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SMC X-1 VARIABILITY OBSERVED FROM *HEAO 1*

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ABSTRACT

The 13–70 keV emission from the 0.7 s X-ray pulsar SMC X-1 was monitored by the UCSD/MIT instrument aboard *HEAO 1* during three ~80 day epochs in 1977 and 1978. The X-ray flux was seen to wander slowly between a maximum value and unobservably small levels with a rough time scale of 60 days. This variability is found to be consistent with a random walk in intensity and could be the result of unsteady mass transfer from the primary. A possible alternate explanation involves regular shadowing of the X-ray emitting neutron star by a tilted, precessing accretion disk, as in the cases of Her X-1 and LMC X-4. If so, the precession period instability of $\Delta P/P = 15\%$ is a factor of 3 larger than for Her X-1. The maximum 13–70 keV luminosity observed was 2.8×10^{-11} ergs $(\mathrm{cm}^2\ \mathrm{s})^{-1}$. The time-averaged spectrum above 15 keV shows a gradual exponential cutoff with a characteristic energy of 10–20 keV. There is no evidence for linelike features such as observed in Her X-1 and A0115+63. The spectrum appears to soften at times of low intensity.

Subject headings: galaxies: Magellanic Clouds — stars: accretion — X-rays: binaries

I. INTRODUCTION

The physical picture, first advanced in 1972 (Pringle and Rees 1972; Davidson and Ostriker 1973; Lamb, Pethick, and Pines 1973), to explain the X-ray pulsars Her X-1 and Cen X-3 consists of a close binary system with sizable mass transfer from a normal or near-normal primary star onto a neutron star secondary. The matter collects into an accretion disk, then eventually plummets toward the magnetic poles of the neutron star, where the release of its gravitational energy produces hot spots which radiate the pulsed X-ray emission. This picture has received extensive observational support in the last decade, which has also seen a growth to ~20 in the number of observed binary systems with X-ray pulsars (see, e.g., Rappaport and Joss 1977; White, Swank, and Holt 1983). Much of this progress has come about through the observation of X-ray variability on time scales of milliseconds to the order of days. Observations of variability on longer scales may reveal much about the nature of the mass transfer, the structure of the system, and of the accretion disk in particular. Such lengthy observations have been achieved to date only for a few systems, but much has been learned from them. In Her X-1, a 35^{d} periodicity has been associated with a precession-like motion of the accretion disk (Katz 1973; Petterson 1975; Gerend and Boynton 1976). The discovery of a similar slow periodicity in the emission from the eclipsing binary source LMC X-4 (Lang *et al.* 1981) led to the further discovery of pulsations (Kelley *et al.* 1983) and thus to the confirmation of a second system with regularly repeating occultations of a binary X-ray pulsar by its accretion disk. Variable flux levels in other binary X-ray pulsars have often been observed, but the generally short, infrequent, and irregularly spaced observations have been insufficient to determine the character of the variability. Sensitive long-term monitoring can demonstrate whether the variability in these systems is primarily regular or random, and can thereby lead to interpretations of the system structure or of statistics of the accretion flow.

The neutron star origin of the X-ray emission has been supported independently by the discovery of features in the >20 keV spectra of Her X-1 (Trümper *et al.* 1978) and A0115+63 (Wheaton *et al.* 1979). Through identification as cyclotron resonance transitions in the intense magnetic field above the polar cap of a neutron star, these features permit study of the inner magnetosphere and of emission processes.

The 0.7 s X-ray pulsar SMC X-1, which has been observed many times (Bonnet-Bidaud and van der Klis 1981 and references therein), is in a 3.89 day eclipsing binary system with a B0 I supergiant companion. As the brightest ($L_x = 5 \times 10^{38}$ ergs s^{-1}) and second fastest binary X-ray pulsar, it is not typical of the class, but it is perhaps more likely to exhibit details of energetic processes in its spectrum or light curve. Its southern location permitted extended monitoring with ~60% duty cycle by the UCSD/MIT instrument on *HEAO 1* from 1977 August through 1979 January. In this paper we report studies of the slow variability of SMC X-1 and of its spectrum and discuss, alternatively, their possible bearing on the system configuration and on the mass transfer process. We employ a recently published (Deeter and Boynton 1982) method for analysis of red-noise random variability.

II. OBSERVATIONS

The UCSD/MIT instrument (described by Matteson 1978) consists of seven collimated scintillator detectors. For the results presented here, data were accumulated from the two slat-collimated Low Energy Detectors, sensitive between 13 and 180 keV. Most of the data were collected during the scanning mode of the *HEAO 1* mission, during which the source was in the field of view for only 15 s of each 30 minute rotation of the satellite. Owing to the 18° FWHM field of view normal to the scan plane, and also to the source's fortuitous location at 67° ecliptic latitude, useful data could be collected during about half of each 6 month all-sky scan. The satellite was also pointed at SMC X-1 for periods of hours on three occasions. The X-ray flux was unfortunately weak during each of these pointings.

With the normal telemetry configuration of the UCSD/MIT instrument the time of arrival of each photon was known to only 0.1 s. This, in combination with the overall weak flux and period uncertainty (Darbro *et al.* 1981), made it impossible to detect the 0.7 s pulsation.

III. RESULTS

a) Light Curve

Figure 1 shows the binary light curve formed by accumulating the individual transits of SMC X-1 into bins by 3^{d}9 binary phase. Very clearly marked is the expected eclipse of duration 0^{d}6 at the epoch calculated from Primini, Rappaport, and Joss (1977). The count rate during eclipse of -0.14 ± 0.09 counts s^{-1} excludes any net count rate at 90% confidence, and at 3 σ a residual rate of 12% of the average rate out-of-eclipse is the maximum permitted by the data. Thus the eclipse appears complete, and the results presented below are not compromised by confusion with known or unknown sources. The indication of a lengthening of the binary period reported by Bonnet-Bidaud and van der Klis (1981) is not supported by these observations.

We have constructed a light curve for the period 1977 September to 1978 December by accumulating the 13–80 keV counts observed during satellite scans into approximate 4 day averages with exclusion of times during binary eclipse. These count rate averages, shown in Figure 2, are grouped into three epochs at 6 month intervals. Each of the three epochs shows the same overall pattern: an initial high level of ~ 1.8 counts s^{-1}, followed by a decline over a period of ~ 10 days to a low level of < 0.7 counts s^{-1}, then a return to the high level. In the second epoch the time scale for the return cannot be determined but in the other two it appears to be ~ 5 days, faster than the decline. This count rate behavior may be roughly characterized as wandering between "high" and "low" states. The behavior during the low state varies: this state lasts about 30 days in the first two epochs but only about 20 days in the

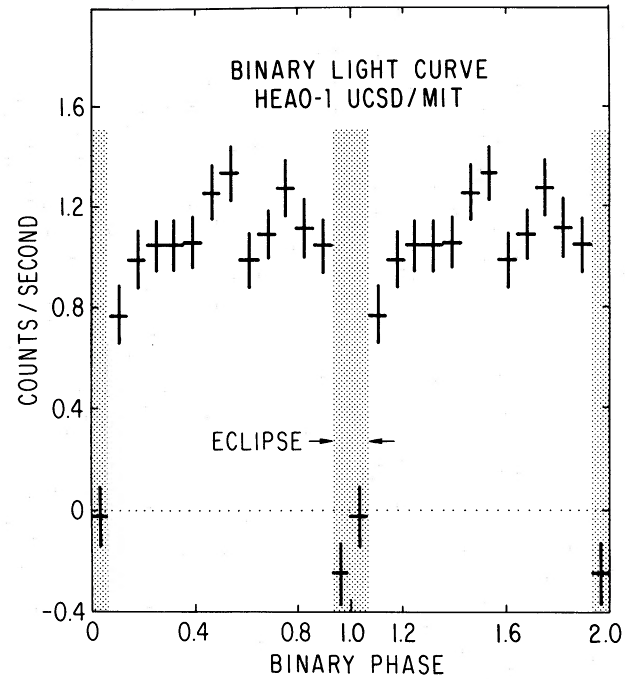

FIG. 1.—The 13–80 keV count rate folded modulo the 3.89 day binary period with the cycle repeated for display. The eclipse by the primary occurs with the expected epoch and duration. Confusion with another source would show itself as a nonzero counting rate during eclipse.

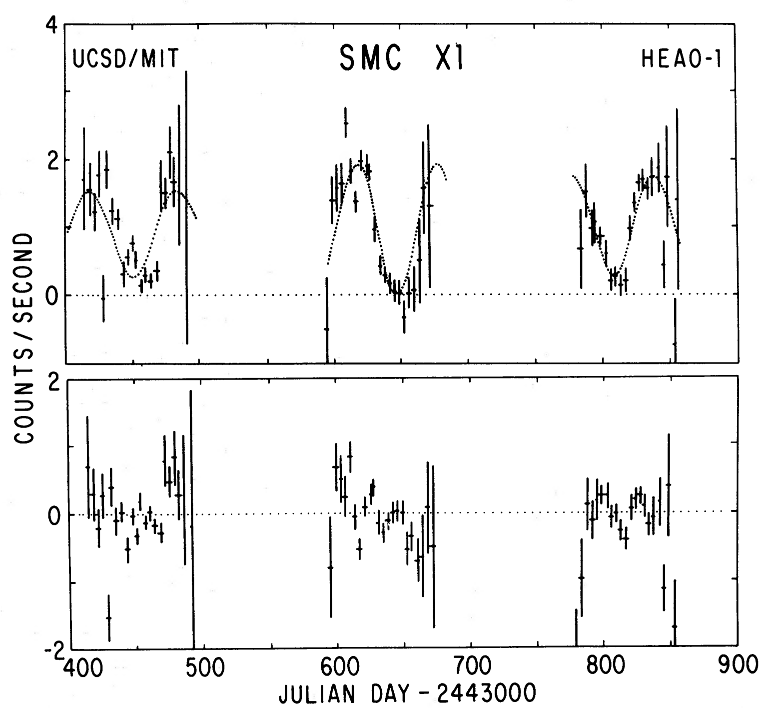

FIG. 2.—The SMC X-1 light curve, with periods of binary eclipse excluded. The three observed epochs extend from 1977 October to 1977 December, 1978 March to 1978 June, and 1978 October to 1978 December. The obvious variability is consistent with a random walk process, but could also be quasi-periodic, with an average period of about 60 days and an instability $\Delta P/P \approx 15\%$. Each epoch has been fitted independently to a 60 day sinusoidal function. The residuals in the lower panel show significant but random variability.

third. A shorter interval of about 10 days during the second epoch is consistent with zero counting rate.

The data in Figure 2 suggest a regular and approximately sinusoidal modulation with a time scale near 60^d. But a strict periodicity can be ruled out at once: no constant + sinusoid model with a constant period can be made to agree in phase with the data from all three epochs. Reasonable agreement (see below) requires phase or period changes between epochs.

The approximately sinusoidal variation of about one cycle in each epoch of observation can also be recognized as signature of band-limited red noise. These data resemble plots of phase residuals from timing observations of the Crab pulsar (Boynton *et al.* 1972; Groth 1975) which were found to be consistent with a random walk in the pulsar frequency. Characteristic of random walk data, which arise naturally as time integrals of a white noise process, is a "red" power spectrum with negative even spectral index (Boynton *et al.* 1972). A conventionally calculated Fourier transform of such data may not accurately estimate the true power spectrum because the direct transform is the convolution of the strongly varying true power spectrum with the Fourier transform of the observing window function, and the product of side lobes of the latter with the former can easily dominate the integral. A power spectrum estimation method which avoids this difficulty (and others) has been developed by Deeter and Boynton (1982).

In Figure 3 are shown the power spectra for the three epochs of Figure 2, calculated from direct Fourier transforms. Ignoring for the moment any but the gross structure, these are roughly consistent with ν^{-2}, suggesting similarity to a random walk process and the suitability[1] of the Deeter and Boynton methodology. Application of this method indeed shows overall consistency with a ν^{-2} spectrum for periods between 10 and 100 days. The power spectrum of the *time derivative* of the observed flux, shown in Figure 4, is reasonably flat on this interval. One more power estimate at 450 days is obtained by treating the three epoch of data as a single ensemble. The 450^d estimate is down by three orders of magnitude from the others; thus, the flat portion of this power spectrum cannot extend to periods much longer than 100 days. In Figure 4 the error bars represent not measurement error, which has been subtracted, but the expected intrinsic variance assuming the observed flux is truly a pure red noise process. It should be noted that the three points above 0.01 day^{-1} in Figure 4 are averages of separate determinations for the three epochs. If a noise process, the scatter of these measurements about their averages is unexpectedly small, with a net χ^2 probability of $P < 0.003$. This indicates that the data actually represent a more ordered process. However, a noise process cannot be ruled out at high confidence from these data, given the newness of the technique and our inability to empirically test the error estimates.

The power spectrum of the observed SMC X-1 flux, estimated with the Deeter and Boynton method, is thus reasonably consistent with a ν^{-2} (red) shape for frequencies greater than 0.01 day^{-1}, and a flat (white) or rising (blue) spectrum below this frequency. This analysis thus formally confirms the similarity of the observed flux to a random walk variable. For the random walk strength these data give the value 0.013 day^{-1} for the quantity $R\langle(\delta I/I_{\max})^2\rangle$, where R is the rate of intensity jumps, δI is their magnitude, and $I_{\max}$ is the observed high state intensity. Of course, a true random walk variable is unconstrained, while the luminosity cannot be negative or increase greatly above the Eddington limit. The bend in the power spectrum near 100^d results from these physical limits.

The interpretation of the spectra in Figure 3 as featureless power laws is somewhat forced. Each spectrum shows a definite, if low, peak near $\nu = 0.017$ day^{-1}, and two of them have similar peaks at odd harmonics of this frequency. The width of

[1] But not the necessity—Deeter (1984) has shown that conventional power spectral estimation is not inaccurate for ν^{-2} spectra.

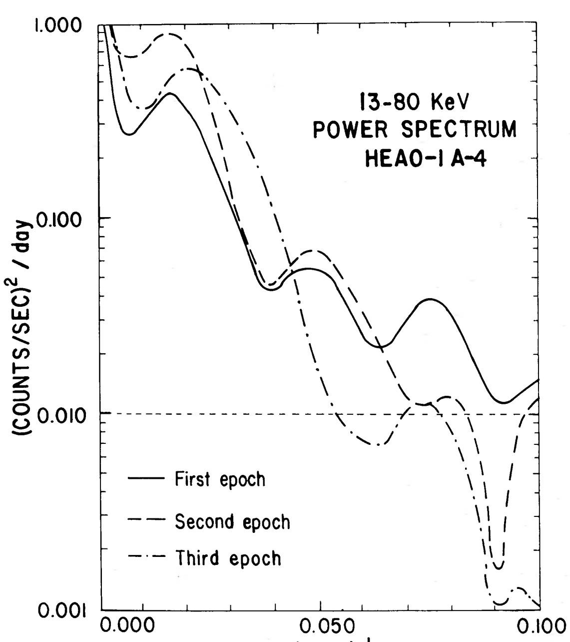

FIG. 3.—Conventional power spectra of the observed 13–80 keV flux from SMC X-1 for the three observed epochs. A broad peak in each power spectrum near 0.017 day^{-1} corresponds to the large $\sim 60^d$ excursions in the data of Fig. 2. Significant power at odd harmonics is also present in two of the spectra. The width of these features is consistent with the 0.012 day^{-1} half-power width of the transform of the observing window function. The rapid increase below 0.01 day^{-1} is attributable entirely to the window function. The dashed line at 0.001 $(\text{counts s}^{-1})^2$ day^{-1} indicates the approximate 1 σ measurement noise level.

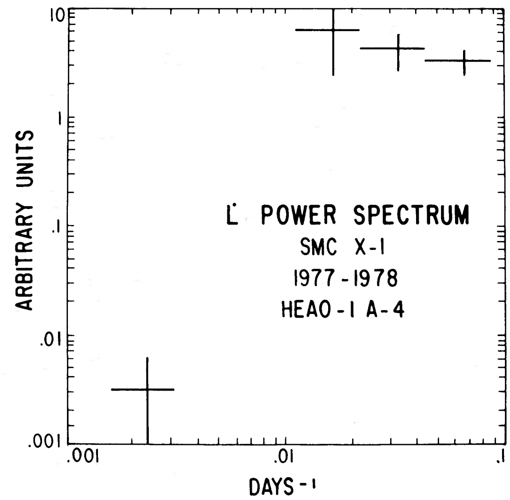

FIG. 4.—The power spectrum of the time rate of change of the SMC X-1 13–80 keV emission, as estimated using the method of Deeter and Boynton (1982). For periods between 10 and 100 days the spectral power density is nearly flat, or white, but the power at 450 days is less by a factor of 1000. The power spectrum of the observed flux itself therefore varies nearly as ν^{-2} and can be described as band limited (above 0.01 day^{-1}) red noise. The observed flux thus resembles a random walk variable. The error bars represent uncertainty from the intrinsic variance if the measured observable is truly a pure noise process. Measurement noise has been subtracted.

all peaks is consistent with the $\Delta\nu = 0.012$ day^{-1} half-power point resulting from the triangular window function of full width 104 days. The rapid rise of the power spectra below 0.01 day^{-1} is entirely attributable to the window function. Filtering of the fundamental at 0.017 day^{-1} and the third harmonic, effectively through least squares fitting and subtraction, leaves residuals whose power spectrum does not depart significantly from the measurement noise level indicated in Figure 3. Interestingly, the ratios of fitted amplitudes for the first, third, and fifth harmonics, in the two cases which can be determined, are reasonably close to those of the corresponding terms in the Fourier expansion of a square wave. Thus power series analysis supports the idea of a stable process with an (at least) approximately steady period and a tendency to stay in either a high or low state with relatively quick transitions between these states. Since a strict periodicity fits very poorly, the flux modulation process is at best quasiperiodic, with an unsteady frequency and/or phase jumps.

This quasi-periodic behavior can be demonstrated heuristically through least squares fitting of a constant + sinusoid model to the data from each epoch. The best fit reduced chi-squares, summarized in Table 1, ranged from 1.6 to 3.3, formally unacceptable, but nevertheless greatly reducing the variance from the null hypothesis of a constant observed flux. Moreover, the remaining excess variance can be reasonably accounted for in one (or both) of two ways. First, the arbitrary assumption of a sinusoidal modulation can be relaxed, and terms for the odd harmonics fitted, as suggested by the power spectra. This procedure yields similar squarish waveforms and reduced χ^2s near unity for the first two epochs, although not for the third. Secondly, a random (white) variability can be allowed in the model. Addition of an average 22% rms variability to the error bars of Figure 2 brings the reduced χ^2s near unity for the best sinusoidal fits in all three cases, and a fourth case treated below. Random variability of this magnitude is commonly observed in the emission from X-ray pulsars. Including this noise component the best fit periods, in days, are 63 ± 7, 68 ± 4, and 47 ± 3 for the three epochs, in order. Formally inconsistent, these results imply a process with a varying period rather than a steady period with phase jumps. The period instability is $\Delta P/P \approx 15\%$. Residuals to sinusoidal fits of 60^d period (Fig. 2, *lower panel*) have only short-term random structure remaining.

We have examined all published observations which include more than a single short look at SMC X-1, that is, all satellite observations. These all show strong variability, but not on time scales shorter than a few days. Schreier *et al.* (1972) observed with *Uhuru* in early 1971 a high state lasting at least 8 days, but in a number of shorter looks over 6 months observed the source variously in a high, low, or intermediate state. Tuohy and Rapley (1975) in 1974 with *Copernicus* observed a transition from low state to high extending over a few days, and in two other short observations spaced by months saw the source once low, once high. From *OSO 7* (Markert *et al.* 1979) SMC X-1 was seen about equally in high and low states in eight brief looks in 1971 and 1972. Recently a high and a low state separated by 30 days were seen with *Einstein* (Marshall, White, and Becker 1983). Extended observations of ~40 days were obtained by *OSO 7* (Ulmer *et al.* 1973) in 1972 and by *COS B* (Bonnet-Bidaud and van der Klis 1981) in 1976. *OSO 7* observed a slow decay and *COS B* a turn-on with a time scale of several days. While these data are too short to calculate a useful power spectrum, they are long enough to fit with the sinusoid model. Allowing for a ~20% random noise component, the fits are significant and satisfactory with periods near 60 days (Table 1). Periods near 40 days would have been more likely if the variability is a red noise process.

All historical observations thus show slow variability. Including those presented here, the five sufficiently extended observations show a dominant time scale which is not constant, but is always near 60 days. All data are thus consistent with the quasiperiodic modulation of X-ray intensity that is familiar from Her X-1, but are also not inconsistent with a previously unrecognized possibility, a band-limited red luminosity noise process. In the Conclusion we discuss implications of the two possible cases.

TABLE 1

SINUSOIDAL FITS TO SMC X-1 LIGHT CURVE

Experiment	Date (m/y)	No. of Data	Reduced χ^2, by Model: Constant	60 Day	Best Fit Period
OSO 7	4/72	10	11.5	1.2	1.2 (65 ± 4 days)
COS B	11/76	10	273	8.6	9.4 (58 ± 1 days)
HEAO 1	10/77	20	9.4	3.1	3.3 (59 ± 3 days)
	4/78	21	19.5	2.4	2.0 (68 ± 3 days)
	10/78	23	9.0	2.3	1.6 (49 ± 3 days)

b) Spectrum

The apparent tendency of SMC X-1 to be in one of two states, high or low, suggests the acquisition of average spectra separately for each state. Pulse-height data and exposure factors were accumulated from the entire data base represented in Figure 2, with the high/low criterion set at 1.0 counts s^{-1}. These pulse-height data were compared to model photon spectra, whose parameters were adjusted for best fit with the pulse-height data after computer simulation of the effects of the detector response properties. The inferred incident spectra are shown in Figure 5. The smooth high state spectrum is poorly fitted by a power law (reduced $\chi^2 = 2$) but is well fit (reduced $\chi^2 = 1$) by an optically thin thermal bremsstrahlung spectrum of temperature $kT = 17 \pm 1$ keV. Other spectral forms dominated by an exponential factor, such as a Wien spectrum at 5 keV, also fit acceptably. The low state spectrum is lower in intensity by a factor of from 4 to 7 (90% confidence limits). The best fit thin thermal temperature for the low state is 9.4 ± 3.8 keV, but a value as high as 17 keV is excluded only at the 90% confidence level. Thus, spectral softening with reduced intensity cannot be firmly claimed.

The high state data fit exponential spectra with no strong localized deviations which might be interpreted as cyclotron resonance features. For example, an absorption feature at 40 keV of 7.4 keV equivalent width, as observed in the Her X-1 spectrum (Gruber *et al.* 1980), is ruled out at 95% confidence.

Measurements of the spectrum of SMC X-1 in the 10–100 keV range have previously been reported from a rocket flight (Price *et al.* 1971), from *OSO 7* (Ulmer *et al.* 1973) and from *Ariel V* (Coe *et al.* 1981). Both the rocket and *Ariel V* observations were probably made during high states. The *OSO 7* observation spanned a high and a low state; rough correction upward by a factor of 2 brings it into agreement with these other two observed spectra. These three observations then lie a factor of 2–4 above our *HEAO 1* average high state spectrum, and thus the SMC X-1 high state luminosity may have been higher before 1975. These three early spectral observations,

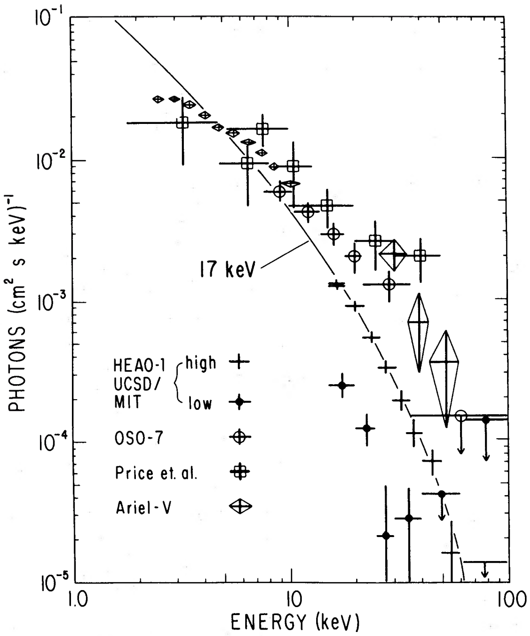

FIG. 5.—The average high state spectrum has an exponential shape. A 17 keV thin thermal bremsstrahlung spectrum is shown fitted. Although poorly measured, the low state spectrum appears softer but is marginally consistent with the high state temperature. Spectra measured in 1975 and earlier show a high state spectrum lying above the present results by a factor of 2–4, but a similar spectral shape is indicated.

taken as a group, indicate a steadily steepening spectrum which has essentially the same shape as our *HEAO 1* spectrum.

Below 12 keV an even flatter spectrum has been measured from *Ariel V* (Coe *et al.* 1981). The phase-averaged spectrum measured from the A-2 instrument on *HEAO 1* also shows a reasonably flat power-law shape from 2 to 15 keV (Marshall, White, and Becker 1983), absorption at lower energies, a gentle cutoff at 17 keV, and above this energy an exponential falloff with *e*-folding energy of ~ 10 keV. The same model fitted to our data yields an *e*-folding energy of 13.4 ± 1.0 keV, in essential agreement.

Thus the SMC X-1 phase-averaged spectrum has the characteristic shape of almost all X-ray pulsars (White, Swank, and Holt 1983). But by comparison with 4U 1626−67, A0115+63, Her X-1, and Cen X-3, which are also fast and bright, the SMC X-1 spectrum differs through a much less distinct cutoff and shares only with Cen X-3 an absence of prominent spectral features above the cutoff.

IV. DISCUSSION

While lacking strong features in the 15–50 keV range, the total (steady plus pulsed) emission from SMC X-1 displays a continuum spectrum with a dominant exponential form which implies a temperature of 17 keV for thin thermal bremsstrahlung emission or 5 keV if the other limit of a Wien spectrum is assumed. An exponential form has been used to fit the high-energy portion of the spectra of 14 X-ray pulsars (White, Swank, and Holt 1983), with *e*-folding energies ranging from 6 to 22 keV. This spectrum is thus characteristic of the class, the sole observed exception being the slow and faint pulsar X Per, which seems to have a power-law tail above 20 keV (Worrall *et al.* 1981). These observed characteristic energies are consistent with the early prediction by Davidson (1973) that the shocked region above the polar caps of the neutron star would have temperatures of the order of 10^8 K, or 10 keV, and emit with an approximately blackbody spectrum. Some recent detailed calculations of pulsar X-ray spectra (e.g., Pravdo and Bussard 1981; Nagel 1981; Mészáros and Bonnazola 1981) yield, in broad terms, such exponentially cutoff spectra. Nearly exponential spectra may also result from electron synchrotron radiation in the neutron star atmosphere. This mechanism has been suggested (Ramaty, Lingenfelter, and Bussard 1981; Liang 1982) for γ-ray burst sources. Spectral features characteristic of a strong $\sim 10^{13}$ gauss magnetic field may yet be found through sensitive examination of the SMC X-1 pulsations in this energy band. Indeed, only analysis of pulsations revealed the 20 keV absorption line in 4U 0115+63 (Wheaton *et al.* 1979).

Strong evidence for the existence of Roche-lobe overflow by the primary is based on the observed fast rotation (Savonije 1979), the elliptical optical light curve (van Paradijs and Zuiderwijk 1977), and the considerable excess of the X-ray luminosity over the maximum calculated for wind-driven accretion (Lamers, van den Heuvel, and Petterson 1976; Petterson 1978). Although an accretion disk about SMC X-1 is likely to form, direct evidence for its existence has been limited. Features in the optical binary light curve have been interpreted (van Paradijs and Zuiderwijk 1977) as due to light from an X-ray heated accretion disk. The possible 60 day quasi periodicity in the X-ray emission of SMC X-1 supports the presence of an accretion disk by analogy with the long-term cycles of Her X-1 and LMC X-4, whose variability arises through shadowing of the line of sight by a tilted (or twisted) precessing accretion disk. The observed SMC X-1 period fluctuations of $\Delta P/P \approx 15\%$ are a factor of 3 greater than the fluctuations of 5% observed for the 35 day cycle of Her X-1 (Boynton, Crosa, and Deeter 1980). The data of Lang *et al.* (1981) permit instability of the 30.5 day cycle of LMC X-4 of 5%–10%. The cause of the precession period instability in these sources is not known.

Assuming, on the other hand, that the observed slow variability is a red noise process, possibly a random walk variation, we can envision two simple scenarios. First, the X-ray variability could again be a shadowing effect: the disk, instead of rotating across the line of sight to the pulsar, would occult the line of sight by inflating its figure. This could occur in response to instabilities in the disk or to strong changes in the rate of mass transfer from the primary. Secondly, the X-ray luminosity itself could be the varying quantity, and this would imply a like variability of the matter input from the inner edge of the disk. The necessity for such processes to have a red power spectrum extending to very low frequencies is not obvious, but some redness, or power deficit at high frequency, seems plausible. If the rate of mass transfer from the primary has some average value with large but random (white) variations from this mean, then corresponding radial density variations will exist initially in the disk. Mixing in the disk will tend to smooth out short scale density variations, and this smoothing effect will increase as the material moves inward. This loss of structure at high spatial frequency is converted by means of a crossing time into a reddened power spectrum for observables, such as in the scenarios suggested above, whose variability results from the mass structure in the disk.

The latter scenario receives some support from our marginal observation of spectral softening during the low state. If, as in Davidson's (1973) treatment, the >10 keV spectrum is the Wien limit of a blackbody spectrum, then a softened spectrum is consistent with a reduced luminosity at the polar cap, in turn resulting from a reduced mass transfer rate to the polar cap. This scenario assumes that the mass flow does not significantly absorb the X-ray flux, as may happen in the case of Cen X-3 (Bonnet-Bidaud and van der Klis 1980). It has observable consequences: the spinup of SMC X-1 should correlate positively with its X-ray brightness, and the effects of X-ray heating in the optical light curve should vary.

Further study of this system is clearly warranted. If the intensity fluctuations can be established to be primarily random, then it may be possible to make inferences (albeit in a model dependent fashion) concerning the mass transfer process from the primary and also the mixing processes in the disk. If, on the other hand, a tilted accretion disk model can be confirmed, then the distribution function for the period fluctuations of this motion may be a valuable diagnostic of the structure and dynamics of the disk, as Boynton, Crosa, and Deeter (1980) have discussed. Coordinated optical and X-ray monitoring of the system would be most helpful in determining the nature of this slow variability.

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