

ULTRAVIOLET HIGH-RESOLUTION SPECTROSCOPY OF THE X-RAY BINARY Sk 160/SMC X-1¹

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ABSTRACT

High-resolution *IUE* spectra of Sk 160, the optical counterpart of the X-ray source SMC X-1, show substantial variations with orbital phase of the resonance P Cygni profiles. These variations are ascribed to the changing ionization state in the stellar wind caused by the X-rays emitted by the companion, as suggested by Hatchett and McCray and first established for the galactic X-ray binary Vela X-1. Furthermore, the profile observed during X-ray eclipse differs significantly from profiles of similar stars in the absence of X-ray ionization.

Subject headings: stars: individual — stars: winds — ultraviolet: spectra — X-rays: binaries

I. INTRODUCTION

SMC X-1/Sk 160 is one of the most distant and most luminous of the known X-ray binaries (Schreier *et al.* 1972; Leong *et al.* 1971; Price *et al.* 1971). Its orbital elements, derived from its 3.9 day orbital period and 0.7 s pulsations (Lucke *et al.* 1976; Primiini *et al.* 1976; Primiini, Rappaport, and Joss 1977), and the spectral type of the primary (B0 Ib; Webster *et al.* 1972; Osmer and Hiltner 1974), are not very different from those of well-studied galactic X-ray binaries such as 4U 0900–40/HD 77581 (Bahcall 1978; Rappaport *et al.* 1976; van Paradijs *et al.* 1977). These facts, together with the low interstellar reddening toward the Small Magellanic Cloud, make the SMC X-1 system well suited for studying the effects of X-ray ionization and heating on the stellar wind emanating from the early-type primary.

The effects of X-ray ionization and heating in systems such as SMC X-1 are particularly apparent in the ultraviolet spectral region, since the ionization fractions of the normally abundant C iv, Si iv, and N v ions are lowered in the gas near the X-ray source, leading to suppression of the UV resonance line features from these ions. The suppression is expected to be greatest when the X-ray source is along the line of sight to the primary, with the line profile being essentially unaffected by X-rays during X-ray eclipse. This orbital-phase modulation of the UV line profiles was first predicted by Hatchett and McCray (1977), and has since been observed in the X-ray binaries Cyg X-1 (Treves *et al.* 1980), 4U 0900–40 (Dupree *et al.* 1980), and SMC X-1 and LMC X-4 (van der Klis *et al.* 1982; Bonnet-Bidaud *et al.* 1981; see also Hammerschlag-Hensberge 1980 for a review). With the exception of 4U 0900–40, all previous studies of UV line variations in X-ray binaries have used the spectrometer on board the *International Ultraviolet Explorer* (*IUE*) satellite in the low-resolution

($\lambda/\Delta\lambda \approx 2 \times 10^2$) mode, which allows only equivalent width variations to be distinguished. In this paper we present results of high resolution ($\lambda/\Delta\lambda \approx 10^4$) *IUE* observations of SMC X-1/Sk 160. The observational results are presented in § II, and their interpretation is discussed in § III.

II. OBSERVATIONS

The SMC X-1 system was observed by the *IUE* satellite, using the SWP camera in the high-resolution mode, on 1982 January 15 and 17. The details of the *IUE* instrumentation are described in Boggess *et al.* (1978*a, b*). The exposures were made using the large (10" × 20") aperture. Each observation lasted approximately 15 hours, and required a collaboration between observers from ESA, SERC, and NASA, to avoid the parts of the orbit affected by a high background level. Since the observed spectra are very weak, much effort has been given to analyzing the data as carefully as possible, using the interactive IUEDR package (Giddings 1983). Each image was scanned perpendicular to the dispersion to accurately locate the echelle orders. The spectrum was then extracted, using a centroid tracking algorithm, at a sampling rate of one full diagonal pixel (instead of every half pixel), to avoid any possibility of an odd-even noise pattern. The final data shown in Figure 1 are very similar to those obtained using the *IUE* standard Image Processing System, implemented since 1981 November 10 (Turnrose, Thompson, and Bohlin 1982).

The two observations correspond to orbital phases $\phi \approx 0.91$ –0.09 and $\phi \approx 0.41$ –0.59, respectively (X-ray eclipse occurs between $\phi \approx 0.90$ and $\phi \approx 0.10$). The spectra in the vicinity of the resonance doublet of Si iv $\lambda 1400$ have considerably better signal-to-noise ratios than those near the N v and C iv lines, due to the effects of camera sensitivity. Low-resolution observations of this source (van der Klis *et al.* 1982) show that orbital phase variations which are greater for C iv than for Si iv. N v variations are also apparent at low resolution. The noise level in the vicinity of C iv and N v is much greater than for Si iv in our high-resolution observations. We can therefore only verify that the N v and C iv behavior

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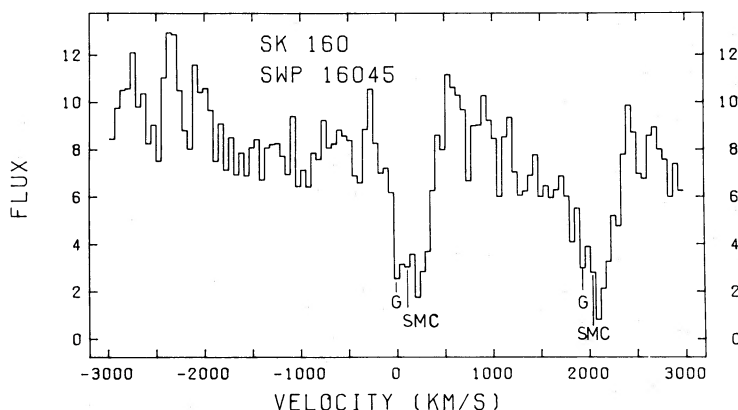


FIG. 1a

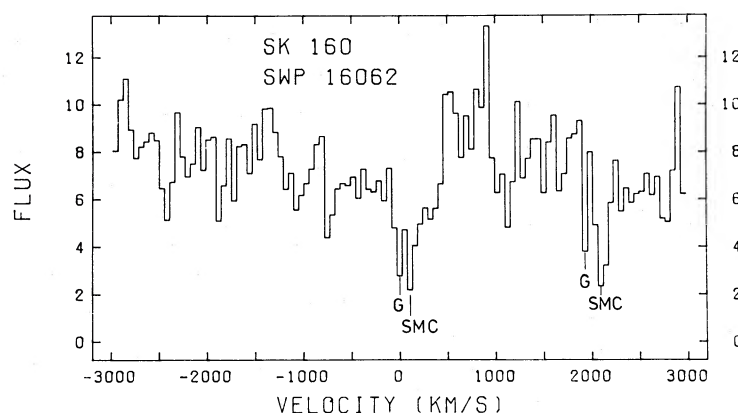


FIG. 1b

FIG. 1.—(a) The Si iv resonance doublet for the spectrum of SMC X-1/Sk 160, obtained during X-ray eclipse. The zero velocity mark corresponds to $\lambda_0 = 1393.755 \text{ \AA}$, the laboratory wavelength of the principal doublet line of the ion. The interstellar galactic and SMC components of Si iv in the direction of the star are indicated by “G” and “SMC,” respectively. A uniform wavelength grid of $0.25 \text{ \AA}$ was used. The vertical scale is in IUE flux units. The continuum level throughout the whole spectrum is arbitrarily set at 10 flux units. (b) Same as Fig. 1a but for the $\phi = 0.5$ spectrum.

that we observe is consistent with the low-resolution results. The Si iv profiles observed at phases $\phi \approx 0$ and $\phi \approx 0.5$ are shown in Figures 1a and 1b, respectively. In the figure, resseau marks were removed and data points were mapped onto a uniform wavelength grid with an interval of $0.25 \text{ \AA}$, using a triangular weighting function. The wavelength calibration was provided by the observatory using on-board platinum lamps which produce reference spectra. No correction was applied for the velocity of the SMC, which is $\sim 150 \text{ km s}^{-1}$.

Both the $\phi = 0$ and the $\phi = 0.5$ profiles show absorption between the velocity of the SMC and -200 km s^{-1} (relative to Earth). The absorption at $\phi = 0$ is stronger than that at $\phi = 0.5$. In addition, the $\phi = 0$ spectrum shows strong absorption at redshifted wavelengths corresponding to velocities up to 300 km s^{-1} . The narrow interstellar absorption components due to the Galaxy and the SMC are also apparent in these spectra.

Table 1 summarizes the changes in the Si iv equivalent width and implied terminal velocity for Sk 160. The equivalent widths we measure are consistent with those reported by Hutchings (1982). The 30% equivalent width variations we measure are consistent with those reported by van der Klis *et al.* (1982), although our derived equivalent widths are smaller than theirs by a factor of 2. Non-phase-

related changes in the X-ray state of SMC X-1 are known to occur (e.g., Schreier *et al.* 1972); existing high-dispersion ultraviolet spectra do not provide a sufficient time base to detect such changes in this wavelength band.

III. DISCUSSION

The line profiles formed in the winds from early-type stars are probes of the density of scattering ions as a function of wind velocity. The correspondence between wavelength and wind velocity, for monotonically accelerated winds, can be used to infer the properties of the Sk 160 wind from the observed Si iv profiles.

Resonance line profiles formed in the winds from early-type stars typically consist of a violet-shifted absorption component, due to wind material seen in projection against the stellar disk, and an undisplaced red emission component, due to

TABLE 1
Si IV EQUIVALENT WIDTHS AND TERMINAL VELOCITIES

Parameter	SWP 16045	SWP 16062
Mean phase.....	0.0	0.5
Terminal velocity (km s^{-1}).....	250	100
Equivalent width ($\text{\AA}$).....	2.9	2.0

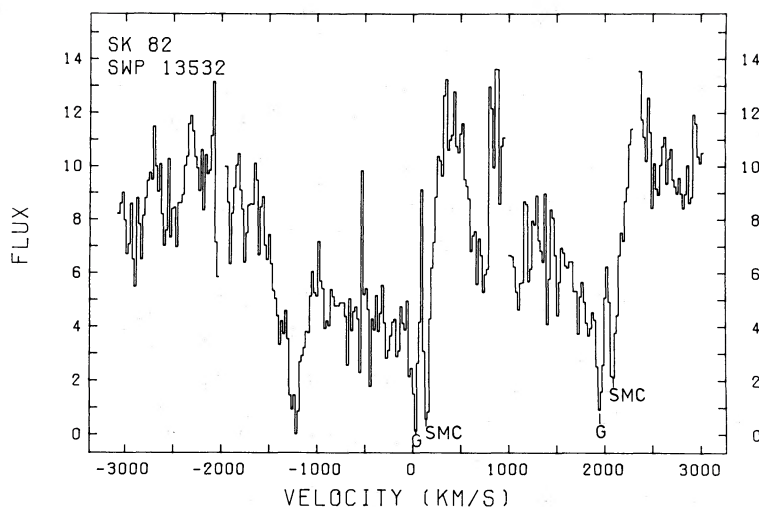


FIG. 2.—The Si iv resonance doublet for the SMC star Sk 82. Velocity scale as in Fig. 1a. A uniform wavelength grid of 0.1 Å was used.

material not seen in projection against the stellar disk. Single galactic stars with spectral type similar to Sk 160 (B0 Ib) typically have wind terminal velocities $v_\infty \approx 1600\text{--}1700$ km s $^{-1}$ (Conti 1978) and mass loss rate $\dot{M} \approx 10^{-7}$ to $10^{-6} M_\odot \text{ yr}^{-1}$. For galactic OB stars, wind mass loss rates are known to be proportional to M_{bol} . In these stars, winds are weak or absent for M_{bol} fainter than about -8.0 (Parsons *et al.* 1979). In the SMC, mass loss rates are similar to those of galactic stars for the most luminous members. SMC stars fainter than $M_{\text{bol}} \approx -9.2$ show weaker winds than galactic stars with similar luminosities (Bruhweiler, Parsons, and Wray 1982) although SMC stars as faint as $M_{\text{bol}} = -8.0$ do show detectable absorption corresponding to outflow velocities of ~ 1300 km s $^{-1}$. The weakness of the SMC star winds may be due to depleted abundances of the trace elements responsible for the wind driving (Hutchings 1982; Prévot *et al.* 1980). Figures 2 and 3 display the Si iv profiles of two SMC stars which are similar to Sk 160: Sk 82 (B1 Ia) and Sk 159 (B0 Ia) (Ardeberg and Maurice 1977). These stars show a wind terminal velocity of $v_\infty \approx 1500$ km s $^{-1}$ and strong absorption indicating a mass-loss rate in excess of $10^{-7} M_\odot \text{ yr}^{-1}$.

The resonance line profiles formed in winds in early type X-ray binaries are susceptible to suppression by X-ray ionization. The importance of ionization in these systems depends on the value of the parameter $q = \xi/\xi_x$ (Hatchett and McGray 1977), where the ionization parameter ξ characterizes the degree of ionization of the gas, and ξ_x depends on the X-ray luminosity, mass loss rate, and orbital separation. For SMC X-1/Sk 160, $\xi_x \leq 10^5$, based on the orbital parameters and wind properties proposed by Conti (1978). Ionization of the wind by X-rays will be important for $\xi \geq 10^2$, corresponding to $q > 10^{-3}$ for this system. This means that the X-rays from SMC X-1 will ionize nearly the entire wind volume which is not eclipsed by the primary star. In the ionized volume Si iv will be destroyed, and line formation will be suppressed. When the system is viewed during X-ray eclipse, Si iv absorption is expected, due to un-ionized material along the line of sight to Sk 160; the emission at this phase is expected to be weak owing to the fact that scattering ions responsible for the emission are almost entirely ionized away. When the system is viewed away from X-ray eclipse, Si iv scattering is expected to be absent, except for scattering by material very close to

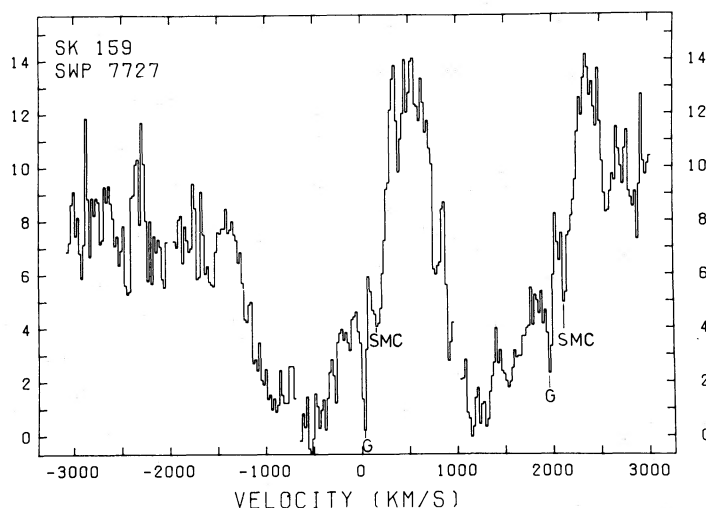


FIG. 3.—Same as Fig. 2 but for the SMC star Sk 159

the Sk 160 photosphere where the X-rays do not penetrate. The amount of absorption observed at $\phi = 0.5$ (Fig. 1b) is roughly in accord with this picture.

The gas which is eclipsed from SMC X-1 by Sk 160 will also be affected by X-rays which Compton scatter around the primary star. The importance of ionization by these scattered X-rays can be illustrated by considering the ratio of the scattered flux F_{scatt} to the gas density n at a distance R from the center of the primary:

$$\xi_{\text{scatt}}(R) = \frac{4\pi F_{\text{scatt}}(R)}{n(R)} = \frac{32\mathcal{A}(R)w(R)L_{38}}{R_{*15}}. \quad (1)$$

This equation is derivable simply from the definitions of the quantities involved: L_{38} is the source luminosity in units of 10^{38} ergs s^{-1} , R_{*15} is the primary radius in units of $15 R_{\odot}$, $w(R)$ is the wind velocity at R in units of the terminal velocity, and $\mathcal{A}(R)$ is a dimensionless number representing the integral over the scattering volume. $\mathcal{A}(R)$ is normalized so that $\mathcal{A}(R) \rightarrow 1$ for $R \rightarrow \infty$. It should be noted that ξ_{scatt} does not depend on the wind mass loss rate or terminal velocity, since both the scattered flux and the wind density depend linearly on these quantities. For example, at $R = 1.7 R_{*}$, $w = 0.4$, $\mathcal{A} \approx 0.1$, so $\xi_{\text{scatt}} \approx 13$ for $L_{38} = 10$ and $R_{*15} = 1$. At this ionization parameter the fractional abundance of Si iv is $q_{\text{Si iv}} \approx 10^{-3}$ (Kallman and McCray 1982), and the line optical depth is $\tau \approx 1.7 \mathcal{M}_6/v_{\infty 1600}$. In this equation $\mathcal{M}_6$ is the wind mass flux in units of $10^{-6} \mathcal{M}_{\odot} \text{yr}^{-1}$, and $v_{\infty 1600}$ is the terminal velocity in units of 1600 km s^{-1} . Thus the scattered X-rays can suppress Si iv absorption for $v > 600 \text{ km s}^{-1}$, for this combination of parameters.

The outstanding feature of the observed Si iv profiles shown in Figure 1 is the lack of absorption for wind velocities more negative than about -200 km s^{-1} . The effects of X-ray ionization are sufficient to explain the absorption at $\phi = 0.5$ shown in Figure 1b. At $\phi = 0$ the effects of scattered X-rays can account for the lack of absorption for velocities more negative than -600 km s^{-1} if the wind mass loss rate and terminal velocity are comparable to those for other stars of similar spectral type. The scattered X-rays cannot account for the lack of absorption at velocities between -200 km s^{-1} and -600 km s^{-1} unless the wind structure is significantly different from that of other stars of similar spectral type. For example, if the wind terminal velocity and mass loss rate were half that considered so far, i.e., $v_{\infty} \sim 800 \text{ km s}^{-1}$ and $\mathcal{M} \sim 5 \times 10^{-7} \mathcal{M}_{\odot} \text{yr}^{-1}$, then the observed degree of suppression could be achieved. These values differ significantly from those derived from the UV line profiles of other similar (single) stars in our Galaxy. These values of the wind parameters may not be implausibly low for the SMC, however, so that the observed $\phi = 0$ profiles could be due to the combination of ionization by scattered X-rays and a weak wind from Sk 160. The weakness of the Sk 160 wind may also be due to the gravitational effects of the compact object (Friend and Castor 1982), or to the decreased radiation pressure in the X-ray ionized wind (MacGregor and Vitello 1982). Both of these effects tend to destroy the spherical symmetry of the wind density by enhancing mass loss on the side of the star facing the compact object. The X-ray source is known to be variable (e.g., Primini, Rappaport, and Joss 1977), and the luminosity at the time of these observations is unknown. A more accurate evaluation of the importance of wind ionization by scattered

X-rays will require simultaneous UV and X-ray observations of this source. Walborn and Panek (1983) have noted a strong variation in the strength of the Si iv resonance line in early-type stars as a function of luminosity class. Our spectra do not allow us to distinguish this effect from that of a weakened wind. The marked differences between the Si iv profiles of Sk 160 and those of Sk 82 and Sk 159, however, suggest that the Sk 160 profiles are dominated by the effects of X-ray ionization.

The Sk 160 profiles also differ from those of otherwise similar stars in that they show redshifted absorption at velocities between 0 and $\sim +400 \text{ km s}^{-1}$. This effect is more pronounced in the $\phi = 0$ spectrum than in the $\phi = 0.5$ spectrum. The large velocities of the absorbing material implied by this redshift argue against wind turbulence as an explanation for this effect (e.g., Lamers and Rogerson 1978). Another possible explanation is that the spectrum from Sk 160 in this wavelength region is dominated by the effects of a gas stream and an accretion disk (Howarth 1982). If the emission near the Si iv resonance line is primarily from an accretion disk centered on the compact object, then absorption by material in a gas stream can produce the observed redshifted part of the profile. If such a gas stream does exist, its effects on the spectrum are expected to be most pronounced during X-ray eclipse. At $\phi = 0.5$ the gas stream and the accretion disk are seen in projection against the stellar disk, and so the spectrum at this phase is likely to be dominated by stellar radiation rather than by the disk or the gas stream. This is consistent with the observed Si iv profile behavior, and also with the phase dependence of the He ii $\lambda 4686$ emission observed by Hutchings *et al.* (1977). The disk and stream will subtend only a small solid angle from the compact object, and so will not significantly affect the wind ionization by X-rays.

IV. CONCLUSIONS

The observations presented in this paper provide a new insight into the wind in the Sk 160/SMC X-1 system. The existence of orbital phase variations of the UV resonance lines previously observed at low resolution is confirmed. The phase variations of the Si iv profile are found to be due to variable redshifted absorption, in addition to the variations in the blueshifted absorption predicted by the theories for X-ray ionization. The Si iv profile during eclipse has a lower implied terminal velocity than can be explained solely either by comparisons with wind lines from similar stars or by the effects of ionization by scattered X-rays. Ionization by scattered X-rays does provide a plausible explanation for the Si iv profile at $\phi = 0$ if the wind terminal velocity is roughly 50% of that expected for similar galactic stars. The redshifted absorption observed at $\phi = 0$ has not been observed previously, and may be due to absorption by material moving from the primary star into an accretion disk around the compact object.

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