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MULTIWAVELENGTH STUDIES OF HERCULES X-1 DURING SHORT HIGH AND ANOMALOUS LOW STATES: ON-AGAIN, OFF-AGAIN

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ABSTRACT

We present results from multiwavelength observations of the Hercules X-1 system during a short high state (SHS) and during an anomalous low state (ALS). The magnitude of deviation from spin-up appears to be positively correlated with duration of the ALS. Such a correlation is consistent with an interpretation of the ALS in terms of a change in mass accretion rate that causes the disk to tilt and twist beyond the normal deviations that cause the 35 day cycle. A larger deviation from the average results in a stronger disruption of the disk and causes the disk to take longer to settle back to its "normal" 35 day behavior. Our model—which includes X-ray heating of the disk and companion star, shadowing of the X-ray flux by the disk, and a contribution to the continuum emission from the accretion stream or hot spot—can consistently explain the observed changes in X-ray, ultraviolet (UV), and optical continuum light curves for both the SHS and ALS. The Hubble Space Telescope (HST) and Space Telescope Imaging Spectrograph (STIS) observations presented here are the first UV observations of sufficient spectral and temporal resolution to construct Doppler tomograms of the line emission. Doppler tomograms of the UV emission lines during SHS and ALS show the majority of the emission coming from the surface of the companion star rather than from the accretion disk. Tomograms made after separating the Nv emission lines into broad and narrow components suggests that while the narrow component is associated with emission from the companion star, the broad component may be associated with emission from a distorted disk. The Doppler maps also show that heating over the inner face of HZ Her is not uniform and imply partial eclipse of the UV line emission by an accretion stream and/or hot spot.

Subject headings: accretion, accretion disks — binaries: close — pulsars: individual (Hercules X-1) — ultraviolet: stars — X-rays: stars

On-line material: color figures

1. INTRODUCTION

The Hercules X-1 system is an accreting X-ray binary consisting of a neutron star (Her X-1) that rotates every 1.24 s while orbiting a "normal" stellar companion (HZ Her) every 1.7 days. The magnetic axis is misaligned with the rotation axis, resulting in a distinctive pulse profile. Variation in optical luminosity by 1.8 mag over the 1.7 day orbital period of the companion is attributed to X-ray heating on the side facing the active neutron star. The X-ray heating is so intense that the companion changes spectral type from A to B. The Her X-1 system is unusual in that, with an approximately 2 $M_\odot$ companion, it is the only known "intermediate-mass" system. It resembles X-ray binaries with high-mass companions (HMXBs) in that it exhibits pulses and its optical luminosity is dominated by emission from the companion, but it accretes matter via Roche lobe overflow through an accretion disk, as do systems with low-mass companions (LMXBs). The location of Her X-1, more than 3 kpc above the Galactic plane, suggests that it is a rather old system like the LMXBs, or that, if it originated in the Galactic plane, the neutron star must have obtained a significant kick from the supernova that formed it. Features in the X-ray spectrum near 40—45 keV have been interpreted as the result of cyclotron absorption, implying a magnetic field strength $B = (2.9 \pm 0.3) \times 10^{12}$ G (dal Fiume et al. 1998; Mihara et al. 1990; Trümper et al. 1978). The pulses and the cyclotron line feature, which attest to the high magnetic field of Her X-1, are difficult to reconcile with theories of stellar evolution which require that the magnetic fields of neutron stars decay over time. The large orbital decay rate is also difficult to reconcile with the relatively low mass accretion rate and lack of evidence for mass loss through a wind (Deeter et al. 1991).
In addition to the 1.24 s rotation period and the 1.7 day orbital period, the system has an approximately 35 day “superorbital” period in which the X-ray emission displays so-called main and short high states separated by relative X-ray quiescence (Giacconi et al. 1973; Gorecki et al. 1982). During the main high states (MHSs), the 2–10 keV fluxes are of order ~100 mcrab; the short high state (SHS) is roughly 30 mcrab; the low or quiescent state (LS) is about 5 mcrab (Parmar et al. 1985). The preferential turn-ons of the 35 day cycle at orbital phases 0.2 and 0.7 have been attributed to the interaction of an accretion disk tilted with respect to the orbital plane with a time-varying torque induced by the companion star, which leads to a wobble or “nodding” motion in the disk (Levine & Jernigan 1982; Katz et al. 1982). The physics that causes the disk to tilt in the first place is not known. The interpretation of superorbital periods in terms of disk precession (Katz 1973; Peterson 1977) has been questioned because, if the disk precession is controlled by the gravitational fields of the neutron and companion stars, any induced precession would be damped rapidly owing to differential precession within the disk (Kondo, van Flandern, & Wolf 1983).

Several models have been put forward that attempt to tilt and precess the disk without invoking precession of the neutron star and/or its companion. One viable suggestion is that the behavior attributed to precession is maintained by the influence of the X-ray emission on the structure of the disk (Peterson 1977; Iping & Peterson 1990); that strong central illumination can maintain disk warping has been shown analytically (Pringle 1996; Maloney, Begelman, & Pringle 1996). Schandl & Meyer (1994) suggest that warping is caused by repulsive torques exerted on the disk by a disk corona/wind. Wijers & Pringle (1999) suggest that the disk can precess without any tidal torques—the radiation instability naturally drives the warp structure around the disk on the 35 day cycle. Another possibility is that shadowing of the companion star by a warped disk may interrupt the accretion stream causing transfer of matter with misaligned angular momentum and further enhancing the warp (Shakura et al. 1999).

In recent years, progress has been made on the dynamics of accretion disks, such as in the radiation-driven warping models of Pringle (1996) and Maloney, Begelman, & Pringle (1996). Much work has been done toward the understanding of momentum transfer in accretion disks by Balbus & Papaloizou (1999); Hawley, Balbus, & Winters (1999); Stone & Balbus (1996); and others. In this paper we will address the mass transfer process and disk structure as deduced from multil wavelengths observations to obtain empirical measurements of disk and mass transfer properties that can be used to test model predictions. The Her X-1/HZ Her system is an ideal target because of the low interstellar absorption toward the system, its relatively short orbital period, and high inclination (nearly 90°), which makes the Doppler velocities of the various components well separated. In 1998 July and 1999 July, we conducted multil wavelength campaigns of Her X-1 using instruments on several satellite missions and ground-based observatories. Our primary goals were to construct a physical image of the system using Doppler tomography, to resolve spectrally the emission components throughout the binary and superorbital periods, and to search for rapid variability and pulsations within the UV continuum and lines. The Hubble Space Telescope (HST) and Space Telescope Imaging Spectrograph (STIS) observations described here represent the first UV data that are of sufficient spectral and temporal resolution to generate Doppler tomograms and search for UV quasi-periodic oscillations (QPOs). In this paper we present the first UV tomograms of the Her X-1 system and find that they are consistent with our model of the Her X-1 system as presented in Vrtilek & Cheng (1996) and Boroson et al. (1996). Quaintrell et al. (2001b, 1999) show that these tomograms exclude the Schandl (1996); Wijers & Pringle (1999); and Larwood (1998) models if it is assumed that the accretion disk is solely responsible for X-ray shadowing over the companion star. Still et al. (2001b, 2001a) make detailed presentations of the X-ray data using the SHS to update orbital and pulsar spin periods and providing an interpretation of the X-ray light curve during the ALS in terms of nearly pure atmospheric reflection from HZ Her. Boroson et al. (2000b), and H. Fiedler et al. (2001, in preparation) present results from searches for optical and UV QPOs during our campaign. O’Brien et al. (2001) present a search for optical QPOs using data from the Keck II telescope taken within a week of our 1998 campaign, and Boroson et al. (2000a) and B. Boroson, S. D. Vrtilek, & T. Kallman (2001, in preparation) model the UV emission lines in terms of hot outflowing gas. In §§ 2 and 3 we present the light curves and spectra; in § 4, results from pulse timing and searches for aperiodic variability; in § 5, specific results from Doppler tomography of N v; and in § 6 we present a discussion and summary.

2. OBSERVATIONS

The observations were conducted using instruments on several satellite missions (the Rossi X-Ray Timing Explorer [RXTE], the Satellite per Astronomia X [BeppoSAX], the Extreme Ultraviolet Explorer [EUVE], and HST) as well as ground-based observatories at La Palma and Calar Alto. The proportional counter array (PCA) on RXTE, described in detail by Jahoda et al., consists of five identical Xe proportional counting units (PCUs) for a combined effective area of 6500 cm². The all-sky monitor (ASM) on RXTE has been described in detail by Levine et al. (1996). BeppoSAX has been described in detail by Boella et al. (1997a); it includes the low-energy concentrator spectrometer (LECS; 0.1–10 keV; Parmar et al. 1997) and the imaging medium-energy concentrator spectrometer (MECS; 1.5–10 keV; Boella et al. 1997b). EUVE supports four telescopes; three are scanning telescopes that feed one detector each, and these constitute the scanning instruments that performed the all-sky survey. A fourth telescope feeds three EUV spectrometers and a deep survey (DS) detector (Bowyer & Malina 1993, and references therein). The STIS instrument design and in-orbit performance have been described by Woodgate et al. (1998) and Kimble et al. (1998). Optical observations were obtained with the 4.2 m William Herschel Telescope at La Palma and the 3.5 m telescope at Calar Alto.

The locations of our observations relative to the 1 day averaged light curves from the ASM on the RXTE (provided courtesy of the RXTE ASM team) are depicted in

1 Based on observations with the NASA/ESA Hubble Space Telescope, obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555.

One-day averages of the flux observed from Her X-1 with the all-sky monitor (ASM) on board the Rossi X-Ray Timing Explorer (RXTE). Quick-look results were provided by the ASM/RXTE team. The short horizontal bars, identified by arrows, indicate the durations of the 1998 and 1999 multiwavelength campaigns. The long horizontal bar shows an interval of length 35 days. The vertical bar shows the size of a typical error. [See the electronic edition of the Journal for a color version of this figure.]

Figure 1 with arrows. These indicate that the 1998 observations took place during an SHS of the 35 day cycle, and the 1999 observations took place during an anomalous low state (ALS; Parmar et al. 1985, 1999; Vrtilek et al. 1994). The superorbital epochs, $\phi_{35}$, are determined using an ephemerides provided by M. Kunz (personal communication), where $T_{35} = JD 2,450,041.5 \pm 34.85$ days corresponds to the onset of the MHS.

2.1. The 1998 July Campaign Light Curves: The Short High State

The 1998 July 10–13 (JD 2,451,004.0–JD 2,451,008.3) observations were taken with RXTE, EUVE, HST, La Palma, and Calar Alto. Serendipitously, the system was observed by BeppoSAX during the time of our campaign (Oosterbroek et al. 2000). The light curves from our observations and a reextraction of the BeppoSAX MECS data are depicted in Figure 2.

The PCA on RXTE observed intermittently for 70,000 s spanning 2.5 binary orbits. The 1998 RXTE observations took place from $\phi_{35} = 0.6–0.7$ corresponding to the latter half of the SHS. The BeppoSAX MECS and LECS had nearly continuous coverage for 3.5 binary orbits encompassing the RXTE observations. The observations were taken during the latter half of the SHS and extended into the LS of the 35 day cycle. The X-ray flux is observed to decrease as expected for the observed orbital and 35 day phases. Scott & Leahy (1999) noted that the preeclipse dips during the short high state are of longer duration (by almost a factor of 2) than during the MHSs. Our 1998 observations of the SHS confirm this result. The X-ray light curve of the
1998 observations (most clearly seen in the BeppoSAX data) indicates that the MHS immediately preceding this SHS had an onset at binary phase 0.2 (Scott & Leahy 1999). Still et al. (2001b) give a detailed presentation of the RXTE data during the SHS, including a determination of the orbital and pulsar spin periods to facilitate future measurements of $P_{\text{spin}}$ and $P_{\text{orb}}$.

The DS on EUVE observed for 2.5 binary orbits. The EUVE fluxes decrease much faster than the hard X-rays (1–10 keV), attesting to the presence of excess absorbing material in the line of sight. They follow very closely the soft X-ray (0.1–1 keV) light curves from the BeppoSAX LECS presented by Oosterbroek et al. (2000; their Fig. 2), suggesting that the soft X-rays and EUV emission originate in a similar region.

The STIS observed for 19 HST orbits (four with the G160M and 15 [of which five orbits were not usable due to a technical error] with the E140M echelle spectrometer) spanning three binary orbits. The four HST orbits with the G160M resulted in 29 spectra with resolution of 200–300 km s$^{-1}$ in the wavelength range 1150–1720 Å. The 10 HST orbits with the E140M grating provided a resolving power of 6 km s$^{-1}$ in the wavelength range 1150–1720 Å. The E140M exposures were taken in the TIMETAG mode, which stamps each photon detected with a time accurate to 125 μs. Figure 2 plots the UV continuum flux averaged over each of the 14 HST orbits that provided useful data. The UV flux is somewhat lower than the average of all IUE observations preceding the 1993 ALS (shown as solid curves which are the average of several previous observations taken from the literature; Petro & Hiltner 1973; Boynton et al. 1973).

2.2. The 1999 July Campaign Light Curves: An Anomalous Low State

The 1999 July observations (JD 2,451,371.3–JD 2,451,375.9) were taken with RXTE, EUVE, HST/STIS, and Calar Alto. The light curves from the 1999 observations are depicted in Figure 3.

The PCA on RXTE observed intermittently from 1999 July 11 to 16 for a total integration of 100 ks. Three of the 5 PCUs were utilized, for a total of 3500 cm$^2$ effective area. The 1999 RXTE observations took place during $\phi_{35} = 0.16–0.29$, which is centered on an MHS. However, the X-ray fluxes are lower than expected by a factor of 50 (see top panel in Fig. 3). This count rate is similar to that observed during the previous ALS states; at minimum, the count rate was down by a factor of 50 in 1993 (Vrtilek et al. 1994) and a factor of 20 in 1983 (Parmar et al. 1985). In addition, the X-ray light curve during the ALS appears similar to the optical light curve which peaks at orbital
phase 0.5. This light curve has been interpreted as due to X-rays reflected from the surface of HZ Her. A detailed discussion of the X-ray reflection model is presented in Still et al. (2001a).

The DS on EUVE observed for somewhat over two binary orbits. The EUVE fluxes are reduced by a factor of \( \sim 100 \) relative to those observed in the short high state in 1998 July and give a hint of showing the same light-curve behavior as the X-rays. However, the counting statistics are too poor to determine this positively.

The STIS observed for 19 HST orbits with the E140M spanning three binary periods. The E140M data, providing a spectral resolution of 6 km s\(^{-1}\) over the wavelength range 1150–1720 Å, were taken in the TIMETAG mode, which stamps each photon detected with a time accurate to 125 μs. Figure 3 plots the UV continuum flux averaged over each of the 19 HST orbits. The 1994 GHRS observations are shown again for comparison in Figure 3. The UV fluxes are reduced from the average with the greatest reduction near eclipse egress and ingress. During the 1999 July campaign, we had optical photometric observations (high-speed \( UBVRI \) with the MCCP on the 3.2 m telescope) from Calar Alto, and the optical fluxes again show little change from the regular behavior (H. Fiedler et al. 2001, in preparation).

3. SPECTRA

3.1. X-Ray

The pulse-averaged X-ray (0.1–200 keV) spectrum of Her X-1 during the MHS is a flat power law with a high-energy cutoff and an excess strong thermal blackbody component at low energies (a characteristic of many binary X-ray pulsars). Spectral features around 1.0 and 6.4 keV are attributed to Fe L- and K-shell emission (Choi et al. 1994; McCray et al. 1982; Pravdo et al. 1977); a feature between 40–45 keV is attributed to electron-cyclotron resonance, which implies a surface magnetic field of a few \( \times 10^{13} \) G (dal Fiume et al. 1998). The spectrum changes as a function of pulse phase: the Fe line and thermal emission are strongest during the off-peak of the pulse. The profile changes as a function of energy: the pulse peak shifts and shows less structure in the low-energy band. The pulse-phase shift suggests that the soft X-rays are likely reprocessed hard X-rays and that the Fe line emission originates at the reprocessing site (Vrtilek et al. 1994; Oosterbroeck et al. 2000).

In Table 1 we present results of our spectral fits to the RXTE PCA data at several epochs. The fitted model is a partial covering fraction absorber (PCFABS in XSPEC) times a power law plus a Gaussian representing the Fe K emission. We do not model either the soft (0.13 keV) blackbody component or Fe L emission, as they are below the energy threshold of the RXTE PCA. Nor do we model the 40–45 keV cyclotron absorption feature, as we had poor counting statistics above 20 keV. We restrict our fits to the energy range 3–20 keV, which avoids the high-energy cutoff observed in Her X-1. This model is the same as that used by Vrtilek & Halpern (1985) and serves our current purpose of a simple comparison of the different states. More thorough analysis of the X-ray data during the SHS and ALS are presented in Still et al. (2001b, 2001a). The contributions attributed to the covered and uncovered power law by Vrtilek & Halpern may be attributed to the presence of separate scattered (from a hot corona) and absorbed (by the disk) components (Sheffer et al. 1992; Parmar et al. 1999; Oosterbroeck et al. 2000), a physically distinct but, as noted by Coburn et al. (2000), numerically similar model. The models corresponding to the parameters are listed in Table 1 and plotted with the data in Figure 4. The peak of the SHS (MJD 51,004.0) does not require a partially covered component, implying that the contribution due to scattered X-rays is negligible at that time. The X-ray spectrum during MJD 51,007.8 is likely already in the LS and is very similar to that of the ALS (MJD 51,372.9). The eclipse data during both the SHS and ALS can be modeled with a simple power law; however Fe K emission appears quite prominent during the ALS. Here we characterized it by holding the power-law photon index fixed and allowing for additional parameters to fit the line.

The X-ray light curve during the ALS (as observed by us in 1999 July) appears remarkably similar to the optical light curve (see Fig. 3) in that emission is modulated with the

### Table 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>SHS1</th>
<th>SHS2</th>
<th>SHS(eclipse)</th>
<th>LS</th>
<th>ALS(eclipse)</th>
<th>ALS</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N_\text{H} ) (cm(^{-2}))</td>
<td>0.6 ± 0.2</td>
<td>25 ± 1</td>
<td>...</td>
<td>134 ± 36</td>
<td>...</td>
<td>6.3 ± 0.8</td>
</tr>
<tr>
<td>( \sigma ) (keV)</td>
<td>1.12 ± 0.01</td>
<td>1.58 ± 0.03</td>
<td>1.05 ± 0.09</td>
<td>0.88 ± 0.07</td>
<td>1.1(^*)</td>
<td>1.1(^*)</td>
</tr>
<tr>
<td>CF</td>
<td>...</td>
<td>0.71 ± 0.01</td>
<td>...</td>
<td>0.41 ± 0.06</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>( A_{\text{PL}} (\times 10^{-2}) )</td>
<td>6.4 ± 0.2</td>
<td>14.1 ± 1.1</td>
<td>0.07 ± 0.02</td>
<td>0.49 ± 0.13</td>
<td>0.02 ± 0.01</td>
<td>0.23 ± 0.01</td>
</tr>
<tr>
<td>( E_{\text{Fe,K}} ) (keV)</td>
<td>6.4 ± 0.02</td>
<td>6.37 ± 0.07</td>
<td>0.00 ± 0.07</td>
<td>0.62 ± 0.05</td>
<td>0.67 ± 0.02</td>
<td>6.4 ± 0.04</td>
</tr>
<tr>
<td>( \sigma ) (keV)</td>
<td>0.57 ± 0.03</td>
<td>0.8 ± 0.1</td>
<td>...</td>
<td>0.3 ± 0.1</td>
<td>0.4 ± 0.2</td>
<td>0.46 ± 0.06</td>
</tr>
<tr>
<td>( A_{\text{Fe,K}} (\times 10^{-7}) )</td>
<td>4.5 ± 0.3</td>
<td>2.0 ± 0.5</td>
<td>0.00 ± 0.07</td>
<td>0.64 ± 0.17</td>
<td>0.06 ± 0.04</td>
<td>0.41 ± 0.06</td>
</tr>
<tr>
<td>( E_{\text{Fe,K}} ) (keV)</td>
<td>557</td>
<td>271</td>
<td>...</td>
<td>663</td>
<td>2350</td>
<td>1220</td>
</tr>
<tr>
<td>( \chi^2/\text{dof} )</td>
<td>51/34</td>
<td>96/38</td>
<td>32/42</td>
<td>33/33</td>
<td>15/36</td>
<td>36/35</td>
</tr>
</tbody>
</table>

* All errors given are 1σ.

a The fitted model is a partial covering fraction absorption (PCFABS in XSPEC) times a power law plus a Gaussian:

\[
A(E) = [CF \times N_\text{H} \sigma(E) + (1 - CF) / (A_{\text{PL}}(E) E^{-\sigma} + A_{\text{Fe,K}}(1 / (\sqrt{2\pi\sigma(E)}))]^{-0.5} \times \exp(-0.5(E - E_0)^2 / \sigma(E)^2),
\]

where \( A(E) \) is in photons cm\(^{-2}\) s\(^{-1}\) keV\(^{-1}\), \( N_\text{H} \) = neutral hydrogen column density (in units of \( 10^{22} \) atoms cm\(^{-2}\)), \( \sigma(E) \) = photoelectric cross section (excluding Thomson scattering), CF = covering fraction (0 < CF ≤ 1) (dimensionless), \( \sigma \) = photon index of power law (dimensionless), \( E \) is energy in keV, \( A_{\text{PL}} \) and \( A_{\text{Fe,K}} \) are normalization constants. When no CF is listed, a simple power law plus Gaussian gave a sufficient fit.

b Photon index fixed at 1.1.
orbital period. The maxima near orbital phase 0.5 (when the inner face of the companion star, irradiated by X-rays from the compact source, is most visible) suggest that the emission is correlated with the emission from the companion star. Fe line emission persists during eclipse at a flux level one-tenth of that present outside eclipse. The energy spectra become harder with increasing intensity, which implies an intrinsic flux increase or opaque obstruction. Still et al. (2001a) show that the 2–10 keV spectrum can be fitted with a partially covered power law (representing a region that moves with the compact object) plus Compton reflection of X-rays from the surface of the companion with the total 2–10 keV flux much reduced from that observed during a normal MHS. In their model, the power-law photon index is restricted to $\alpha = 0.9$, the value measured during the MHS. Using the system binary geometry and the cold reflection model, Still et al. are able to compute the incident X-rays which are removed from the direct line of sight by the accretion disk and obtain a value that is within a factor of 2 of the peak MHS flux. Reflection of X-rays from the atmosphere of the companion star has been suggested as an explanation of the EUV light curves by Leahy & Marshall (1999) and Leahy, Marshall, & Scott (2000).

3.2. Ultraviolet

Ultraviolet spectra taken with the low resolution G140L and the medium resolution E140M echelle gratings on STIS are shown in Figures 5 and 6. The continua are flatter than those of normal stellar spectra, presumably due to X-ray heating effects (Vrtilek & Cheng 1996). Emission lines from C iv $\lambda 1548$ and 1551, and He ii $\lambda 1640$ are seen during both the SHS and the ALS.
at similar flux levels. That sharp absorption features in the Si IV and C IV lines do not move with orbital phase implies interstellar origin. Absorption in the O V line moves with orbital phase, indicating that its origin is within the binary. P Cygni absorption is found at \( -400 \text{ km s}^{-1} \) on the blue wings of the N V \( \lambda 1239 \), O V \( \lambda 1371 \), Si IV \( \lambda 1394 \), and C IV \( \lambda 1548 \) during the ALS. The orbital phases during which we see significant P Cygni absorption in the ALS are not sampled during the SHS. The line emission is variable during eclipse and eclipse egress, and line emission due to N V, C IV, and He II persists during eclipse.

The orbital phase dependence of the N V emission observed in 1994 persists during the 1998 and 1999 observations (Fig. 7). The GHRS on HST resolved two moving emission components of the N V emission doublet: a broad emission line that can be attributed to the X-ray–illuminated surface of a Keplerian accretion disk and a narrow line associated with the X-ray–heated atmosphere of the companion star, HZ Her [Boroson et al. 1996].) During the 1999 ALS, the broad lines (attributed to emission from the disk) are reduced as expected if parts of the accretion disk are eclipsed. The GHRs N V profiles are plotted as dotted curves on Figure 7 when available. It is clear that while the narrow line fluxes are similar during the MHS, SHS, and ALS, the broad component fluxes are considerably reduced during the ALS. The sum of the narrow and broad N V line fluxes appears to be independent of the superorbital state (Fig. 8), but this is due to the fact that the broad component is weak relative to the narrow component. This is consistent with the accepted picture of the system where X-ray illumination of HZ Her continues throughout the 35 day cycle, but the warped, precessing disk presents different surface areas to the viewer.

During the ALS, the UV continuum emission is reduced more than during the SHS, particularly near eclipse egress and ingress, consistent with a scenario in which emission from the disk is blocked from our line of sight as the disk is eclipsed. Figure 8 shows fluxes from all available UV observations, as well as the model predictions for extremes of \( M \) and disk opening angle (Vrtilek & Cheng 1996). The continuum flux peaks at orbital phase 0.5, but the flux is not symmetric around this phase. The continuum flux during orbital phases 0.6–0.8 is somewhat higher than during orbital phases 0.2–0.4. This behavior, first noted in the lower resolution IUE data (Vrtilek & Cheng 1996), is confirmed by the higher resolution STIS data. We suggest that this may be due to the presence of UV continuum emission from the heated surface of the accretion stream; the optical continuum which is dominated by light from the companion star does not show this effect.

3.3. Optical

Optical spectra of HZ Her show Balmer absorption lines down to the series limit (see, e.g., Quaintrell, Still, & Roche 2001a). Absorption lines are seen in the spectrum at both minimum and maximum light. At minimum light the
optical spectrum of HZ Her corresponds to a spectral type of A7 \( T_{\text{eff}} = 8100 \) K; Cheng, Vrtilek, & Raymond 1995). At maximum light the spectral type ranges from B3 to B6 depending on the lines used. The dramatic change in spectral type from minimum to maximum is attributed to X-ray heating of the side facing Her X-1; the lack of a good match to a single spectral type is attributed to X-ray heating effects. The optical flux is mainly from the X-ray-heated star surface with the disk surface contributing less than 15% of the total optical flux. Most of the disk contribution comes from the outer disk edge and is not strongly affected by changes in disk inclination angle. This provides a natural explanation for the slight modulation of the optical flux (at a specific orbital phase) over the 35 day period (Vrtilek & Cheng 1996).

3.4. Broad Band

In Figure 10 we have plotted the energy flux versus frequency for the 1998 SHS and 1999 ALS observations. For purposes of comparison, we have included the broadband behaviors during the 1993 ALS and 1994 MHS. In all cases (representing a transition state between MHS and ALS, two ALS, one MHS, and one SHS), the optical flux is roughly constant. The UV flux is somewhat reduced during the SHS with respect to the MHS and reduced by as much as a factor of 2 during the ALS. The extreme UV flux is reduced by a factor of 10 during the ALS (shown as upper limits). The X-rays show by far the greatest deviations: the SHS is reduced by a factor of 3 from the MHS; the ALS is reduced by factors of 2–100 from the MHS; and the X-ray LS is typically reduced by a factor of 20 (the dotted line during the 1998 observations is the last RXTE orbit which took place during an X-ray low state). All of this is consistent with a compact source of X-rays that is obscured to varying degrees along the line of sight. The EUVE emission is due to the tail end of the soft thermal blackbody radiation and is located near to the X-ray source and, hence, shows behavior consistent with the soft X-rays. The UV, which comes from a slightly larger region (X-ray–heated emission from the inner edge of the disk, X-rays reflected from the surface...
of HZ Her, an accretion disk corona, etc.), is less affected, and the optical, which is dominated by emission from the normal star and the outer edge of the disk, remains relatively unchanged (for a given orbital phase) throughout the 35 day cycles.

4. PULSE TIMING, ORBITAL EPHEMERIDES, AND APERIODIC VARIABILITY

The X-ray pulse period measured during the 1998 SHS \{1.2377257(4) s\} continued the secular spin-up trend since the spin down observed during the 1993 ALS. The pulse period measured during the 1999 ALS \{1.237746(1) s\} showed a sharp increase from the previous measurement, confirming that the neutron star (NS) undergoes spin-down during ALS. The pulse period history is depicted in Figure 11 (with the durations of the ALS indicated by solid line segments). Observations of the rapid spin-down by BeppoSAX during the same ALS (but not simultaneous with our campaign) have been reported by Parmar et al. (1999). The pulse period history indicates no other times of significant spin-down. However, there are gaps in the data that are long enough to contain unobserved ALS. The 1999 ALS is currently longer than 10 35 day cycles with a deviation of 25 \(\mu s\) (Coburn et al. 2000).

The pulse profiles during the ALS are similar to the profiles during the SHS and the tail-end of the MHS (Deeter et al. 1998; Coburn et al. 2000). In Figure 12 we show the pulse profile averaged over the orbital period during the ALS; this should be compared to Figure 3c of Coburn et al. (2000).

The orbital period during the SHS was determined by minimizing \(\chi^2\) between pulse-arrival times and a linear-plus-circular function following the method described in Still et al. (1994). This gives \(P_{\text{orb}} = 1.700167427(9)\) days at \(\text{JD } 2,451,005.229549(7)\) and \(P = -1.33(7) \times 10^{-8} \text{ days yr}^{-1}\) (Still et al. 2001b), consistent with the results of Deeter et al. (1991). The pulsations are too weak during the ALS to determine a period measurement with this technique.

No UV pulsations were detected in the 1999 data with upper limits of 1%; a pulse was marginally detected in the 1998 STIS data at phase 0.76. The probability that the feature is due to noise is about 1%. The pulse period measured was 1.23774 s with rms power of about 0.3% rms. Pulsations observed from Her X-1 in the UV during the main high state (Boroson et al. 1996) show an rms pulsed fraction of order 0.5%, 2-4 times that of the optical pulsed fraction and less than a tenth of the MHS X-ray pulsed fraction. The UV and optical pulses are in phase with the hard X-rays during orbital phases when X-ray dips occur.

Fig. 7.—(a) HST/STIS N v, C iv, and He ii at several orbital phases during the 1998 July campaign. (b) HST/STIS N v, C iv, and He ii at similar phases during the 1999 July campaign. The dashed lines superposed on both show the GHRS observations taken during a normal main high state in 1994 (Boroson et al. 1996).
The lack of UV/X-ray delay indicates that the dips and the UV pulses may originate in the same material near the line of sight (Joss et al. 1980; Boroson et al. 1996). The X-ray-pulsed fraction is down by a factor of 5 during the 1998 SHS relative to the MHS and down by a factor of 15 during the 1999 ALS, so it is likely that any UV pulsations are below our detection limit.

The STIS data obtained during the 1999 ALS showed evidence for QPOs at 6 and 43 mHz with rms fractions of 2% and 4% (Boroson et al. 2000b). The 6 mHz QPOs are also detectable in the GHRS data during the 1994 MHS. The optical photometric data from Calar Alto show QPOs similar to those observed in the UV (H. Fiedler et al. 2001, in preparation) during both 1998 and 1999. Data taken with the Keck telescope within a week of our 1998 observations showed 35 mHz QPOs in the optical (O’Brien et al. 2001).

We detected no QPOs in any of the simultaneous X-ray data, implying that the UV and optical QPOs cannot be due to reprocessed X-ray QPOs.

5. DOPPLER TOMOGRAPHY

A collection of orbitally resolved line spectra may be transformed into a kinematic map of the line-emitting regions in a binary system (Marsh & Horne 1988; Horne 1991). Certain structures within the binary system have well-defined positions on a Doppler map, e.g., the centers of mass and the Roche lobes of the donor and accretor. The disk appears as a diffuse ring in Doppler images with intensity increasing from its center outward. The disk emission peaks at the outermost part of the ring (which represents higher velocities than the center); emission from the innermost part of the disk is smeared out because of the high-velocity gradient there.

Such “Doppler tomograms” have been made of the lines in Her X-1’s optical spectrum, using data taken from ground-based observatories (Still et al. 1997; Quaintrell et al. 2001a), but spectral lines found in the optical are dominated by the heated inner face of HZ Her rather than the accretion disk. HST GHRS spectra showed evidence of disk emission (Boroson et al. 1996); consequently, we decided to construct maps of Her X-1’s UV lines in order to gain information about Her X-1’s accretion disk. The STIS observations described here represent the first UV data of an X-ray binary that are of sufficient spectral and temporal resolution to generate Doppler tomograms.

Prior to constructing the UV tomograms, the HST/STIS data that were obtained in TIMETAG mode were divided into 10 intervals per HST orbit, giving a total of 100 spectra.
during 1998 and 1990 during 1999, corresponding to bins of 1/500th the binary orbital period. The bins are not uniformly distributed over the orbital period.

Figure 13 shows Doppler tomograms produced using the

![Doppler tomograms](image)

**Fig. 10.**—log νF vs. log ν during several states. The dashed line in the 1998 July panel is the flux during the normal low state (visible at the end of the 1998 July light curves in Fig. 2).

1999 STIS data. These show that the majority of the UV emission-line fluxes (N v, O v, Si v, and He ii) are consistent with an origin on the X-ray–irradiated inner face of the donor star, HZ Her, rather than an accretion disk around the neutron star, Her X-1 (Fig. 13). From the Doppler maps it is evident that the heating over the inner face of HZ Her is not uniform, with the emission coming preferentially from the trailing side of HZ Her. This could be caused by shadowing from an accretion stream and/or disk. Similar asymmetric behavior is seen in the optical emission lines of N v j 4604, N iii j 4634 and 4641, and C iii j 4647 and 4650 (Quaintrell et al. 2001a). The O v line has an absorption feature centered on the velocity of the HZ Her center of mass; the Si iv lines are contaminated by a narrow interstellar absorption feature. P Cygni–like absorption features are observed on the blue wings of the N v j 1239, O v j 1371, Si iv j 1394, and C iv j 1548 emission lines during the ALS.

Tomograms made from the 1998 STIS data are consistent

![Tomograms](image)

**Fig. 9.**—Optical spectra from (a) 1998 SHS and (b)–(e) 1993 ALS

![Flux Density](image)


**Fig. 11.**—History of the pulse period. Error bars for ROSAT (Vrtilek et al. 1994), ASCA (Xu et al. 1995), BeppoSAX (Parmar et al. 1999; Oosterbroek et al. 2000; Coburn et al. 2000), and RXTE (Still et al. 2001a, 2001b; Parmar et al. 1999) observations are plotted. With the exception of a few pre-1981 points, other errors are smaller than the symbols used. [See the electronic edition of the Journal for a color version of this figure.]
Fig. 13.—Trailed spectrograms (upper panels), Doppler tomograms (middle panels), and computed trails (lower panels) of HZ Her’s UV emission lines using the 1999 STIS/E140M TIMETAGed data divided into 190 phased spectra. The gray scale goes from white to black with increasing flux, where white corresponds to the continuum level. Each line is plotted with a separate linear gray scale. Velocities of the primary, center of mass, and the neutron star (Reynolds et al. 1997) are marked by crosses. The primary and secondary Roche lobes are depicted by dashed and smooth lines, respectively.

Since Doppler tomography is particularly sensitive to narrow line emission and we have reason to believe that the \( \text{N}_\text{V} \) emission has two moving components, we generated separate tomograms for fits to the narrow component of the \( \text{N}_\text{V} \) lines and the residuals when the narrow line fits are subtracted from the data; the residuals should then reflect emission due to the \( \text{N}_\text{V} \) broad lines. The fits are entirely empirical; a physical model of the velocity and depth of absorption versus phase was not made. The narrow lines are represented by narrow Gaussians with absorption.

Figure 14 shows tomograms from the \( \text{N}_\text{V} \) data from 1999 (taking an average spectrum for each of the 19 HST orbits), from the fits to the narrow lines (from the 16 orbits in which good fits are found; the other three may be times when the narrow line is not present), and from the residuals when the narrow, line fits are subtracted from the data (these latter represent the contribution from the broad lines). The maps were constructed using Fourier-filtered back projection (FFBP), which is suitable for reasonably strong, unblended lines. The Fourier filter consists of a ramp that can cut out low wavenumbers and an exponential cutoff that can cut out noise. The user defines the cutoff, which can sharpen broad features in really good spectra but can also end up amplifying the noise. Hence, in Figure 15, we show the results from Figure 14 before application of Fourier filtering. The narrow lines are consistent with emission from the companion star, and the broad lines show weak emission that appears on or near the circle that defines the outer edge of the disk. A problem is that there is some emission inside the tidal circle, i.e., emission from material with too low a velocity to belong to a Keplerian accretion disk with parameters appropriate to Her X-1. The emission could be from material above the disk, such as a wind. At the disk precession phase during the 1999 observations, we expected to see emission from the heavily irradiated inner regions of the accretion disk; however, since the source was in an ALS, the neutron star and likely these very hot inner parts of the accretion disk were partially obscured.

The expected spatial distribution and the time-resolved line profiles in the optical and UV according to several disk models have been synthesized by Still et al. (1997) and Quaintrell et al. (2001a, 2001b). Disk emission dominated by X-ray reprocessing on the warped surface of such disks results in distinctive emission profiles. Their work indicates that if the accretion disk is assumed to be solely responsible for X-ray shadowing of the companion star, the models of Schandl (1996), Schandl & Meyer (1994), Wijers & Pringle (1999), and Larwood (1998) can be excluded.

6. DISCUSSION AND CONCLUSIONS

Overall, the pulse period of Her X-1 shows a secular decrease or spin-up, as is expected for a system accreting mass (and, hence, angular momentum). However, during
FIG. 14.—Doppler tomograms from 1999 N v data with each of 19 HST orbits binned as one spectrum, narrow N v fits to 16 spectra (empirical using Gaussians), and residuals. The gray scale goes from white to black with increasing flux, where white corresponds to the continuum level. Each panel is plotted on a separate linear scale. In addition to the Roche lobes and center of mass velocities, the gas stream trajectory (solid lines originating from the inner Lagrangian point) and the Keplerian velocity along the gas stream (dotted lines originating close to the centroid of the secondary lobe) are indicated. Both trajectories are marked by circles in steps of 10% of the distance between the inner Lagrangian point and the neutron star.

ALS, the system shows a distinct spin-down. The ALS are characterized by substantial, unexpected drops in X-ray flux, with no substantial change in absorbing column density, little or no change in UV and optical fluxes, and an increase in pulse period. The lack of pulses above 1 keV during the ALS suggested by Vrtilek et al. (1994) is likely the result of an inadequate signal-to-noise ratio: pulses above 1 keV with the rms pulsed fraction down by a factor of 14 from that during the normal MHS of Her X-1 have recently been reported (Coburn et al. 2000). We have detected pulses at a similar level during the 1999 ALS. With the exception of the increase in pulse period and the degree of X-ray flux reduction, these characteristics are similar to those observed during normal 35 day LS. However, during ALS states, the turn-on of the MHS has been seen to drift by over 6 days—or twice the normal maximum excursion of 3 days (Ögelman et al. 1987). The degree of deviation from spin-up appears to be positively correlated with duration of the ALS. This correlation is consistent with our interpretation of the ALS in terms of a change in mass accretion rate that causes the disk to tilt and twist beyond the normal deviations causing the 35 day cycle. A larger deviation from the average $M$ would result in a stronger disruption of the disk causing it to take longer to settle back to its “normal” 35 day behavior. The correlation between times of low hard X-ray luminosity and episodes of spin-down is predicted by models which suggest that a decrease in mass accretion rate causes the Alfvén radius, at which material joins the magnetosphere, to move out, thereby increasing the drag-producing torques of the field lines threading the disk outside the corotation radius, leading to spin-down (Ghosh & Lamb 1979). The question of paramount interest then becomes: what causes the sudden changes in mass accretion rate in the first place? If we accept the Ghosh & Lamb
model, we must conclude that the mass accretion rate can decrease rapidly but can never increase rapidly since no episodes of sudden spin-up have been detected.

We note that the SHS observed by us in 1998 appears to be the last “normal” SHS before onset of the ALS. For several superorbital cycles preceding the ALS, no SHS are distinguished, and the MHS flux drops with each succeeding cycle. This fact, combined with the similar X-ray spectral shapes during the LS and ALS, is consistent with the interpretation of Vrtilek & Cheng (1996) that the ALS and LS are both due to occultation of the X-ray source by the accretion disk.

Extensive work has been done on the orbital period evolution of Her X-1 using *Ginga* data by Deeter et al. (1991). They find the orbital period to be decreasing at an average rate of $-2 \times 10^{-8}$ days yr$^{-1}$ over the interval 1971–1998. If all the mass lost by the companion is accreted by the neutron star, the mass transfer rate needed to explain the decrease in orbital period is $1.4 \times 10^{-8} M_{\odot}$ yr$^{-1}$, nearly an order of magnitude greater than the mass-loss rate required to provide the observed X-ray luminosity. Mass loss through a simple self-excited wind also cannot explain the observed period decrease. Braking of the companion star by a magnetically channelled stellar wind provides a mechanism for the angular momentum loss rate. While the UV spectra during the normal states do not show the presence of P Cygni profiles, the Doppler tomograms constructed with our STIS UV data suggest modest line shifts indicative of wind flows; P Cygni profiles are present during the ALS. It is possible that the high X-ray luminosity during the regular states ionizes the material in the wind flows (Hatchett-McCray effect), precluding spectroscopic detection of a wind.

Deeter et al. (1991) note that the data are consistent with the total decrease in pulse period occurring during a single glitch, which could be associated with the ALS of 1983. The orbital period and $\dot{P}$ determined by us during the SHS is consistent with a single glitch associated with the ALS of 1983 (Still et al. 2001b). Further analysis of data from *BeppoSAX* and *RXTE* are necessary to determine if ALS are related to shifts in orbital period. As suggested by Deeter et al. (1998), analysis of *EXOSAT* data immediately following the 1983 ALS could verify or disprove the hypothesis that the observed orbital phase decrease is con-
sistent with a single glitch. As far as we know, no suitable data are available following the 1993 ALS for such a study. However, analysis of data from BeppoSAX and RXTE when Her X-1 emerges from its current ALS will also help to determine if shifts in orbital period are directly related to ALS.

Doppler tomograms constructed from the UV emission-line data indicate that the majority of the UV emission-line flux comes from the X-ray–irradiated inner face of the donor star, HZ Her, rather than an accretion disk around the NS, Her X-1. Doppler tomograms of most optical emission lines (the exception is He II λ4686, which appears to be associated with disk emission) also indicate origin on the inner face of the donor star (Still et al. 1997; Quaintrell et al. 2001a). The heating over the inner face of HZ Her does not appear uniform, with the emission coming preferentially from the trailing side of HZ Her. However, tomograms constructed from the fits to the narrow N V lines show emission more closely matched with the tip of HZ Her, suggesting that the narrow lines are offset in the N V tomogram because of effects of N V absorption. Lines in which strong absorption is not expected (O V and He II) also show narrow lines whose tomograms more closely match with the tip of HZ Her. The lack of uniformity over the inner face of HZ Her may also imply shadowing from an accretion stream and/or disk. Tomograms constructed with the broad lines alone indicate emission from a more extended region that may be associated with segments of a distorted disk. Since the HST observations were made when the source was in an ALS, it is likely that the NS, and possibly the very hot inner parts of the accretion disk, were obscured.

The multiwavelength campaigns that we conducted on the Her X-1 system in 1993 and in 1999 were meant to capture 35 day MHSs; however, in both instances the system was found to be in an ALS. The Doppler tomograms constructed from the ALS and SHS data are consistent with our model explaining the multiwavelength behavior of Her X-1/HZ Her in terms of X-ray heating of the disk and companion star, shadowing of the X-ray flux by the disk, and a contribution to the continuum emission from the accretion stream or hot spot. However, while high-resolution UV observations around a full binary orbit during an MHS have been hard to come by, they are essential if we want to utilize Doppler tomograms to determine if the disk structure changes with precession phase.

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