ION-BY-ION DIFFERENTIAL EMISSION MEASURE DETERMINATION OF COLLISIONALLY IONIZED PLASMA. II. APPLICATION TO HOT STARS

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ABSTRACT

In a previous paper we have described a technique to derive constraints on the differential emission measure (DEM) distribution, a measure of the temperature distribution, of collisionally ionized hot plasmas from their X-ray emission line spectra. We apply this technique to the Chandra HETGS spectra of all of the nine hot stars available to us at the time that this project was initiated. We find that DEM distributions of six of the seven O stars in our sample are very similar, but that \( \theta^1 \) Ori C has an X-ray spectrum characterized by higher temperatures. The DEM distributions of both of the B stars in our sample have lower magnitudes than those of the O stars, and one, \( \tau \) Sco, is characterized by higher temperatures than the other, \( \beta \) Cru. These results confirm previous work in which high temperatures have been found for \( \theta^1 \) Ori C and \( \tau \) Sco and taken as evidence for channeling of the wind in magnetic fields, the existence of which is related to the stars’ youth. Our results demonstrate the utility of our method for deriving temperature information for large samples of X-ray emission-line spectra.

Subject headings: plasmas — stars: early-type — X-rays: stars

1. INTRODUCTION

In hot stars, X-rays are emitted by gas heated in shocks in the wind. In most cases, these shocks are thought to result from an instability inherent in the mechanism that drives the wind: absorption of stellar UV radiation in line transitions. In some cases, however, other physical processes may play a role in the heating of gas to X-ray–emitting temperatures. For example, in very young hot stars, channeling of the wind by magnetic fields may play a strong role in heating the wind (e.g., ud-Doula & Owocki 2002). Among the evidence that X-ray emission from some hot stars may be due to a mechanism other than the instability of the radiative driving mechanism is the fact that the X-ray spectra of some hot stars are characteristic of emission by plasma of a higher temperature than for others.

Line emission from hot plasmas is highly sensitive to temperature. Therefore, insofar as theories of hot star winds make predictions for the temperature of X-ray–emitting plasmas in them, high-resolution X-ray spectroscopy offers a powerful method with which to test those theories. However, there are two obstacles in using high-resolution spectroscopy to study the winds of hot stars. First, in most hot stars, the winds from which the X-ray emission arises have velocities in excess of 1000 km s\(^{-1}\). Owing to this fact, X-ray emission lines are broadened and blended, making it difficult or impossible to measure fluxes of many emission lines (e.g., Cassinelli et al. 2001; Kahn et al. 2001; Schulz et al. 2003). Second, the theory of hot star winds is not sufficiently developed to the point where detailed predictions for X-ray emission line spectra can be made for direct comparison with observations.

While there are open questions regarding the origin of the X-ray–emitting plasma in hot stars, it is well established that the emitting plasma in hot stars is in collisional ionization equilibrium (CIE; see, e.g., Paerels & Kahn 2003). In a previous paper (Wojdowski & Schulz 2004, hereafter Paper I), we have described a method for measuring the differential emission measure (DEM) distribution, a measure of the temperature distribution of a hot, optically thin plasma in CIE. In this method, a number of templates, each of which contains all of the emission lines of a single ion, are fit to an observed high-resolution spectrum. The best-fit normalization for each of these templates then provides a measure of the product of the elemental abundance and a weighted average of the DEM distribution over the range where the ion emits. These measurements can then be plotted in a way that may be described as a one-dimensional “image” of the DEM distribution. This method is well suited to the study of hot stars, because the use of templates makes use of the information available from line blends, and because it does not require that assumptions about the form of the DEM distribution be made.

In § 2 we describe our sample of nine early-type stars that have been observed with the Chandra High-Energy Transmission Grating Spectrometer (HETGS), the data, and the application of the method of Paper I to it. In § 3 we discuss the implications of our results.

2. SPECTRAL DATA ANALYSIS

We obtained the data from the observations of all of the nine bright O stars observed with the Chandra HETGS. In Table 1, we list these nine stars, the distances and interstellar absorption columns to them that we adopt, the effective exposure times, and instrument response files described by Schulz et al. (2003). For all of the other stars, we employ the following procedure. We use spectra extracted as in the standard pipeline processing done by the Chandra X-ray Center. We calculate the appropriate effective area and exposure time for the positive and negative first orders of the High-Energy Grating (HEG) and the Medium-Energy Grating (MEG) for each observation using a

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standard procedure.\(^2\) For each of the two gratings we add the spectra and effective areas for the positive and negative first orders. For those stars observed in two pointings, we add the spectra and exposure times and average the effective areas for the two pointings. In all cases we use the standard redistribution functions. The background expected for these spectra is very low, and we make no correction for it.

For each of the nine data sets, we apply the procedure described in Paper I—i.e., we fit the spectra using templates, each of which contains all of the emission lines of an ion. In each of our fits to the stellar data, we use two bremsstrahlung components, except in the case of \(\tau\) Sco, \(\theta^1\) Ori C, and \(\zeta\) Ori where three are necessary to fit the continuum. In each case, the model spectrum includes neutral, interstellar absorption fixed at the value listed in Table 1. As explained in Paper I, the normalization parameter of each emission line template obtained in the fit implies a constraint on the product of the elemental abundance and a weighted average of the DEM distribution,

\[
D_{Z,z} \equiv A_Z \frac{\int_{\infty}^{\infty} \theta_{Z,z}(T) D(T) d \log T}{\int_{-\infty}^{\infty} \theta_{Z,z}(T) d \log T},
\]

where \(Z\) is the atomic number of the element, \(z\) is the charge state, \(A\) is the elemental abundance defined relative to solar, \(D\) is the differential emission measure distribution, \(T\) is temperature, and \(\theta\) is the sum of the power functions (described in Paper I) for the lines of the ion. In Figures 1 and 2 we plot \(D\) versus \(T_p\), where \(T_p\) is the temperature at which the function \(\theta_{Z,z}\) peaks. In all of these plots, we use the same temperature range on the horizontal axis as in the plots in Figures 2 and 3 of Paper I, and also as in those figures, the vertical axes span 3 orders of magnitude. Therefore, slopes of lines in these various plots may be compared. The observed spectra of the nine stars and best-fit models are shown in Figures 3 and 4. As in Paper I, we model the emission lines as Gaussians and allow the centers and widths of all of the Gaussians to vary together. The parameters that describe the centers and widths of the lines are \(v_1\) and \(v_2\), respectively, and we tabulate the best-fit values of these parameters in Table 2. The exact dependence of the model line profiles on these parameters is given in equations (16) and (17) of Paper I. While we have not quantitatively assessed the quality of the fits, it may be seen from the spectral plots that the fits are quite good, considering the large number of lines apparent in the data.

As we have described in Paper I, some excited states of some ions are metastable and may undergo further excitation before decaying to ground (pumping), and this leads the luminosities of some emission lines to depend on physical variables other than the DEM distribution. In the vicinity of a hot star, ions in many metastable states are susceptible to excitation by the absorption of UV radiation from the stellar photosphere. As we have also described in Paper I, we account for any line pumping by letting the line ratios in the templates vary as with collisional pumping with one free density parameter for each ion. This approach is somewhat ad hoc. However, the fact that we obtain good fits to the spectra indicates that pumping is well accounted for. Therefore, we do not expect significant errors in our constraints due to line pumping or inaccuracies in our treatment of it.

In the plots of \(D\) versus \(T_p\), for nearly every two ions with close values of \(T_p\), the corresponding values of \(D\) generally appear to be consistent with each other or differ by no more than a factor of 2, indicating that the emission line spectrum is consistent with emission from a plasma with solar abundances. One exception to this is the fact that, for \(\zeta\) Pup, the values of \(D\)

\(^2\) See http://asc.harvard.edu/ciao/threads/.

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### Table 1

| HR No. | HD No. | Name     | Type   |
|--------|--------|----------|--------|
| 3165   | 66811  | ζ Pup    | O4 I(e)(f) |
| 1899   | 37022  | θ Ori    | O4–6p var |
| 8281   | 206267A|          |         |
| 2782   | 57063  | τ CMa    | O9 II   |
| 1899   | 37043  | ι Ori    | O9 III(b) |
| 1852   | 36484  | δ Ori A  | O9.5 II |
| 1948   | 37742  | ζ Ori A  | O9.7 Ib |
| 6165   | 149438 | τ Sco    | B0.2 V  |
| 4853   | 111123 | β Cru    | B0.5 IIIk |

### References
- (1) Walborn 1972; (2) Maiz-Apellániz et al. 2004; (3) Walborn 1981; (4) Walborn 1973; (5) Walborn 1971; (6) Hiltner et al. 1969; (7) Brandt et al. 1971; (8) Schaerer et al. 1997; (9) Berghofe et al. 1996; (10) Simonson 1968; (11) Moitinho et al. 2001; (12) Consistent with Hillenbrand 1997 and references therein; (13) Perryman et al. 1997; (14) Cohen et al. 2003; (15) Alcala et al. 2002; (16) Schulz et al. 2000; (17) Shull & van Steenberg 1985; (18) Code et al. 1976; (19) Cassinelli et al. 2001; (20) Schulz et al. 2001, 2003; (21) Schulz 2003; (22) Miller et al. 2002; (23) Waldron & Cassinelli 2001.
Fig. 1.—Plots of $D$ as a function of temperature for $\zeta$ Pup, $\theta^1$ Ori C, HD 206267A, $\tau$ CMa, $\epsilon$ Ori, and $\tau$ Sco. The horizontal location of the data points is at the temperature where the ion’s emission peaks. The horizontal extents of the diamonds give the temperature range over which the ion’s emission is significant, and the vertical extents of the diamonds give the statistical confidence intervals for the values of $D$. The designation “(ul)” indicates an upper limit.
for oxygen are approximately an order of magnitude less than the values for ions with similar values of $T_e$. A similar result has been obtained by Kahn et al. (2001). The values of $D$ for nitrogen appear to fit better with the rest of the data points than do the values for oxygen. Therefore, it is probably the case that oxygen is underabundant in the wind of ζ Pup. However, from this analysis alone, it is impossible to exclude a hypothesis in which the DEM distribution of ζ Pup peaks at approximately $3 \times 10^6$ K, the abundance of nitrogen is greater than the solar value, and the abundance of oxygen is near the solar value. In addition, there is significant scatter in the data points for ζ Pup in the temperature range $4 \times 10^6$–$10^7$ K. Some, but not all, of this scatter might be accounted for by an underabundance of iron. For τ Sco, like ζ Pup, the values of $D$ for oxygen fall below the values for other ions at nearby temperatures, although not by as much.

Another exception to our results being consistent with solar abundance is θ Ori C. For this star, most of the values of $D$ appear to lie on a single curve, except for those of the ions Fe xx–Fe xxiv, which lie below it by a factor of approximately 4. Schulz et al. (2003) fit this spectrum using an explicit parameterized empirical model for the DEM distribution with variable element abundances. The best-fit DEM distribution these authors derive has three peaks at 7.9, 25, and 63 MK, troughs at 13 and 40 MK, and vanishes toward temperatures higher and lower than the three peaks. This three-peaked structure is not immediately apparent in our constraints for θ Ori C shown in Figure 1. We have explicitly evaluated the right-hand side of equation (1) for the element abundances and DEM distribution of Schulz et al. (2003), and while the values of $D$ for some ions have statistically significant differences, there does not appear to be an overall systematic difference between the values of $D$ obtained by the two methods. In particular, as with the values of $D$ obtained by our method, the triply peaked DEM distribution is also not immediately apparent in the values of $D$ obtained from the abundances and triply peaked DEM distribution of Schulz et al. (2003). This is somewhat puzzling. However, while a triply peaked DEM distribution is not immediately apparent in our results, from a closer look it may be seen how a triply peaked DEM distribution may be found with the method of Schulz et al. (2003).

In the method of Schulz et al. (2003), the formula for the quality of fit includes a penalty for variations in the DEM distribution, so if possible, elemental abundances will be adjusted to produce a flat DEM distribution. Variations in the DEM distribution will be found only when lines of the same element require it. Following our values of $D$ for Fe xvii–Fe xxiv, the first peak, the following trough, and the rise to the second peak may be seen. The trough after the second peak can be seen in the drop from Ar xvii to Ar xviii and from Ca xix to Ca xx. The rise to the third peak may be seen from the fact that the point for Fe xxiv is higher than the one for Fe xxiv.

3 Schulz et al. (2003), in their Fig. 7 plot the “DEM.” However, this is not the DEM as we define it (emission measure per temperature decade) but the emission measure per temperature bin (with $\Delta \log T = 0.05$). Therefore, it must be multiplied by a factor of 20 to be compared with our results.
Fig. 3.—MEG spectral data (black) and best-fit models (red) for ζ Pup, θ¹ Ori C, HD 206267A, τ CMa, ε Ori, and δ Sco. We include a number of line labels, although not all of the labeled lines are detected in every spectrum.
In order to compare our constraints on the DEM distributions of the stars in our sample with each other, we plot a composite of the nine stars in Figure 5. This figure is constructed as follows. For each star, we ignore those values of $D$ without lower limits. For the case of oxygen, we then ignore the value of $D$ for oxygen. Then, for those ions with the same value of $T_p$ as given in Table 1 of Paper I, we average the values of $D$, weighting by the inverse square of the uncertainties. The lines connect the averaged values of $D$ for individual stars. Because the method used to construct this figure is ad hoc and because doing so would make the figure harder to read, we do not attempt to include errors in this figure. However, the magnitude of the errors for this figure may be inferred from Figures 1 and 2 and may also be inferred from the jagged curves. The lines for HD 206267A, $\epsilon$ Ori, $\zeta$ Pup, $\zeta$ Ori A, $\epsilon$ CMa, and $\delta$ Ori A are very similar and difficult to show together. Therefore, we show the line for $\zeta$ Pup and a filled polygon that encloses the lines for the other five stars. The axes and aspect ratio of this plot are chosen so that slopes in this figure can be compared with Figures 2 and 3 of Paper I and Figures 1 and 2 of this paper.

With the exceptions of $\epsilon$ Sco and $\theta^1$ Ori C, it may be inferred from these plots that, in the temperature range $10^6$–$10^{8.5}$ K, the DEM distributions have peaks at temperatures of a few times $10^6$ K and decrease toward higher temperatures. The DEM distribution of $\beta$ Cru, in addition to having a smaller magnitude than the other stars, declines more rapidly toward high temperatures. For $\tau$ Sco, the peak of the DEM distribution and the majority of the emission appear to be at approximately $10^7$ K. Most of the emission measure for $\theta^1$ Ori C appears to lie near $3 \times 10^7$ K. In Figures 1 and 2, it may be seen that for many of the stars, the points for some or all of the ions Fe xxiv, Fe xxv, and Fe xxvi are higher than those of lower charge states of iron. This suggests the possibility that these DEM distributions increase at temperatures near $10^8$ K. However, all of these high-temperature points have low statistical significance, and it is not possible from this analysis to confirm the presence of any such high-temperature increase in the DEM distribution.

We give the best-fit line shifts and widths from our fits in Table 2. If we add the systematic uncertainty of the Chandra
HETGS absolute wavelength calibration (a few tens of km s$^{-1}$)$^4$ to the tabulated statistical confidence intervals, all of the line shifts we measure are consistent with zero, with the exception of ζ Pup and the possible exception of ζ Ori. The blueshift we find for ζ Pup is consistent with those reported by Kahn et al. (2001) and Cassinelli et al. (2001). The latter authors attribute this blueshift to obscuration of the far side of wind by photoelectric absorption in nearer parts of the wind. The blueshift we observe for ζ Ori A may also be due to this effect. This possibility is discussed by Waldron & Cassinelli (2001).

3. DISCUSSION

We use a method, described in Paper I, to determine the DEM distribution for a sample of nine hot stars, which works by fitting entire X-ray spectra. The fact that for all of the nine stars in our sample good spectral fits are obtained suggests that the method is free of significant systematic errors. We find that the magnitudes of the DEM distributions of the two B stars τ Sco and β Cru are much lower than those of the O stars, as expected from previous results (e.g., Berghöfer et al. 1996). For all of the stars in our sample except for θ$^1$ Ori C and τ Sco, we find the DEM distributions to be peaked at a temperature of a few times $10^6$ K or less, and to decline up to several times $10^7$ K. Although we cannot confirm it, the DEM distributions of these stars may also increase at temperatures near $10^8$ K. In contrast, we find that the peak of the DEM distribution of τ Sco is near $10^7$ K, and that the peak of the DEM distribution of θ$^1$ Ori C is near $3 \times 10^7$ K. For those two stars we also find that the emission lines are narrow compared to stars of similar stellar type. High-temperatures and narrow lines have previously been found for τ Sco by Cohen et al. (2003) and for θ$^1$ Ori C by Schulz et al. (2001, 2003) using these same data from Chandra. In both cases, it has been noted that the stars are young and that the high temperatures and narrow lines have been attributed to channeling of the wind in fossil magnetic fields. In this scenario, wind travels up the sides of magnetic loops, then shocks as wind from the two sides of the loop collides. Because the postshock gas is stationary, narrow lines are predicted. The fact that the postshock gas is stationary also results in a larger velocity difference between the gas before and after the shock and therefore higher temperatures (ud-Doula & Owocki 2002).

The fact that the X-ray-emitting plasma in the wind of τ Sco is hotter than the X-ray-emitting plasma in most stars has been apparent from spectra of much lower resolution (e.g., Cohen et al. 1997a, 1997b). A hot X-ray-emitting plasma has also previously been detected from the Orion Trapezium Cluster, which contains θ$^1$ Ori C (Yamauchi et al. 1996), although it was not until a high-resolution image was obtained with Chandra by Schulz et al. (2001) that this hot plasma could be conclusively associated with θ$^1$ Ori C. Therefore, our finding that the temperatures of the X-ray-emitting plasmas θ$^1$ Ori C and τ Sco are high is neither a new result of high-resolution spectroscopy nor of our analysis technique. However, as we have shown here, the method described in Paper I is useful in deriving well-defined quantitative constraints on elemental abundances and differential emission measure distributions from high-resolution X-ray spectra and, in particular, large samples of high-resolution X-ray spectra. We expect that these results and the results of similar observations and analyses will provide direction for developing theory on X-ray emission in hot stars.

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4 See http://cxc.harvard.edu/proposer/POG/.