at a C/N ratio for Algol; these ratios are indicated in Figure 4 and are $C/N = -0.95$ for initial solar C/N ratios, and $C/N = -1.2$ for an initial ratio equal to that of Brinkman et al. (2001).

4. COMPARISON WITH THEORETICAL MODELS

As discussed above in §3, the assumption that the present-day C/N coronal abundance ratio in HR 1099 is representative of the ratio in the original unprocessed envelope of Algol B, and that this ratio in HR 1099 is similar to the solar ratio, implies the change in the C/N abundance ratio in Algol B as a result of nuclear processing and dredge-up is $\Delta \log C/N \approx -1.44$ dex. In comparison, the changes expected at the surface of normal G and K giants in the post-dredge-up phase is $\Delta \log C/N \approx -0.3$ to $-0.7$ (eg Lambert & Ries 1977, 1981; see also §4.2 below). Main-sequence CN-processing in the core of Algol B is expected to have been essentially the same as that in a single star of the same mass; the extreme decrease in the post-dredge-up phase in Algol B is simply a result of a lower dilution factor of this CN-processed material because of the loss of material from its outer envelope to Algol A.

4.1. Close Binary Evolutionary Predictions

Stellar evolution calculations for Algol-type binaries that follow the surface abundances of C and N have been undertaken for intermediate mass systems by de Greve (1989,1993; see also de Greve 1986), and Sarna (1992,1993). These authors conclude that the mass transfer in Algol corresponds to early case B, in which transfer is initiated by the expanding stellar envelope filling its Roche Lobe after turn-off from the main-sequence and the establishment of hydrogen shell burning. In the early stages of mass transfer, the convection zone of the initially more massive Algol B would not have been fully-developed and so the envelope from which material was lost would only be partially mixed with deeper layers that had been subjected to CN-processing. During later stages, after most of the pristine outer envelope had been lost to Algol A, material from layers in which CN-processing had reached equilibrium, and that would also have been He-rich from H-burning, was transferred. Being He-rich, this material would have induced thermohaline mixing on Algol A (mixing resulting from the larger molecular weight of the overlying material), diluting the CN-processed material with the rest of the envelope of Algol A.

I compare the abundance results derived here with the detailed binary model evolutionary calculations specifically for Algol performed by Sarna (1993). These models include the effects of non-conservative mass transfer, and mass and angular momentum loss through magnetic activity and stellar winds—effects that have been shown to be important for intermediate and lower mass Algols that include a magnetically-active late-type component by, e.g., Sarna et al. (1997), Eggleton (2000) and Nelson & Eggleton (2001). Sarna (1993) was able to derive a model that successfully matched the present day observed parameters of the system, including the C abundance in Algol A obtained by Cugier & Hardorp (1988) based on C II lines observed by the International Ultraviolet Explorer (IUE). The C abundance appears depleted in Algol A by about a factor of 2 because of the dilution of its original envelope by material strongly depleted in C from Algol B. Changes in C and N abundances in Algol B are predicted as part of these calculations and amount to $\Delta \log C = -1.0$ (Sarna 1993) and $\Delta \log N = +0.4$ (M. Sarna, private communication), yielding a change in the C/N abundance ratio of $\Delta \log C/N = -1.4$.

Within reasonable uncertainties, the Sarna (1993) abundances are quite consistent with the values derived in this study. As discussed at length above, the individual C and N abundances depend on the adoption of the metallicity for these elements. Formally, then, our adopted N abundance is 0.1 dex higher than the model prediction and to lower it by this amount requires a lower C abundance of $-1.03$. Since our C abundance is a $3\sigma$ upper limit, it does seem possible that the C/N decrease could be significantly greater than $-1.4$ dex predicted by the Sarna (1993) best-fitting model and it might be of interest to determine what changes to this model might accommodate a larger depletion. However, at the present day phase in its evolution, this model also predicts quite a steep decline in the C abundance and it seems plausible that a greater depletion in the C/N ratio might be accommodated by the model uncertainties.

4.2. Simple Two-Zone Model

It is worth comparing the C/N ratio we have obtained for Algol with the values expected in single G and K giants following convective dredge-up of CN-processed material during the ascent of the red giant branch. Lambert & Ries (1977,1981) obtained typical values by number of $n(C)/n(N) \approx 1.2$ for a sample of field giants, to be compared with their adopted solar (initial) ratio of 4.8, or a logarithmic change in the C/N ratio of $\Delta \log C/N \approx -0.3$ to $-0.7$. These values were in good agreement with the evolutionary models of Dearborn, Tinsley & Schramm (1978), which, for a star of mass 2.8 $M_\odot$ and the same initial C/N ratio, predicted a surface abundance ratio of $[C/N] = -0.55$ after dredge-up.

Following Parthasarathy, Lambert & Tomkin (1983), by adopting a crude two-zone model for the envelope and CN-processed shell we can make a very rough estimate of the fraction of mass lost from the star based on the (assumed) initial abundances and (measured) final abundances. In this model, one assumes that mass transferred onto Algol A is comprised of only pristine unprocessed material prior to deep mixing of envelope and processed core. At dredge-up, a remaining outer envelope of mass $M_p$ containing only unprocessed material is mixed with a mass $M_p$ of matter processed through the CN-cycle on the main-sequence. We can then equate the number of atoms of C or N per unit mass in the mixed material, $n_m$, to the numbers per unit mass in the processed core, $n_p$, and unprocessed envelope, $n_u$, as follows:

$$n_m(M_u + M_p) = n_u M_u + n_p M_p$$

The ratio of the processed and unprocessed masses is then simply

$$\frac{M_p}{M_u} = \frac{n_u - n_m}{n_m - n_p}$$

Since we have only an upper limit for the C abundance $n_u$, I estimate $M_p/M_u$ based on the observed N abundance. As before, I adopt the initial solar C abundance of Allende-Frieto et al. (2002) and the N abundance of Grevesse & Sauval (1998). The observed N abundance is then $[N/H] = -0.56$, where the value in Table 3 has been lowered by 0.05 dex to be in accordance with the metallicity $[M/H] = -0.25$ indicated for the adopted solar C
and N abundances in Figure 4. Assuming that in the processed mass $M_p$ essentially all the C is converted to N, the mass ratio given by Equation 11 is $M_p/M_u = 8.2$.

As pointed out by Parthasarathy et al. (1983) based on the work of Iben (1967), in the absence of strong mass loss, and over a fairly wide range of stellar masses, standard evolutionary models for intermediate mass stars such as the Algol B progenitor have an unprocessed envelope mass fraction of about half the total stellar mass, or $M_p/M_u \sim 1$. The simple two-zone model then provides a “0th order” proof that Algol B must have lost nearly all of its outer envelope, or about half its mass. How applicable is such a simple two-zone model to Algol? It implicitly assumes that mass loss occurred only during a rapid phase that was short compared to evolutionary timescales. Empirically, this cannot be the case because the C abundance of Algol A indicates that He-rich material that induced thermohaline mixing must have been transferred, otherwise the surface abundances of the two stars would be about the same. Such He-rich layers in Algol B also correspond to layers in which C and N abundances would have reached the equilibrium values of CN-processing, where C is reduced to about 3% of its initial value ([C/H]$_{\text{eq}} \sim -1.5$). The C abundance is larger than this equilibrium value because of mixing of the pristine envelope with the CN-processed layer during mass-transfer. The two-zone model estimate is therefore a lower limit to the actual mass loss. The model of Sarna (1993) suggests an initial mass of Algol B of 2.81$M_\odot$, to be compared with its present mass of 0.81$M_\odot$; in this non-conservative model, 15% of the total mass is lost to the system.

Prior to the Chandra LETGS observations, the only direct nucleosynthetic observational clue as to the past evolution of the Algol system was the C abundance estimate for Algol A of Cugier & Hardorp (1988). As pointed out by Sarna (1993), this value remained too uncertain to be of quantitative value in constraining evolutionary models. The Chandra observations present the first direct and definitive observational evidence of the strong modification of the surface C and N abundances of Algol B through exposure to main-sequence nuclear burning and subsequent shedding of its outer envelope. These observations provide the best observational confirmation of theoretical models for the evolutionary history and present status of Algol.

5. FURTHER CONSIDERATION OF UNCERTAINTIES

The formal abundance results in Table 3 quote only statistical uncertainties, which are very small owing to the use of prominent and well-observed spectral features. The advantage of the relative study adopted here is that the uncertainties inherent in absolute abundance studies tend to cancel each other out because they are the same for both stars. These include uncertainties in the instrument calibration, in the measurement and extraction of line fluxes, and in the atomic data relevant for the radiative emission of interest.

The largest uncertainties in this study instead arise from the two main assumptions adopted (supplementary to the common underlying assumption that the sources can be adequately described by collision-dominated, optically thin plasmas, an assumption that we expect to be reasonably accurate). These are:

1. the temperature dependences of the source DEMs are essentially the same; and
2. there is no strong differential compositional fractionation at work between the two stars, especially among C and N, so that inferred abundance differences represent underlying stellar compositional differences.

These two assumptions are partly correlated: one might expect that any compositional fractionation at work in one corona might be duplicated in another that is in some respects very similar, provided the fractionation mechanism(s) are at least partly dependent on the common parameters. I argue that this is indeed the case below. Regarding the temperature structures of the source plasmas, it has been found that the ratios of He-like to H-like resonance lines in the abundant elements O, Ne, Mg, Si, and S are very similar to within statistical uncertainties (Drake et al. in preparation), with deviations typically of order 20% or less. These ratios are not sensitive to abundances but are quite sensitive to temperature. Based on this evidence, provided assumption (2) is valid, we might expect uncertainties in abundance ratios of order 0.1 dex to result from small differences in source temperature structure.

5.1. Similarities in Stellar Parameters and Coronae

The principal stellar parameters currently thought to drive coronal formation can be coarsely defined as spectral type and rotation rate. In this regard, the similarity in spectral type of the active subgiant primary in the HR 1099 system that dominates its coronal activity and Algol B (Algol A being X-ray dark), together with their similar rotation periods, suggests at the outset that their coronae might also share very similar characteristics. Further parameters for the X-ray dominant components are summarised in Table 1. These values indicate that, indeed, the effective temperatures appear to be consistent within experimental uncertainty, as, likely, are the masses and radii. These are known to an accuracy $\sim 5\%$ for Algol (e.g. Richards et al. 1988), but for HR 1099 formal uncertainties are difficult to estimate. I have listed the Donati (1999) values of these parameters which correspond to a system inclination $i = 38\degr$; this author notes the sensitivity of the derived values to the adopted inclination, and that for an inclination similar to that of Fekel (1983), both derived mass and radius are larger. Also of note is the temperature for Algol B derived by Kim (1989), of “4888 ± 96 K”, which is very similar to the HR 1099 effective temperature of Randich et al. (1994). Indeed, based on parameters derived, Kim (1989) adopted a spectral type for Algol B of K0 IV—very similar to the K1 IV type of the primary of HR 1099.

I have not considered stellar metallicity here—a parameter that could also influence coronal activity through alteration of convection zone properties (e.g. Pizzolato et al. 2001), in addition to outer atmosphere radiative loss rates. I address the stellar metallicities below; again these appear to be similar in both stars. A further parameter is the He abundance, which is expected to be higher in Algol B owing to a smaller dilution of H-burning products with an envelope depleted through mass transfer. I return to this below in §6.

In summary, the remarkable similarity in the stellar parameters of active Algol and HR 1099 components, as noted above, in addition to their identical rotation rates, leads me to suggest that their coronae are likely to be superficially identical. This conjecture is borne out in a detailed comparison of their X-ray spectra, in which variations in relative line intensities are generally well within a factor of two—see Figure 2. Similar conclusions were also reached in a comparison of radio observations of Algol and HR 1099 by Mutel et al. (1998). They found that the mean radio luminosity, luminosity distribution functions, and spectral index correlations with flux density from Very
Long Baseline Array and Green Bank Interferometer (GBI) observations were nearly indistinguishable. Some difference in circular polarisation fraction was attributed naturally to differences in system inclination. Some palpable differences have been found, however: Richards, Waltman & Ghigo (2002) have recently presented evidence that apparent periodicities in radio flaring in the time from 1995 to 2000 at frequencies of 2.3 GHz and 8.3 GHz are different, with the strongest periodicities found being 49 ± 5 days and 120 ± 5 days for Algol and HR 1099, respectively. Nevertheless, all other characteristics appearing very similar, I feel that assumption (1) is justified and that, indeed, the temperature structures of the coronae of HR 1099 and Algol are essentially the same.

The similarity in the X-ray spectra of these stars also argues against any significant role in coronal formation for their different Roche lobe filling factors, or for the ongoing mass transfer in Algol, again in agreement with the conclusions of Mutel et al. (1998) based on radio properties.

5.2. Coronal Abundance Anomalies and Compositional Fractionation

The possibility that the coronae of either, or both, Algol and HR 1099 have compositions that differ from their underlying photospheres would affect this analysis and conclusions if there were to be a relative fractionation between C and N that differed between the two stars; ie, if the observed difference in the ratio C/N in the coronae of Algol and HR 1099 were to be attributable to effects other than purely CN-processing.

As noted in §1, both EUVE (Stern et al. 1995) and ASCA (Antunes et al. 1994) studies of Algol obtained low values for its coronal Fe abundance. Both studies estimated \( [\text{Fe/H}] \sim -0.5 \), a result that was confirmed by BeppoSAX observations reported by Favata & Schmitt (1999), and that is further supported here by our analysis relative to HR 1099. While a mild Fe deficiency of \( [\text{Fe/H}] = -0.5 \) is not unusual for stars of the Galactic disk population, young systems involving early-type stars are not generally expected to be so metal-poor. The best-fit evolutionary model of Sarna (1993) suggests an age for Algol of about 0.45 Gyr (see also Nelson & Eggleton 2001 whose best-fit model is 1.1 Gyr old). The recent statistical age-metallicity relationships for the Galactic disk of Feltzing, Holmberg & Hurley (2001) indicate that it would indeed be quite unusual for stars earlier than F0 \( (\geq 1.5M_\odot) \) to have such low Fe abundances. Sarna (1993) and Nelson & Eggleton (2001) Algol models suggest Algol B was either a late B or early A zero-age main-sequence star, with predicted masses of 2.8 and 2.2 \( M_\odot \), respectively, confirming the statistical likelihood that Algol should not be significantly metal-poor. We conclude, then, that Fe is very likely depleted in the corona of Algol B relative to the underlying star.

A recent review of coronal abundance studies for RS CVn systems for which estimates of both coronal and photospheric abundances exist also supports the idea that Fe is in fact depleted in their coronae relative to their underlying photospheres, possibly by as much as 1 dex (Drake 2002). There are no definitive photospheric abundance studies that tell us whether or not this is also the case for HR 1099. In addition, the evolutionary status of HR 1099 is more difficult to infer than for Algol because derived stellar masses are dependent on the adopted system inclination (e.g. Fekel 1983; Donati 1999). If the estimate of \( \sim 1M_\odot \) for the primary listed in Table 1, corresponding to an inclination \( i \sim 40^\circ \), is correct, then its evolved state would imply an age of \( \sim 10 \) Gyr. Such an old disk star would be expected on a statistical basis to be somewhat metal-poor.

While no detailed photospheric abundance studies have been undertaken for HR 1099, estimates of Fe abundances have been made as part of other studies. Randich et al. (1994) obtained \( [\text{Fe/H}] = -0.6 \) for the primary in a study of the Li region near 6708 Å, but obtained \( [\text{Fe/H}] = 0 \) for the secondary component, a metallicity pattern apparently found also by Vogt & Penrod (1982 private communication to Fekel 1983). Interestingly, Randich et al. (1994) derived similar metallicity differences between primary and secondary components for several other RS CVn binaries in their sample. Such a differences in metallicity between components of a close binary are difficult to understand on evolutionary grounds, but similar differences had been suggested earlier based on spectroscopic analyses of a handful of both Algol-type and RS CVn-type binaries by Naftilan (1975) and Naftilan & Drake (1977,1980). However, Ottmann et al. (1998) have refuted claims of significant metal paucity for some systems in the Randich et al. (1994) sample based on more extensive spectroscopic analyses, while a detailed study of the AR Lac secondary by Gehren (1999) that obtained \( [\text{Fe/H}] = 0 \), in contrast to the result \( [\text{Fe/H}] \sim -1 \) of Naftilan & Drake (1977), casts doubt on the reality of true intra-binary photospheric abundance differences. More recently, in a Doppler imaging study of HR 1099, Strassmeier & Bartus (2000) estimated \( [\text{Fe/H}] = -0.1 \) and \( [\text{Ca/H}] = -0.2 \) for the secondary of HR 1099.

It is difficult to draw firm conclusions regarding the true photospheric metallicity of HR 1099 based on this summary of disparate results. Clearly, the issue of possible abundance differences between primary and secondary components of close binaries warrants further study: if true, such differences would provide a strong challenge to structural and evolutionary models for such systems. At present, I appeal to the differential nature of this study and tentatively suggest that HR 1099 is not significantly more metal-poor than Algol, and that the very similar X-ray dominant components of these systems are undergoing very similar fractionation processes that results in Fe being depleted in their coronae by of order 0.5 dex.

In addition to this apparent depletion of Fe, the recent Chandra and XMM-Newton studies of HR 1099 based on high resolution X-ray spectra (Drake et al. 2001, Brinkman et al. 2001) indicate that other element abundances are strongly modified in the corona. In particular, both studies found enhancements of Ne relative to Fe of about a factor of 10, and of O relative to Fe of factors of 3-4. Brinkman et al. (2001) argued that the differences followed an inverse First Ionization Potential (FIP) effect—a situation opposite to that in the solar corona where elements with FIP \( \lesssim 10 \) eV appear to be enhanced relative to elements with FIP \( \gtrsim 10 \) eV. Considering the magnitudes of these abundance anomalies, the Ne and O abundances are strikingly similar in the two systems, differing in their ratios relative to Fe by only 0.2 dex. Regardless of whether the fractionation in these stars is FIP-related or otherwise, I conclude that the element fractionation processes at work in HR 1099 and Algol B are remarkably similar and produce essentially the same abundance pattern. On this basis, I suggest that there is no significant difference between the two stars in any coronal fractionation at work between C and N.

Further support for this argument comes from the adopted C depletion and N enhancement. As discussed at length in §3, the depletion and enhancement are linked through the adopted
metallicity: a lower metallicity implies a smaller C depletion and larger N enhancement, and vice-versa. I demonstrated in §3 and Figure 4 that the derived C and N abundances for Algol are consistent with the metallicity derived from O and Ne provided that conservation of C and N nuclei held in the zone subjected to CN-processing. It therefore appears that the elements C, N, O and Ne undergo very similar differential fractionation in both Algol and HR 1099.

5.3. Surface C and N abundance changes in HR 1099?

The XMM-Newton study of HR 1099 by Brinkman et al. (2001) and the Chandra LETG study by Schmitt & Ness (2002) both obtained C/N ratios for HR 1099 that appear to be significantly lower than solar values ([C/N] = −0.4 relative to Anders & Grevesse 1989; and [C/N] < −0.16 relative to “cosmic abundances”, respectively). Schmitt & Ness (2002) interpreted their result as indicating that the surface N abundance of HR 1099 has been modified by CN-cycle processing and subsequent dredge-up (these authors noted an N abundance increase, though the C/N ratio decreases primarily as a result of C depletion because N would initially be ~4 times more abundant than C). It would be interesting to see CN-cycle products in HR 1099 because the X-ray dominant star is still a subgiant and has not yet crossed the Herzsprung gap. It should not, then, have a fully-developed deep convective envelope and so dredge-up would have only just started. Indeed, Lambert & Ries (1981) noted that the subgiants in their sample of evolved G and K stars appeared to have started the dredge-up phase based on observed 12C/13C ratios.

If HR 1099 does indeed have modified surface C and N abundances, the C/N ratio for Algol derived here relative to HR 1099 will need to be modified: the change in C/N abundance ratio caused by CN-cycle processing relative to its initial composition would be larger by the magnitude of the depletion in the C/N ratio of HR 1099. In this regard, it is worth examining the Brinkman et al. (2001) and Schmitt & Ness (2002) results in more detail.

The Brinkman et al. (2001) result is based on abundances derived relative to O. Since the temperature dependence of the emissivities of the H and He-like lines of C, N and O are significantly different, estimating the relative abundances of these elements based only on these lines can be hazardous: errors in the adopted temperature structure (Φ[Nα(T), V(T)]) can induce errors in derived abundance ratios. Instead, the Schmitt & Ness (2002) result is based on the observed line strength ratio of the H-like Lyα lines of C and N, compared to the theoretical emissivity ratio as a function of temperature. Their upper limit to the C/N abundance ratio is based on the maximum theoretical value for the line strength ratio (expressed as N/C rather than C/N used here), and is therefore temperature-independent. Their maximum theoretical value is 0.42 in photon units (0.57 in energy units), which is to be compared with their measured ratio of 0.61 ± 0.05. The N/C line strength ratio computed with the PINToFALE software (Kashyap & Drake 2000), using the CHIANTI v3 (Dere et al. 2001) implementation of the collision strengths of Aggarwal & Kingston (1991) together with the ionization balance of Mazzotta et al. (1998) yields maximum values of the N/C line strength ratio (in photon units) of 0.53, 0.59, 0.48 and 0.65 for the abundance mixtures of Allen (1973), Anders & Grevesse (1989), Grevesse & Sauval (1998), and Grevesse & Sauval (1998; N) combined with Allende-Prieto et al. (2002; C), respectively. My observed line flux ratio, based on C and N line strengths from Table 2 normalised by the instrument effective areas at the appropriate wavelengths (15.2 and 11.6 cm² for N and C, respectively; Pease et al. 2002b) is 0.67 ± 0.07. This ratio is consistent with that of Schmitt & Ness (1998), but is also consistent with the theoretical upper limit for the N and C abundances of Grevesse & Sauval (1998) and Allende-Prieto et al. (2002), respectively, and is only marginally higher than the upper limits corresponding to the other abundance mixtures. Based on this comparison, I then find no firm evidence that the surface abundances of HR 1099 have been modified significantly by CN-processing. The difference between this conclusion and that of Schmitt & Ness (2002) lies predominantly in the adopted theoretical line ratio maximum and in the assumed abundance mixture: for example, the C abundance of Allende-Prieto et al. (2002) is 0.17 dex lower than that of Anders & Grevesse (1989).

As pointed out by Schmitt & Ness (2002; Figure 2) and Drake et al. (in preparation), the theoretical N/C line strength ratio is fairly flat for temperatures log T > 6.4. For coronae dominated by emission from plasma hotter than 2-3 × 10⁶ K, such as that of HR 1099, one can then interpret directly an observed N/C line strength ratio in terms of the N/C abundance ratio. The theoretical N/C ratio corresponding to the Grevesse & Sauval (1998) N abundance and Allende-Prieto et al. (2002) C abundance for the temperature range 6.4 ≤ log T ≤ 7.2 is 0.63 ± 0.03. Our observed ratio is consistent with this value. I therefore conclude that the ratio of C and N abundances in the corona of HR 1099 is similar to that in the Solar photosphere. This also suggests that the inferred C/N ratio from the abundances relative to O of Brinkman et al. (2001) might be too low by a factor of ~2; again, 0.17 dex of this ~0.3 dex difference can be attributed to these authors having used the Anders & Grevesse (1989) abundance mixture.

Based on this result, and on the arguments cited above in §5.2, I conclude that there is unlikely to be any differential compositional fractionation between C and N in the corona of HR 1099 or Algol.

5.4. X-ray Emission from Algol A?

In this analysis, I have assumed that there is not a significant contribution to the LETGS spectrum from Algol A. With a spectral type of B8 V, Algol A is in the range of types from mid-B to late-A that do not possess either strong radiatively-driven winds or outer convection zones that are thought necessary to sustain shocks or magnetic dissipation sufficient to heat and maintain plasma at X-ray emitting temperatures. These expectations were observationally confirmed for B-type stars by Grillo et al. (1992) in an Einstein Observatory survey. In the few cases where X-ray emission was detected for late-B and early-A stars, it was found to originate from a cool companion. X-ray fluxes of up to 10⁻¹⁵ erg s⁻¹ were found for 86 dwarfs of spectral types B7-B9 seen in the ROSAT All-sky Survey (Berghöfer et al. 1996), but it has since been discovered that these stars are also either spectroscopic binaries or have young, lower mass companions (e.g. Berghöfer et al., 1997; Hubrig et al. 2001). That late-B and early-A main-sequence stars are X-ray dark is also supported by the non-detection in X-rays of single A stars like Vega (Pease et al. in preparation; < 9 × 10⁻¹⁴ count s⁻¹ ROSAT PSPC; see also Schmitt 1997). In principle, then, X-ray wavelengths offer the chance to obtain a clear view of the surface abundances of Algol secondary stars.

While it then appears that single or non-interacting late-B
main-sequence stars are X-ray dark, it is plausible that the accretion activity associated with Algol systems sustains hot plasma. Singh et al. (1996) considered this problem in a comparison between RS CVn-type binaries comprised of two late-type stars in which neither component filled their Roche lobes, and Algol-type binaries. They found that the Algol-type binaries are in fact slightly X-ray deficient relative to their RS CVn cousins, suggesting strongly that the accretion activity of Algos is not a significant source of X-rays. I discuss this further in §6, below.

Evidence for plasma associated with accretion and with temperatures of at least 10^5 K has, however, been found in the Algol systems V356 Sgr and TT Hya from recent FUSE observations (Polidan et al. 2000) and Peters et al. 2001, respectively). Emission detected from O VI appeared to be associated with a bipolar flow that makes a large angle with the orbital plane. In order for this plasma to contribute significantly at X-ray wavelengths, it must be comprised of components at least an order of magnitude hotter than the formation temperature of O VI. In the case of Algol, though the presence of such plasma cannot be ruled out with certainty, Doppler shifts in X-ray lines also suggest that Algol B is the only significant source of X-rays. A recent investigation of spectral lines seen in the Chandra HETG spectrum of Algol obtained in 2004 April clearly reveals the orbital velocity of Algol B and locates the X-ray emission on the late-type star, leaving only a maximum of ~ 10% of the observed line emission as possibly arising from accretion in the vicinity of Algol A (Chung et al., in preparation).

At this time, then, I conclude that significant X-ray emission from sources other than the corona of Algol B remains possible, though unlikely, and that any such emission contributes at most 10% of the total observed emission. It also seems unlikely that such a contribution would significantly change any of the conclusions derived here, since the accreting material would be expected to have the same abundances of C and N as the corona of Algol B.

6. A COMMENT ON THE X-RAY LUMINOSITY DEFICIENCY OF ALGOL BINARIES

In their comparative analysis of X-ray observations of Algol-type and RS CVn-type systems, Singh et al. (1996) noted that the Algols appeared systematically fainter in X-rays than the RS CVn’s, even after allowing for the likely X-ray dark nature of the primaries of the former systems. By comparing X-ray luminosity to Roche lobe filling factors, Singh et al. (1996) ruled out mass transfer and accretion in the Algol systems as significant factors in their X-ray luminosity “deficiency”. Sarna et al. (1998) have successfully explained the gross characteristics of the large X-ray luminosity differences among Algol-type systems in terms of convection zone parameters responsible for generating magnetic flux within an α-ω dynamo formalism. Nevertheless, it is not clear that the systematic trend of the RS CVn’s appearing systematically more X-ray bright than the Algols, as illustrated in Figures 4a and 4b of Singh et al. (1996), can be entirely explained within such a framework.

For what other reasons might what are otherwise very similar star systems have notably different X-ray characteristics? One conspicuous difference between the RS CVn’s and the Algols is the mass transfer history of the secondaries of the latter. Loss of a substantial fraction of the outer envelope leads to less dilution of the layers processed by main-sequence nuclear burning, as is manifest in the C/N abundance ratio. While trace elements such as C and N will have little effect on a star or its corona, another element whose surface abundance can be substantially altered is He.

It was shown by Drake (1998) that a corona substantially enhanced in He might appear metal-poor owing to the dependence of thermal bremsstrahlung on the square of the nuclear charge: the enhanced continuum lowers the line-to-continuum ratio. In the Algol case, however, Drake (1998) also noted that the large He abundance should not appreciably change the emitting characteristics of the corona. This is because the enhancement in He occurs at the expense of the loss of H, where four H nuclei are transformed into one He nucleus. In this case, the line-to-continuum ratio remains about the same because the He continuous emissivity is four times that of H. The net emissivity of coronal plasma therefore remains about the same.

Instead, I speculate that raising the He abundance could affect the corona in two possible ways: (i) through changes in the convective envelope in which magnetic fields thought to fuel a corona are generated; (ii) through a possible dependence of the coronal heating efficiency on the He abundance or plasma mean molecular weight. Suggestion (i) would have been implicitly included in the work of Sarna et al. (1998), and a comparison between convection zone parameters of otherwise very similar systems differing only in the He abundance in the envelope might prove interesting. In the case of the latter scenario, that the He abundance in the corona might directly affect the coronal heating efficiency, Algol systems might prove valuable for helping discriminate between different coronal heating mechanisms.

7. SUMMARY

I have investigated the C and N abundances in the corona of Algol B through a differential study relative to HR 1099. Chandra LETG spectra obtained for both stars during times of quiescence show that the temperature structure and abundances in these coronae are very similar, in accordance with naive expectations based on the similarity of the parameters of the stars that dominate the X-ray emission. The differential analysis presented here therefore avoids errors associated with determining the underlying DEM, in addition to all systematic uncertainties involving atomic data, line flux measurement and instrument calibration.

The C/N abundance ratio in HR 1099 is found to be consistent with that of the solar photosphere, and no evidence is found for modification of the surface abundances of the X-ray-dominant subgiant through CN-cycle processing. The difference between this conclusion and that of Schmitt & Ness (2002), who concluded that these elements exhibited signs of CN-processing, can be attributable to adoption of a different solar abundance for C. In contrast, C is not detected in the corona of Algol and N appears enhanced relative to HR 1099 by a factor of 2. The change in the C/N abundance ratio in the atmosphere of Algol B as a result of CN-cycle processing is found to be \( \Delta \log C/N \leq -1.44 \). Based on this result, a simple two-zone model demonstrates that Algol B must have lost at least half of its original mass. This result is also consistent with predictions of detailed evolutionary models for Algol computed by Sarna (1993) in which Algol B has an initial mass of \( 3.5 M_\odot \) and loses about \( 2.7 M_\odot \).

A detailed examination of the abundance patterns in HR 1099 and Algol B for elements Fe, Ne and O confirms that they have very similar fractionation patterns, consistent with the view that
they are “coronal twins”. Consideration of the likely photospheric abundances for these stars leads to the conclusion that Fe must be depleted in their coronae relative to photospheric values by about 0.5 dex. One notable difference in their coronal properties will be an enhanced He abundance in the corona Algol B owing to the mixing of the products of core H-burning into the remnant envelope. I speculate that the enhanced He abundance in some Algol systems might explain some of the previously observed X-ray deficiency of these systems as compared to similar RS CVn-type binaries.

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C and N abundances in Algol B

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| Star    | Spectral Type | Period [d] | Distance [pc] | Active Component Parameters | Obs ID | Start [UT]   | Exposure [s] |
|---------|---------------|------------|---------------|----------------------------|--------|--------------|--------------|
| Algol   | B8 V + G8 III | 2.87       | 29.0$^d$      | $4500 \pm 300^{+300}_{-200}$ K | 3.5$^e$ | 0.8$^e$      | 0002         | 2000-03-12T18:23:15 | 79531 |
| HR 1099 | K1 IV + G5 V  | 2.84$^d$   | 28.5$^d$      | $4750 \pm 200^{+200}_{-150}$ K | 3.7$^f$ | 1.0$^f$      | 1879         | 2001-01-10T23:14:49 | 94867 |

$^a$The component that dominates X-ray Activity: Algol B and the K1 IV component of HR 1099.

$^b$Soderhjelm (1980)

$^c$Fekel (1983)

$^d$Perryman et al. (1997)

$^e$Richards et al. (1988)

$^f$Eaton (1975)

$^g$Kim (1989). This work obtained $4888 \pm 96$ K; type K0 IV was assigned to the secondary based on this temperature, combined with the values of the mass and radius similar to those of Richards et al. (1988).

$^h$Randich et al. (1984)

$^i$Donati (1999), who notes that these values are for $i = 38^\circ$ and are somewhat sensitive to the inclination adopted; in particular the mass and radius are larger for smaller inclinations.
### Table 2
Identifications and Fluxes for Spectral Features Used in this Analysis

| $\lambda_{\text{obs}}$ (Å) | $\lambda_{\text{pred}}$ (Å) | Ion | $\log T_{\text{max}}^a$ (K) | Alglob | HR1099 | Ratio$^b$ | Transition | Notes |
|---------------------------|---------------------------|-----|--------------------------|--------|--------|----------|------------|-------|
| 15.019                    | 15.015                    | Fe XVII | 6.75 | 1179 ± 54 | 1315 ± 54 | 0.89 ± 0.06 | (2p$^3$3d)$^1$P$^1$ → (2p$^5$)$^1$S$^0$ |
| 18.957                    | 18.967                    | O VIII | 6.50 | 2877 ± 98 | 5612 ± 141 | 0.513 ± 0.022 | (2p$^5$)$^3$P$_{5/2}$ → (1s$^2$)$^3$S$^1/2$ |
| 20.914                    | 20.910                    | N VII  | 6.35 | 148 ± 49  | 88 ± 30  | 1.69 ± 0.80  | (3p$^5$)$^3$P$_{3/2}$ → (1s$^2$)$^3$S$^1/2$ |
| 21.608                    | 21.602                    | O VII  | 6.30 | 290 ± 35  | 557 ± 53  | 0.522 ± 0.080 | (1s, 2p)$^3$P$^1$ → (1s$^2$)$^3$S$^0$ |
| 24.252                    | 24.779                    | Ne X   | 6.80 | 133 ± 28  | 244 ± 45  | 0.55 ± 0.15  | (2p$^5$)$^3$P$_{1/2}$ → (1s$^2$)$^3$S$^1/2$ 2nd order |
| 24.785                    | 33.734                    | C VI   | 6.20 | < 44      | 718 ± 53  | < 0.064    | (2p$^5$)$^3$P$_{1/2}$ → (1s$^2$)$^3$S$^1/2$ 2nd order |
| 33.744                    | 33.734                    | C VI   | 6.20 | < 44      | 718 ± 53  | < 0.064    | (2p$^5$)$^3$P$_{1/2}$ → (1s$^2$)$^3$S$^1/2$ 3rd order |
| 36.398                    | 12.132                    | Ne X   | 6.80 | 273 ± 32  | 430 ± 41  | 0.63 ± 0.10  | (2p$^5$)$^3$P$_{3/2}$ → (1s$^2$)$^3$S$^1/2$ |
| 37.920                    | 18.967                    | O VIII | 6.50 | 130 ± 27  | 242 ± 43  | 0.54 ± 0.15  | (2p$^5$)$^3$P$_{3/2}$ → (1s$^2$)$^3$S$^1/2$ 2nd order |
| 26.75                     | ···                      | Cont   | ···  | 7530 ± 87 | 9065 ± 95 | 0.83 ± 0.01 | b-f, f-f; 25.5-28.0 Å | Continuum |

$^a$The temperature at which the function $G_{ij}(T)$ peaks (Eqn. 1).

$^b$The ratio of observed integrated counts; this is proportional to the ratio of fluxes $F_A/F_H$ (Eqn. 3).

### Table 3
Derived Abundances Relative to HR 1099

| [Fe/H]$_{1099}$ | [O/H]$_{1099}$ | [Ne/H]$_{1099}$ | [M/H]$_{1099}^b$ | [C/M]$_{1099}$ | [N/M]$_{1099}$ |
|----------------|----------------|----------------|----------------|---------------|---------------|
| 0.03 ± 0.03    | −0.21 ± 0.02   | −0.13 ± 0.06   | −0.20 ± 0.02   | < −0.93$^c$   | 0.51 ± 0.02   |

$^a$Expressed in the conventional logarithmic bracket notation where [X/H] represents the abundance of element X relative to a standard star (usually the Sun, though here relative to HR 1099). NB: Quoted uncertainties are based on propagation of statistical uncertainties only; true errors are expected to be of order 0.1 dex.

$^b$The error-weighted mean of the O and Ne abundances relative to HR 1099.

$^c$3σ upper limit.
Fig. 1.— *Chandra* LETG+HRC-S X-ray light curves of HR 1099 (top) and Algol (bottom) obtained from 0th order events. Each light curve is binned at 100s intervals. Based on the ephemeris of Kim (1989), the Algol light curve spans phases $\phi = 0.74$ to $0.07$. 
Fig. 2.— Illustration of the remarkable similarity in the combined positive and negative order LETG+HRC-S spectra of Algol and HR1099 binned at 0.0125 Å intervals.
FIG. 3.—Comparison of the 20-35 Å range containing spectral lines due to C, N, O and Ne in Algol and HR 1099 LETG+HRC-S spectra.
The derived C/N abundance ratios by number in Algol and HR 1099 as a function of the logarithmic metallicity difference between the two stars ($[M/H]_{1099} = \log_{10}(n(M)/n(H))$; see also Equation 8). Unprocessed C/N ratios in HR 1099 corresponding to solar photospheric C and N abundances from Allende Prieto et al. (2001, 2002; C abundance combined with the N abundance from Grevesse & Sauval 1998; APAL), Anders & Grevesse (1989; AG), and to the estimates for the corona of HR 1099 derived by Brinkman et al. (2001; BEA), are indicated by the thicker horizontal straight lines. The C/N ratio for Algol and the metallicity parameter corresponding to these C/N ratios in HR 1099 are indicated by the thinner solid lines.