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EXTENDED OBSERVATIONS OF VELA X-1 BY OSO-8

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ABSTRACT

The Goddard Space Flight Center Cosmic X-Ray Experiment aboard OSO-8 viewed the X-ray binary pulsar, Vela X-1, on three occasions from late 1975 through late 1976. The X-ray spectrum is well represented by a power law modified by photoelectric absorption, a high energy cutoff, and a line feature at $\sim$6.8 keV. When combined with other observations, our measurements show that the pulse period is not decreasing monotonically. The three eclipses observed all indicate a significant eclipse flux.

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I. INTRODUCTION

The six known X-ray binary pulsars (Her X-1, Cen X-3, Vela X-1, SMC X-1, 3U1223-62, and 3U1538-52) have binary periods differing by as much as a factor of 5 and pulse periods differing by more than two orders of magnitude. Nonetheless, in many respects these systems show great similarity. The GSFC Cosmic X-ray Spectroscopy Experiment on OSO-8 observed Vela X-1 (3U0900-40) for more than 30 days during a one year period from November 1975 to December 1976. The spectral and temporal results presented here are based on those observations, and are compared with similar observations of other X-ray binary sources.

II. EXPERIMENT AND OBSERVATIONS

The Goddard Space Flight Center Cosmic X-ray Spectroscopy experiment on OSO-8 consists of three proportional counter systems. The A detector is xenon filled with $5\overset{\circ}{.}1$ FWHM collimation inclined 5° from the negative spin axis, enabling it to scan a small annulus on the sky every satellite rotation. The B detector is an argon counter with $3\overset{\circ}{.}4$ FWHM field of view aligned with the negative spin axis. The C detector is a xenon counter with a $5\overset{\circ}{.}1$ FWHM collimator aligned along the positive spin axis. The two xenon counters have a nominal energy range of 2-60 keV while the argon detector is sensitive between 2-20 keV. The A, B, and C detectors are described in more detail in Becker et al. (1977), Becker et al. (1976), and Pravdo et al. (1976) respectively.

During the first two years in orbit, all three detectors have observed Vela X-1. The C detector exposure was between Nov. 27 - Dec. 7, 1975 and Nov. 28 - Dec. 2, 1976, while the A and B detectors viewed the source alternatively for 14 days in May 1976. The 283 second pulsations first discovered by McClintock et al. (1976) were clearly observed during all three occasions.

The spectrum of this source was examined at various times during the exposure which corresponded to differing situations--flares, dips, and eclipses. In general the continuum could be described by the following functional form:

$$e^{-\sigma \cdot N_H} E^{-\alpha} e^{-(E_1-E)/E_2} \qquad E > E_1$$

$$e^{-\sigma \cdot N_H} E^{-\alpha} \qquad E < E_1$$

where E is photon energy, α is the power law number index, σ is the energy dependent absorption cross section per hydrogen atom assuming solar abundances of cold matter (Withbroe 1971), N_H is the equivalent column density of hydrogen in the line of sight, and E_1 is a high energy cutoff energy characterized by an e-folding energy E_2.

The parameters α, N_H, E_1, and E_2 are highly interdependent, and statistically acceptable fits to the data were not always obtained (see Pravdo et al. 1976 for a description of the fitting process). In part this is due to the observed high variability of N_H over timescales of several hours. N_H was found to vary by over an order of magnitude in going from dips to flares, similar to the results of Watson and Griffiths (1977) and Eadie (1975). This variation of N_H is apparent in the two spectra shown in Figure 1. The spectrum on the left is best fit with 6 x 10^{22} H atoms/cm^2 while the one on the right needs 3 x 10^{23} H atoms/cm^2. The more highly absorbed spectrum displays an absorption edge at 7.1 keV due (presumably) to neutral iron. In this one instance, a simplistic interpretation of the depth of this edge relative to the low energy cutoff indicates that the iron is overabundant by a factor of 3 compared to solar composition where we have assumed a number ratio of iron to hydrogen of 3.9×10^{-5} for normal solar abundance (Withbroe 1971). This highly absorbed spectrum was accumulated during the last 15000 secs of an absorption dip of 65000 sec duration. The dip was centered at phase 0.28 of the binary period. The spectra from the first 75% of the absorption dip have an iron edge which is consistent with normal solar abundance of iron when compared to the low energy absorption. In fact, all spectra from Vela X-1 other than that from the end of the extended dip are consistent with a solar abundance of iron.

No absolute relationship between observed X-ray intensity (2-20 keV) and N_H could be established from our observations, but in general the value of N_H anticorrelates with intensity. On occassion relatively high values of intensity are measured during intervals of high absorption, indicating that some of the observed variability is intrinsic to the source. The 2-20 keV non-eclipsed X-ray flux from Vela X-1 was seen to vary between 1.2×10^{-9} and 6.7×10^{-9} ergs/sec cm^2.

The parameters describing the high energy cutoff depend strongly on the assumed power law index, which had best-fit values between -1.05 and -1.25. The cutoff energy increases for higher values of α, but for the range in power law index quoted above, E_1 ranged between 16 and 20 keV while E_2 varied between 18 and 22 keV.

6.8 keV Line Feature

In all the spectra obtained for Vela X-1 the fit to the data is improved by the addition of a line feature at 6.8 ± 0.3 keV. The exact strength and energy of the line is confused in many instances by the presence of the iron absorption edge at 7.1 keV, since the intrinsic detector resolution at 6.8 keV is about 1.1 keV. This line feature can be studied best during intervals of minimum absorption when the edge, too, is minimal.

The B detector is better suited to study the line due to its narrower PHA energy channels as compared to the xenon detectors. Table 1 contains derived spectral parameters for two sets of argon detector data from May 1976. The quoted uncertainties are all single parameter 90% confidence ranges. The line feature appears significantly broader than expected for a narrow line broadened only by detector resolution, and the equivalent width seems to vary. The line intensity, however, is consistent with a constant value in these two exposures. The response of the argon detector to the line can be seen in Figure 2 which displays the residuals for the first of the spectra in Table 1 after the best fit continuum has been subtracted.

The line feature may not always be broad. Some of the spectra from the observation by the C detector in Nov. 1975 are consistent with a narrow line. The equivalent width was variable in these earlier observations also.

III. DISCUSSION OF SPECTRA

Qualitatively, the X-ray spectrum of Vela X-1 is very similar to that of Her X-1 (Pravdo et al. 1977; Becker et al. 1977). Both can be characterized by a power law spectrum modified by a high energy cutoff and by variable amounts of low energy absorption. Furthermore both show significant excesses near 6.7 keV, which can be interpreted as line emission from iron.

The high energy cutoff we observe for Vela X-1 is not as steep as that for Her X-1 (Becker et al. 1977). Boldt et al. (1976) have suggested that the X-ray cutoff in the spectrum of Her X-1 could result from the energy dependence of severely modified Thomson scattering that dominates the radiative transfer in a highly magnetized plasma near the poles of a neutron star.

Other authors (Illarionov and Sunyaev 1972; Ross, Weaver, and McCray 1977) have shown that Comptonization of an X-ray spectrum in a region of low magnetic field strength can also result in a high energy cutoff. Since the high energy cutoff in Her X-1 is ∿ 3 times as sharp as that observed in Vela X-1 [E_2 (Vela X-1) = 3 E_2 (Her X-1) where E_2 is defined in Section II], the dominant mechanisms are not necessarily the same for the two sources.

Comptonization of the X-ray spectrum of Vela X-1 could also explain the broadened emission feature. The broadening due to Comptonization is given approximately by

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$$\frac{\Delta E}{E} \approx \sqrt{\frac{2kT}{M_e C^2}} \quad \tau,$$

where T is the temperature of the electrons, and τ is the optical depth to Compton scattering. For Vela X-1, where $\Delta E/E \sim .25$, the optical depth to Compton scattering would have to be in excess of .7 for kT $\leq$ 20 keV to explain the broadening, implying a column density of electrons in excess of 1 x 10^{24} cm^2. If the line feature is Comptonized, the energy of the line may be shifted from its intrinsic value. Pravdo et al. (1977) suggested that the line emission seen in Her X-1 may be Dopper broadened. In that model, the line is produced by fluorescence from material corotating with the neutron star at the Alfven radius. This model may be applicable to a fast rotator such as Her X-1, but cannot explain the broad features in the much more slowly rotating Vela X-1 if the magnetic field strengths in the two systems are comparable.

Alternatively, the broadened feature observed in Her X-1 and Vela X-1 may result from Zeeman splitting of the line emission (Sarazin and Bahcall 1977). The observed width of the line requires fields of several times 10^{11} gauss--as expected near the surface of a neutron star.

Our observations have indicated that the line intensity is not necessarily reduced during intervals of increased photoelectric absorption. If so, the line emission would have to originate away from the compact object so as to be free of obscuration by the absorbing material. Then, the line intensity would depend on the intrinsic luminosity of the compact object, independent of the line-of-sight absorption.

The data indicate that gaseous material exists within the Vela X-1 system at several different levels of ionization. Most of the absorption must be due to cool, nonionized material as evidenced by the location of the 7.1 keV K-absorption edge due to iron. However, as mentioned earlier, during one extensive absorption dip lasting 24 hours, the iron absorption edge was deeper than expected after fitting the low energy portion of the spectrum. The most plausible explanation for the apparent inconsistency is that the absorbing material is highly ionized. Partial ionization of the lighter elements of the gas causes a reduction in the absorption and thereby a lower calculated N_H. Another argument in support of significant amounts of ionized matter is the line broadening which may be due to Compton interactions. The optical depth to Compton scattering required to broaden the line implies an electron column density greater than that expected from the calculated neutral hydrogen column density. Hence, we might expect the system to contain a large amount of highly ionized material.

Binary Eclipses

Eclipses of Vela X-1 were observed on each of the three observing periods. On all three occasions, the entrance into and exit out of eclipse was gradual, the spectra showing increasing low energy absorption near the eclipse boundaries. The eclipse boundaries were sharply defined by X-rays above 6 keV, i.e., those least effected by absorption from the stellar corona. During the Nov. - Dec., 1976 observation, both the entrance into and the exit out of eclipse were well observed. The entrance occurred no earlier than Nov. 30.46 and the exit no later than Dec. 2.13, so that the eclipse duration could be set at $\leq$ 1.67 days, in good agreement with the results of Watson and Griffiths (1977).

During all our eclipse observations of Vela X-1, a residual intensity was present. With our large fields of view, we can only state that the observed flux was consistent with coming from Vela X-1, and that no other known X-ray sources were in the field of view at these times.

A typical eclipse intensity was 7.5×10^{-11} ergs/s cm^2 between 2-20 keV, $\sim$ .02 of the uneclipsed flux. The X-ray spectra during eclipses were consistent with a power law with number index $1.2 \pm .4$ modified by photoelectric absorption, consistent with the non-eclipsed spectral form. The eclipse spectra can also be fit with thermal bremsstrahlung continua of kT > 15 keV. The derived column density N_H varied from eclipse to eclipse with a range of values of 4×10^{22} to 2×10^{23} atoms/cm^2. This high variability of column density is typical of the non-eclipsed behavior of Vela X-1 and suggests that the eclipse flux does indeed originate from Vela X-1. During the eclipses, no pulsations were observed. The 3σ upper limit for the pulsed fraction is 0.38, compared to a typical pulsed fraction of 0.68 during non-eclipsed portions of the orbit.

The X-ray emission during the eclipse can be explained naturally in terms of X-rays from the compact source scattering around the primary star. In such a case, we would expect the eclipse spectra to be the same form as the uneclipsed spectra, which (within limits) it is. Alternatively, if the eclipse emission were thermal emission, as has been suggested for Cen X-3 (Giacconi 1974), it would require a cloud of hot material larger in extent than the primary maintained at kT > 15 keV. In addition, this hot material would have to be obscured by variable amounts of cool material. Of the two models, the scattered emission appears more likely. Sensitive measurements of time variability during an eclipse could resolve the question. Scattered flux should vary as the compact source, exhibiting flares, while a thermal source would vary more slowly. If the eclipse flux is scattered, the pulsed fraction should be small, since the light travel time across the Vela X-1 system is comparable to the pulsation period.

282 Sec Pulsations

The first two observations of Vela X-1 lasted longer than a full binary period, allowing an unambiguous determination of the pulsation period, independent of the exact parameters of the binary orbit. This determination was accomplished by counting the number of pulses during a binary orbit using the sharp minimum in the Vela X-1 pulsed light curve as phase marker. The third observation lasted a fraction of a binary orbit, so that the period determination depends on the assumed values of a sin i, the degree of ellipticity of the orbit, and the zero phase of the orbit. We have used the orbital parameters given by Rappaport et al. (1976) to calculate pulse period during the third observation. The pulse periods for all three intervals are shown in Figure 3 along with other previously reported values.

Our first two values agree very well with those from COS B and SAS-C for the same epochs. Excluding the COS B and OSO-8 values from Nov. and Dec. 1975, the Vela X-1 pulse period is consistent with a monotonic spin-up at a rate of $\sim$ .03 sec per year. However, between July and Nov., 1975, the pulse period appears to have increased significantly confirming the COS B result (Ogelman et al. 1977) that Vela X-1 does spin down as well as up, similar to the behavior of Her X-1 (Tananbaum et al. 1972) and Cen X-3 (Fabbiano and Schreier 1977).

An analysis of pulse arrival times during the two extended observations of Vela X-1 confirms the report by Rappaport et al. (1976) that the binary orbit is elliptical. We find the orbital eccentricity e = .10 $\pm$ .04 and the longitude of periastron w = $166^o \pm 30^o$ where the errors quoted are 90% confidence intervals. These values are consistent with those determined from SAS-3 (Rappaport et al. 1976) and COS B (Ogelman et al. 1977).

IV. CONCLUSIONS

The severe absorption dips seen in the Vela X-1 type systems have been interpreted in terms of accretion wakes formed as the compact object moves through the material leaving the primary star (Jackson 1975). The motion of the compact object through the stellar wind causes shocks which both compress and heat the stellar wind material. During one dip (no other dip was observed well enough to detect such an effect), we observed an apparent change in the ionization of the absorbing material. This conclusion was based on the change in iron absorption edge relative to the low energy absorption. The high ionization state could result from the passage of the accretion wake shock front through the absorbing material. Since this enhanced ionization was only present during part of the dip, the material must cool quickly after the passage of the shock front.

The eclipse flux observed from Vela X-1 also implies the presence of an extended cloud of ionized material of a size comparable to that of the binary system. Insofar as the spectrum of eclipse x-rays is apparently the same as that of the uneclipsed source, the eclipse X-rays may not represent an independent source of emission. Rather, we may be seeing X-rays from the compact object which have been scattered around the primary star by its extended atmosphere and wind.

If the broad feature associated with iron K-emission can be attributed to a Compton scattering of an intrinsically narrow feature, than we have additional evidence for a large amount of scattering material within the binary system. The line emission may originate away from the compact object and out of the line of sight to the material responsible for the absorption dips.

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TABLE 1

SPECTRA OF VELA X-1 WITH ARGON DETECTOR

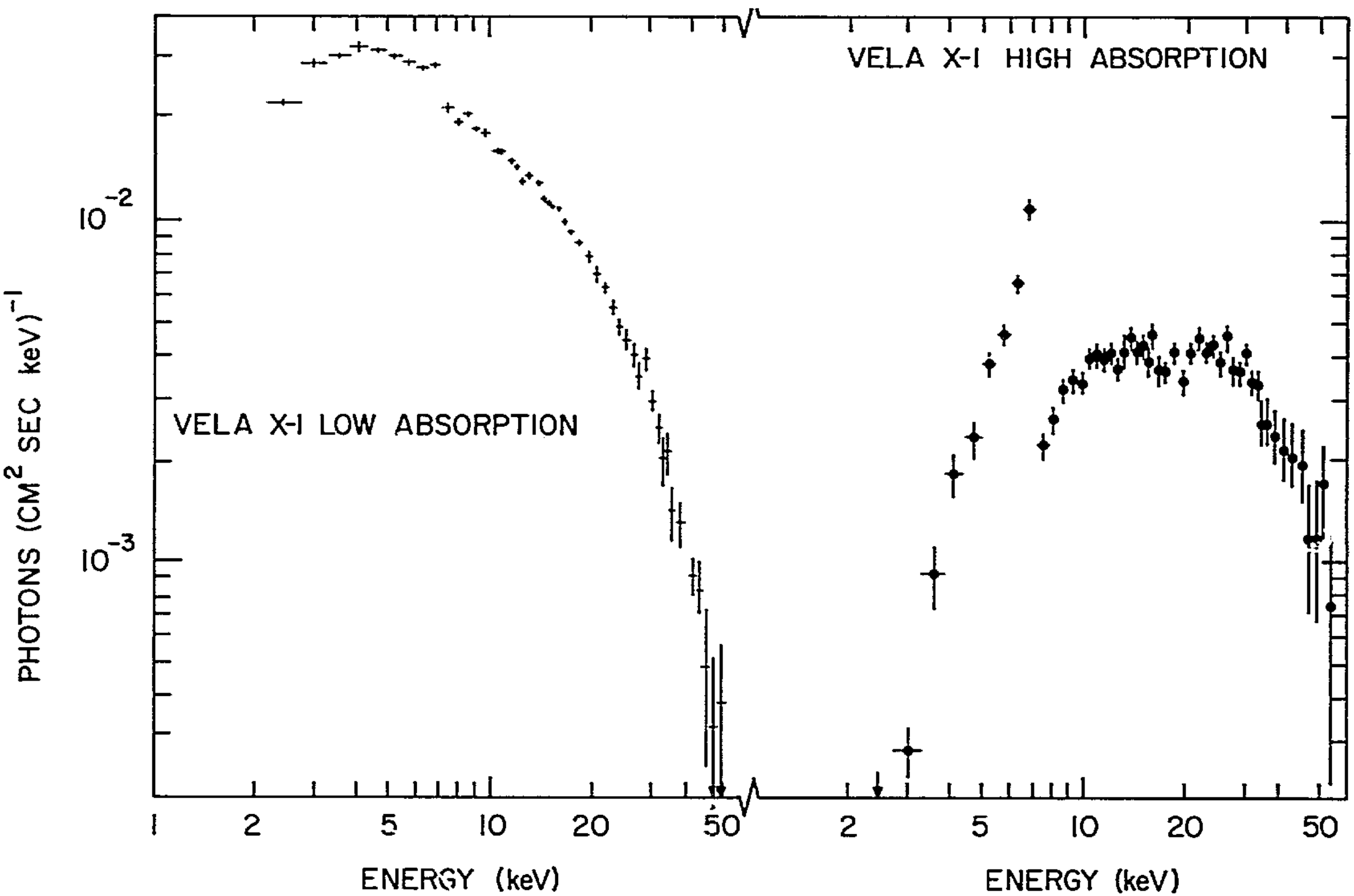
DATE (Day of 1976)	α	N_H (atoms/cm^2)	Intensity (2–20 keV) (ergs/s-cm^2)	Line Parameters			
				FWHM (keV)	Energy (keV)	Equivalent Width (eV)	Intensity (photons/s-cm^2)
144.0–144.6	$1.16 \pm^{.03}_{.05}$	$.93 \pm .01 \times 10^{23}$	5.2×10^{-9}	3.7 ± 1.7	$6.8 \pm .3$	480 ± 120	$.014 \pm .003$
144.7–146.5	$1.17 \pm^{.04}_{.10}$	$1.7 \pm .02 \times 10^{23}$	3.2×10^{-9}	4.7 ± 1.6	$6.8 \pm .3$	710 ± 180	$.012 \pm .003$

FIGURE CAPTIONS

Figure 1 The derived incident spectra of Vela X-1 illustrating extremes in photo-electric absorption.

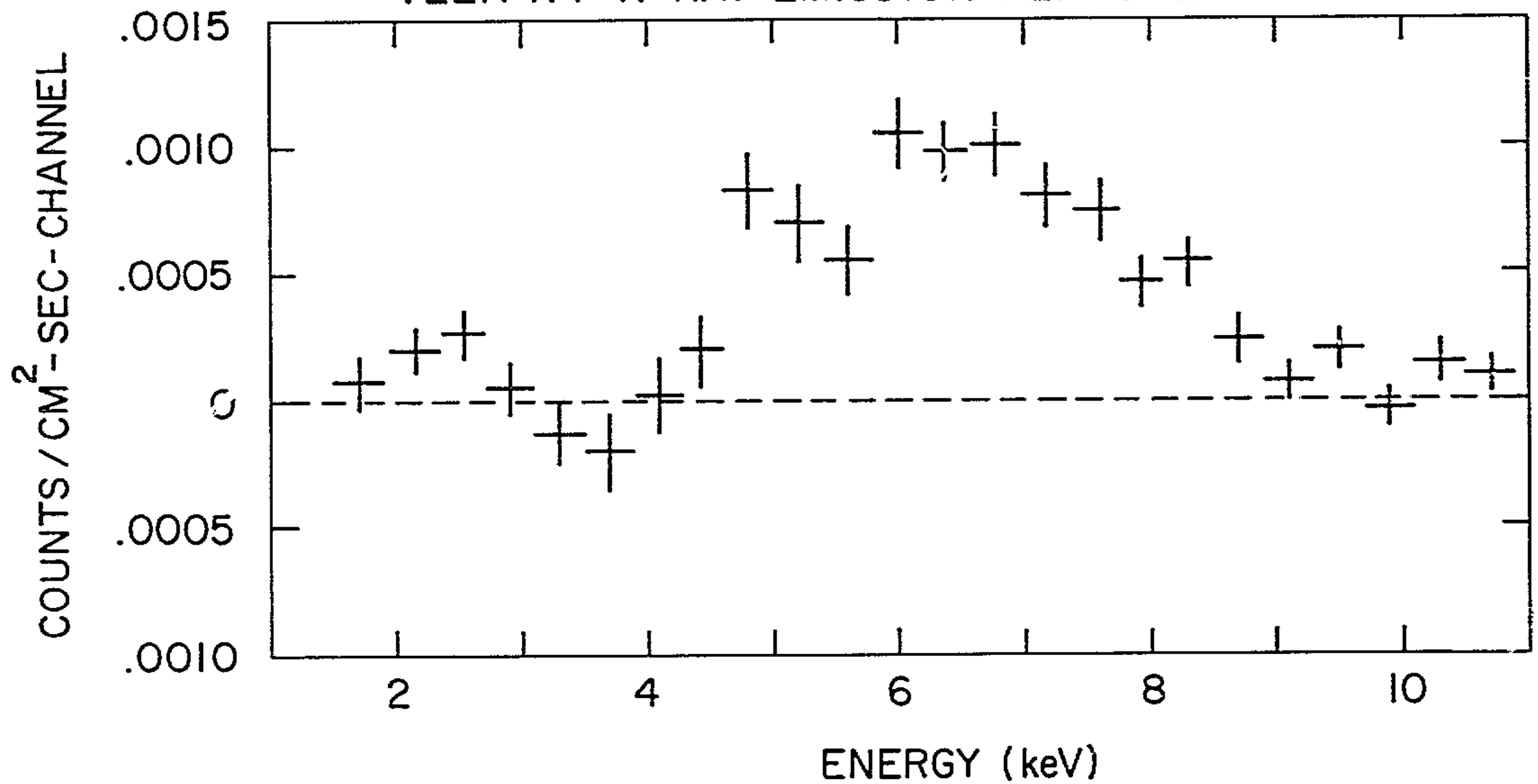
Figure 2 The residuals of an uneclipsed Vela X-1 spectrum after subtraction of the best fit continuum spectrum. The residuals can be represented by a single broad emission feature centered at $\sim$ 6.8 keV.

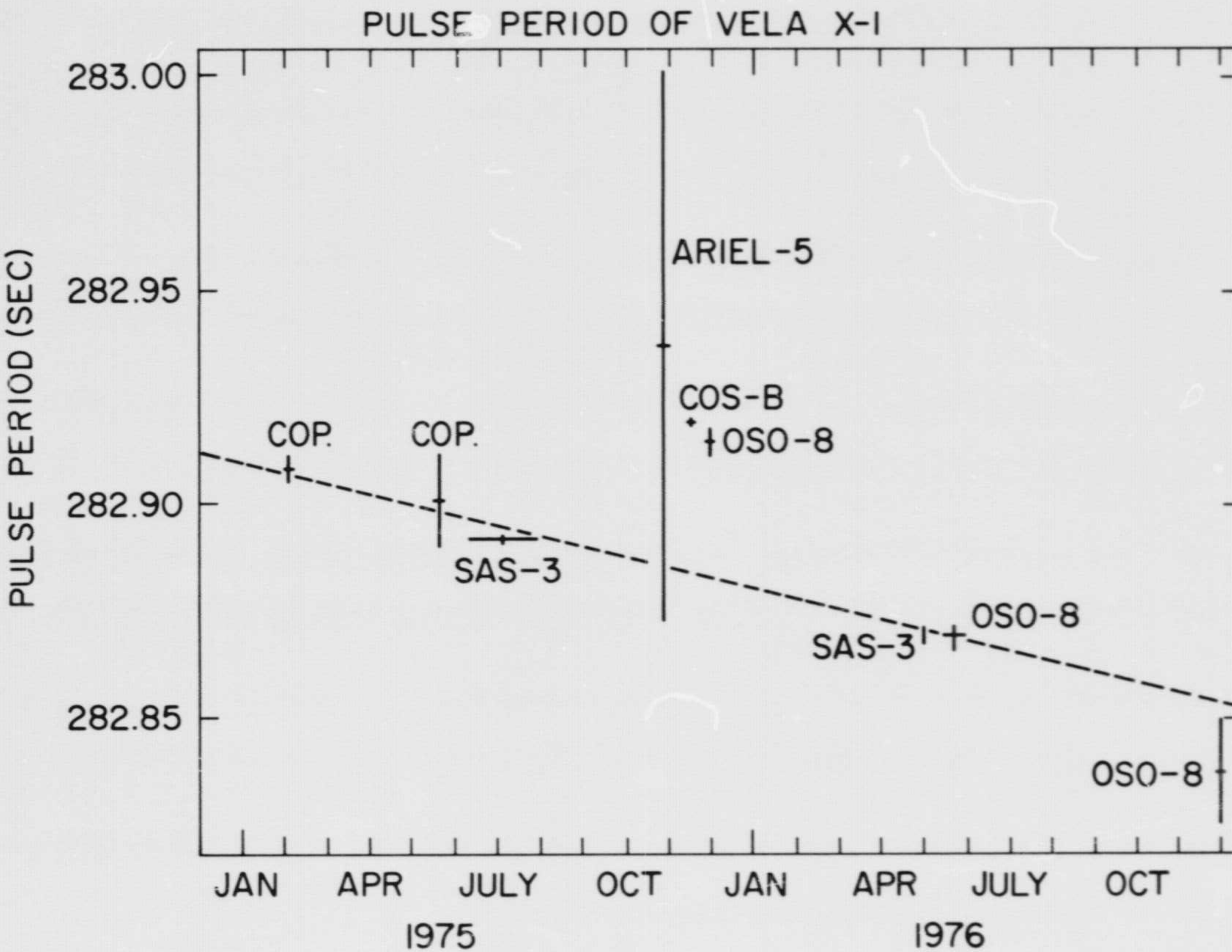
Figure 3 Measured values of the pulse period of Vela X-1. The three OSO-8 points are 282.019 $\pm$ .003 s (Nov.-Dec. 1975), 282.869 $\pm$ .003 s (May 1976), and 282.838 $\pm$ .012 (Nov. - Dec. 1976). The other points are taken from Rappaport et al. (SAS-3) 1976, Charles et al. (Cop and Ariel) 1977, Ogelman et al. (COS B) 1977, and Rappaport and Joss (SAS-3) 1977.



VELA X-I LOW ABSORPTION
VELA X-I HIGH ABSORPTION
PHOTONS (CM^2 SEC keV)$^{-1}$
10^{-2}
10^{-3}
1
2
5
10
20
50
ENERGY (keV)
2
5
10
20
50
ENERGY (keV)

VELA X-I X-RAY EMISSION FEATURE




PULSE PERIOD OF VELA X-I
PULSE PERIOD (SEC)
283.00
282.95
282.90
282.85
COP.
COP.
SAS-3
ARIEL-5
COS-B
OSO-8
SAS-3
OSO-8
OSO-8
JAN
APR
JULY
OCT
JAN
APR
JULY
OCT
1975
1976

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