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THE ANOMALOUS X-RAY ABSORPTION SPECTRUM OF VELA X-1[1]

T. R. KALLMAN
Center for Space Research and Department of Physics, Massachusetts Institute of Technology

AND

N. E. WHITE
NASA Goddard Space Flight Center, Greenbelt, Maryland; and Department of Physics, University of Maryland
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ABSTRACT

We present the results of observations during one orbit of the massive X-ray binary Vela X − 1 (2U 0900−40/HD 77581) using the Solid State Spectrometer and Monitor Proportional Counter on the *Einstein Observatory* (*HEAO 2*) satellite. Using spectral fits to the data as a function of orbital phase, we are able to infer the column density and state of the material along the line of sight to the X-ray source. The spectrum near orbital phase 0.2 compares favorably with absorption by neutral material with a column density corresponding to plausible values for the stellar wind velocity law and total primary mass loss rate. Spectra at later orbital phases show unexpected strong absorption features near 2 and 2.5 keV. We interpret these spectra as being due to absorption by material with suppressed opacity below 2 keV. The opacity required to produce the observed features implies either the presence of an intense flux of soft X-rays or altered elemental abundances in the gas near Vela X-1.

Subject headings: X-rays: binaries — X-rays: sources

I. INTRODUCTION

Past X-ray studies of Vela X − 1 (2U 0900−40) have noted a variety of different spectral and temporal behaviors in addition to the 283 s pulsations (McClintock *et al.* 1976; Rappaport, Joss, and McClintock 1976) and the eclipse by the primary, the B0.5 Ib supergiant HD 77581 (Hiltner, Werner, and Osmer 1972), every 8.95 days (Forman *et al.* 1973). The source flares by a factor of 5–10 on a time scale as short as minutes (Charles *et al.* 1978), with no detectable change in spectrum. Evidence for persistent absorption is found at orbital phases $\gtrsim 0.5$; the spectral hardening and diminution in flux during these phases are not consistent with absorption by neutral material, suggesting that the absorbing gas is partially ionized (Watson and Griffiths 1977; Charles *et al.* 1978). Further evidence for absorption by partially ionized material is provided by an apparent enhancement of the strength of the Fe K edge relative to absorption at energies below 7 keV, compared with what would be expected from neutral material (Becker *et al.* 1978). There is also evidence for a second, less stable region of absorption between $\phi \sim 0.2$–0.4 (Watson and Griffiths 1977). Optical studies (Zuiderwijk, van den Heuvel, and Hensberge 1974; Bessell, Vidal, and Wickramasinghe 1975) also provide evidence for absorption by gas which trails the X-ray source.

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The results of observations of Vela X − 1 using the Solid State Spectrometer (SSS) and Monitor Proportional Counter (MPC) on the *Einstein Observatory* (*HEAO 2*) satellite, which are presented in this *Letter*, allow much more detailed inferences to be drawn about the state of the X-ray absorbing gas near the X-ray source than have been possible before. These observations show, at later orbital phases, remarkable absorption features which suggest that part of the stellar wind of HD 77581 has a previously unsuspected peculiar ionization structure or elemental composition.

II. OBSERVATIONS

The SSS, a cryogenically cooled Si (Li) detector at the focus of the *Einstein* telescope, had an energy resolution of ~ 160 eV FWHM over the range 0.5–4 keV (Holt *et al.* 1979; Becker *et al.* 1979). Co-aligned with the SSS, the MPC had an energy resolution of ~ 20% FWHM over the range 2–10 keV (Giacconi *et al.* 1979). The SSS and MPC observed Vela X − 1 for a total of 16,551 s during 1979 May 10–15, with the exposures clustered near orbital phases $\phi = 0.2$ and $\phi \approx 0.7$–0.8. Figure 1 displays the MPC flux and hardness ratio (defined as the ratio of the count rates in the 3–10 keV band to the rate in the 1–3 keV band) binned into 10 minute intervals, as a function of time and orbital phase. The count rate near $\phi = 0.19$ is dominated by a flare in intensity

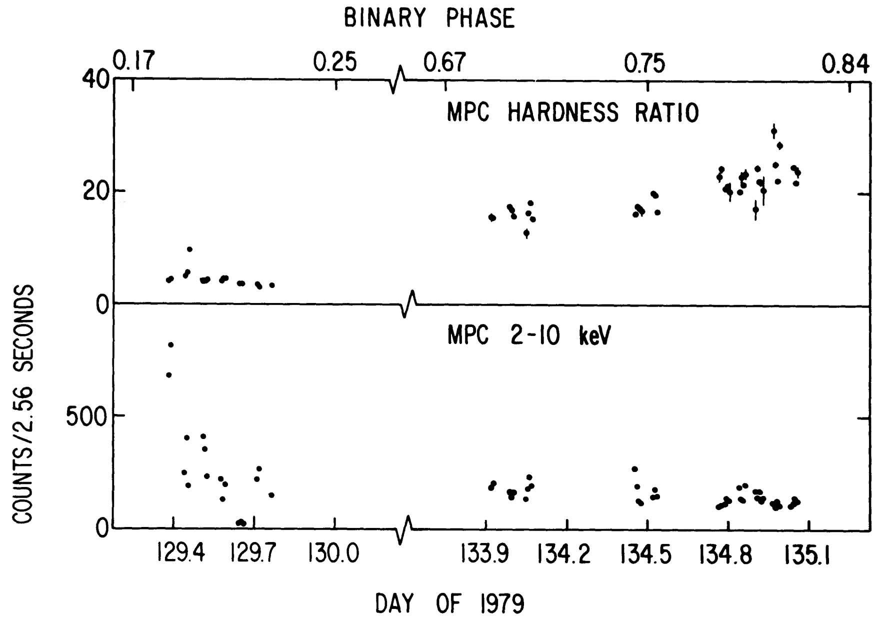

FIG. 1.—MPC counts and hardness ratio as a function of time during Vela X − 1 observations. Hardness ratio is defined as the ratio of the count rate in the 3–10 keV band to the rate in the 1–3 keV band.

by a factor of ~ 3 with a duration of a few minutes, showing no detectable spectral change. Later, near $\phi = 0.21$, the source displays a brief absorption event that lasts ~ 6 minutes. The SSS count rate during this event was too low to accumulate a statistically meaningful spectrum. At later orbital phases, $\phi \sim 0.7$–0.8, the MPC hardness ratio increases dramatically, accompanied by an overall decrease in the total flux.

We have divided these observations into three phase groups corresponding to the flare near $\phi = 0.19$, the remainder of the $\phi = 0.19$–0.22 data excluding the brief absorption event near $\phi = 0.21$, and the sum of the data from $\phi = 0.71$ to 0.82. We fit to the SSS data a model consisting of a power-law spectrum, together with absorption by neutral gas (e.g., Brown and Gould 1970; Fireman 1974) and absorption edges. The systematic errors in the SSS spectral response and this fitting procedure are discussed in more detail in Becker *et al.* (1979). Table 1 summarizes the parameters of the spectral fits for each of the observations of Vela X − 1,

TABLE 1

SSS SPECTRAL PARAMETERS FOR VELA X − 1 OBSERVATIONS

Parameter	Orbital Phase 0.19	0.19–0.22	0.71–0.82
Duration (s)	2502	3482	8233
Total MPC counts	22785	10269	9607
Source flux ($\times 10^{-9}$ ergs s^{-1} cm^{-2})(0.5–5 keV)	2.3	0.72	1.6
Power law index	$-0.28^{0.30}_{0.10}$	$-0.17^{0.40}_{0.40}$	0.100[a]
Edge depths and energies:			
τ_1	...	...	$2.3^{0.5}_{0.2}$
ε_1 (keV)	...	...	$2.0^{0.1}_{0.1}$
τ_2	...	...	$1.1^{0.3}_{0.3}$
ε_2 (keV)	...	...	$2.5^{0.2}_{0.1}$
τ_3	...	...	$0.34^{0.50}_{0.26}$
ε_3 (keV)	...	...	$3.0^{0.3}_{0.4}$
Neutral column density $N(\times 10^{22}$ cm$^{-2})$	$2.5^{0.5}_{0.2}$	$3.6^{0.9}_{0.5}$	$9.0^{0.7}_{0.5}$
Unreduced χ^2; 67 energy channels	203	88	98

[a]Parameter fixed.

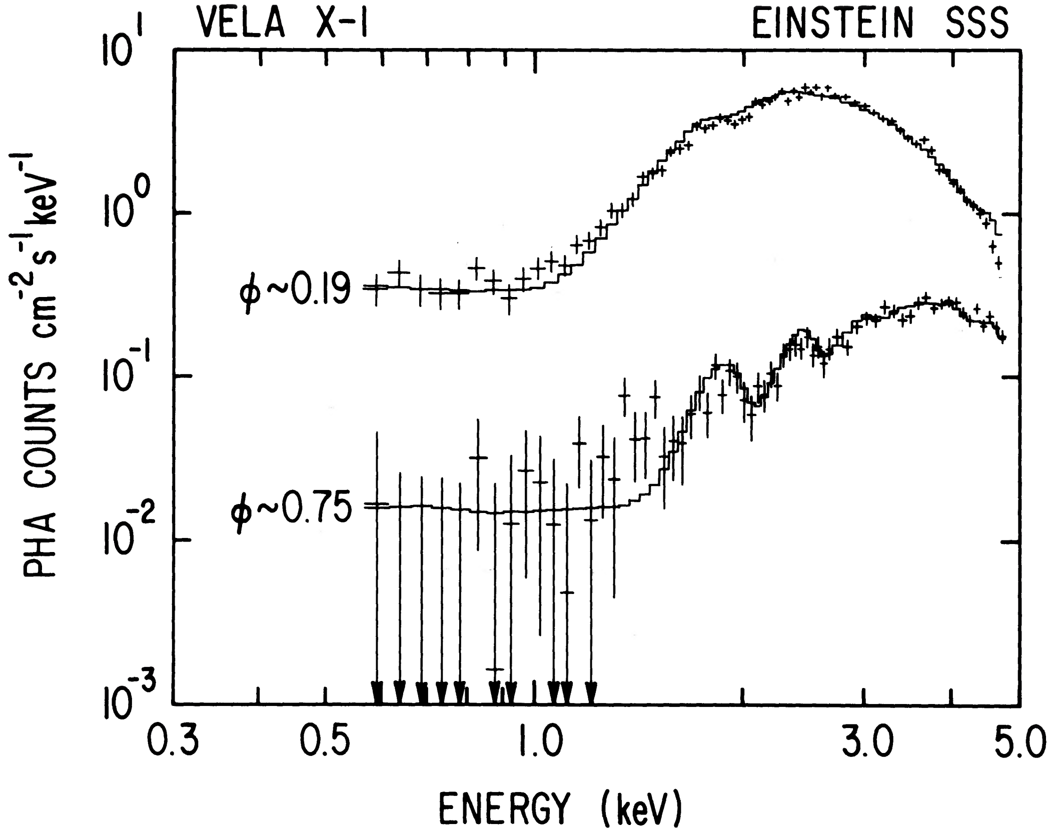

FIG. 2.—SSS spectrum at 0.19 and at 0.75, with the best fit model given in Table 1 shown as the histogram

mean orbital phase and exposure time; summarizes model parameters, cold column density, threshold optical depths and threshold energies for up to 3 absorption edges, and spectrum normalization; and also gives χ^2 values (unreduced) for 67 energy channels. All uncertainties represent 99% confidence values and are found using the procedure described by Avni (1976) and Cash (1976). We have also tested the effects of our choice of grouping with orbital phase by slicing the observations near $\phi = 0.71$–0.82 into shorter intervals and performing a similar analysis on the spectra from each of these intervals. While there is some evidence for changes in MPC hardness, this procedure reveals no statistically significant spectral changes detected by the SSS which might be obscured by our choice of time-averaging intervals.

III. RESULTS

a) $\phi = 0.19$–0.22 *SSS Spectra*

Figure 2 shows the SSS pulse-height spectrum at $\phi \sim 0.19$, together with the best fit model of a simple power law attenuated by neutral material with column density $N_{\rm H} = 2.5 \pm^{0.5}_{0.2} \times 10^{22}$ H cm^{-2}. The model shown in Figure 2 does not provide a statistically acceptable fit to the flare spectrum (see Table 1) primarily because of departure from simple neutral absorption below 2 keV. This we attribute to a decreased opacity of the absorbing material at these energies due to partial ionization. The general features of the observed spectrum, notably the excess flux below 1.5 keV relative to neutral absorption, are reproduced by photoionization models for the stellar wind (Kallman and McCray 1982; Castor *et al.* 1982). The excess flux in these models is due to leakage of photons below 1.5 keV past stellar wind material with partially ionized C, N, and O, the elements which dominate the opacity at these energies. The low-energy excess is probably not due to changes in the absorbing column during our observation, although such changes are suggested by the MPC data (Fig. 1), since the column required to produce the low-energy excess is far outside our derived error limits. The nonflare spectrum near $\phi = 0.20$–0.22 (see Table 1) yields an acceptable fit to simple neutral absorption, because of poorer statistics in this interval.

In the absence of X-ray illumination, the gas in the stellar wind will have a temperature comparable to that of the primary $T \sim 26{,}000$ K, and the wind opacity in the 1–2 keV range will not differ significantly from that of neutral matter. The total line-of-sight column density implied by the fit to the $\phi \sim = 0.19$–0.22 data in Table 1 can therefore be compared with that expected if the absorbing material were supplied by the stellar wind. That is, given the known values of the primary radius (Conti 1978), together with a plausible wind velocity law $v(x) \approx v_\infty(1-1/x)^\gamma$, where x is the distance from the center of the primary in units of the primary radius and $v_\infty = 1700$ km s^{-1} (Dupree *et al.* 1980), we can derive the gas density as a function of x, γ, and the stellar mass loss rate. The column density along the line of sight to the X-ray source at orbital phase 0.20 is then $N_{1/2} = 1.1 \times 10^{22}$ cm^{-2} $\dot{M}_6$ for $\gamma = 1/2$, and $N_1 = 1.6 \times 10^{22}$ cm^{-2} $\dot{M}_6$ for $\gamma = 1$. Here $\dot{M}_6$ is the stellar mass loss rate in units of 10^{-6} $M_\odot$ yr^{-1}. Estimates for the stellar wind mass loss rate of HD 77581 range from $\dot{M}_6 = 1$–2 (Dupree *et al.* 1980) to $\dot{M}_6 = 4$ (Castor *et al.* 1982). In fact, the X-rays will photoionize a fraction of the wind along the line of sight, so that the apparent neutral absorbing column will be smaller than the total. Fits of neutral absorption spectra to detailed X-ray photoionization models (Kallman and McCray 1982; Castor *et al.* 1982) show that the apparent neutral column density at $\phi = 0.20$ is smaller than the total by about 40%, which is consistent with the observed spectrum if $\dot{M}_6 = 2$–4.

b) $\phi = 0.71$–0.82 SSS Spectra

The spectrum at later orbital phases, $\phi = 0.71$–0.82, does not allow as simple an interpretation as do the spectra at $\phi = 0.19$–0.22. The integrated spectrum at these later phases is shown in Figure 2, and strong absorption edges near 2 and 2.5 keV can be clearly seen in addition to a weak absorption feature near 3.0 keV. These features could also be interpreted as emission lines superposed on cold absorption. However, the equivalent widths required are implausibly large (EW = 1–2 keV) for fluorescence at these energies, and we discount this possibility. Although the χ^2 value for the fit shown in Figure 2 is only marginally acceptable, the spectral features and differences from the spectra at earlier phases are so striking that the implications are only weakly dependent on our values of χ^2.

Comparison of the measured edge energies with known K thresholds for abundant elements reveals two alternative explanations for the origin of the absorption edges. The 2, 2.5, and 3 keV edges may be due to either neutral or near-neutral Si, S, and Ar, respectively, or to hydrogenic or helium-like Mg, Si, and S, respectively. The latter hypothesis is unlikely because, for reasonable elemental and ion abundances, we expect the 3 keV S edge to be at least as strong as the 2 keV Mg edge, which is contrary to the observations.

The ranges of allowed energies for the 2 and 2.5 keV edges span several known edge energies for ions of Si and S. The edge near 2 keV may correspond to any of the ions Si IV–Si X, and the edge near 2.5 keV may correspond to any of the ions S I–S IX (Clementi 1964). Since the K shell ionization cross section is only weakly dependent on ionization stage for these ranges of ionization stage (Manson 1978; Reilman and Manson 1978), we can use the observed edge strengths to infer the total column density of material producing the 2 and 2.5 keV edges along the line of sight to the source. Assuming cosmic abundances (Withbroe 1971) and K shell threshold cross sections taken from Reilman and Manson (1978) and Manson (1978), the total equivalent hydrogen column density implied by the 2 and 2.5 keV edges is $N_2 = 5.9 \pm^{1.3}_{0.5} \times 10^{23}$ H cm^{-2}, and $N_{2.5} = 7.1 \pm^{1.9}_{1.9} \times 10^{23}$ H cm^{-2}, respectively. Thus both of the edge strengths are consistent with absorption by a large column density of cosmic gas. However, the column density producing the edges greatly exceeds that producing the continuum absorption below 2 keV, which is $N_{\rm H} = 9.0 \pm^{0.7}_{0.5} \times 10^{22}$ H cm^{-2}. This suggests that the absorbing gas is deficient in the ions which dominate the opacity at low energies.

The photoelectric opacity at energies below 2 keV is dominated by absorption from the K shell of O, with contributions of $\sim 20\%$ from the K shells of Ne and Mg and from the L shell of Fe. The column densities $N_{\rm H}$, N_2, and $N_{2.5}$ imply that the ratio of the abundances of the ions responsible for this absorption relative to Si and S is depleted by a factor of 5–11 relative to the cosmic ratio (Withbroe 1971) in the absorbing gas. One possible explanation for this abundance difference is that the elemental abundances in the absorbing material are altered, relative to the cosmic ratios. An alternative explanation for the apparent depletion of O relative to Si and S in the $\phi = 0.71$–0.82 spectra is that the low-Z elements are more highly ionized than the high-Z elements along the line of sight to the X-ray source. For cosmic element abundances, we require that the fractional abundance of hydrogenic oxygen be no more than 0.4 with the remainder fully ionized. The opacity due to Ne, Mg, and Fe in the 1–2 keV energy range must also be suppressed by a factor ~ 2. An additional constraint is provided by the observed edge energies of Si and S—these elements must not be ionized past Si X and S IX, respectively. Comparison with existing models shows that such an ionization distribution could not be produced by collisions in a thermal equilibrium gas (Summers 1974; Allen and Dupree 1969) or by photoionization by a single power-law X-ray spectrum (Kallman and McCray 1982). Note also that this conclusion is only very weakly dependent on our error estimates for the edge energies, since the edge energies are strongly dependent on ionization state only for ions with no L shell electrons.

The observed ionization could be produced by photoionization by a strong soft X-ray flux in the energy range 0.8–1.0 keV. A total soft flux of $\sim 10^{10}$ ergs cm^{-2} s^{-1}, corresponding to a total luminosity $\sim 10^{35}$ ergs s^{-1} at a distance of $\sim 10^{12}$ cm, could produce the required degree of ionization. The additional overlying cold column density of $\sim 10^{22}$ cm^{-2} provided by the stellar wind would shield the soft flux from observation by the SSS. Other constraints on such a picture are that the soft flux not ionize Si and S past the observed stages by L shell ionization, and that the photoionization heating not heat the gas so as to collisionally ionize Si and S unduly. Detailed photoionization models, using the code of Kallman and McCray (1982), show that these conditions can be met. However, the chief difficulty with such a model is that such soft X-rays could not penetrate a column density $N \sim 5 \times 10^{23}$ cm^{-2} required to explain the observed absorption edges, even if the opacity in the 0.8–1 keV range is reduced by partial ionization. Thus we require that the source of the soft photons be dispersed throughout the absorbing material in order that the full observed column be partially ionized.

IV. CONCLUSIONS

The absorption phenomena of Vela X − 1 seem to be of two types: transient dips lasting from minutes (this paper) to longer than a day (Becker *et al.* 1978), occurring preferentially near orbital phase $\phi \sim 0.2$; and an extended region of absorption seen after phase 0.5. The latter phenomenon has been attributed to an "accretion wake" behind the X-ray source (Eadie *et al.* 1975;Jackson 1975), although the persistence and long duration of the observed absorption tends to discount this idea. The SSS results presented here show that the spectra at $\phi \sim 0.2$ are consistent with absorption by the stellar wind from the primary, including ionization by the X-ray source.

The spectra at $\phi \sim 0.71$–0.82 differ from the earlier orbital phases in that: (1) they show evidence for absorption at energies below 2 keV by a column of material roughly twice as large as was seen at $\phi \sim 0.2$; and (2) they show strong spectral features near 2 and 2.5 keV, which we attribute to K shell absorption by Si and S. Although the enhanced absorption below 2 keV is consistent with the results of past studies (Bessell, Vidal, and Wickramasinghe 1975; Watson and Griffiths 1977; Charles *et al.* 1978), the absorption edges have not been observed before and can only be produced by material with altered opacity relative to neutral matter. This opacity could be due either to altered elemental abundances or to partial ionization of the absorbing material by soft X-rays. Soft X-rays of the required flux could perhaps be produced by reprocessing of hard X-rays in an accretion disk or neutron star Alfvén shell, such as has been proposed for Her X-1 (Catura and Acton 1975; McCray and Lamb 1976; McCray *et al.* 1982; although such soft X-rays could not fully penetrate the observed ionized column), or in a shock-heated structure in the stellar wind (Lucy and White 1980; Fransson and Fabian 1980).

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T. R. Kallman: Massachusetts Institute of Technology, Room 37-415, Cambridge, MA 02139

N. E. White: Code 661, NASA Goddard Space Flight Center, Greenbelt, MD 20771