THE ASTROPHYSICAL JOURNAL, 306:230–237, 1986 July 1


# DISCOVERY OF RAPID QUASI-PERIODIC OSCILLATIONS IN SCORPIUS X-1

J. MIDDLEDITCH[1] AND W. C. PRIEDHORSKY[1,2]

*Received 1985 October 18; accepted 1985 December 20*


## ABSTRACT

The X-ray flux from Sco X-1 can vary quasi-periodically. Fourier analysis of 5–20 keV X-ray data taken while the source was quiescent ($\sim$10% flaring) shows a power density peak at 6 Hz, with a 2 Hz FWHM, and which corresponds to 5% of the flux (rms amplitude). No 6 Hz peak was observed when the source was more active (>25% flaring), but rather a broad distribution of excess power up to 25 Hz was seen. The mode of variability switched from one to the other within 500 s, settling into the 6 Hz mode about 1 hr into quiescence. A different mode of quasi-periodic oscillation with power in a broad band between 14 and 24 Hz, corresponding to a 6% rms amplitude, occurred for short periods during the active phase whenever the flux reached the quiescent level. The frequency of the 6 Hz peak varies by $\sim$10% in anticorrelation with $\sim$20% intensity variations, contrary to what would be expected from the simplest form of the beat-frequency model recently published by Lamb and colleagues. No coherent X-ray pulsations were detected. We are sensitive to pulsations up to 250 Hz; upper limits to the pulsed fraction range from 0.1% to 0.8%, depending on the frequency and nature of the pulsations.


*Subject headings:* pulsars – X-rays: binaries

## I. INTRODUCTION

Scorpius X-1 is easy to observe, but more difficult to unravel. Extremely bright in X-rays, it was the first nonsolar X-ray source discovered (by rocket experiment; Giacconi *et al.* 1962). Later, it was optically identified with a bright (12th mag) blue emission-line object (Sandage *et al.* 1966). A paucity of regular phenomena—e.g., the lack of pulsations or orbital luminosity variations—have made analysis of this object difficult. Its inclusion in the standard neutron star binary model has been mostly by association with other sources of high X-ray luminosity which show X-ray pulsations, orbital luminosity variations, or bursts. Even its distance is poorly known. If as close as 300 pc, as suggested by early workers (see Hiltner and Mook 1970), it is a "relatively" low-luminosity object of $5 \times 10^{36}$ ergs s$^{-1}$; if at 1–2 kpc (Crampton *et al.* 1976), it joins a more select group: the dozen or so Galactic bulge sources with luminosities near the Eddington limit (the GX objects).

Optical data reveal a $0^{d}.787$ orbital period, manifested by a weak (0.25 mag) brightness variation (Gottlieb, Wright, and Liller 1975), and emission-line velocity excursions of $\pm 60$ km s$^{-1}$ (Cowley and Crampton 1975). Lewin, Clark, and Smith (1968) discovered short-term flaring in Sco X-1, the first such activity observed in any cosmic X-ray source. Long-term monitoring showed the X-ray source to have quiescent and active (flaring by factors of 2–3) states. Sco X-1 persists in a given state for a few hours to a few days (Bradt *et al.* 1975; Canizares *et al.* 1975). Rapid, correlated flaring in the X-ray and optical light suggests that most of the optical light comes from reprocessing in the accretion disk, rather than the companion star (Petro *et al.* 1981). Any X-ray modulation at the orbital period is less than 1% (Holt *et al.* 1976); this and the weak photometric and radial velocity modulations suggest that we see the system nearly pole-on, at an inclination of about 30° (Crampton *et al.* 1976).

The spectrum of Sco X-1 has two components: the hard component is believed to come from a neutron star surface (Mitsuda *et al.* 1985; White, Peacock, and Taylor 1985; however, see Lewin and van Paradijs 1985). Accretion torques will force the neutron star to rotate; pulsations at some amplitude might express that rotation. One must search down to the millisecond regime, because the neutron star in Sco X-1 is probably rapidly spinning (Alpar *et al.* 1982). No pulsations have been found to date. Boldt, Holt, and Serlemitsos (1971), examining 0.75–1500 Hz frequencies for some 340,000 total counts, found no coherent X-ray pulsations at levels of a few percent. Pulsations were likewise not seen by Friedman *et al.* (1969) in the 0.25–14 Hz range (1–12 keV); they recorded only 64,000 total events and were therefore sensitive to sinusoidal modulations above the 3% level. These analyses were based on short intervals of data—about 100 s. When longer data spans are used, as required to look more sensitively, Doppler variations of pulse frequency become important. The 60 km s$^{-1}$ emission-line variation implies a line-of-sight displacement of the emission-line source, and probably the X-ray source, of $\pm 2$ lt-sec. A 100 Hz pulsation would drift in phase by 400 cycles over an orbit, thus smearing the power in the pulsation peak over many Fourier frequencies, if the data were to be analyzed with no compensation for the orbital motion.

We observed Sco X-1 with the *EXOSAT* ME detector to search more sensitively for coherent pulsations. Instead, we found a strong quasi-periodic oscillation (QPO) at about 6 Hz (Middleditch and Priedhorsky 1985). Similar effects have been discovered in the bright bulge source GX 5−1 (van der Klis *et al.* 1985*a*, *b*) and subsequently in Cyg X-2 (Hasinger *et al.* 1985*a*, *b*; Norris and Wood 1985), GX 349+2 (Lewin *et al.* 1985), the Rapid Burster MXB 1730−335[3] (Stella *et al.* 1985), and GX 17+2 (Stella, Parmar, and White 1985). Sources which display QPO also tend to have red noise, i.e. excess Fourier power increasing toward the lowest frequencies (van der Klis *et al.* 1985*b*, *c*).

Analysis of archival *EXOSAT* Sco X-1 data confirms our detection of quasi-periodic oscillations (van der Klis *et al.*

[1] Earth and Space Sciences Division, Los Alamos National Laboratory.
[2] Visiting Scientist, Max Planck Institute for Extraterrestrial Physics.

[3] A much narrower 2 Hz quasi-periodic oscillation was observed by *Hakucho* in 1979 August (Tawara *et al.* 1982).

1985c). Also, in a 1970 rocket observation of Sco X-1, Angel, Kestenbaum, and Novick (1971) almost certainly observed the effect of QPO in $\sim 1.6 \times 10^6$ total counts. They reported short-lived narrow oscillations, which occurred at multiple frequencies, tending to recur at the same frequency in successive 20 s Fourier spectra. They did not show a smoothed Fourier spectrum. However, most of their persistent Fourier maxima were between 7 and 8 Hz, suggesting that they, too, were seeing a broad band of excess oscillatory power.

## II. OBSERVATIONS AND ANALYSIS

The *EXOSAT* observatory offers large area, high time resolution, and long uninterrupted pointings. We used it to search once again for pulsations from Sco X-1. All eight large area (ME) detectors pointed at Sco X-1 from 3.6 to 13.2 hr UT 1985 February 25 (the date quoted in *IAU Circular* 4060 was a typographical error; Middleditch and Priedhorsky 1985). Only the xenon detectors were on, giving a total count rate of 2800–10,000 $s^{-1}$. The front argon detectors were off to avoid damage from excessive count rate. We wished to maximize counts in the higher energy xenon band, where the harder (neutron star?) spectral component was strongest. The response band was 5–50 keV; assuming a typical spectrum for Sco X-1, most of the detected events were between 6 and 20 keV. Counts were summed into consecutive 2 ms bins. For Sco X-1 observations, background is relatively insignificant—below, we assume $\sim 20\%$ of the source strength, or 600 $s^{-1}$, based on past *EXOSAT* performance. No spectral data were telemetered.

### a) *The 6 Hz and Other Modes of Oscillation*

The 9 hr of time series data ($\sim 10^8$ source counts) were Fourier analyzed to search for coherent periodicities. An obvious 6 Hz quasi periodicity surprised us in the very first transform calculated (Fig. 1, *upper*). The 6 Hz feature was

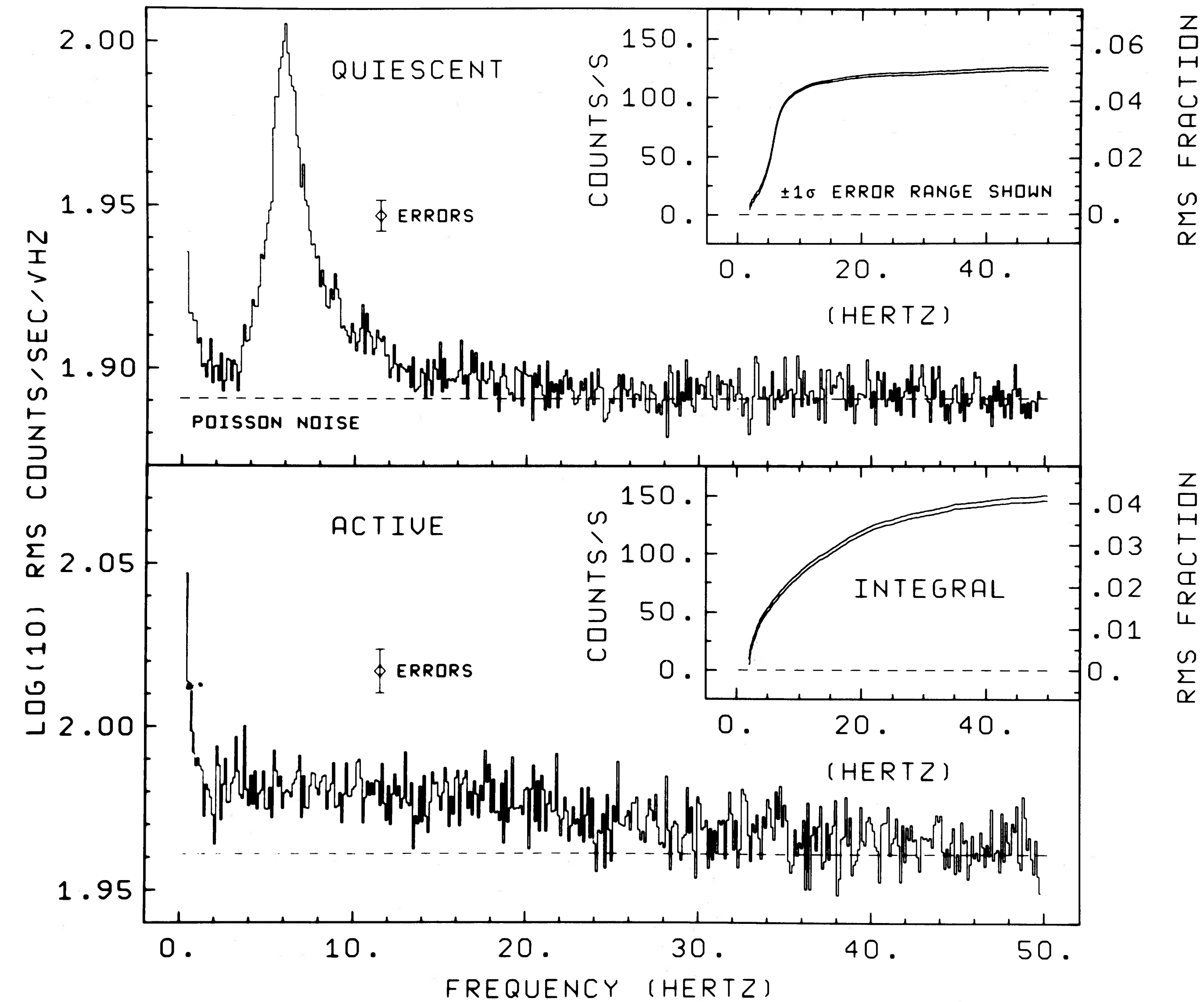


FIG. 1.—Power spectra of Sco X-1 time series data from the *EXOSAT* ME detectors. Fig. 1 (*lower*) displays the power spectrum of an 8389 s interval during the "active" or flaring state of Sco X-1. Each frequency bin displayed is the average of 2048 individual Fourier resolution elements. Fig. 1 (*upper*) displays the power spectrum of a 16,777 s interval during the "quiescent" low or nonflaring state of Sco X-1. Each frequency bin displayed is the average of 4096 individual Fourier resolution elements. Fig. 1 (*insets*) give the integrals of the respective power spectra (minus counting statistics power) above 1.8 Hz.

present through the last half of the data, when the X-ray flux from Sco X-1 was relatively low and quiescent ($\sim 10\%$ flaring, 2400 counts $s^{-1}$), while only a broad excess of power up to 25 Hz was present in the first part of the data (3.6–6.0 UT, 3600 counts $s^{-1}$—Fig. 1, *lower*), when Sco X-1 was flaring by more than 25%. We have smoothed the power spectra by summing many adjacent Fourier elements to reduce continuum noise. Except for the very lowest frequencies, this is equivalent to summing power spectra from many successive time intervals, per van der Klis *et al.* (1985*b*). Poisson statistics alone give frequency-independent noise, indicated by the dashed horizontal lines in Figure 1. All the phenomena we report are significant excesses over the Poisson background.

The 6 Hz feature is asymmetric, with a broad high-frequency tail extending past 12 Hz. Its full width at half-maximum power (FWHM) is 2 Hz. The power in the 6 Hz feature, integrated above 1.8 Hz, corresponds to a 5% rms amplitude variation (Fig. 1, *upper insert*, shows the integral power distribution).

The active state excess power, integrated from 1.8 to 25 Hz, corresponds to 3% of the active flux (rms amplitude); this integrated excess power rises to 4% when integrated to 50 Hz (see Fig. 1, *lower insert*). Since no correction has been applied for the instrumental dead time, these numbers are underestimates of the nonstatistical power. We can observe the effects of dead time in the deficit of high-frequency (126–250 Hz) power below the expected Poisson level at the highest count rates; the effect is consistent with the known dead time in the fast data mode (HTR3) of 1.91 $\mu$s. Our dead-time fraction was thus only 0.5%–1.9%.

The oscillations change mode within 500 s (Fig. 3). This occurs about one hour following the onset of X-ray quiescence (between the vertical dashed lines of Figure 2; this time period is shown in detail in the inset). However, during the entire interval prior to 8.2 hr UT, the 6 Hz feature never appears, to a limit of 1% (rms) of the mean flux. In particular, three intervals at the minima between active state flares show no sign of the 6 Hz feature, although the flux dropped to the quiescent level. These three intervals *do* show a striking excess of power in the 14–24 Hz range (Fig. 4*a*; Fig. 4*b* [Pl. 13]) that corresponds to a 6% rms modulation of the quiescent flux.

The 6 Hz feature is related in amplitude and frequency to the flux. The centroid frequency was measured for eight consecutive 2097 s sections from the last half of the data (Table 1) by fitting to the template profile of Figure 1 (*upper*). Figure 5 shows that the centroid frequencies, $f_c$, are well fitted by the relation $f_c \approx I^{(-0.52\pm0.06)}$. This correlation is in the opposite sense to that observed by van der Klis *et al.* (1985*b*) for GX

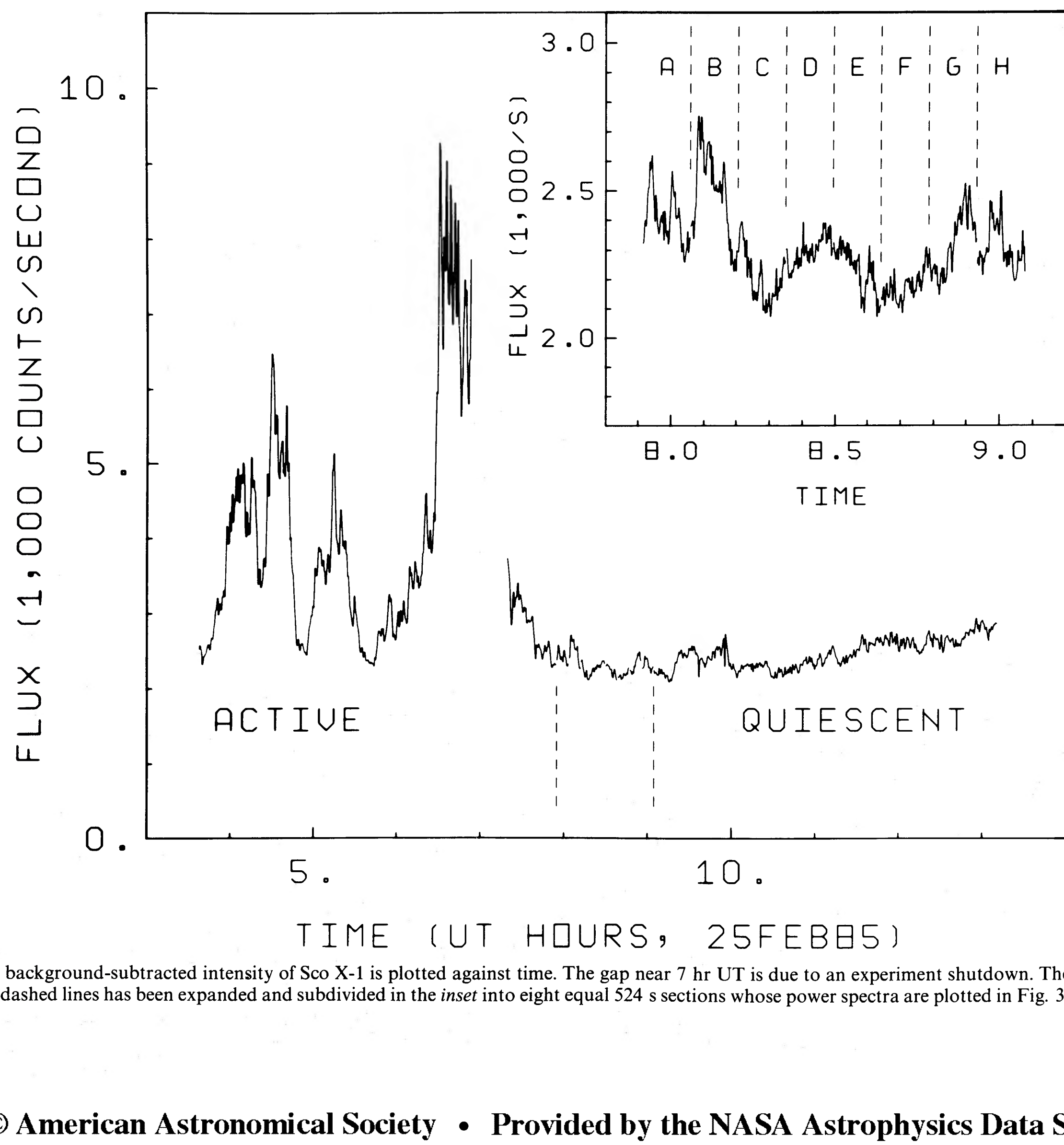


FIG. 2.—The background-subtracted intensity of Sco X-1 is plotted against time. The gap near 7 hr UT is due to an experiment shutdown. The interval between the two vertical dashed lines has been expanded and subdivided in the *inset* into eight equal 524 s sections whose power spectra are plotted in Fig. 3.

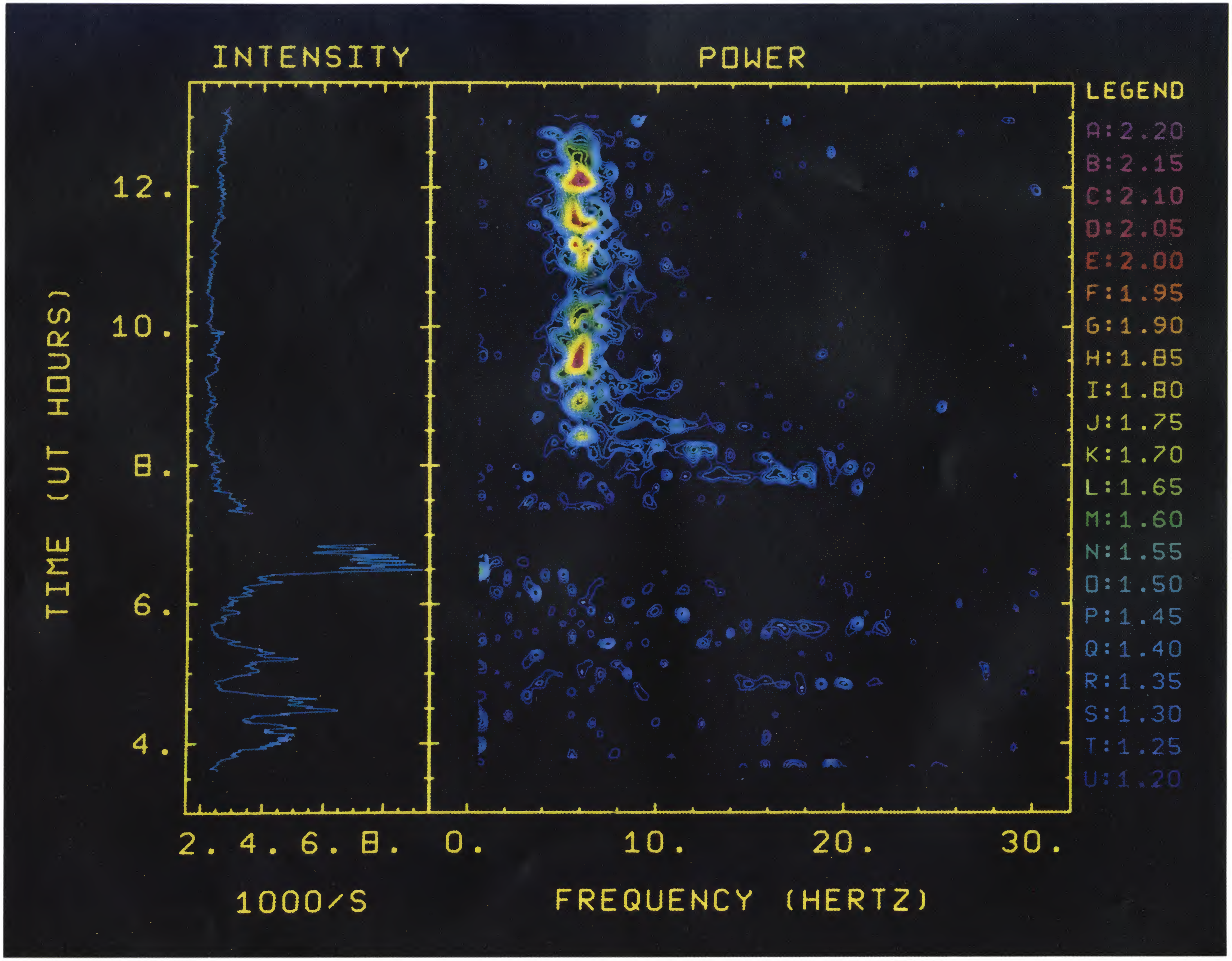


FIG. 4*b*.—A color-coded contour plot of all 524 s Sco X-1 power spectra plotted vs. time (vertical), with the source intensity plotted at the left (see Fig. 4*a*).

MIDDLEDITCH AND PRIEDHORSKY (*see* page 232)

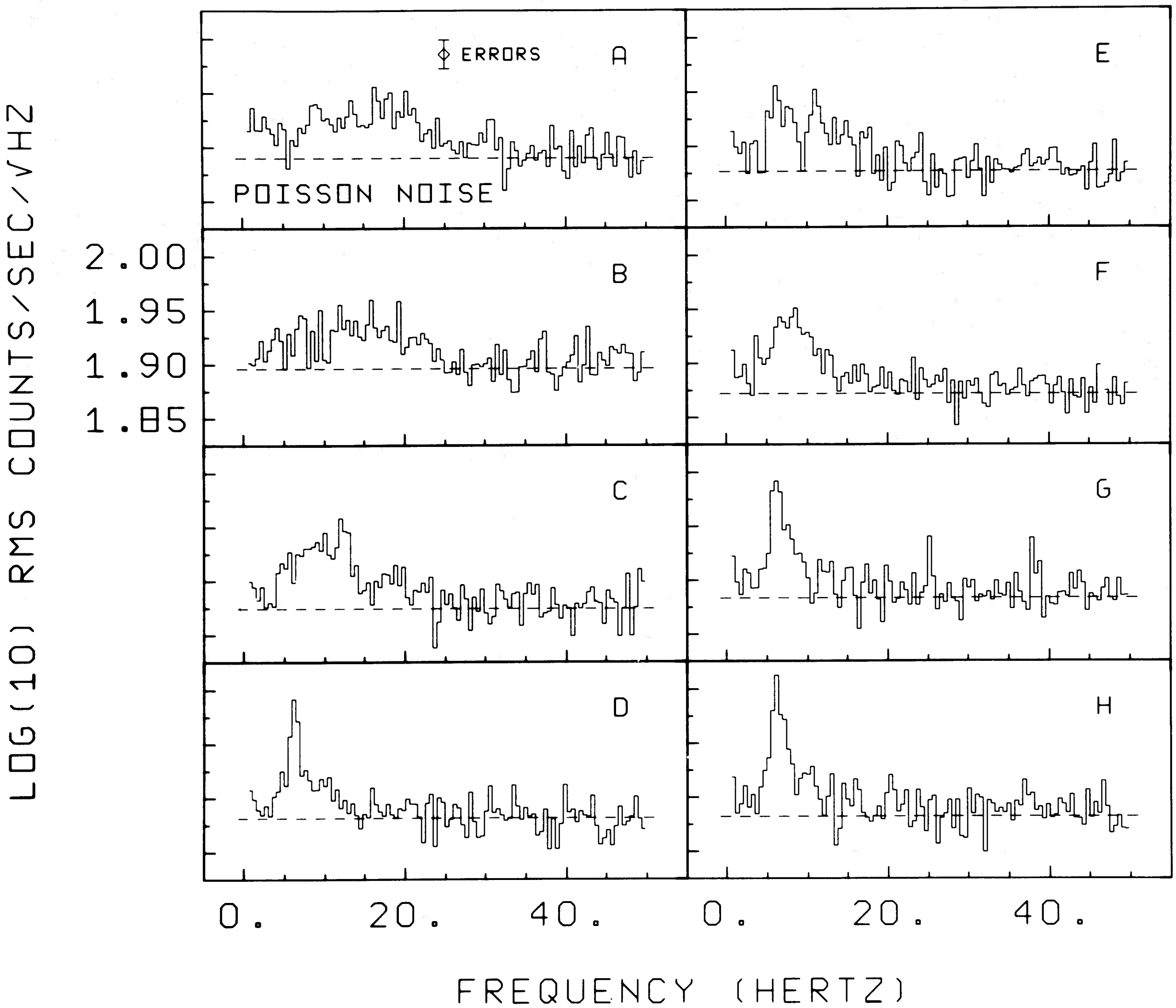


FIG. 3.—The power spectra of the eight contiguous 524 s data intervals of the inset of Fig. 2. The alphabetic labels A–H indicate the progression in time.

5−1. The relation represents more than a single monotonic trend in flux and frequency. Decreases in frequency are associated with both the small flare centered on 9.7 hr UT, and the general increase in flux toward the end of the observation. The amplitude $A$ (rms) of the 6 Hz feature follows a power law $A \approx I^{(2.3 \pm 0.2)}$ for intensities below 2550 counts s$^{-1}$. The amplitude is a maximum at that intensity and falls for higher ones.

TABLE 1

SCORPIUS X-1 6 HZ AMPLITUDES AND FREQUENCIES VERSUS MEAN FLUX

| | PARAMETER | | | |
|---|---|---|---|---|
| INTERVAL | Time (1985 Feb 25 UT) | Mean Flux (s$^{-1}$) | Amplitude (4.9–7.1 Hz) s$^{-1}$ | Frequency (Hz) |
| 1............ | 8.20–8.79 | 2225 | 62.2(1.9) | 6.42(13) |
| 2............ | 8.79–9.37 | 2256 | 76.2(1.8) | 6.21(08) |
| 3............ | 9.37–9.95 | 2466 | 89.8(1.8) | 5.88(04) |
| 4............ | 9.95–10.53 | 2281 | 80.1(1.8) | 6.15(07) |
| 5............ | 10.53–11.12 | 2291 | 69.4(1.9) | 6.21(07) |
| 6............ | 11.12–11.70 | 2472 | 92.8(1.8) | 5.92(04) |
| 7............ | 11.70–12.28 | 2608 | 96.1(1.8) | 5.74(04) |
| 8............ | 12.28–12.87 | 2632 | 81.2(1.9) | 5.81(06) |

This is confirmed by finer time resolution spectra (524 s). Of course, active-state interflare intervals, which do not show the 6 Hz peak although in the right range of flux, do not fit these relationships. No correlation was found between the width of the 6 Hz feature and any other physical parameter.

The 6 Hz feature vanishes for the last 1000 s of the data set, which ends at 13.2 hr UT (Fig. 4*a*; Fig. 4*b*). The excess Fourier power between 4.9 and 7.3 Hz has a mean rms amplitude of 127 counts s$^{-1}$, but falls to 83 counts s$^{-1}$ during the last 1049 s—a value only slightly greater than the active phase mean amplitude of 67 counts s$^{-1}$ (which represents the 4.9–7.3 Hz fraction of the broad 25 Hz excess). Thus the 6 Hz feature persists from 8.4 to 12.9 hr UT, or 4.5 hr. We do not know whether it comes back on. We cannot state whether 6 Hz QPO is typical of the quiescent state, or only appears for a while after *transition* to quiescence.

### *b*) *Red Noise*

Excess power at low frequencies is evident in Figure 1, as one would expect from the noisy looking time history (Fig. 2). The power at frequencies in the $10^{-4}$ to $10^{-3}$ Hz band corresponds to the large-scale flaring. Integrated over the band 0.0025–0.122 Hz, the red noise totals 2.7% (rms amplitude) of

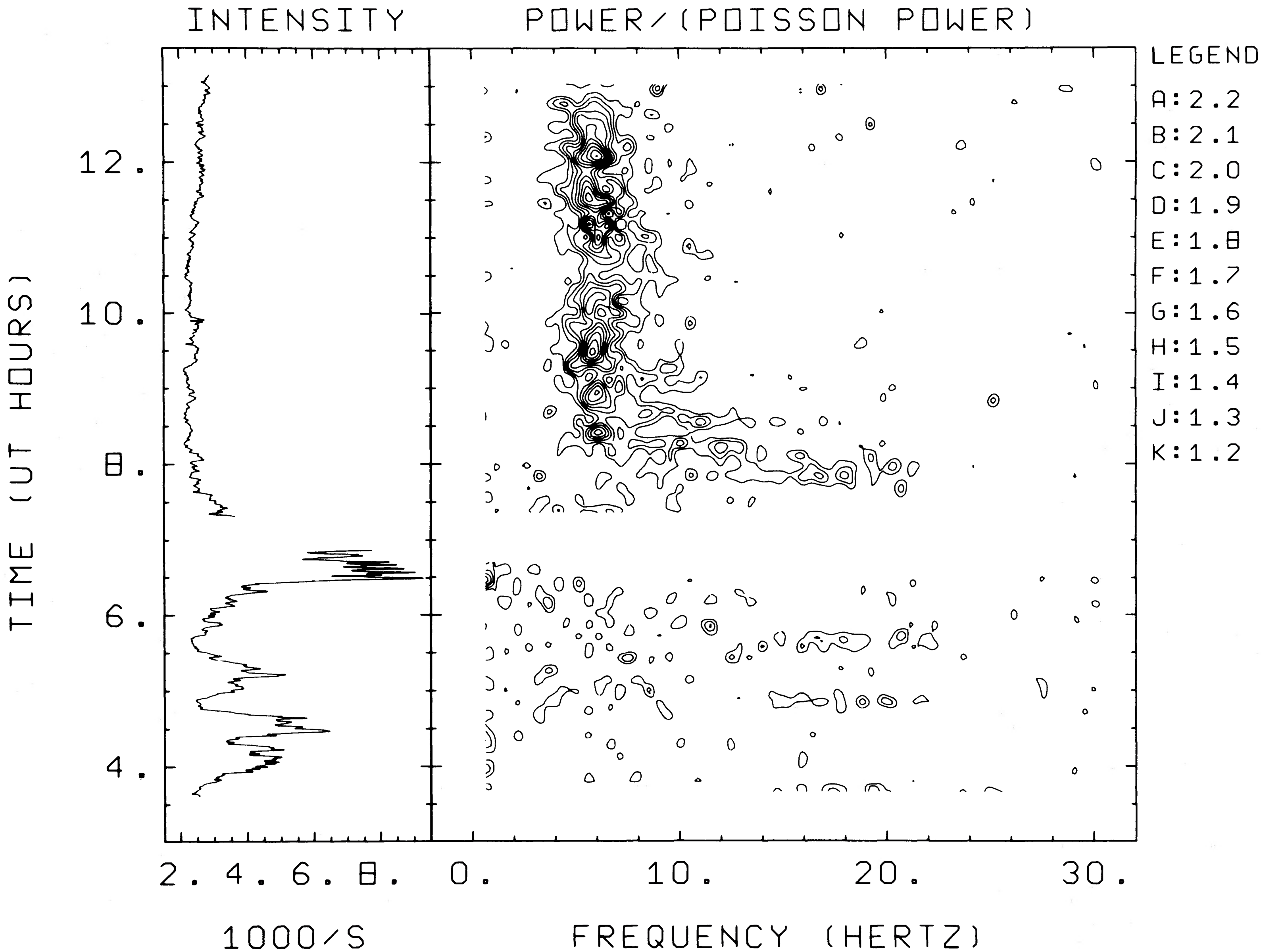


FIG. 4*a*.—A contour plot of all 524 s Sco X-1 power spectra plotted vs. time (vertical), with the source intensity plotted at the left. The numerical values of the contours correspond to the ratio of actual power to the power level due to counting statistics. Each point represents the sum of 256 Fourier elements and thus will vary by $\pm 6.25\%$ due to statistical fluctuations. The gap near 7 h UT is due to an experiment shutdown. The prominant vertically aligned peaks in the upper left are due to the 6 Hz oscillation mode, while the horizontally elongated regions of excess power coinciding with the interflare intensity minima near 3.6, 4.9, 5.6, and 8 hr UT are caused by the 14–24 Hz mode. See also the color plate, Fig. 4*b*.

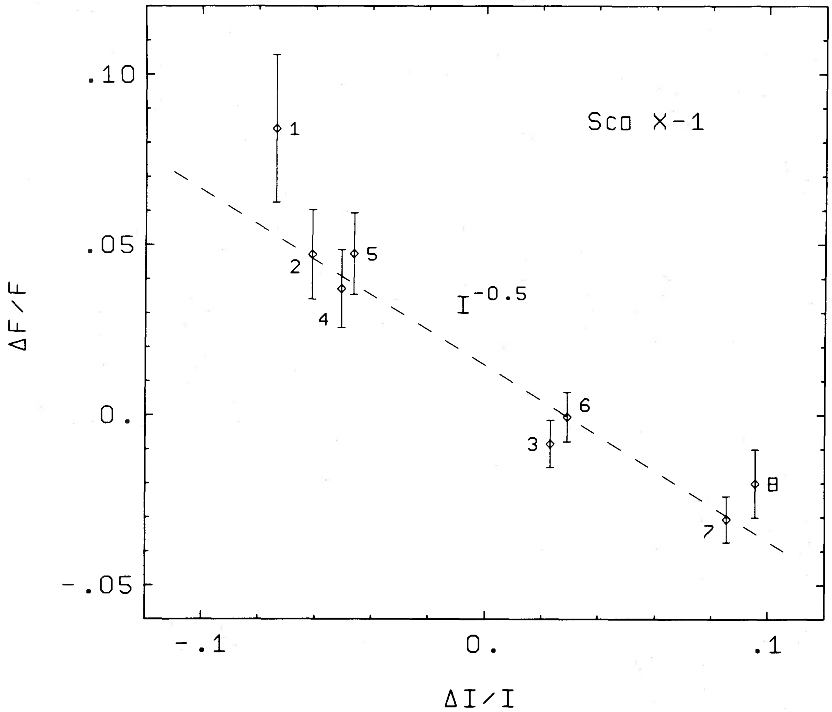


FIG. 5.—The centroid frequency of the 6 Hz QPO of Sco X-1 plotted against the X-ray flux for 2097 s intervals of data. The dashed line represents a statistically good linear fit to the points which is also consistent with $f_c \approx I^{-0.52\pm0.06}$ power-law relation.

the mean flux, for the quiescent Fourier transform of Figure 1 (*upper*). The corresponding value for Figure 1 (*lower*) is 5.5% of the mean active flux (3.6–6.0 UT), reflecting the flaring activity. The intensity of the low frequency noise is maximum during the largest flare (just before 7 hr UT), as might be expected. As van der Klis *et al.* (1985*c*) reported, red noise in Sco X-1 is strongest when the source is bright and active, that is, when the quasi-periodic oscillations are absent.

### *c) The Search for Coherent Periodicities*

We have searched for coherent periodicities up to 250 Hz, adjusting the data for orbital Doppler effects from all circular orbits with $v_x \sin i \leq 100$ km s$^{-1}$. The apparent line-of-sight velocity of Sco X-1 is probably comfortably less than 100 km s$^{-1}$, for two reasons: first, the radial velocity of the optical emission-line source, inferred by Crampton *et al.* (1976) to be the velocity of the X-ray object, is $\pm 60$ km s$^{-1}$. Second, given a 0$^d$787 orbital period, a neutron star of about 1.4 $M_\odot$, and inclination $i$ about 30°, $v_x \sin i$ will be less than 100 km s$^{-1}$ for all companion masses less than 2 $M_\odot$. A more massive companion would be detected optically, which is not the case.

The time series data were divided into 16 consecutive subseries of 2152 s each. Since the entire 34,439 s of data covered just over half an orbital cycle, at least one of the 16 was near orbital phase 0.25 or 0.75, i.e., quadrature, where the rate of change of an apparent pulsar frequency, $f' \equiv \partial f/\partial t$, goes to zero. The 16 subseries were then rebinned and transformed as described in Middleditch and Kristian (1984). We used trial frequency drifts $f'/f$ of 0 and $2.04 \times 10^{-9}$ s$^{-1}$ (also $-2.04 \times 10^{-9}$ s$^{-1}$ for the first and last intervals). These were enough to match the small correction required for the interval nearest quadrature. Less than 9% of the Fourier power in any steady pulsation is lost due to $f'$ mismatch, and less than 15% is lost due to mismatch of $\partial^2 f/\partial t^2$ (for which we did not compensate) for the best matched correction. This holds for steady pulsations with frequencies up to 250 Hz and $v_x \sin i$ up to 100 km s$^{-1}$. We are thus sensitive to weak fast pulsations only during the interval near quadrature. Should the source pulse only sporadically, like LMC X-4, for example (Kelley *et al.* 1983; Pietsch *et al.* 1985), we could have missed the pulsations. The moment of quadrature is unfortunately only tentatively known (Crampton *et al.* 1976).

We find no coherent pulsations, to a limit of 0.8% of the quiescent flux ($f \leq 250$ Hz), with a better limit of 0.5% for frequencies less than 125 Hz.[4] Correcting only for $v_x \sin i \leq 50$ km s$^{-1}$ in 8610 s data segments, we can limit the pulsed fraction for frequencies less than 7.8 Hz to 0.25% of the quiescent flux. However, at frequencies near 6 Hz, the excess power in the QPO reduces our sensitivity to 0.35%.

We made two, more sensitive searches for coherent periodicities by assuming that the optical ephemeris of Crampton *et al.* (1976), as confirmed and slightly refined by Lasala and Thorstensen (1986), was applicable to the neutron star orbit. Their quadrature occurred ~2200 s before the end of our observation. The 4304 s data section centered on this quadrature was analyzed for frequencies up to 250 Hz, correcting for orbital velocities in the range 52–72 km s$^{-1}$. The upper limit pulsed fractions were 0.55% of the quiescent flux for frequencies up to 250 Hz and 0.35% for frequencies below 125 Hz. In addition, we searched for slower pulsations by adjusting the entire observation for orbits in the same velocity

[4] The limits quoted correspond to the level of pulsation which would have a 90% probability of being measured with more Fourier power than the highest peak which actually occurs in the power spectrum. The pulsed fractions quoted for *coherent* pulsations are given as $b/a$, where the intensity can be written as $a + b \cos \omega t$. Note that rms relative amplitudes are quoted above for QPO, and these correspond to $1/2^{1/2}$ of the pulsed fractions quoted for coherent pulsations.

range. We rule out pulsations of amplitude greater than 0.2% of the quiescent flux for frequencies up to 8 Hz, and pulsations stronger than 0.1% for frequencies between 0.5 and 4.0 Hz.

A candidate regular periodicity, with apparent frequency 220.73383(2) Hz, was seen in one 4194 s segment of data (4.8–6.0 hr UT). The peak is statistically significant, standing at least 23 times above the local mean power and thus representing 0.5% of the quiescent flux level. The chance of any peak that large, considering all the power spectra scanned, is less than $10^{-3}$. Curiously, there is no evidence for Doppler-induced frequency drift. The lack of any frequency change during the 4194 s would require that the interval center was within 200 s of orbital quadrature, even for a low-amplitude orbit of $v_s \sin i = 50$ km s$^{-1}$. The ephemeris of Crampton *et al.* (1976) places quadrature 0.11 cycle (7500 s) before the center of our candidate detection. The observation could not have been at quadrature if, as they argue, the X-ray source moves with the optical lines. Moreover, no evidence of the pulsations was found in the neighboring 4194 s intervals, correcting for all circular orbits with $v_x \sin i \leq 200$ km s$^{-1}$. Thus we tentatively reject the $\sim 220$ Hz peak as indicating the rotation period of Sco X-1.

## III. DISCUSSION

Excess Fourier power in the range 2–25 Hz was *always* present during our observation always with approximately the same rms amplitude of 5%–6% of the quiescent flux. At its lowest flux levels, Sco X-1 oscillates in either a narrow 6 Hz or a broad 14–24 Hz band. The 6 Hz feature seems to require an extended (about 1 hr) quiescent interval to develop. Detectable red noise is comparable in rms amplitude with the QPO feature. When the 6 Hz feature was well developed, its frequency was anticorrelated with intensity. There is no contradiction with the behavior reported by van der Klis *et al.* (1985*c*), i.e., erratic frequency changes, because they did not see Sco X-1 in as quiescent a state as we did, nor did their QPO frequency ever settle in the stable 6 Hz mode. Compared to GX 5−1 and Cyg X-2, Sco X-1 oscillates at lower frequencies and has the opposite correlation with intensity. However, our bandpass for Sco X-1 is very hard and may not vary as the bolometric luminosity. There is not a unique relation between intensity and QPO frequency behavior, as was found for GX 5−1 by van der Klis *et al.* (1985*b*).

All other QPO X-ray sources, with the exception of the peculiar Rapid Burster, are very luminous, with $L_x$ about $10^{38}$ ergs s$^{-1}$. Thus, the QPO behavior of Sco X-1 suggests that it is a member of the same class and is also very luminous, placing it at a distance of 1–2 kpc. Other arguments—the lack of X-ray bursts as seen in low-luminosity sources, and spectral similarities with bright bulge sources—suggest the same conclusion (N. E. White, private communication). It has been argued that the only adequate fuel supply for the bright bulge sources is the nuclear evolution of the companion (Webbink, Rappaport, and Savonije 1983). In Sco X-1, the orbital period is direct evidence for an evolved companion, further suggesting the similarity of Sco X-1 and the bright bulge sources (Lewin and van Paradijs 1985).

Beat-frequency models of X-ray source QPO have received the most attention so far (Alpar and Shaham 1985; Lamb *et al.* 1985). The pulse frequency, $f_p$, is explained as the difference $f_K - f_S$, where $f_S$ is the spin frequency of the neutron star, and $f_K$ is the Keplerian frequency of the structured inner edge of an accretion disk. Other scenarios for QPO are discussed by van der Klis *et al.* (1985*b*); in particular, they call attention to some similarities between QPO in X-ray sources and cataclysmic variables. We would also note the phenomenological similarity between the $\sim 2$ s "noisar" variability found in the AM Her-type binaries, AN UMa and E1405−451 (Middleditch 1982) but caution that the physical conditions near the magnetic white dwarf members of such binaries differ from the conditions near the neutron star members of the galactic bulge sources by many orders of magnitude.

The QPO frequency-intensity relationship for GX 5−1, $f \approx I^{+2.3}$, implies in the beat frequency model a dipole field $\sim 10^{10}$ G and neutron star spin rate $\sim 100$ Hz. This model is obviously inconsistent with the idea that these sources have no significant magnetic field. As modeled, QPO frequency increases with intensity because, as a higher accretion rate squeezes the magnetosphere, the inner disk moves farther in from the co-rotation radius, and the difference $f_K - f_S$ increases. Thus, $f \approx I^\alpha$, where the power-law scales roughly as:

$$\alpha = \frac{3}{7\beta}\left(\frac{3}{\beta - \omega_S}\right),$$

where the fastness parameter $\omega_S = f_S/f_K$ (Lamb *et al.* 1985). The relation between mass-accretion rate through the boundary layer and detected intensity is expressed by $\beta$, where $I \approx M^\beta$. In the simple case where the X-ray count rate is proportional to bolometric flux, and all mass passing through the boundary layer is accreted, $\beta$ is equal to 1. For Sco X-1, with $\alpha \approx -0.5$, we face a dilemma. Either $\omega_S$ is greater than 1, or $\beta$ is negative. The inner edge of the accretion disk lies outside the corotational radius if $\omega_S$ is greater than 1. In that case, matter entrained by the magnetic field would be pushed out, not in; it is not clear how accretion could proceed against centrifugal force (Ghosh and Lamb 1979). On the other hand, it might seem perverse for Sco X-1 to look brighter when it accretes less ($\beta$ negative), but Lamb *et al.* (1985) have made several specific suggestions as to how this might happen. Our view of Sco X-1 might be dominated by geometric effects. Several optical depths of scattering are needed for the observed Comptonized spectrum (White, Peacock, and Taylor 1985); as the mass flux decreases, the scattering cloud might thin, and the emitted flux increase in preferred directions such as toward the pole. The Lamb *et al.* (1985) scenario of a filled ($\tau$ of a few) polar funnel through which we see the neutron star could yield our observed (inverse) luminosity-frequency relationship.

In the beat frequency model, at least modest pulsations at the rotation frequency should be expected from the spinning magnetosphere. We find no evidence for them, either at high frequencies or in the vicinity of 6 Hz. This absence is puzzling: in this model, the field must be misaligned to modulate the accretion rate, thus creating an asymmetry that should give pulses. Even if the neutron star is surrounded by a scattering, isotropizing cloud, intrinsic beaming should not be completely destroyed. Simple Monte Carlo calculations show that even a cloud of $\tau = 10$, surrounding a monodirectional point source, leaves a front-back output asymmetry of 15%. Several effects may conspire to reduce the pulsed fraction: intrinsically weak beaming, because of the large polar cap associated with a small magnetospheric radius; some scattering; gravitational lensing near the neutron star (Pechenick, Ftaclas, and Cohen 1983; Ftaclas, Kearney, and Pechenick 1986); and our near pole-on view of the system. These suggest that pulsations should be present at some level. More sensitive searches may yet find the rotating neutron star in Sco X-1.

This work was performed under the auspices of the Department of Energy, with additional support from NASA grant H83899B. One of us (W. P.) would like to thank the Max Planck Institute of Extraterrestrial Physics for their hospitality during the final stage of preparation of this paper. We thank the *EXOSAT* control team for support during the observation. For helpful discussions and a critical review of the manuscript, we thank France Córdova, Fred Lamb, John Laros, Walter Lewin, and Hakki Ögelman. Discussions at the 1985 Los Alamos Workshop on Astrophysics of Time Variability in X-Ray and Gamma-Ray Sources were important in guiding our interpretation.

## REFERENCES

Alpar, M. A., Chang, A. F., Ruderman, M. A., and Shaham, J. 1982, *Nature*, **300**, 728.
Alpar, M. A., and Shaham, J. 1985, *IAU Circ.* 4046.
Angel, J. R. P., Kestenbaum, H., and Novick, R. 1971, *Ap. J.* (*Letters*), **169**, L57.
Boldt, E. A., Holt, S. S., and Serlemitsos, P. J. 1971, *Ap. J.* (*Letters*), **164**, L9.
Bradt, H. V. D., *et al.* 1975, *Ap. J.*, **197**, 443.
Canizares, C. R., *et al.* 1975, *Ap. J.*, **197**, 457.
Cowley, A. P., and Crampton, D. 1975, *Ap. J.* (*Letters*), **201**, L65.
Crampton, D., Cowley, A. P., Hutchings, J. B., and Kaat, C. 1976, *Ap. J.*, **207**, 907.
Friedman, H., Fritz, G., Henry, R. C., Hollinger, J. P., Meekings, J. F., and Sadeh, D. 1969, *Nature*, **221**, 345.
Ftaclas, C., Kearney, M. W., and Pechenick, K. R. 1986, *Ap. J.*, **300**, 203.
Ghosh, P., and Lamb, F. K. 1979, *Ap. J.*, **232**, 259.
Giacconi, R., Gursky, H., Paolini, F. R., and Rossi, B. 1962, *Phys. Rev Letters*, **9**, 439.
Gottlieb, E. W., Wright, E. L., and Liller, W. 1975, *Ap. J.* (*Letters*), **195**, L33.
Hasinger, G., Langmeier, A., Sztajno, M., Trumper, J., Lewin, W. H. G., and White, N. E. 1985*a*, *Nature*, **319**, 469.
Hasinger, G., Langmeier, A., Sztajno, M., and White, N. E. 1985*b*, *IAU Circ.*, 4080.
Hiltner, W. A., and Mook, D. E. 1970, *Ann. Rev. Astr. Ap.*, **8**, 139.
Holt, S. S., Boldt, E. A., Serlemitsos, P. J., and Kaluzienski, L. J. 1976, *Ap. J.* (*Letters*), **205**, L27.
Kelley, R. L., *et al.* 1983, *Ap. J.*, **264**, 568.
Lamb, F. K., Shibazaki, N., Alpar, M. A., and Shaham, J. 1985, *Nature*, **317**, 681.
Lasala, J., and Thorstensen, J. R. 1986, *A.J.*, in press.
Lewin, W. H. G., Clark, G. W., and Smith, W. B. 1968, *Ap. J.* (*Letters*), **152**, L55.
Lewin, W. H. G., and van Paradijs, J. 1985, *Astr. Ap.*, **149**, L27.
Lewin, W. H. G., van Paradijs, J., van der Klis, M., Jansen, F., Sztajno, M., and Trümper, J. 1985, *IAU Circ.*, 4101.
Middleditch, J. 1982, *Ap. J.* (*Letters*), **257**, L71.
Middleditch, J., and Kristian, J. 1984, *Ap. J.*, **279**, L57.
Middleditch, J., and Priedhorsky, W. 1985, *IAU Circ.*, 4060.
Mitsuda, K., *et al.* 1983, *Pub. Astr. Soc. Japan*, **36**, 741.
Norris, J. P., and Wood, K. S. 1985, *IAU Circ.*, 4087.
Pechenick, K. R., Ftaclas, C., and Cohen, J. M. 1983, *Ap. J.*, **274**, 846.
Petro, L., Bradt, H., Kelley, R., Horne, K., and Gomer, R. 1981, *Ap. J.* (*Letters*), **251**, L7.
Pietsch, W., Pakull, M., Voges, W., and Staubert, R. 1985, *Proc. 18th ESLAB Symposium on X-Ray Astronomy*, in press.
Sandage, A. R., *et al.* 1966, *Ap. J.*, **146**, 316.
Stella, L., Parmar, A., and White, N. 1985, *IAU Circ.*, 4102.
Stella, L., Parmar, A., White, N., Lewin, W. H. G., and van Paradijs, J. 1985, *IAU Circ.*, 4110.
Tawara, Y., Hayakawa, S., Kunieda, H., Makino, F., and Nagase, F. 1982, *Nature*, **299**, 38.
van der Klis, M., *et al.* 1985*a*, *IAU Circ.*, 4043.
van der Klis, M., Jansen, F., van Paradijs, J., Lewin, W. H. G., van den Heuvel, E. P. J., Trümper, J. E., and Sztajno, M. 1985*b*, *Nature*, **316**, 225.
van der Klis, M., Jansen, F., White, N., Stella, L., and Peacock, A. 1985*c*, *IAU Circ.*, 4068.
Webbink, R. F., Rappaport, S. A., and Savonije, G. J. 1983, *Ap. J.*, **270**, 678.
White, N. E., Peacock, A., and Taylor, B. G. 1985, *Ap. J.*, **296**, 475.

J. MIDDLEDITCH: Los Alamos National Laboratory, MS D436, ESS 9, P. O. Box 1663, Los Alamos, NM 87545

W. C. PRIEDHORSKY: Max-Planck-Institut für Extraterrestrische Physik, Karl-Schwarzschild-Strasse 1, D-8046, Garching bei München, Federal Republic of Germany