Her X-1: Another Window on Neutron-Star Structure

Of all the x-ray binaries, none shows a more complex pattern of regular variability than Hercules X-1 (Her X-1). In this system, as in many others, a low-mass normal star transfers mass to a neutron star via a thin accretion disk. What makes Her X-1 so curious is its variability, which exhibits no less than three concurrent periodicities.

The general picture has been known since the first extensive observations were made by the x-ray astronomy satellite Uhuru over a decade ago. The fastest periodic variation is a stable 1.24-second pulsation. Two effects related to the rotation of the star probably play a role in producing this pulsation. First, because accreting matter funnels down the stellar magnetic field lines toward the magnetic poles. the emitted x rays are preferentially beamed in certain directions. The star's rotation sweeps these beams past us every 1.24 seconds in a manner analogous to the way the light from a lighthouse seems to pulse as the lamp assembly rotates. Second, because the orientation of the magnetic field with respect to the disk changes as the star rotates, the inward flow of mass, and hence the luminosity of the star, is likely to vary at the rotation frequency.

The pair of stars in the Her X-1 binary orbit each other with a 1.7-day period. This motion also modulates the x rays at earth by periodically obscuring them once per orbit when the neutron star is eclipsed by its companion.

The most interesting cycle is the 35-day one. The source follows a slightly irregular pattern in which it is bright for about 9 days and then relatively dim for about 26 days (figure). For years the most popular explanation for this 35-day cycle has been periodic obscuration by a tilted, twisted, and processing accretion disk. However, the cause of the tilt and precession has not been well understood. One popular explanation, that the companion star is processing (see the section entitled "Long-Term Periodic Variables" in the main article), has been questioned because the required precession of the fluid companion star has yet to be modeled successfully.

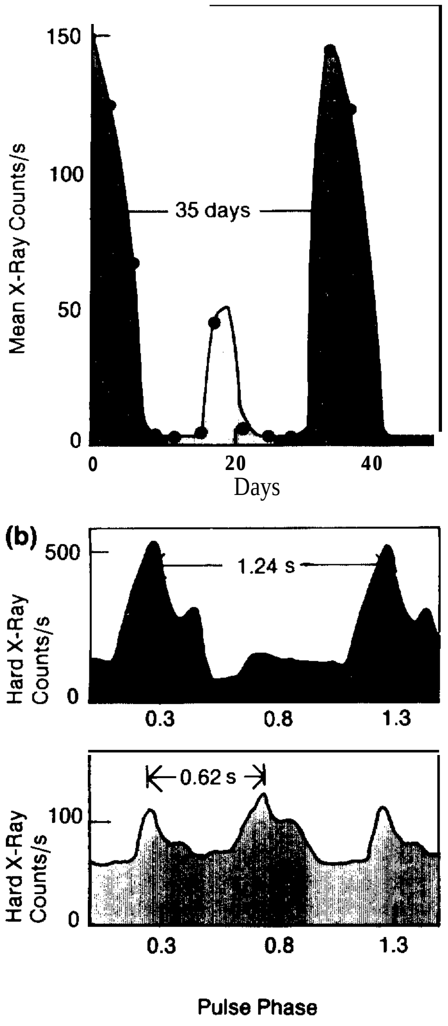
New studies by the EXOSAT satellite, reported at the Taos workshop, strongly support an alternative suggestion. In this study Her X-1 was monitored for hundreds of hours and approximately thirty times more x rays were recorded than in all previous studies put together. As a result, the pulse shape and its variation with the 35-day cycle were measured with unprecedented accuracy. These observations indicate that the neutron star itself is processing with a 35-day period.

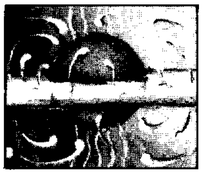
The neutron star is expected to have two x-ray beams emanating from the two magnetic poles. If the neutron star does not precess, then the orientation of these beams relative to the rotation axis does not change, and the observed pulse pattern is constant. However, if the neutron star precesses, the magnetic poles, and hence the beams, drift with respect to the rotation axis, causing the corresponding peaks to appear or disappear from the observed pulse waveform.

The EXOSAT data indicate such a drift in Her X-1. During the bright phase of the 35-day cycle, we see a main peak at phase 0.3 coming from the pole that swings almost directly toward us. Six-tenths of a second later at phase 0.8, we see a hint of a peak from the edge of the opposite pole.

(a) Changes in the x-ray flux from Her X-1 (averaged over its 1.24-second pulse period) during one-and-a-half periods of the 35-day cycle. The bright state (red) lasts about 9 days. Midway between the bright peaks there is a smaller rise in intensity for several days (blue). (b) During the bright peak (red), the hard (1 to 30 keV) x rays show one large pulse every 1.24 seconds, revealing the neutron star's rotation. During the smaller, dim peak (blue), a second hard x-ray peak occurs *half a cycle later. This is evidence that the neutron star has precessed so that both magnetic poles sweep into view.* ▼

X-RAY FLUX FOR HER X-1





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 interior of a 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 are 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 previ-