Spectral Evolution of Her X-1 over the 35-Day Cycle

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Abstract

Her X-1 is an unusual accretion-powered pulsar system exhibiting a great wealth of phenomena. This eclipsing system contains a 1.24 second period pulsar in a 1.7 day circular orbit with its optical companion HZ Her. In addition, the system displays a longer 35-day cycle. This cycle has Main High and Short High states, lasting about ten and five days respectively, which are separated by ten day long Low states. Here the changes in X-ray spectrum observed with the GINGA satellite are studied as a function of the 35-day cycle. The spectral changes are discussed in terms of physical causes, such as the effects of the precessing accretion disk in Her X-1.

1 Introduction:

Her X-1 is a well known x-ray pulsar with processes occuring on a variety of interesting timescales. Here the goal is to study further the 35-day cycle by studying the changes in x-ray spectrum. The x-ray intensity is strongly modulated on the 35-day period, with a high state followed by a low state, another less bright high state (called the short high state) followed by a second low state.

A comprehensive set of observations of the 35-day cycle by the Rossi X-ray Timing Explorer (RXTE) All-Sky Monitor (ASM) have been analyzed, and the properties of the 35-day cycle were reviewed, in Scott & Leahy (1999). The 35 day cycle is generally accepted as due to varying obscuration of the pulsar by a tilted precessing accretion disk (e.g. see Ogelman et al 1985 and references therein). However the details are not yet well understood. A review of many of the competing theories for the 35-day cycle is given by Priedhorsky and Holt (1987).

Her X-1 has been studied with several previous satellite instruments. Pravdo et al. (1978) fit the OSO-8 spectrum with a power-law-with-cutoff model and find a pulse phase dependence of the spectrum, primarily in power law index. Becker et al. (1977) find evidence in the OSO-8 spectra for variations in absorption during the turn-on, using the same power-law-with-cutoff model. Variations in absorption are also seen in Tenma observations (Ohashi et al., 1984, Ushimaru et al., 1989). EXOSAT observed an extended low state of Her X-1 in 1983 (Parmar et al. 1985). EXOSAT observations of high state eclipse egresses were analyzed to study the structure of the atmosphere of HZ Her (Day et al. 1988). Soong et al. (1990) report a HEAO-1 observation of Her X-1.

Spectra from only small portions of the set of GINGA observations have been studied previously, although Leahy (1995a) has studied light curves and color variations for the whole data set. Mihara et al. (1990), using GINGA data give unambiguous evidence for the cyclotron absorption feature near 35 keV. Mihara et al. (1991) find a two component emission model is needed to model the low-state spectrum. The high state spectrum of Her X-1 was shown to also require a two component continuum model (Leahy et al. 1991). A detailed study of spectral changes during pre-eclipse dips for Her X-1 is presented in Leahy et al. (1994). Spectra during eclipses have been studied by Leahy & Yoshida (1995) and Leahy (1995b).

Here is given a summary of the spectral analysis of the comprehensive set of Ginga observations, to give an observational picture of spectral changes in Her X-1 over its 35 day cycle.

2 Observations and Spectrum Analysis

The observations of Her X-1 were taken by GINGA in several time periods between 1988 August and 1989 June. The set of observations is described in more detail in Leahy (1995a). A summary of the data is given here in Table 1. The GINGA observations covered a comprehensive range of 35- day phase as can be seen from Table 1. The data coverage includes the important phases of the 35-day cycle: low state, early main high, mid main high, late main high, early short high, mid short high, and late short high.

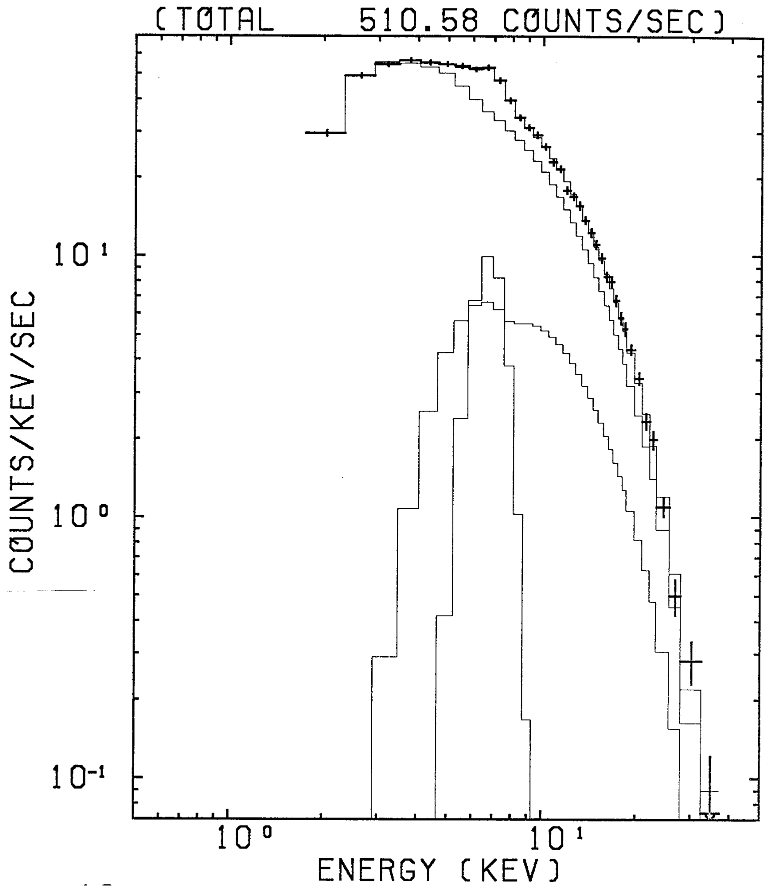

Figure 1: The GINGA spectrum of Her X-1 during the bright part of the short high state, and best-fit two component continuum model.

Spectra were constructed for all of the data, as listed in Table 1. For each day of observation, the satellite typically made three to eight earth orbits, with only part of each earth orbit available for on-source observing. Thus the spectra were generally constructed on the basis of one spectrum per satellite orbit. Spectra that occured during times of other Her X-1 events were excluded from this analysis. Such events include pre-eclipse and anomalous dips, and eclipse ingresses and egresses. The GINGA spectral analysis software was used to model the spectra. This software includes a large number of spectral models, the GINGA instrument response, and a non-linear least squares fitting routine.

Previous analyses of spectra of Her X-1 have shown that a two-component spectrum is required to model the spectrum during various parts of the 35-day cycle: Mihara et al. (1991) for the low state; and Leahy et al. (1991) for the high state, both for times when dips are present and times when dips are not present.

Here it is first demonstrated that short high state requires a two- continuum component spectrum. The GINGA spectrum from the brightest part of the short high state (from data taken on 1989 May 4) is shown in Figure 1 with the best fit two continuum component model. In Fig. 1 (and Fig. 2 below): the crosses are the data (with the width representing the energy bin width and the height giving the $\pm 1\sigma$ error bars); the narrow histogram is the iron line folded with the intrument response (thus demonstrating the instrument resolution); the histogram which turns over sharply at low energy (below $\sim 3-4\ keV$) is the absorbed cyclotron continuum component; the histogram which is relatively flat at low energy is the unabsorbed cyclotron continuum; and the histogram which goes through the data points is the sum of the above model components.

The short high state spectrum cannot be fit by any single continuum component model, even allowing for cold matter absorption and fluorescent iron line emission. However it can be fit by the same two component model as used previously for main high and low state: two cyclotron continuum components, one with no absorption and the second with significant cold matter absorption; and fluorescent iron line emission. See Leahy et al. (1994) for a complete description of the spectral model.

For comparison, Figure 2 shows the GINGA spectrum taken during the main part of the main high state (from data taken on 1989 April 30) with the best fit two component continuum model. The major differences between this spectrum and the short high spectrum are: the count rate is much higher; the absorbed component for the main high spectrum is much weaker; and the absorbed component for the main high spectrum has a much higher column density for cold matter absorption. These differences are consistent in comparing main high spectra with short high spectra.

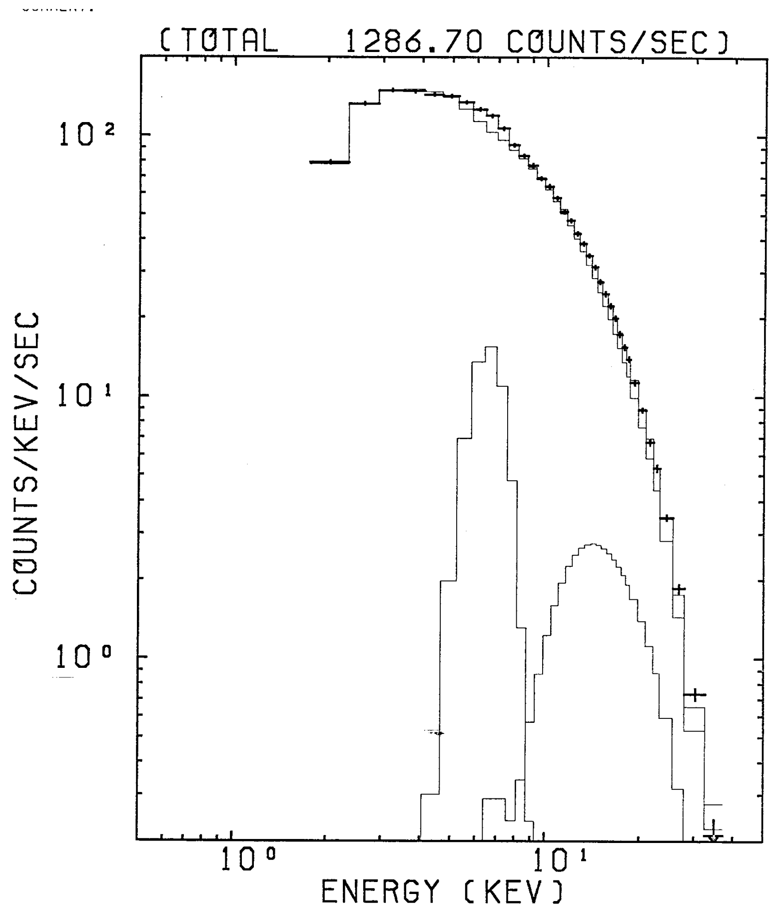

Figure 2: The GINGA spectrum of Her X-1 during the bright part of the main high state, and best-fit two component continuum model.

Similar to the two example spectra presented, satisfactory spectral fits to all of the GINGA spectra of Her X-1, at all 35-day phases, were obtained using the two component continuum model.

3 Discussion

The physical interpretation of the two component model is as follows. The unabsorbed continuum component can originate directly from the pulsar or be such radiation which undergoes electron scattering, such as by an ionized corona on the accretion disk. The absorbed continuum component can be line-of-sight radiation from the pulsar which passes through absorbing matter, such as the edge of the disk. Or it can be such radiation which undergoes electron scattering. The amount of absorbed and unabsorbed radiation provides useful constraints. For example, during the low state there is no direct unabsorbed or line-of-sight absorbed radiation from the pulsar, so the GINGA spectra during low state give a direct measure of the electron scattered components. Comparing this to the strength of these components during the main high state when there is no obscuration to the pulsar, allows one to measure the amount of electron scattering material in the system.

A further goal is to combine the present measurements of absorption and scattering with the knowledge about the accretion disk from studies of pulse shape changes and optical shadowing measurements to obtain a more complete picture of the Her X-1 system.

References

Table 1: GINGA observations of Her X-1

Date	MJD	Orbital Phase	UT Interval	35-d Phase
1988,8,17	47390	.413-.503	21:01:53-00:41:21	0.78
1988,8,19	47392	.555-.599	19:35:36-21:24:08	0.84
1988,8,28	47401	.735-.849	14:57:32-19:38:00	0.09
1988,9,01	47405	.082-.216	14:43:48-20:11:52	0.21
1989,4,26	47642	.582-.662	18:54:43-22:13:07	0.02
1989,4,27	47643	.087-.299	15:31:31-00:09:30	0.05
1989,4,30	47646	.867-.021	16:08:50-22:24:34	0.13
1989,5,01	47647	.441-.575	15:34:46-21:01:58	0.16
1989,5,02	47648	.002-.022	14:28:30-15:26:06	0.18
1989,5,03	47649	.578-.742	13:56:54-20:37:58	0.22
1989,5,04	47650	.166-.332	13:57:14-20:44:38	0.24
1989,5,16-17	47662	.049- .839	06:48:50 -15:02:10	0.58
1989,5,18	47664	.264-.384	08:23:18-13:17:38	0.64
1989,5,19	47665	.812-.973	06:44:18-13:19:14	0.67
1989,5,20	47666	.438-.561	08:16:54-13:18:10	0.70
1989,6,02-3	47679	.453- .614	23:19:29 -05:53:05	0.09
1989,6,05-6	47682	.587-.746	21:36:41 -04:05:01	0.17
1989,6,08	47685	.307-.346	19:46:53-21:23:45	0.25
1989,6,09	47686	.499-.775	03:36:17-14:52:33	0.27

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