During the dim phase of the cycle, there are two almost equal peaks in the pulse pattern. In this case, it is thought that the magnetic poles have precessed so that both swing equally near us during the 1.24-second rotation. Neither comes as close as the pole producing the main peak did earlier, so neither resulting peak is as large as the main peak during the bright phase.

Precession of the neutron star also causes the pattern of x-ray flux falling on the near side of the companion star to vary with the 35-day period. This variation in the illumination of the companion star may introduce an asymmetry in the stream of material leaving the companion, causing the accretion disk to be tilted. Such a tilt leads naturally to precession of the outer rim, resulting in periodic obscuration of the x rays from the neutron star.

The idea that the neutron star in Her X-1 might be processing has major implications for two key aspects of neutron-star structure. First, it would imply that the super-fluid vortices in the inner crust (see “Internal Dynamics of Neutron Stars”) are unpinned; otherwise, their gyroscopic motion would cause the star to precess far too rapidly. Second, it would indicate that the neutron star has a thick crust; otherwise, the star would not be sufficiently rigid to maintain its oblateness and hence could not precess fast enough. Detailed measurements of the 35-day cycle thus give us new insight into one of the most hidden parts of our universe-the intenor ofa neutron star. ■

Quasiperiodic Oscillations

In the spring of 1985, the phenomenon of Quasiperiodic oscillations was discovered by EXOSAT in the bright galactic-bulge sources GX 5-1, Cygnus X-2 (Cyg X-2), and Scorpius X-1 (Sco X-1). Such oscillations have now been looked for in more than a dozen other galactic-bulge sources, and four more examples have been found. Quasiperiodic oscillations are revealed in a power-density spectrum as a broad peak covering many frequencies rather than a sharp spike at one frequency. Moreover, in the bulge sources the position of this broad peak is seen to vary with time. and the changes seem to be correlated with changes in the source intensity.

For example, GX 5-1 has a broad peak in its averaged power-density spectra whose central frequency systematically increases from 20 to 36 Hz as the source intensity increases from 2400 to 3400 counts per second (Fig. 1). The peaks in Cyg X-2 and Sco X-1 change in frequency from 28 to 45 Hz and from 6 to 24 Hz, respectively.

All the GX 5-1 and most of the Cyg X-2 data for 1- to 18-keV x-ray photons show a strong positive correlation between the peak frequency and the source intensity. In Sco X-1 the oscillation frequency, at times, shows a strong positive correlation with the intensity of the 5- to 18-keV photons but, at other times, exhibits a weak *negative* correlation (Fig. 2). Whether the oscillations in Sco X-1 have the same origin as those in GX 5-1 and Cyg X-2 is not yet clear.

A variety of physical mechanisms have been discussed for the Quasiperiodic oscillations in these bright galactic-bulge sources, but, at the moment, the *beat-frequency* model appears the most promising. If this model is correct, the Quasiperiodic oscillation frequency is a measure of the difference between the rotation frequency of the neutron star and the orbital frequencies of the plasma in the inner disk.

The model assumes that a *clumped* plasma is accreting from an accretion disk onto a weakly magnetic neutron star. Such clumping can be caused by magnetic, thermal, or shear instabilities. Once formed, clumps drift radially inward and are stripped of plasma by interaction with the magnetospheric field. Plasma stripped from the clump is quickly brought into coronation with the neutron star and falls to the stellar surface, where it produces x rays.

Inhomogeneities in the stellar magnetic field cause the rate at which plasma is stripped to vary with time, which, in turn, changes the intensity of the x-ray emission. Unless the stellar magnetic field is axisymmetric, aligned with the rotation axes of the disk and star, *and* centered in the star, the interaction of' a given plasma clump in the disk with the magnetosphere is greater at some stellar azimuths than at others. Because the clumps of plasma and the magnetosphere arc rotating at different frequencies, the strength of the magnetic field seen by a given clump will vary at the beat frequency or one of its harmonics. causing the x-ray emission to vary at the same frequency,

A simple version of the beat-frequency model predicts power-density spectra that are very similar to the spectra observed for GX 5-1 and Cyg X-2 (Fig. 3). The theory also predicts that changes in accretion rate should cause a shift in beat frequency similar to that actually observed for these two bright galactic-bulge sources (Fig. 1b), Moreover, the neutron-star rotation rate (about 100 Hz) and magnetic field strength (about 10^9 G) inferred from the beat-frequency model are consistent with previous theories that binary systems like GX 5-1 and Cyg X-2, when disrupted, produce the observed millisecond rotation-powered pulsars.

The most direct evidence in favor of the beat-frequency model would be detection of weak x-ray pulsations at the predicted spin rate. Though several sources have been examined carefully and pulsations smaller than 1 per cent would have been observed, regular pulsations in the sources that exhibit Quasiperiodic oscillations are yet to be seen. One explanation for the absence of strong pulsations is that the magnetic fields of these neutron stars are too weak (less than 10^7 G) to channel the accretion flow onto the magnetic poles. This, however, does not agree with the strength of 10^9 G inferred from the beat-frequency model, which is large enough to produce some channeling and x-ray beaming.

In the context of the beat-frequency model, there are three distinct physical effects that could prevent observation of pulsations at the rotation frequency of the star. Radiation pressure within the magnetosphere could be supporting the accreting plasma, causing it to settle over a large fraction of the star's surface. Evidence for this effect comes from analyses of the hard x-ray components, which yield emitting areas comparable to the star's surface area. The resulting broad x-ray beam would produce only weak modulation and then at relatively high harmonics of the rotation frequency. Any modulation might be further weakened by bending of the photon paths in the strong gravitational field of the neutron star.

QUASIPERIODIC OSCILLATIONS OF GX 5-1

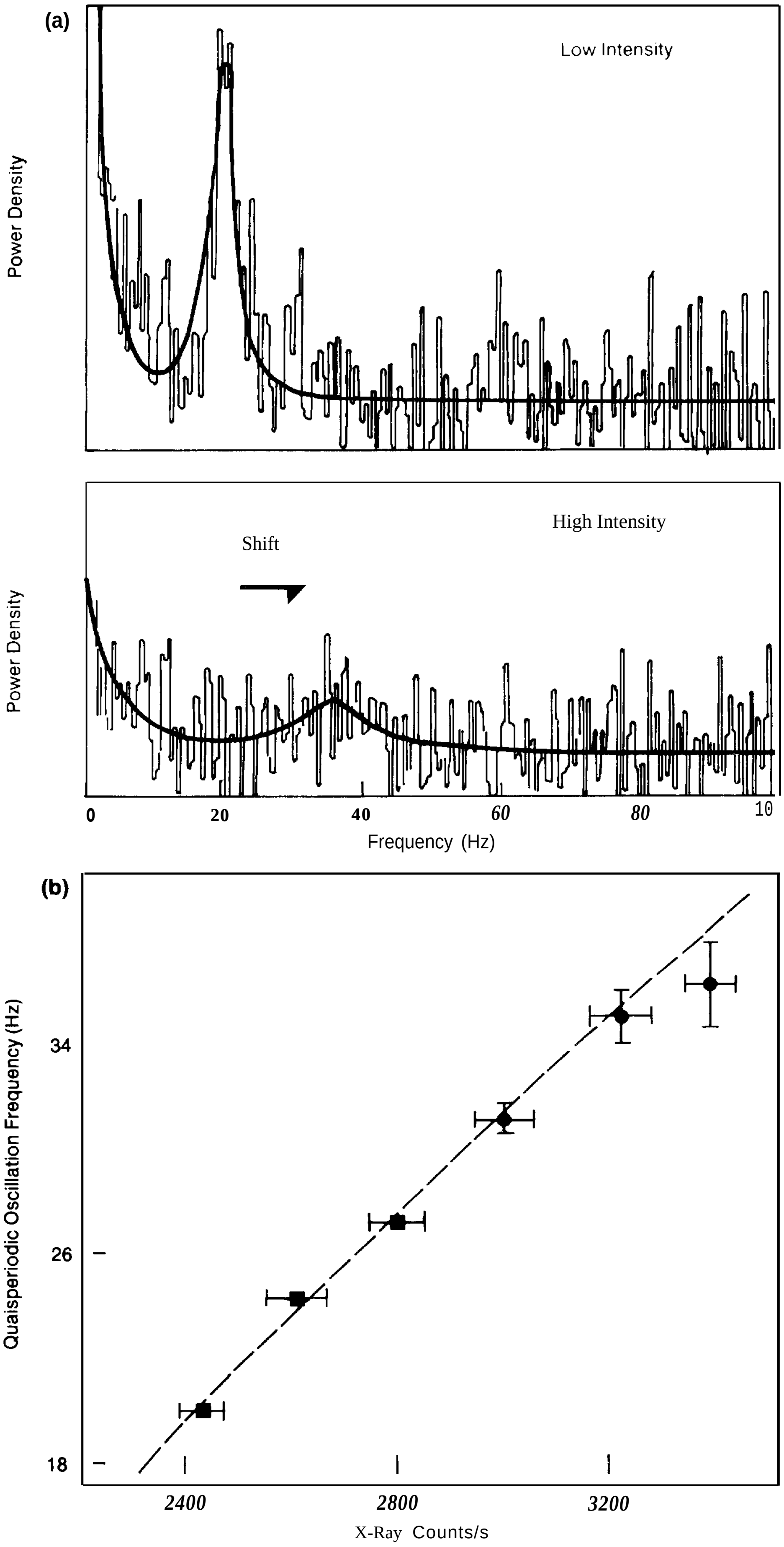


***Fig. 1.** (a) **The Quasiperiodic oscillations of GX 5-1 are seen as a broad peak in averaged power-density spectra that shifts from 20 to 36 Hz as the intensity of the source increases. (b) A strong positive correlation exists between the centroid frequency of the Quasiperiodic oscillations and source intensity. The dashed line is the behavior predicted by the beat-frequency model.** ➤*

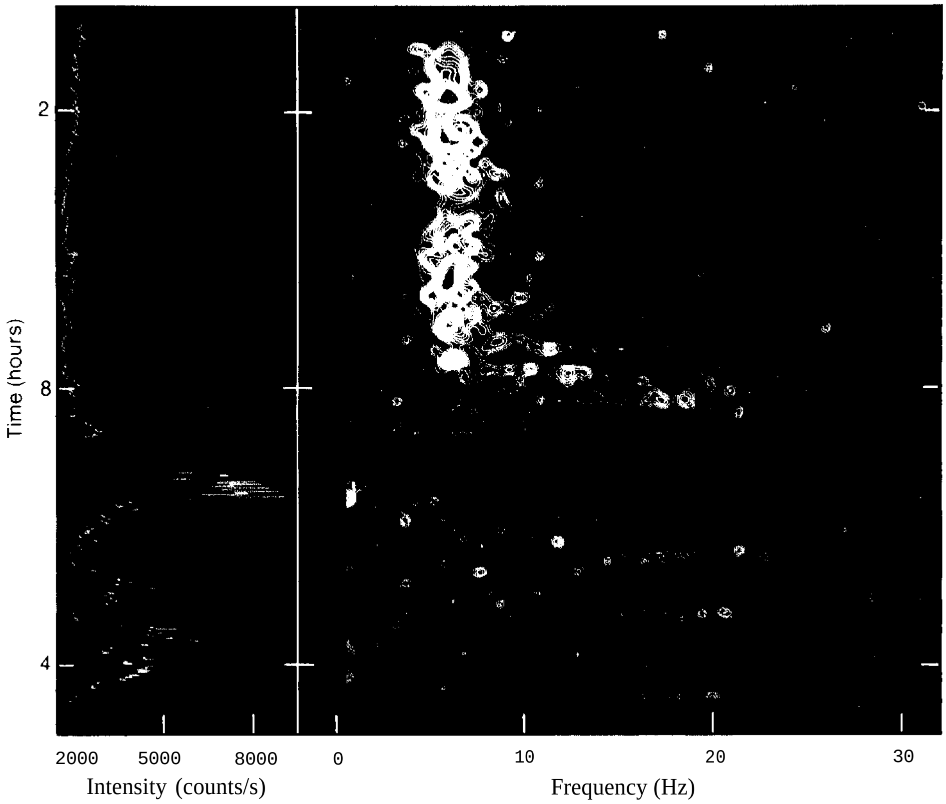
The second effect has to do with the thick central corona that may be surrounding each bright galactic-bulge source. Analyses of the x-ray spectra indicate that these coronae may have dimensions on the order of 100 kilometers (about 10 neutron-star radii) and electron-scattering optical depths on the order of 10, which should drastically reduce the modulation due to x-ray beaming. In contrast, Quasiperiodic oscillations produced according to the beat-frequency model would not be affected if the mean time for photons to propagate through the corona is less than the oscillation period. Calculations for a typical system show that pulsations at the 100-Hz rotation frequency are strongly suppressed, whereas the amplitude of Quasiperiodic oscillations at 30 Hz is unaffected and is therefore equal to the modulation in the accretion rate.

Finally, there is evidence that the inner and outer parts of the disks of bright galactic-bulge sources are both geometrically and optically thick. Such disks would prevent us from seeing x-rays that come directly from the neutron star except when our line of sight is close to the star's rotation axis. X rays emerging near the rotation axis would, at most, be only weakly modulated.

Work currently underway on Quasiperiodic oscillations in galactic-bulge sources has benefited from previous work on this phenomenon in cataclysmic variables. In turn, the new observations and theoretical work may, when scaled appropriately, help us understand the oscillations observed in some of the cataclysmic variables. ■

Fig. 2. Power-density contours for Sco X-1 as a function of time and frequency with high power in red, medium power in yellow, and low power in blue. The curve at the left is x-ray intensity as a function of time and shows flaring episodes (bottom) followed by an extended low-intensity state (top). The regions of concentrated color are the 6-Hz oscillations present during the extended low-intensity state. Power is spread over the range of 14 to 24 Hz between flares and at the start of the extended low-intensity state (horizontal clusters of blue circles). The gap in the data occurred when the detector was shut off for fear the intensity of the flare might damage the detectors.

POWER DENSITY CONTOURS FOR **Sco X-1**



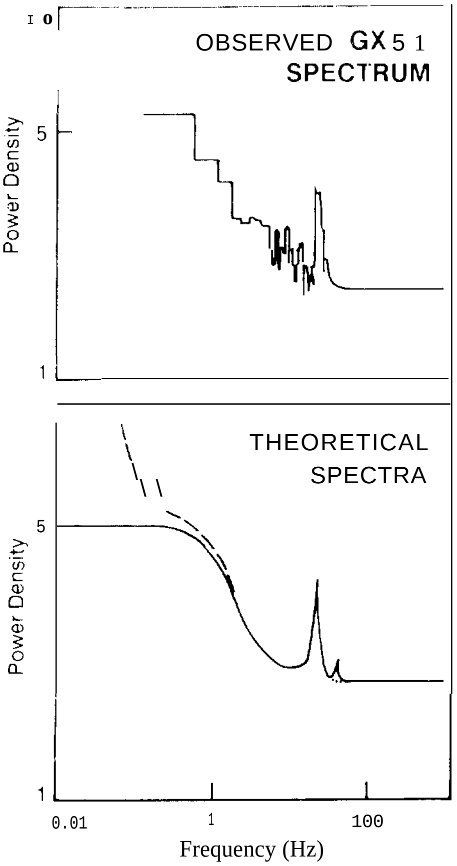


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Fig. 3. An observed power-density spectrum for GX 5-1 (top panel) compared to two theoretical power-density spectra (bottom panel) calculated for the beat-frequency model using different parameter values. Because the low-frequency behavior of the two calculated spectra differ markedly, future observations should be able to constrain the values of the model parameters.