THE X-RAY SPECTRUM AND GLOBAL STRUCTURE OF THE STELLAR WIND IN VELA X-1

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ABSTRACT

We present a quantitative analysis of the X-ray spectrum of the eclipsing high mass X-ray binary Vela X-1 (4U 0900−40) using archival data from the ASCA Solid-State Imaging Spectrometer. The observation covers a time interval centered on the eclipse of the X-ray pulsar by the companion. The spectrum exhibits two distinct sets of discrete features: (1) recombination lines and radiative recombination continua from mostly hydrogenic and helium-like species produced by photoionization in an extended stellar wind; and (2) fluorescent K-shell lines associated with near-neutral species also present in the circumsource medium. These features are superposed on a faint continuum, which is most likely non-thermal emission from the accreting neutron star that is scattered into our line of sight by free electrons in the wind. Using a detailed spectral model that explicitly accounts for the recombination cascade kinetics for each of the constituent charge states, we are able to obtain a statistically acceptable ($\chi^2_r = 0.88$) fit to the observed spectrum and to derive emission measures associated with the individual K-shell ions of several elements. From calculations of the ionization balance using the photoionization code, XSTAR, we assign ionization parameters, $\xi$, to several ions, and construct a differential emission measure (DEM) distribution. The DEM distribution spans a broad range in $\xi$ ($\Delta \log \xi \approx 2$) and is centered around $\log \xi = 2.5$. We find that the total emission measure of the visible portion of the highly ionized wind is $\sim 3 \times 10^{53} \text{cm}^{-3}$. The qualitative aspects of the inferred DEM distribution are consistent with a wind model derived from the Hatchett & McCray picture of an X-ray source immersed in a stellar wind with a generalized Castor, Abbott, & Klein velocity profile. Using this formalism, theoretical DEM distributions, parameterized only by a mass-loss rate and a wind velocity profile, are calculated and used to predict the detailed X-ray spectrum, which is then compared to the ASCA data. Again, we find a statistically acceptable fit ($\chi^2_r = 1.01$), with a best-fit mass-loss rate of $\sim 2.7 \times 10^{-7} M_\odot \text{yr}^{-1}$. This is approximately a factor of 10 lower than previous estimates of the mass-loss rate for the Vela X-1 companion star, which have primarily been determined from C IV and Si IV P Cygni profiles, and X-ray absorption measurements. We argue that this discrepancy can be reconciled if the X-ray-irradiated portion of the wind in Vela X-1 is structurally inhomogeneous, consisting of hundreds of cool, dense clumps embedded in a hotter, more ionized gas. Most of the mass is contained in the clumps, while most of the wind volume (>95%) is occupied by the highly ionized component. We show quantitatively that this interpretation is also consistent with the presence of the X-ray fluorescent lines in the ASCA spectrum, which are produced in the cooler, clumped component.

Subject headings: binaries: eclipsing — pulsars: individual (Vela X-1) — stars: neutron — stars: winds, outflows — X-rays: stars

1. INTRODUCTION

In wind-driven high-mass X-ray binaries (HMXBs), an intense X-ray continuum flux is produced through gravitational capture of a stellar wind by a neutron star or a black hole. A small fraction (~0.1%) of the total mass lost by the companion is accreted onto the compact object, and a fraction of the gravitational potential energy is then converted into X-radiation, which ionizes and heats the surrounding gas. The wind reprocesses hard X-rays from the compact object, resulting in discrete emission lines and continuum radiation. X-ray emission lines can be produced in a wide range of ionization states, ranging from cold fluorescent emission-line regions to highly ionized recombination-line regions. The resulting spectrum carries information that should, in principle, allow us to derive physical parameters that characterize the state and structure of the circumsource material.

Vela X-1, the archetypal wind-fed X-ray pulsar, has been the most well-studied object in its class since its discovery (Chodil et al. 1967). It is an eclipsing HMXB with a pulse period of 283 s (McClintock et al. 1976) and an orbital period of 8.96 days (Forman et al. 1973). The optical counterpart, HD 77581, is a B0.5 I supergiant (Brucato & Kristian 1972; Hiltner, Werner, & Osmer 1972) with an inferred mass-loss rate lying in the range $(1−7) \times 10^{-6} M_\odot \text{yr}^{-1}$ (Hutchings 1976; Dupree et al. 1980; Kallman & White 1982; Sadakane et al. 1985; Sato et al. 1986). Its intrinsic X-ray luminosity is $\sim 10^{36} \text{ergs s}^{-1}$, consistent with accretion from laminar flow past a stellar object (Bondi & Hoyle 1944) for a mass-loss rate and velocity structure characterizing a typical OB supergiant.

Prior to the launch of ASCA, X-ray emission-line studies of Vela X-1 were typically limited to the iron K complex near 6.4 keV; emission lines from lighter elements were not resolved (White, Swank, & Holt 1983b; Ohashi et al. 1984; Lewis et al. 1992). The solid state detectors on board ASCA are capable of resolving bright spectral features from H-like and He-like ions, although, for the most part, distinguishing
the effects produced by various emission mechanisms is still problematic. The first analysis of the ASCA spectrum of Vela X-1, which emphasized line emission, was presented by Nagase et al. (1994, hereafter N94). The hard X-ray spectrum (3–10 keV) is highly absorbed and contains bright iron K fluorescent lines. During eclipse (−0.1 ≤ φ ≤ +0.1), the continuum radiation from the compact source is occulted by the companion, and emission lines that form in extended regions gain contrast with respect to the ionizing continuum, resulting in the line-dominated appearance of the soft X-ray band (0.5–3 keV). N94 tentatively identified most of the bright emission lines, while some of the fainter mid-Z fluorescent lines were identified in a later article (Nagase 1997).

Although it was suggested in N94 that the more highly ionized X-ray emission lines observed in the Vela X-1 spectrum are formed by cascades following radiative recombination, those authors did not have access to an appropriate, self-consistent, recombination spectral model suitable for a detailed quantitative analysis of the emission-line intensities. While it is all but certain that many X-ray lines in HMXBs are recombination lines, it is, in fact, difficult to distinguish recombination from other emission mechanisms in CCD spectra, thereby disallowing a quantitative interpretation of the spectra. Liedahl & Paerels (1996, hereafter LP96) applied a suitable recombination cascade model to the interpretation of the ASCA spectrum of the HMXB, Cyg X-3. Infrared line spectroscopy of this object indicates the presence of a dense stellar wind from a Wolf-Rayet companion (van Kerkwijk et al. 1992). As demonstrated in LP96, the characteristics of the X-ray line spectrum, including the shape and magnitude of the emission measure distribution, conform to what one would expect according to a simple model of a photoionized stellar wind in an X-ray binary system.

The purposes of this paper are to extend and refine the analyses of LP96 and N94 and to demonstrate that the X-ray spectrum of Vela X-1 can be interpreted in terms of an explicit stellar wind model. Our approach improves upon the method of LP96 in several ways. First we take explicit account of wind acceleration according to a modified Castor, Abbott, & Klein (1975, hereafter CAK) wind model. We model the orbital phase dependence of the apparent differential emission measure, taking advantage of the fact that the system parameters (binary separation, companion radius, inclination angle, ephemeris, etc.) are much better constrained in Vela X-1 than in Cyg X-3. The LP96 method of fitting the data with model ionic spectra, each of which is assumed to be at a single temperature, is adopted as an initial step in the course of our analysis. However, we also analyze the data with a more elaborate model that accounts for temperature variations in each ionization zone. Using the Hatchett & McCray (1977, hereafter HM77) picture of an X-ray source immersed in a stellar wind, coupled with a generalized CAK wind, we show that the shape and magnitude of the differential emission measure (DEM) distribution in HMXBs depend sensitively on stellar wind parameters. From a grid of model DEM distributions, theoretical spectra are generated and compared directly to the spectral data, leading to the determination of the rate at which highly ionized material is accelerated and the corresponding mass-loss rate.

This paper is organized as follows. In § 2, we describe the data reduction performed, the details of our explicit spectral model, and the derivation of the empirical DEM distribution for the ionized stellar wind. In § 3, we discuss physical models for the stellar wind and our derivation of wind parameters. In § 4, we present a quantitative analysis of the K-shell fluorescent lines. Finally, in § 5, we discuss the implications of our results in terms of previous models for the Vela X-1 system and show that all of the data can be reconciled through a model of an inhomogeneous wind were most of the mass is contained in relatively dense cool clumps, while most of the volume is occupied by a lower density, more highly ionized tenuous medium.

2. SPECTRAL ANALYSIS

2.1. Data Reduction

Vela X-1 was observed with ASCA on three occasions: twice in 1993 and once in 1995. The first set of observations in 1993 was performed during the performance verification phase and covered the entire transition from ingress to egress (−0.13 ≤ φ ≤ +0.16). The observation in 1995 covered only part of the eclipse phase (−0.05 ≤ φ ≤ +0.10). For the purpose of our analysis, we use only data obtained in 1993. We separate the observations into three phase ranges: pre-eclipse (−0.13 ≤ φ ≤ −0.10), eclipse (−0.10 ≤ φ ≤ +0.10), and post-eclipse (+0.12 ≤ φ ≤ +0.16). For the eclipse phase, we use data from SIS0 and SIS1. For the pre- and post-eclipse phases, which we analyze principally to derive the intrinsic X-ray continuum spectrum of the compact source, we use only data from GIS2.

The data reduction was performed with FTOOLS v4.0. The data were screened through standard criteria: rejection of hot flickering pixels and data contaminated by bright earth, event selections based on grade, etc. The observation during eclipse was performed in four-CCD mode with all chips collecting a significant number of counts. In order to maximize statistical quality, source and background counts were separately extracted from each individual chip. Data, background, response matrix, and ancillary response matrix files were generated for each CCD chip and were combined using standard methods. The resulting spectra contained 1.1 × 10^4 and 9.0 × 10^3 counts from SIS0 and SIS1, respectively, collected during a total exposure time of 38 ks. The net exposure times of the pre- and post-eclipse phases were 6.0 and 8.4 ks, which contained 2.5 × 10^4 and 7.4 × 10^4 counts, respectively.

2.2. Spectral Model

Our spectral model for Vela X-1 is comprised of three principal components: (1) continuum radiation from the neutron star, which consists of both direct emission from the central source, absorbed through the intervening wind, and scattered radiation from free electrons in the extended wind; (2) discrete recombination-line and radiative recombination continua (RRC) from highly ionized ions; and (3) fluorescent lines from near-neutral ions. Our treatment of each of these components is described in the following subsections.

2.2.1. Continuum Emission

The spectra of Vela X-1 require two continuum components. The intrinsic continuum radiation, which originates near the neutron star, is highly absorbed as it propagates through the surrounding stellar wind. A fraction of this radiation is scattered into our line of sight through
electron scattering and is less absorbed relative to that of the direct continuum. The direct continuum is also required by the eclipse spectrum, since near eclipse ingress ($\phi \sim -0.10$) and egress ($\phi \sim 0.10$), the line of sight to the compact object is not entirely blocked by the companion. The monochromatic photon flux (photon cm$^{-2}$ s$^{-1}$ keV$^{-1}$) of the total observed continuum radiation, therefore, has the following functional form:

$$F_{\text{cont}}(E) = A^{\text{cat}} e^{-\sigma(E)N_H^{\text{cat}}} E^{-\Gamma} + A^{\text{dir}} e^{-\sigma(E)N_H^{\text{dir}}} E^{-\Gamma},$$

(1)

where $A^{\text{cat}}$ and $A^{\text{dir}}$ are the normalizations (in units of photon cm$^{-2}$ s$^{-1}$ keV$^{-1}$ at 1 keV) of the scattered and direct components, respectively. Since electron scattering should not appreciably alter the spectral shape of the continuum, the photon indices of the two components are set equal. The absorption cross sections are adopted from Morrison & McCammon (1983), and we assume solar abundances for the absorbing medium.

### 2.2.2. Discrete Recombination Emission

Our recombination cascade model is an outgrowth of that described in LP96, which was successfully applied to the analysis of the ASCA spectrum of Cyg X-3. Several updates have been made, and the current version includes line emissivities of K-shell carbon, nitrogen, oxygen, neon, magnesium, silicon, sulfur, argon, calcium, and iron, as well as the iron L species (Fe xvi–xxiv), and the associated RRC. We have written an interface to the XSPEC spectral analysis package (Arnaud 1996) that calculates line and RRC emissivities for a given ionization stage and electron temperature. Each ion is treated as an individual model component in XSPEC, with the temperature and normalization as adjustable parameters.

Atomic structure and transition rates are calculated with an atomic physics package, the Hebrew University/Lawrence Livermore Atomic Code (HULLAC; Klapisch et al. 1997). Ionic spectra are calculated for each ion using radiative cascade models that include detailed atomic structure through $n = 6$ and averaged structure for $n = 7$–10. The $n = 10$ level is a “superlevel” that accounts for recombination into shells with $n > 10$. Radiative rates, including E1, E2, M1, and M2 transitions are calculated with HULLAC. For the two E1 two-photon decay rates of hydrogenic 2s$_{1/2}$ states, we use Parpia & Johnson (1982). We assume an $E^{-3}$ dependence in the photoionization cross sections, where threshold cross sections and ionization potentials are adopted from Saloman, Hubble, & Seward (1988). The RRC are calculated from the photoionization cross sections using the Milne relation, assuming that the recombining electrons are Maxwellian distributed. The line and RRC emissivities are self-consistently calculated for each ionic species to produce the correct line-to-RRC ratios.

We define specific line power $S_{ul}(T)$ for a radiative transition connecting an upper level $u$ to a lower level $l$ to be $S_{ul}(T) = n_{ul} \sigma_{ul}(T)$, where $n_{ul}$ is the fraction of recombinations onto the relevant charge state that produce the transition $u \rightarrow l$ and $\sigma_{ul}$ is the total radiative transition (RR) rate coefficient for that charge state. The dimensions of $S_{ul}$, like $\sigma_{RR}$, are in cm$^3$ s$^{-1}$. We calculate $S_{ul}$ by solving the set of coupled rate equations, assuming that only the ground state of the recombining ion is populated. This is an excellent approximation for K-shell ions at most astrophysical densities. For the recombined ion, however, the level populations $N_u$ (dimensionless) are computed explicitly. Thus $S_{ul}$ is simply the photon line power per ground state of the recombining ion. For a transition with energy $E_{ul}$, $S_{ul}$ is related to the conventional recombination-line power $P_{ul}$ (erg cm$^{-3}$ s$^{-1}$) by $P_{ul}(T) = n_{ul}/n_e A_Z f_{1+1}(T) S_{ul}(T) E_{ul}$, where $A_Z$ is the elemental abundance and $f_{1+1}$ is the ion fraction of the recombining ion. The quantities $n_H$ and $n_e$ are the hydrogen and electron densities, respectively.

Operationally, $S_{ul}$ is found directly from the inversion of the rate matrix according to $S_{ul}(T) = N_{ul}(T)/n_{ul}$, where $A_{ul}$ is the radiative decay rate corresponding to the transition $u \rightarrow l$. The rate matrix is solved over a grid of temperatures, and, for each X-ray transition in the model, $S_{ul}$ is fit to a power law, $S_{ul}(T) = C_{ul} T^{-\gamma}$, which provides an adequate description for our purposes. Values of $\gamma$ lie in the approximate range 0.6–0.8.

In constructing the spectral model, a number of physically plausible approximations are invoked. First of all, we do not include line flux contributions from collisional excitations since we expect the local temperatures to be much lower than the ionization potentials ($kT/e \ll 1$). Collisional transfers in the He-like ions are also not included. This approximation is valid in the low-density limit ($n \lesssim 10^{10}$ cm$^{-3}$) and, in any case, the ASCA CCDs do not have the resolving power to separate these lines to observe variations of line ratios in He-like ions. We also do not take into account inner-shell ionization of Li-like ions, which can lead to the production of the forbidden line in He-like ions.

Although they are available in our spectral model, we do not include the forest of iron L transitions in our analysis of the Vela X-1 spectrum. For X-ray photoionized plasmas, the line power of individual iron L lines is low compared to those of H-like and He-like ions of lower Z elements that exist at similar ionization parameters (Kallman et al. 1996). In addition, at ASCA SIS resolution, the iron L lines are not resolvable—they produce a more-or-less smooth continuum component between 0.7 and 2.0 keV, which provides only a minor perturbation to the true continuum in the same energy range. As we show later, the omission of these features has a negligible effect on our derived wind for the Vela X-1 system.

As indicated earlier, the line power of a particular transition produced by recombination cascade depends on temperature through the temperature dependence of the recombination coefficient. In principle, the temperature appropriate to the relevant charge state can be inferred from the shape of the associated RRC feature, as was done using ASCA data for Cyg X-3 (LP96) and 4U 1626–67 (Angelini et al. 1995). However, for the Vela X-1 data set, the RRC are blended with other features, and the spectra are of somewhat lower statistical quality, so this is not practical in this case. Instead, we must assume a temperature for each ionic species. A natural choice for the temperature corresponds to that at which line powers of the brightest lines for that ion have their maximum. A large fraction of the total ionic line emission originates near this temperature. Therefore, for each ion, we fix the temperature at the value where the product $f_{1+1}(T) S_{ul}(T)$ peaks. In photoionized plasmas, however, the charge state distribution of the gas is determined not by the temperature but by the ionization parameter, $\xi = L_X/n_e r_X$, where $L_X$ is the X-ray luminosity, $n_e$ is the proton number density, and $r_X$ is the distance from the ionizing source (Tarter, Tucker, & Salpe-
We use XSTAR (Kallman & Krolik 1995) to calculate fractional ionic abundances, $f_{i+1}$, and temperatures, $T$, as functions of \( \xi \). For each ion in the model, we then use the $T(\xi)$ relationship, and fix the electron temperature according to the value of \( \xi \) for which $f_{i+1}(\xi)S_d(\xi)$ attains its maximum. For each charge state $i$, we define the ionization parameter of formation ($Z_{\text{form}}$) to be that value of \( \xi \) corresponding to the maximum of $f_{i+1}S_d$. We assign the temperature of formation according to $T_{\text{form}}(Z_{\text{form}})$.

XSTAR requires an input shape for the ionizing continuum X-ray spectrum. At energies below 10 keV, this is constrained by the shape of the continuum visible in the ASCA spectrum itself, but the ionization and temperature structure is also sensitive to the shape of the spectrum at higher energies, outside of the ASCA bandpass. We assume the spectrum determined for Vela X-1 using HEAO 1 data by White et al. (1983b), which involves a broken power law with an exponential cutoff at 20 keV with an \( e \)-folding energy of 16 keV. In Table 1, we list the $Z_{\text{form}}$ and their respective $T_{\text{form}}$ values for the H-like and He-like species of oxygen, neon, magnesium, silicon, sulphur, and iron, given this assumed ionizing spectrum.

### 2.2.3. Discrete Fluorescent Emission

We do not explicitly model the atomic physics of fluorescent-line production, but rather, represent it as isolated Gaussian components. Apart from the iron K-line complex in which the characteristic line width can be determined from the data, the mid-Z fluorescent-line widths are fixed at $\sigma = 50$ eV. Their centroid energies and normalizations are left as free parameters. The lines widths were chosen to represent typical spreads in fluorescent-line energies for the low charge states of each element. In fact, the line fluxes are not sensitive to our choice of $\sigma$ as long as they lie within realistic values.

#### 2.3. Results of Spectral Fitting

Spectral fits were performed to the SIS0 and SIS1 data during eclipse phase with XSPEC. We have modified the code to incorporate the specific spectral model described in § 2.2.2. Parameters for the fit include the normalizations, absorbing column densities, and power-law indices for both the direct and scattered continuum components, the emission measures (proportional to the normalization of the recombination-line spectrum and associated RRC) of the H-like and He-like charge states of oxygen, neon, magnesium, silicon, sulfur, argon, calcium, and iron, and the normalizations and line centroid energies of the K-shell fluorescent features associated with magnesium, silicon, sulfur, argon, calcium, iron, and possibly nickel. Most of these are left “free” to be constrained by the fit; however, we forced the power-law index of the scattered component to agree with that of the direct component and applied the attenuation associated with the derived absorbing column density of the scattered component of the line and RRC radiation as well. The latter is justified if both the scattered continuum and all of the discrete features originate in the same extended stellar wind, as we have assumed.

Despite the large number of free parameters, there are still many (262) independent degrees of freedom. Nevertheless, we find an excellent fit with this model with $\chi^2 = 0.88$. The data and best-fit model are shown in Figure 1, along with the residuals. Note that all of the subtle discrete structure in the spectrum is accurately reproduced.

The derived line fluxes and centroid energies for the fluorescent features are listed in Table 2. The detection of many of these features was previously reported by Nagase (1997). The centroid energies suggest that most of this emission arises in material that is partially ionized, as indicated by the likely ion identifications listed in the second column of the table. Partial ionization is indeed expected for even dense components of the wind, given the intense ultraviolet field of the companion star that irradiates this material. The reality of each fluorescent feature can be assessed by the change in $\chi^2$ that results when it is omitted from the fit, as listed in the fourth column of Table 2. Except for the nickel line at 7.52 keV, which is required at a 91.7% confidence level, all of the features are highly significant ($> 99.9\%$ confidence level).

Because of significant line blending at ASCA resolution, there is ambiguity in the derived fluxes of the fluorescent lines. While the sulfur, argon, and calcium fluorescent features are well separated from the bright recombination lines and RRC from the more highly ionized material, the magnesium and silicon lines are blended. For example, the magnesium line at 1.30 keV lies close to Mg Kα (1.34 keV).

### Table 1

| Ion | Line Energy* (keV) | $Z_{\text{form}}$ | $T_{\text{form}}$ (eV) |
|-----|-------------------|-------------------|-------------------------|
| O vii          | 0.562             | 1.49              | 7                       |
| O vii          | 0.654             | 1.92              | 18                      |
| Ne ix          | 0.910             | 1.76              | 12                      |
| Ne x           | 1.022             | 2.30              | 97                      |
| Mg xi          | 1.337             | 1.98              | 21                      |
| Mg xii         | 1.473             | 2.58              | 123                     |
| Si xiii        | 1.847             | 2.15              | 75                      |
| Si xiv         | 2.005             | 2.73              | 145                     |
| S xv           | 2.441             | 2.39              | 105                     |
| S xvi          | 2.622             | 2.90              | 183                     |
| Fe xxv         | 6.667             | 3.11              | 250                     |
| Fe xxvi        | 6.966             | 2.73              | 650                     |

* Centroid energy of the line complex.
and the Ne x RRC edge (1.36 keV). If we allow the temperatures of Ne x and Mg xi to be additional free parameters in the spectral fit, the necessity for the 1.30 keV feature can be removed by lowering the temperature of Ne x, which has the effect of increasing the contrast in the RRC with respect to the corresponding lines. However, the required temperatures we obtain from this procedure (1.1 eV for Ne x and 5.3 eV for Mg xi) are factors of ~100 and ~4 lower than what would be expected from photoelectric heating in photoionization equilibrium at this level of ionization. Since these temperatures are unphysical, we choose to fix the temperatures at their respective temperatures of formation to derive the fluorescent-line fluxes and centroid energies.

Similar spectral fitting procedures were performed for the GIS2 data during the pre-eclipse and posteclipse phases. Our goal, in these cases, was merely to characterize the continuum so as to better constrain the ionizing spectrum and luminosity. Thus, although we include contributions from discrete emission in the spectral fit, we do not attempt to quantify the detailed characteristics of the line spectrum, which are poorly determined anyway, given the lower spectral resolution of the GIS. The best-fit continuum parameters for the three phases are listed in Table 3. The derived power-law indices agree well with those determined by previous experiments. Note that the absorbing column density inferred for the scattered component of ($5$–$10) \times 10^{21}$ cm$^{-2}$ is roughly consistent with the interstellar reddening to this source observed in the optical and ultraviolet (Nandy, Napier, & Thompson 1975; Conti 1978). Adopting a distance to Vela X-1 of 1.9 kpc (Sadakane et al. 1985), we derive an average X-ray luminosity, which we define as the continuum luminosity above $E = 1$ ryd, of $L_X = 4.5 \times 10^{36}$ ergs s$^{-1}$.

### 2.4. Derivation of the Empirical DEM

Since radiative recombination is a two-body process, the emissivity of each recombination line and RRC feature is proportional to the density squared: $j_{ul}(\xi) = n_e^2 P_{ul}(\xi)$, where $P_{ul}$ is the line power, defined earlier in § 2.2.2. If we define the emission measure to be $EM = \int n_e^2 dV$, the line luminosity produced at the source over a narrow range of $\xi$ (or $\log \xi$)—the differential line luminosity—can be expressed as $dL_{ul} = P_{ul}(\xi)[d(EM)/d \log \xi]d \log \xi$. In HMXBs, and probably most accretion-powered sources, the observed spectrum is likely to be a superposition of individual spectra, each of which can be characterized by a single ionization parameter, provided that radiative transfer does not deform or attenuate the ionizing spectrum. Therefore, the line luminosity that one would infer from a measurement of the line flux is given by

$$L_{ul} = \int d \log \xi \left[ \frac{d(EM)}{d \log \xi} \right] P_{ul}(\xi).$$  

The bracketed quantity is known as the differential emission measure (DEM) distribution. For each value of $\xi$, the DEM acts as a weighting factor that determines the contributions of each ionization zone to the total line flux. Spectroscopic analysis in this context is analogous to the use of a temperature-dependent DEM distribution in interpreting spectra from plasmas in coronal equilibrium. DEM analyses are used widely for modeling the structure of stellar coronae, for example, and have proven to be an effec-

### Table 2: Measured Fluorescent-Line Energies and Intensities

| Line Energy (keV) | Average Ionization Stage | Flux (photons cm$^{-2}$ s$^{-1}$) | $\Delta \chi^2$ |
|-------------------|--------------------------|----------------------------------|----------------|
| 1.30 ± 0.02       | Mg II–XII                 | $(2.8 \pm 0.8) \times 10^{-5}$    | 15             |
| 1.77 ± 0.02       | Si IV–V                  | $(2.0 \pm 0.8) \times 10^{-5}$    | 21             |
| 2.32 ± 0.03       | S I–IV                   | $(2.5 \pm 0.8) \times 10^{-5}$    | 33             |
| 2.99 ± 0.02       | Ar II–V                  | $(2.3 \pm 0.8) \times 10^{-5}$    | 26             |
| 3.74 ± 0.05       | Ca II–VIII                | $(1.5 \pm 0.8) \times 10^{-5}$    | 11             |
| 6.42 ± 0.01       | Fe II–IV (Kα)            | $(2.5 \pm 0.8) \times 10^{-6}$    | 242            |
| 7.13 ± 0.04       | Fe II–IV (Kβ)            | $(7.2 \pm 0.8) \times 10^{-5}$    | 31             |
| 7.52 ± 0.09       | Ni II–VIII                | $(2.2 \pm 0.8) \times 10^{-5}$    | 3              |

Note: All errors correspond to 90% confidence ranges for one interesting parameter.

* The range in ionization stages are based on the uncertainties in the line energies.
* The widths of the lines are fixed at $\sigma = 50$ eV.
* The increase in $\Delta \chi^2$ when the line is excluded from the spectral model.

### Table 3: Measured Continuum Parameters

| Orbital Phase   | $N_H$ (10$^{22}$ cm$^{-2}$) | $A$ (1 keV) (photons cm$^{-2}$ s$^{-1}$ keV$^{-1}$) | $N_H$ (10$^{22}$ cm$^{-2}$) | $A$ (1 keV) (photons cm$^{-2}$ s$^{-1}$ keV$^{-1}$) |
|-----------------|------------------------------|---------------------------------------------------|------------------------------|---------------------------------------------------|
| Pre-eclipse     | 1.4                          | 1.7                                               | $2.4 \times 10^{-3}$         | 58.2                                              |
|                 |                              |                                                   |                              | 1.7                                               |
|                 |                              |                                                   |                              | $7.2 \times 10^{-1}$                              |
| Eclipse         | 0.5                          | 1.7                                               | $9.0 \times 10^{-4}$         | 23.0                                              |
|                 |                              |                                                   |                              | 1.7                                               |
|                 |                              |                                                   |                              | $9.1 \times 10^{-3}$                              |
| Posteclipse     | 1.9                          | 1.7                                               | $3.1 \times 10^{-3}$         | 18.5                                              |
|                 |                              |                                                   |                              | 1.7                                               |
|                 |                              |                                                   |                              | $5.8 \times 10^{-2}$                              |

* Fixed to the corresponding absorbed power-law index.
the brightest line in each ion is a function of \( \log \xi \), we make a simple approximation that the line power of account for in the model. well as the RRC, emitted by that ion, and that this is fully temperature-dependent relationship to every other line, as note, however, that each recombination line has a definite range within a given range \( \Delta \log \xi \). For most H-like and He-like ions, \( \Delta \log \xi \approx 1 \). We plot in Figure 2 the derived empirical DEM distribution as determined from the H-like and He-like lines and RRC of oxygen, neon, magnesium, silicon, sulfur, and iron.

For a given line flux, the derived EMs are relatively weak functions of the assumed temperature: \( EM_{i+1} \propto T^\gamma \), where \( \gamma \approx 0.7 \). Nevertheless, there is some arbitrariness in the construction of the empirical DEM distribution, and we estimate that our derived DEM values may be uncertain by up to a factor of 2–3.

### 3. Physical Model of the Ionized Stellar Wind

The empirical DEM distribution derived in § 2.4 is useful for guiding the interpretation of the spectrum in terms of realistic physical models of the ionized stellar wind in the system. By constructing this distribution, we have effectively removed the “spectroscopic physics” from the problem and produced a curve that can be directly compared to that expected for simple wind models. In this section we explore the dependence of the DEM distribution on various wind parameters. This is described in §§ 3.1–3.3. Given the uncertainties inherent in the derivation of the empirical DEM, however, the final determination of the constraints on wind parameters can come only from direct comparison of fully self-consistent wind spectral models with the ASCA spectrum itself. This is described in § 3.4.

#### 3.1. General Characteristics of DEM Distributions for the Ionized Stellar Wind in HMXBs

We begin by considering the simple case of a hard X-ray point source located near to a companion star with a spherically symmetric stellar wind. We note that there are several mechanisms that may distort the wind from spherical symmetry: tidal forces of the compact object, which may enhance the mass-loss rate along the binary axis (Friend & Castor 1982; Stevens 1988), suppression of the wind velocity through photoionization (Blondin 1994), nonstatic accretion (Ho & Aarons 1987; Taam & Fryxell 1988), and the presence of a bow shock and accretion wake (Fryxell & Taam 1988; Blondin et al. 1990). However, these effects, with the exception of the accretion wake, are relatively localized near the compact object. Since our purpose here is to calculate the DEM during the eclipse phases \((-0.1 \leq \phi \leq +0.1)\), their effect on the DEM is small. Therefore, we neglect all such effects and assume that the density distribution is spherically symmetric around the companion star. We also ignore the presence of the extended stellar atmosphere. Sato et al. (1986) adopt an atmosphere in which the particle density decays exponentially with distance from the stellar surface. This affects the DEM distribution only below \( \log \xi \sim 1 \), which is outside the range constrained by our spectral fits.

We also assume that the radiation field of the compact object is isotropic, and we ignore transient effects that may be produced in the wind by X-ray pulsation. The pulse profile of Vela X-1 is complex (McClintock et al. 1976), indicating that the emission is not strongly beamed. Recent HST observations showed weak \((-3\%)\) pulsations in Si IV and N v absorption lines, while the X-ray continuum varies by \(-50\%\) from the mean intensity (Boroson et al. 1996). Since the gas density in X-ray emission-line regions is most likely to be lower than in UV emission/absorption regions, we expect the recombination timescales to be comparable to the Vela X-1 pulse period, as will be checked later. The wind, therefore, responds to the time-averaged flux, rather than to the instantaneous flux of the compact object. In addition, recombination timescales are also much shorter compared to the timescales for individual ions to traverse ionization zones. For these reasons, we ignore the dynamical behavior of the ionization structure of the wind, so that it is meaningful to speak of local zones of ionization balance fixed in the system.

In a stellar wind of massive young stars, the material accelerates radially from the stellar surface through momentum transfer due to absorption and scattering of UV continuum radiation in the resonance lines from low charge states of the abundant elements (Lucy & Solomon 1970). We assume that the wind has an initial velocity, \( v_0 \), equal to the thermal velocity of the stellar atmosphere (typically \(-30 \text{ km s}^{-1}\)) and accelerates until it reaches a terminal velocity, \( v_r \). Generalizing the results of CAK, we can write the velocity profile as

\[
\begin{align*}
v(r) &= v_0 + v_r \left(1 - \frac{R_*}{r}\right)^{\beta},
\end{align*}
\]
where $R_*$ is the radius of the companion, $r$ is the distance from the center of the companion, and $\beta$ is a parameter that determines the shape of the velocity profile. For typical isolated OB stars, it has been shown that $\beta \sim 0.8$ (Friend & Abbott 1986; Pauldrach, Puls, & Kudritzki 1986).

To derive an expression for the ionization parameter for all points in the wind, we invoke the relation for mass conservation in a spherically symmetric flow ($M = 4\pi r^2 \mu n \rho (r)$, where $\mu$ is the mean atomic weight). The density can then be written in terms of the mass-loss rate, the velocity of the wind, and the distance from the companion star. Therefore, the ionization parameter near the binary system can be recast in terms of position and stellar wind parameters:

$$
\xi(r, r_0) = 4.3 \times 10^2 \frac{(L_X)_{10^36}(v_\infty)^5}{M - 7} \frac{(r)^2}{R_X} \times \left[ \frac{v_0}{v_\infty} + \left( 1 - \frac{R_*}{r} \right)^4 \right] \text{ergs cm s}^{-1}
$$

where $(L_X)_{10^36}$ is the X-ray luminosity (in multiples of $10^{36}$ erg s$^{-1}$), $(v_\infty)^5$ is the terminal velocity (in multiples of $10^8$ cm s$^{-1}$), and $M - 7$ is the mass-loss rate of the companion (in multiples of $10^{-7} M_\odot$ yr$^{-1}$). We note that $\xi(r, r_0)$ is insensitive to $v_0$ for $v_0 \ll v_\infty$. The key parameters that determine the distribution of $\xi$ are the companion radius $R_*$, binary separation $a$, the X-ray luminosity $L_X$, the mass-loss rate in the wind $M$, the terminal wind velocity $v_\infty$, and the wind velocity profile parameter $\beta$. We adopt the following values: companion radius, $R_* = 30$ $R_\odot$; binary separation, $a = 53.4$ $R_\odot$ (van Kerkwijk et al. 1995); X-ray luminosity, $L_X = 4.5 \times 10^{36}$ ergs s$^{-1}$ (as determined from the pre- and post-eclipse GIS2 spectra); and a terminal wind velocity, $v_\infty = 1700$ km s$^{-1}$ (Dupree et al. 1980). These are listed in Table 4 together with the derived wind parameters, as described below.

The ionization zones of a spherically symmetric wind, ionized by a point source of X-radiation offset from the center of the wind, have approximate bispherical symmetry (HM77). The symmetry is exact in the case of a constant-velocity wind. An example of the contours of constant $\xi$ for a Vela X-1 wind model is shown in Figure 3. For any particular wind model, we calculate $\xi(r, r_0)$ and construct a theoretical DEM distribution as follows. We adopt a spherical coordinate system, centered on the companion, with a variable radial cell dimension increasing with radius as $(r - R_*)^2$, from an initial cell size of $\Delta r = 10^{-7} R_\odot$. In both the polar and azimuthal directions, the cells are divided into

### Table 4

| Parameter and Derived Parameters for the Vela X-1 System |
|--------------------------------------------------------|
| Parameter     | Value    | Reference          | |
| $T_{\text{eff}}$ (K)                                  | 26000    | Conti 1978         |
| $a$ ($R_\odot$)                                       | 53.4     | van Kerkwijk et al. 1995 |
| $R_* R_\odot$                                         | 30.0     | van Kerkwijk et al. 1995 |
| $i$ (deg)                                             | 74       | Conti 1978         |
| $E_e$ (keV)                                           | 20       | White et al. 1983b |
| $E_f$ (keV)                                           | 16       | White et al. 1983b |
| $L_{\text{X}}$ (ergs s$^{-1}$)                        | $4.5 \times 10^{36}$ | This paper       |
| $\beta$                                                 | 0.79     | This paper         |
| $v_\infty$ (km s$^{-1}$)                              | 1700     | Dupree et al. 1980 |
| $\dot{M}$ ($M_\odot$ yr$^{-1}$)                      | $2.7 \times 10^{-7}$ | This paper       |

**Fig. 3.**—Ionization contours for the parameters shown in Table 4. The contours represent surfaces of constant ionization parameter. Absymmetric surfaces of revolution can be derived by rotating the figure about the line of centers. The numbers labeled are $\log \xi$. The cross at $(0, 0)$ marks the position of the neutron star, and the shadow cone corresponds to region in which the compact X-ray source is occulted by the companion. The coordinate axes are scaled in units of solar radii.

720 bins. The maximum radius of the volume is $20R_*$. For each cell, we calculate the electron density from the wind model, and evaluate $\xi$, except for those cells lying in the shadow cone, where X-radiation from the compact object is blocked by the companion. We separate $\xi$ into logarithmically spaced bins, with each bin having a width of $\Delta \log \xi = 0.025$. The DEM contribution is evaluated for each cell and added to the appropriate $\xi$ bin. Convergence to within a few percent at all values of $\log \xi$ is achieved with this procedure. We refer to the DEM distribution calculated in this way as the intrinsic DEM distribution.

For comparison to the empirical DEM distribution we need to take explicit account of the occultation of various parts of the wind by the companion star, which is a function of inclination angle and orbital phase. We refer to the phase-dependent, visible portion of the intrinsic DEM as the apparent DEM distribution. The phase dependence is shown in Figure 4, where apparent DEMs at three orbital phases are plotted. Note that the calculations are carried out for an assumed inclination angle of $74^\circ$. This permits a partial view of regions of high $\xi$ near the X-ray source, regions that would be entirely occulted if the inclination angle were sufficiently close to $90^\circ$. Since regions inside the shadow cone and within the occulted region must be excluded when calculating the apparent DEM distribution, the total apparent EM (integrated apparent DEM distribution) reaches a minimum at $\phi = 0.0$, where there is minimal (although nonvanishing) spatial overlap between these regions. Conversely, the apparent EM reaches its maximum value when there is maximal overlap, i.e., when $\phi = 0.5$. This behavior is illustrated in Figure 4, along with the intermediate case, $\phi = 0.25$. The DEM increases monotonically for all $\xi$ between phases 0.0 and 0.5.

### 3.2. $\beta$ Dependence of the DEM Distribution

The $\beta$ dependence of the DEM distribution is illustrated in Figure 5, where we have plotted the apparent DEM distribution for the eclipse phase for various values of $\beta$, assuming a mass-loss rate, terminal velocity, and X-ray luminosity as given in Table 4. For a constant velocity wind
emission measure during eclipse is 30% of the total emission measure.

Fig. 4.—Apparent DEM at three different orbital phases. The top curve is for phase, \( \phi = 0.5 \), which corresponds to the intrinsic DEM of the system. The middle and bottom curves are the apparent DEM curves at quadrature and eclipse of the X-ray source, respectively. The apparent emission measure during eclipse is 30% of the total emission measure.

\( \beta = 0 \), the DEM peaks sharply at the value of \( \xi \) corresponding to the midplane \( r = r_X \) of the binary system—the plane perpendicular to the line of centers at the midpoint. We refer to the position of this peak as \( \xi_{\text{mid}} \). The peak owes its existence to a purely geometrical effect; the volume that covers a given range in \( \xi \) has a global maximum at \( \xi = \xi_{\text{mid}} \), and since the density is a smooth function of position, the DEM peaks at that value. The narrow width of the DEM distribution \( \Delta \log \xi \approx 0.6 \) results in an emission-line spectrum dominated by only a few ions. The \( \beta = 0 \) case is the simplest and does not account for the dynamical effects associated with the UV field of the companion. It may, however, have some relevance to the case of a “coasting” wind, in which the ions responsible for driving the wind have been ionized away by the combined UV and X-ray fields (MacGregor & Vitello 1982).

For an accelerating wind, \( \beta > 0 \), the wind velocity near the companion is significantly lower than the terminal velocity. For a given mass-loss rate, the density in this region is thus higher than that of the constant-velocity case. Since, locally, \( d(\text{EM}) \propto v^{-2} \), the DEM increases for \( \xi \lesssim \xi_{\text{mid}} \) (the companion half-space) as \( \beta \) increases. In fact, even for the \( \beta = 0.2 \) case, which corresponds to extremely rapid acceleration, the DEM distribution has started to broaden, with a rapid increase in the DEM near the lower edge of the distribution. All traces of a peak in the distribution have vanished for the intermediate values of \( \beta \). For \( \beta \) in the range 0.4–0.7, the distribution resembles a trapezoid, with a width \( \Delta \log \xi \approx 1.2 \). For more slowly accelerating winds \( \beta \gtrsim 0.8 \), a peak develops near \( \log \xi = 2.0 \). Comparison with the empirical DEM distribution depicted in Figure 2 suggests that the value of the \( \beta \) for the Vela X-1 wind lies in the range 0.4\textendash}0.8.

Regions with \( \xi \gtrsim \xi_{\text{mid}} \) (the X-ray source half-space) are nearly unaffected by variations in \( \beta \), since, by the time the material reaches the X-ray source half-space, it has acquired a large fraction of its terminal velocity and, therefore, is nearly independent of the value of \( \beta \). For higher values of \( \xi \), say \( \log \xi \gtrsim 4.0 \), the surfaces of constant \( \xi \) approach perfect spheres concentric with the X-ray source. Moreover, in this idealized smooth wind approximation, the density does not vary drastically across a surface of constant \( \xi \) in this region (i.e., \( n_e \) is independent of \( \beta \)). Therefore, the asymptotic form of the intrinsic DEM distribution is given by

\[
\text{DEM} \approx \frac{2\pi}{10\log(L_X n_e)^{1/2}} \xi^{-3/2}
\]

Figure 5 also shows that the total EM (the integrated DEM) increases monotonically with \( \beta \). For this example, EM changes by a factor of 8 in comparing the \( \beta = 0.0 \) and \( \beta = 1.0 \) distributions. However, for the most likely range of values, say \( \beta = 0.4–0.8 \), the EM increases by less than a factor of 3. We can use this fact to derive a simple way to estimate the mass-loss rate, as discussed in the next section.

### 3.3. Total Emission Measure

The total emission measure is simply the volume integral of \( n_e^2 \) over the wind. The electron density, \( n_e \), is related to the mass density, \( \rho \), by \( n_e = \kappa \rho / m_p \), where \( \kappa \) is the mean number of electrons per nucleon. In general, \( \kappa \) depends on the local value of the ionization parameter. However, for near-cosmic abundances, free electrons come mainly from hydrogen and helium, so if these two elements are fully ionized throughout the wind, then \( \kappa \) is only very weakly dependent on position. In that case, for a spherically symmetric smooth wind with a CAK velocity profile, we get

\[
\text{EM} = \frac{M^2 \pi^2}{4 \pi \mu^2 m_p v_{\infty} R_*} \int_0^1 dx \left( \frac{v_0/v_{\infty} + x^2}{v_{\infty}} \right)^2,
\]

where \( x \) is a dummy variable of integration.

This is the total emission measure in the wind. To compare with the integral of the empirical DEM depicted in Figure 2, we need to convert to an apparent emission measure \( \text{EM}_{\text{app}} \), which is related to \( \text{EM} \) by a geometric scale factor, \( f \ll 1 \), such that \( \text{EM}_{\text{app}} = f \times \text{EM} \). If we denote the integral by \( I \), equation (6) can be inverted for \( M \) to give

\[
M = 2.7 \times 10^{-7} (fI)^{-1/2} \left( \frac{v_{\infty}}{1700 \text{ km s}^{-1}} \right)
\]

\[
\times \left( \frac{\text{EM}_{\text{app}}}{10^{56} \text{ cm}^{-3}} \right)^{1/2} M_\odot \text{ yr}^{-1}.
\]

A lengthy calculation is required to determine \( f \) in a general case. For the Vela X-1 system during eclipse, \( f \approx 0.30 \). The integral \( I \) depends on \( \beta \) and the ratio \( v_0/v_{\infty} \). We find that,
for typical values of these parameters, $I$ falls into the range $\sim 10^{-20}$. By inspection of Figure 2, we see that a reasonable estimate for $EM_{\text{app}}$ is $3 \times 10^{56} \text{ cm}^{-3}$. Therefore, the implied mass-loss rate is $\sim (1-3) \times 10^{-7} \, M_\odot \, \text{yr}^{-1}$.

3.4. Self-consistent Spectral Fit to the Physical Wind Model

Having determined approximate values of $\beta$ and $M$, we can now work backward and use our physical model of the wind to generate an explicit spectral model that can be compared with the ASCA eclipse phase data. We assume a specific set of chemical abundances, a detailed model for the charge state distribution, and a global model of the wind to determine the density and temperature distribution. For the chemical abundances, we take the solar photospheric set from Anders & Grevesse (1989). The ion fractions and temperature are calculated for each value of $\xi$ with XSTAR, as described in § 2.2.2. The density at each point in the model wind follows from specifications of $M$ and $\beta$. The model DEM distributions are calculated by averaging the apparent DEMs over the orbital phases $-0.1 \leq \phi \leq 0.1$, which correspond to the eclipse phases of Vela X-1 and mimic the time integration of spectra accumulated during an interval of changing orbital configuration.

The 0.0–5.0 range in log $\xi$ is divided into 200 bins of width $\Delta \log \xi = 0.025$, as before. At each $\xi$ on the grid, $T$ and the set $g_{i,j}$ are found from XSTAR. The line powers of each recombination line in the model are evaluated according to our temperature-parameterized line power model. The process is repeated for the next value of $\xi$ on the grid, and so forth, until a set of 200 spectral $\xi$ components have been calculated. Each DEM model assigns a different weighting to each $\xi$ component; the product of this weighting factor and the line power constitutes the integrand of equation (3). A sum over the log $\xi$ grid gives us $EM_{\text{fit}}$ as in equation (3). Continuum and fluorescent lines are added to the recombination spectrum. The model spectrum is modified by geometrical dilution, and by attenuation by a column density of neutral material, then convolved with the SIS instrument response and compared to the data. Values of $\chi^2$ are determined on a $50 \times 70$ grid in $log \, M - \beta$ parameter space. The domains of log $M$ ($M_\odot \, \text{yr}^{-1}$) and $\beta$ are $(-6.85, -6.34)$ and $(0.45, 1.14)$, respectively, with a grid spacing of 0.01 in both dimensions.

We first perform these comparisons by fixing the continuum fluxes and column densities to their best-fit values of the original fit with the recombination cascade model (§ 2.4). With $M$ and $\beta$ left as free parameters, we find that $\chi^2$ attains its minimum for $M = 2.5^{+0.3}_{-0.5} \times 10^{-7} \, M_\odot \, \text{yr}^{-1}$ and $\beta = 0.65^{+0.11}_{-0.18}$, where the errors correspond to 90% confidence ranges for two interesting parameters. Although the fit is statistically acceptable ($\chi^2 = 1.27$ for 297 degrees of freedom), a better fit is obtained if the column density of the scattered component is allowed to vary. The data are then fit with three free parameters: $M$, $\beta$, and $N_{\text{H}}^{\text{ion}}$. We find that the best-fit values in this case are $M = 2.65^{+0.29}_{-0.56} \times 10^{-7} \, M_\odot \, \text{yr}^{-1}$, $\beta = 0.79^{+0.23}_{-0.22}$, and $N_{\text{H}}^{\text{ion}} = 6.8^{+0.8}_{-0.7} \times 10^{21} \text{ cm}^{-2}$, with $\chi^2 = 1.01$ for 296 degrees of freedom. The errors here correspond to 90% confidence ranges for three interesting parameters. The 90% and 99% confidence contours for the two wind parameters, $M$ and $\beta$, are plotted in Figure 6, together with some previous determinations using other techniques.

The best-fit $M$ found here agrees well with the estimate based on the much simpler approach using equation (7).

The close agreement is somewhat fortuitous, since our earlier estimate does not take account of the details of the DEM distribution. This validates our earlier claim that $M$ can be determined to within factors of a few from an estimate of the total emission measure. Our earlier estimate for $EM_{\text{app}}$ was $3 \times 10^{56} \text{ cm}^{-3}$. From a detailed spectral analysis, our best-fit value is $2.63 \times 10^{56} \text{ cm}^{-3}$.

The best-fit column density is higher than the Galactic value ($4 \times 10^{21} \text{ cm}^{-2}$) by roughly a factor of 2. The excess absorption could be ascribed to material local to the Vela X-1 system. Note that $\beta$ and $N_{\text{H}}^{\text{ion}}$ are highly correlated; since increasing $\beta$ increases the DEM of low-$\xi$ material (see Fig. 5), a higher column density can offset this effect by absorbing the low-energy line fluxes.

As illustrated in Figure 6, our derived range in $\beta$ is consistent with that inferred from UV observations (Dupree et al. 1980) and close to the value calculated by Friend & Abbott (1986), while our derived mass-loss rate is at least a factor of 4 lower than previously published results and approximately an order of magnitude lower than the midrange of typically quoted values ($1-7) \times 10^{-6} \, M_\odot \, \text{yr}^{-1}$ (Hutchings 1976; Dupree et al. 1980; Kallman & White 1982; Sadakane et al. 1985; Sato et al. 1986). The best-fit model parameters are summarized in Table 4, and the best-fit DEM curve is shown in Figure 7. Also, for completeness, the best-fit spectrum and residuals using the three-parameter model are shown in Figure 8.

It should be noted, however, that our derived mass-loss rate depends on the assumed metal abundances. If we assume that the abundances are 1/10 that of solar, the inferred mass-loss rate will be higher by a factor of $10^{1/2}$ because of the $M^2$ dependence on the magnitude of the DEM curve. Therefore, $M = 2.7 \times 10^{-7} \, A_{Z_\odot}^{1/2}$, where $A_{Z_\odot}$ is the abundances relative to solar. Similarly, $\beta$ can be decreased if the abundances of low-Z elements (O, Ne, and Mg) are increased. The exact dependence of the inferred $\beta$ on $A_{Z_\odot}$ is more complex, because the $\beta$ dependence on the DEM curve is nonuniform. For example, the DEM at

![Fig. 6.—90% and 99% $\chi^2$ contour levels for a smooth wind model. Also shown are two sets of wind parameters derived using different techniques.](image-url)
log \( \xi \approx 2 \) and \( \beta = 0.8 \) is a factor of \( \sim 3 \) higher than that of \( \beta = 0.6 \). Since an increase in DEM can be offset by an increase in the abundance of elements for which \( \xi_{\text{form}} \) lies near that value of \( \log \xi \), a large deviation in the assumed low-\( Z \) metallicity corresponds to only a small change in the derived \( \beta \).

As a cross-check on the wind parameters, we can calculate the implied Thomson scattering depth through the wind. Since Thomson scattering is responsible for all of the scattered continuum observed during eclipse, the ratio of the normalizations of the scattered and absorbed continuum components \( A_{\text{scat}}/A_{\text{dir}} \) gives a rough estimate of the average Thomson optical depth through the surrounding wind. The ratio of the scattered continuum flux to that of the direct continuum is \( \sim 1.2 \times 10^{-3} \) during pre-eclipse and \( \sim 1.6 \times 10^{-3} \) during post-eclipse. This is roughly consistent with the angle-averaged electron scattering optical depth \( \langle \tau_e \rangle \alpha = 2.3 \times 10^{-3} \) calculated using stellar wind parameters inferred from the DEM analysis. Were \( M \) an order of magnitude larger than our best-fit value, the normalization \( A_{\text{scat}} \) would also have been an order of magnitude larger.

In order to justify the elimination of iron L-shell ions from our spectral model, we calculated a model iron L-shell spectrum in accordance with the best-fit DEM distribution. Assuming that the iron abundance is solar, we find that iron L line and RRC flux is 12% of the total line flux, where the total includes emission from all other elements used in the fit. When folded through the SIS response, the iron L-shell spectrum resembles a faint continuum, owing to the high line density in L-shell spectra. This introduces a small error into the normalizations of the true continuum components but does not have a significant bearing on our results concerning the DEM analysis. The exclusion of iron L-shell ions leads to a great simplification in the spectral fit.

Using the best-fit parameters listed in Table 4, we estimate typical recombination timescales of highly ionized ions in the wind. The electron densities in the visible portion of the wind during eclipse are on the order of \( n_e \sim 10^{8-9} \) cm\(^{-3} \). For a typical recombination coefficient of \( \alpha_{\text{Kr}} \sim 10^{-11} \) cm\(^{3} \) s\(^{-1} \), the recombination timescales are longer than \( \sim 100 \) s, which is comparable to the pulse period of Vela X-1 (283 s). Since the ionizing emission is not strongly beamed, this justifies our approximation of an isotropic radiation field from the compact X-ray source.

### 4. K-Shell Fluorescent Lines

The physical model for the stellar wind that we have used to derive a mass-loss rate and velocity profile accounts only for highly ionized material (H-like and He-like ions). As indicated, however, our spectral fits also require the presence of fluorescent lines from much lower charge states of many of the same elements. The fluorescent lines have been incorporated into the model on an ad hoc basis, as required by the data. In this section, we use the observed fluxes in these lines to infer the conditions in the reprocessing gas that is responsible for their emission.

Fe K\( \alpha \) fluorescence has been previously detected in the Vela X-1 X-ray spectrum with a number of earlier observations (Becker et al. 1978; Ohashi et al. 1984; Lewis et al. 1992), and several candidate sites for its origin have been posited. Ohashi et al. (1984) noted that the iron-line intensity during eclipse is roughly an order of magnitude lower than that at other binary phases and concluded that a large fraction of this emission must be produced within \( \sim 5 \times 10^{11} \) cm of the neutron star. However, in the simple undisturbed model of the wind, the local ionization parameter within this region is much too high (log \( \xi \gtrsim 3 \)) to support near-neutral ions. Hence, fluorescent lines must be produced in anomalous, dense structures in this region. As shown by Blondin et al. (1990), disruption of the wind due to the presence of the X-ray source produces dense filaments in the accretion wake that may be 100 times denser than the undisturbed wind. Therefore, these filaments have local ionization parameters that are up to 2 orders of magnitude lower than the ambient wind and are capable of supporting ions of low charge state. The atmosphere of the companion is also a possible site for fluorescent-line emission. The atmosphere has densities as high as a few times \( 10^{12} \) cm\(^{-3} \) out to a few tenths of a stellar radius from the photosphere (Friend & Castor 1982). These regions have relatively low ionization parameters (\( \Delta \log \xi \sim 1 \)) and enough column density (\( N_H \sim 10^{23} \) cm\(^{-2} \)) to produce the observed line fluxes. During eclipse, however, regions near the neutron star, as well as the irradiated face of the companion, are mostly out of our line of sight. Thus a non-negligible fraction of the observed line flux must originate from more extended regions.
Assuming that the fluorescing medium is optically thin to the ionizing continuum, the luminosity of a single K-shell fluorescent-line with line energy \( E_k \) and fluorescence yield \( Y_k \) can be approximated by

\[
L_k = L_X Y_k G \frac{2 - \Gamma}{2 + \Gamma} \frac{(E_k/\chi)^{\chi - 2}}{\chi} \langle \tau(\chi) \rangle_\Omega, \tag{8}
\]

where we use the same cutoff power law as in the XSTAR calculations for the shape of the ionizing continuum, and a photoionization cross section of the form \( \sigma(E) = \sigma(\chi/\chi)^3 \), where \( \chi \) is the ionization potential. The continuum source has an X-ray luminosity \( L_X \). The factor \( G \) is a rather complicated function that depends on \( \chi, E_k, E_\gamma, \) and \( \Gamma \). For a given spectrum, it depends only on \( \chi \). The final factor in equation (8) is the solid-angle averaged photoionization optical depth at threshold. The optical depth here refers to paths from the X-ray source to points in the surrounding wind. Explicitly, \( \langle \tau(\chi) \rangle_\Omega \) is given by

\[
\langle \tau(\chi) \rangle_\Omega = \sigma(\chi) \int_\Omega \frac{d\Omega}{4\pi} N_Z, \tag{9}
\]

where \( N_Z \) is the column density of a given element, i.e., a sum over all charge states of a given element. The evaluation of equation (9) is simplified by assuming that \( N_Z \) is angle independent. The integral then becomes \( N_Z \Delta \Omega / 4\pi \), where \( \Delta \Omega / 4\pi \) is the covering fraction of the fluorescing material with respect to the X-ray source.

We use fluorescent yields from Kaastra & Mewe (1993) and photoionization cross sections from Verner et al. (1996) to calculate the values of \( N_Z \) required to produce the observed fluorescent-line fluxes. We define \( N_{H}^{\text{equiv}} \) to be the hydrogen column density of the region that produces the observable fluorescent lines (the “equivalent” hydrogen column density), such that \( N_Z = N_{Z}^{H} N_{H}^{\text{equiv}} \).

In evaluating these quantities, we assume solar abundances. For the ionizing spectrum of Vela X-1, we find that \( G = 0.937 \), which is accurate to within 1% for all elements used in our spectral model.

We have used equations (8) and (9) and the measured fluorescent-line fluxes to infer values of \( N_{H}^{\text{equiv}}(\Delta \Omega / 4\pi) \). The results are plotted in Figure 9 versus the atomic number \( Z \) of the element involved. As can be seen, there is a clear, monotonic dependence on \( Z \). In particular, the derived value of \( N_{H}^{\text{equiv}}(\Delta \Omega / 4\pi) \) is a factor of \( \sim 20 \) higher for iron (\( Z = 26 \)) than it is for magnesium (\( Z = 12 \)). This obvious trend may be a result of a process known as resonant Auger destruction (Ross, Fabian, & Brandt 1996), which can be significant for low-\( Z \), L-shell ions in regions of moderate line optical depth. If the optical depth is significant, a K-shell fluorescent line emitted by one atom can be resonantly absorbed by another as long as there is a vacant hole in the L-shell. Since the autoionization yield for low-\( Z \) ions is high in comparison to the fluorescence yield, the second excited atom will preferentially Auger decay, thereby destroying the original fluorescence photon. Even line optical depths of only a few can almost entirely suppress fluorescent \( K \alpha \) emission for such species. The required column densities are typically \( \sim 10^{20} \text{ cm}^{-2} \), which is well below that inferred from our fluorescent-line measurements.

Resonant Auger destruction is not effective for M-shell ions, where the L-shell is entirely filled and resonant K-shell line absorption is prohibited. However, the presence of such very low charge states may be suppressed by the intense UV field of the companion star, HD 77581, in the Vela X-1 system (\( T_{\text{eff}} = 26,000 \text{ K}; L = 5 \times 10^5 L_\odot \); Hutchings 1974), which can effectively ionize all atoms in the wind with ionization potentials less than \( \sim 50 \text{ eV} \) (Kallman & McCray 1982). The low-\( Z \) elements—neon, magnesium, silicon, and sulfur—should exist almost entirely in L-shell species because of this effect, where resonant Auger destruction is effective. By contrast, the UV field is not sufficiently intense to fully strip the M-shell of higher \( Z \) elements such as calcium and iron. These combined effects at least qualitatively account for the lower values of \( N_{H}^{\text{equiv}}(\Delta \Omega / 4\pi) \) inferred for magnesium, silicon, and sulfur and the complete absence of fluorescent emission from neon. If this interpretation is correct, then the true column density of cold reprocessing gas in the wind is probably closest to that inferred for iron, \( \gtrsim 10^{22} \text{ cm}^{-2} \).

As a final comment, note that there are two values plotted for iron in Figure 9, one derived from the Fe \( K \alpha \) line and the other from the Fe \( K \beta \) line. The two incommensurate values of \( N_{H}^{\text{equiv}}(\Delta \Omega / 4\pi) \) arise from the apparently anomalous \( K \beta / K \alpha \) ratio (0.28 ± 0.08) compared to the expected value of 0.13 (Kaastra & Mewe 1993) under most conditions. A similar anomaly was reported by White, Kallman, & Angelini (1997) for the ASCA spectrum of the low-mass X-ray binary 4U 1822–37. It should be noted, however, that the fluorescent emission-line regions are optically thin to both Thomson scattering and Fe K-edge absorption as evident from the inferred equivalent hydrogen column density. The spectrum of the primary continuum radiation reflected from this medium does not produce an appreciable Fe K-edge structure and, hence, does not contaminate the Fe \( K \beta \) fluorescent line. Therefore, we believe that this anomalous \( K \beta / K \alpha \) ratio is real, and the origin of this effect is still mysterious.

5. DISCUSSION

We have shown that the ASCA eclipse phase spectrum of Vela X-1 is quantitatively well described by a simple spectral model incorporating direct and scattered continuum
radiation from the compact X-ray source, hydrogenic and helium-like recombination lines and their associated RRC from a range of intermediate-Z elements (oxygen through iron), and fluorescent-line emission from near-neutral species of many of the same elements (magnesium through iron). The derived ion emission measures for the ionized component were assembled into an empirical DEM distribution, which was shown to closely resemble predicted DEM distributions from a simple, spherically symmetric CAK model of a stellar wind, ionized by a compact X-ray source offset from the center of the wind. We then showed that this same physical model of the wind can be used to generate a self-consistent spectral model that also provides a remarkably good fit to the ASCA eclipse-phase spectrum. The derived mass-loss rate for the wind from this analysis is $M = 2.65^{+0.65}_{-0.50} \times 10^{-7} \, M_\odot \, \text{yr}^{-1}$, and the derived velocity profile parameter is $\beta = 0.79^{+0.23}_{-0.33}$.

Although our derived velocity profile is in good agreement with previous estimates, our derived mass-loss rate is roughly a factor 10 lower than typical values quoted in the literature for this source. For example, Dupree et al. (1980) and Sadakane et al. (1985) found $M \sim 1 \times 10^{-6} \, M_\odot \, \text{yr}^{-1}$ by measuring P Cygni line profiles of Si IV and C IV resonance lines during eclipse and comparing them to theoretical predictions. However, it should be noted that the fractional abundance of both Si IV and C IV is quite low throughout the wind in their models. Thus their inferred mass-loss rates are strong functions of their assumed ionization fractions on the “tails” of the charge state distribution, making them quite sensitive to the assumptions of the model.

Mass-loss estimates have also come from X-ray absorption measurements close to eclipse egress. For example, Kallman & White (1982) found $M = (2-4) \times 10^{-6} \, M_\odot \, \text{yr}^{-1}$, based on column densities inferred from \textit{Einstein} Solid State Spectrometer spectra in the phase interval $\phi = 0.19-0.22$. However, the observed phase dependence of the absorbing column density is incompatible with the profile expected from simple stellar wind models. In general, the observed column densities are high ($N_\text{H} \sim 10^{24} \, \text{cm}^{-2}$) right after eclipse egress ($\phi \sim 0.1$), then decrease rapidly until $\phi \sim 0.2$, and then increase slowly throughout the remainder of the orbit. In contrast, smooth stellar wind models predict a steep decrease in absorbing column density only within a narrow phase range, $0.10 < \phi < 0.12$.

Sato et al. (1986) invoked an extended stellar atmosphere for the companion star to explain this behavior. In their model, the wind contribution to the absorption is small compared to that of the atmosphere for phases $0.10 < \phi < 0.15$. However, they still require a mass-loss rate $\sim 10^{-6} \, M_\odot \, \text{yr}^{-1}$ in order to get their minimum observed column density, which is $\sim 10^{22} \, \text{cm}^{-2}$, significantly above that expected for the interstellar contribution alone.

Our own best-fit wind model for the ASCA eclipse phase data also requires an absorbing column density of $\sim 7 \times 10^{21} \, \text{cm}^{-2}$, which is higher than the canonical interstellar value. Since the Vela X-1 system is highly inclined ($i > 74^\circ$; Conti 1978), it is possible that the excess absorption is specific to the equatorial plane, where the stellar wind is preferentially enhanced (Blondin et al. 1990). However, it seems unlikely that a factor of 10 discrepancy in the mass-loss rate can be due to that effect alone, especially during the eclipse phase, when emission from the vicinity of the equatorial plane is largely suppressed by occultation.

It is interesting to compare Figure 3 with Figure 9 of Dupree et al. (1980) and Figure 1 of McCray et al. (1984), which show values of $\log \xi$ near the Vela X-1 midplane close to 1.0 rather than 3.0. The higher mass-loss rates deduced from the UV observations translate directly into larger emission measures at low ionization parameters and are fundamentally incompatible with the observed ASCA eclipse phase spectra for smooth stellar wind models. Our calculations show that the DEM distribution at $1.8 < \log \xi < 2.0$, for example, would exhibit emission measures that are approximately 2 orders of magnitude larger than derived, which means that the expected intensities of O VIII, Mg XI, and Si XIII recombination lines would be 100 times larger than actually observed.

This conflict between the previously derived mass-loss rates and our own estimate based on the highly ionized component of the X-ray spectrum is exacerbated by the presence of fluorescent emission in the ASCA data. Fluorescent emission is the dominant line-emission process in lower charge states. However, inspection of Figure 3 indicates that in our smooth-wind model there is insufficient low-$\xi$ (log $\xi \leq 1$) material in the observable portions of the Vela X-1 system to produce these lines. Therefore, irrespective of the details of the fluorescent lines, it is clear that their mere existence in the eclipse spectrum signals a problem with the simple wind model used to describe the recombination spectrum.

One way to reconcile the coexistence of highly ionized and near-neutral ions is to consider inhomogeneous stellar wind models, where cool, dense clumps of material are embedded in a more tenuous, highly ionized wind. Such inhomogeneities are, in fact, expected theoretically for line-driven stellar winds, as a result of various instabilities (MacGregor, Hartmann, & Raymond 1979; Lucy & White 1980; Carlberg 1980; Abbott 1980; Owocki & Rybicki 1984). For example, Rayleigh-Taylor instabilities should produce clumps with sizes $\sim 10^{11} \, \text{cm}$ at intermediate distances from the star (Carlberg 1980). There is also observational evidence for the existence of clumps in the wind. Nagase et al. (1986) suggested that partial obscuration, produced by clumps with typical column densities $\sim 10^{22} \, \text{cm}^{-2}$, could produce the soft excess observed at particular orbital phases in Vela X-1. White, Kallman, & Swank (1983a) invoked overdense clumps with characteristic sizes $\sim 10^{11} \, \text{cm}$ to account for observed short-term variability in the luminosity and the absorbing column density for the similar HMXB system 4U 1700–37. In that context, it is interesting to note that the second ASCA observation of Vela X-1 performed in 1995 exhibited a flare lasting $\sim 10^4 \, \text{s}$, in which the X-ray luminosity increased by as a much as a factor of 3. It is conceivable that this flare was the result of an increase in the accretion rate resulting from a collision of the neutron star with such an overdense region of the wind. Since the orbital velocity of the neutron star in Vela X-1 is $\sim 300 \, \text{km} \, \text{s}^{-1}$, the required size of this region is again of order $10^{11} \, \text{cm}$.

The presence of cool, low-ionization clumps in the wind can be quantitatively constrained by our observed fluorescent-line intensities. If mass is being lost by the companion star in the form of low-ionization clumps at a rate $\dot{M}_c$, then for a spherically symmetric outflow of these clumps at a constant velocity, $v$, the solid angle subtended by clumps as seen from the compact X-ray source is approximately given by $\Omega = \pi \dot{M}_c r_c^2/(m v R_*)$, where $r_c$ is the...
typical radius of a clump and $m_c$ is a typical mass. For a uniform density, the mass of a clump is given by $m_c = (4\pi/3)r_c^3\mu n_p$, where $n_p$ is the proton density within the clump and $\mu$ is the mean atomic weight. These last two expressions can be combined to give

$$M_c \approx 2 \times 10^{-6} \left( \frac{N_e \Omega/4\pi}{10^{23} \text{ cm}^{-2}} \right) \left( \frac{v_\infty}{1700 \text{ km s}^{-1}} \right) M_\odot \text{ yr}^{-1},$$

(10)

where $N_e = n_p r_c$ is the column density of a single clump and we have taken the value for $R_\star$ in Table 4. Equating $N_e \Omega/4\pi$ to the values of $N_e^{\text{HII}}$ plotted in Figure 9 for the high-Z fluorescent lines (where resonant Auger destruction is ineffective; see § 4), we infer mass-loss rates in this clumped component that are now quite commensurate with previous estimates.

The fact that the fluorescent lines are produced in near-neutral species imposes an upper limit, $\xi_{\text{max}}$, on the ionization parameter in the clumps, which, for a given distance, implies a lower limit on the clump particle density: $n_p > 3 \times 10^{11} \xi^{-1}(r_c/a)^{-2} \text{ cm}^{-3}$, where $r_c$ is the distance from the X-ray source and $a$ is the binary separation. For a clump column density of $\sim 10^{22} \text{ cm}^{-2}$, the implied value of $r_c$ is $\sim 10^{11} \text{ cm}$, in good agreement with theoretical expectations. In addition, at the required $\xi_{\text{max}}$, the gas temperature within the clump is about a few eV, which means that, for the inferred values of $n_p$, the clumps are in near pressure equilibrium with the lower density, higher temperature wind.

As demonstrated, the clumped component of the wind accounts naturally for the observed fluorescent lines and for the variability in the luminosity and the inferred absorbing column density. Since it enhances the column density in low-ionization material, it also helps to explain the strength of the low charge state absorption lines (C IV and Si IV) measured in the UV. A concern might be raised about the apparent smoothness of the observed P Cygni profiles in these lines: since individual clumps should have well-defined velocities, the lines might appear “choppy” if only a few clumps contribute to each absorption line at any particular time (sometimes called “discrete absorption components”). However, a simple estimate shows that the number of clouds per velocity interval is approximately given by

$$\frac{dC}{dv} \approx \frac{M_c R_\star}{m_c v_\infty}$$

$$= \frac{0.7(M_{\odot})^{-6}(N_e)^{-3} \left( \frac{v_\infty}{1700 \text{ km s}^{-1}} \right)^{-2}}{(10^3 \text{ km s}^{-1})^{-1}},$$

(11)

which leads to approximately one clump per $1-2 \text{ km s}^{-1}$ velocity interval. The IUE high-dispersion spectra of Vela X-1 had a velocity resolution of $\sim 20 \text{ km s}^{-1}$, which suggests that the observed profile should indeed be smooth. The fraction of the companion disk that should be covered by the clump ensemble is approximately

$$f_{\text{disk}} = g \left( \frac{M_c}{m_p v_\infty N_e R_\star} \right)^{1/2}$$

$$= 0.6(M_{\odot})^{-6}(N_e)^{3/2} \left( \frac{v_\infty}{1700 \text{ km s}^{-1}} \right)^{-1}.$$

(12)

where $g$ is a numerical factor of order 1/10. Thus, the large covering factor with respect to the companion appears to be easily attainable in this picture. The presence of the clumped component is also supported by the orbital phase variability of the P Cygni lines that show evidence of non-monotonicity in the velocity structure of the wind (Kaper, Hammerschlag-Hensberge, & van Loon 1993).

Given our estimates derived above, the clumped component of the wind dominates the mass-loss rate from the companion. Nevertheless, the hot ionized component dominates the volume of the wind. Within an outer radius comparable to the binary separation, we find that the volume filling factor of the clumps is only ~0.04. Therefore, the presence of the clumped component only mildly perturbs the otherwise smooth wind of ionized gas and does not significantly affect our DEM analysis.

This interpretation of the Vela X-1 spectrum can be quantitatively tested with much higher precision when high-resolution X-ray spectra become available from AXAF, XMM, and Astro-E. At the resolution expected for the spectrometers on these missions, the iron L spectrum will be especially constraining. The iron L ions sample a large range in $\xi$ (log $\xi = 1.8-2.8$) that roughly brackets the DEM distribution inferred from our ASCA observations. The advantage of using iron L lines is that only a single elemental abundance must be assumed in establishing the scale for the DEM distribution. In the case of the ASCA data, in which only hydrogenic and helium-like lines are available, the actual shape of the inferred DEM distribution is affected by assumed abundances.

Future observations will allow the K$\alpha$ fluorescent-line complexes to be resolved into their individual charge state contributions. This may allow us to study the acceleration zone of the wind, the atmosphere of the companion, and the formation and evolution of the dense structures that we have postulated here.

We have shown that the orbital phase variations of the apparent DEM can be dramatic for some ranges of $\xi$. Observations made at different orbital phases will provide the information needed to refine the simple wind model and to describe the extended components of the wind. Substructures such as the accretion wake and the magnetosphere may reveal themselves as perturbations to the DEM distribution predicted by extrapolating our model distribution to orbital phases away from eclipse. Line flux and temperature measurements extracted from orbital phase-dependent, high-resolution spectra, when coupled with velocity information obtained from Doppler shifts and broadening, will provide access to a formidable set of diagnostic tools.

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