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Magnetic Features in the Spectrum of Her X-1

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Spectral study of three observations of the accreting X-ray pulsar Her X-1 during RXTE observing round 1 show that the values of two spectral parameters, the cut energy and the cyclotron line centroid, appear to be much more stable than for the other shape parameters. These two parameters have been closely linked to the strength of the teragauss magnetic field above the polar cap of the neutron star. The RMS stability of 1% implies an equal constraint on the average value of the magnetic field at the site of emission, and in a dipole field this constrains the average height of emission to within 50 meters. It may be possible to discriminate between emission in the very thin neutron star atmosphere and in an extensive accretion mound.

1. INTRODUCTION

The accreting x-ray pulsar, Hercules X-1, emits a spectrum with a localized feature at about 35 keV which has been observed repeatedly and is generally interpreted as an absorption line resulting from transitions between quantized levels in an intense magnetic field at the neutron star's polar cap. It thus affords a diagnostic of plasmas under such extreme conditions, as well as providing a key to the structure of the magnetosphere and to the mass flow. RXTE has observed Her X-1 three times in observing round 1 with 10000 seconds for the shortest observation. This rich data set permits spectral analysis to a new level of precision. We have analyzed the average spectra from each of these three sets [1] and find that the line centroid and break energy remain steady to about one percent, while the other spectral shape parameters vary by ten percent. Possible interpretations are 1) the cutoff energy is a feature imposed by the strong magnetic field, just as for the cyclotron line and 2) the geometrical region of emission is stable with respect to the magnetic field to within about 50 meters.

Detection of cycloton lines has been claimed for nine accreting x-ray pulsars [2], but repeated measurements have been made only for Her X-1. The large area and wide energy range of RXTE and SAX have made it possible for the first time to pursue sensitive detailed spectroscopy on this class of object, as well as studies of variability and its converse, stability.

2. RXTE OBSERVATIONS AND ANALYSIS

Average spectra were accumulated from each of the three RXTE observations of Her X-1 in observing round 1, from in-orbit checkout data in February, from a deep exposure in July, and from a monitoring campaign in Sept/Oct. Exposures for the three average spectra averaged 25000 sec. Data from the monitoring campaign were selected to be during the "High-On" phase, lasting about 10 days, of the 35-day cycle.

The standard suite, sometimes the development versions, of XTE Ftools was used to accumulate phase-average spectra for each of the three data sets. A substantial live-time correction was applied to the HEXTE data and background was directly measured from the 16-second rocking. For PCA data the released background model produced an obvious overestimate of the detector background at higher energies, so in analysis the PCA data was limited to energies less than

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27 keV. Although pulse-phase resolved spectra were accumulated for portions of these observations, only phase-averaged spectra were used in this analysis.

The HEXTE response matrices did not produce noticeable systematics in the fits, but the PCA data showed clearly 1-2 percent ripples in the residuals to fits, which we attribute to errors in the matrix. The effect of these systematics on the fit results was reduced by applying a 1 percent systematic error to each channel with xspec, and by excluding PCA channels below 4 keV.

Since the goal was to measure stability of the spectral shape and to permit comparison with earlier results, the traditional power-law continuum with high-energy cutoff model was employed in fitting with xspec, even though this model has a discontinuous first derivative at the cut-off energy and can thus introduce an artifact, an apparent absorption line, at this energy. Figure 1 shows results of a fit to the July data.

3. RESULTS FROM RXTE ROUND 1

Table 1 displays aspects of the best fits of the data, conditioned as described above, to the model of a power law continuum with exponential cutoff with single Gaussian absorption line. No convincing evidence was obtained for a harmonic overtone of the line.

The numbers in parentheses are the 90 percent confidence limits from the joint fit, and apply to the final decimal places of the best-fit value. The reduced chi-squares are very poor, but the dominant contribution appears to be from the inaccuracy of the PCA response matrix. The next largest appears to be from incorrect PCA background subtraction above 20 keV. A more interesting pattern consists of low residuals on the low-energy side of the 39 keV line, and high residuals on the other side. Clearly, the subtractive gaussian line profile incorrectly describes the data, and the next attempt should be with a multiplicative line. Such a form makes more physical sense anyway, because it is likely that the line is a resonance absorption of the continuum.

The formal errors of the fits are so small that it makes sense to compare the shape parameters of the three observations in terms of their dispersions, expressed as RMS. One sees that three of the five parameters have RMS about 10 percent of the mean value, while two, the cutoff and line centroid, are stable to one percent. The chance probability that the true RMS for these quantities is near 10 percent, like the other parameters, seems very small, of the order of the gaussian integral probability P(0.1) - P(-0.1) cubed, or $(0.08)^3 = 0.0005$.

The power law index, the e-folding energy, and the 38 keV line width are thus seen to be variable on a 10 percent scale on timescales of months. This is about the level seen for variability of the index from previous experiments (see [3] and references therein), although intercalibration errors have certainly contributed in the past. The fold energy is more variable than was seen in the HEAO-1 data [4], which had a number of looks and good statistics. The sensitive measurement of the line width and its variability is new to this set of observations. Previous scintillator measurements (see [3], [4]) were severely limited by detector resolution comparable to or larger than the line width. Although having better resolution than scintillators, observations to date above 20 keV with proportional counters [5] and germanium [6] have been limited by counting statistics. The pulsation waveform of her X-1 has been convincingly shown [7] to vary regularly with 35-day phase. Although no spectral variation with 35-day phase has been reported, some caution is warranted, and it is worth mentioning that the spectra analyzed in this study represent a well-sampled average over the 10-day main-on state.

The very stable values for the cut energy and line centroid are new and surprising. The value of about 18 keV for the cut energy is different from that obtained in scintillator experiments (e. g. [4], 20 keV or higher, or even with proportional counters, where a value of 20 keV is also reported [8]. The present measurements should be considered superior because they have very good spectal leverage with good statistics to both sides of the cutoff energy. The measurement of the line centroid also differs from earlier scintillator measurements, which centered near 35 keV [3]. The cause of this disparity is not understood, but the

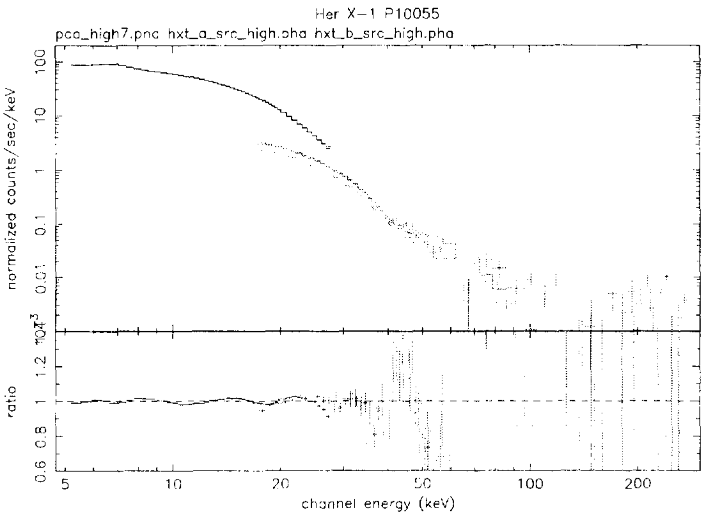

Figure 1. Results of fitting a cutoff powerlaw with a negative 38 keV Gaussian line to a portion of the 50 ksec July observation. See table for best-fit parameters of the fit.

present result should be more reliable because of the combination of better statistics and much better detector resolution. The stability of the values of these spectral parameters in the three observations is surprising in light of the variability of the other parameters, and the factor of two variability of the overall x-ray flux level.

4. INTERPRETATION

The 38-keV line is widely regarded to result from resonance absorption of electrons in a 3×10^{12} Gauss magnetic field [9]. In fact, the line centroid is usually accepted as providing a direct measure of the field strength at the site of emission above the polar cap of the neutron star [10]. Likewise, the cutoff energy has been interpreted [11] as resulting from the onset of opacity in an extreme magnetic field of this order. If both are accepted as measures of the magnetic field strength, then it is very natural to conclude that the average magnetic field in the region of emission into the line of sight remains nearly constant for the three observations. Since the magnetic field is anchored on the neutron star, the average height of emission of the line photons also is constrained. This one percent RMS corresponds to a 50 meter constraint on the average height of emission for a dipole field, and 20 meter for quadrupole, after an r^{-1} is subtracted for gravitational blueshift with increasing height above the pole.

There seems to be no general agreement on the structure of the radiating region of the polar cap of an x-ray pulsar. If a shock forms in the flow above the pole there could be an accretion mound (e. g. [12]) of some extent. Some theorists, most recently Bulik *et al.* [13] assume that deceleration of the accretion flow takes place in the neutron star atmosphere, with a scale height of probably less than a meter. These RXTE results are automatically consistent with the latter scenario, but they do not necessarily constrain the accretion mound scenario unless the accretion mound can be shown to be hundreds of meters or more in height. However, if the observed line sigma of 7 keV or 15% is due to a mix of magnetic field

Table 1
Results of Spectral Fitting

parameter	Feb	July	Oct	mean	RMS
continuum					
norm(2-10)	2353(2)	1671(1)	1128(1)		
index	.931(1)	.788(1)	.870(1)	.863	.072
cutoff	17.95(5)	17.83(2)	17.53(3)	17.77	.22
fold	15.41(20)	15.04(6)	12.72(9)	14.4	1.5
Fe line					
norm	.00629(8)	.00488(3)	.00395(4)		
abs. line					
norm	.0153(10)	.0162(4)	.0047(4)		
centroid	39.27(36)	38.68(15)	38.74(32)	38.90	.32
sigma	7.46(39)	8.43(16)	6.54(35)	7.48	.94
chi-square	2.8	9.5	4.5		

strengths in a dipole field, then the mound must have a height of at least 750 meters.

The model of Burnard, Arons and Klein [12] gives for the parameters of Her X-1 a mound of height 600 meters, and this height has an inverse dependence on luminosity. If the typical photon comes from half the peak height, then the decrease in line centroid should be about 1.5% for a factor of two decrease in luminosity, if the observed x-ray luminosity accurately reflects the mass transfer rate. The three RXTE observations in fact span about a factor of two in x-ray intensity, and the observed decrease of 1.1 ± 1.0 %, while not significantly different from zero, at least has the right sign and is consistent in magnitude with the model. Thus, while a significant improvement, the RXTE data cannot yet decide between two interesting models for the structure of the emitting region, but give support for both. It is useful here to recall that the observation of a change of line centroid with pulse phase [4] rather favors the accretion mound model over the thin atmosphere model of Bulik *et al.* [13].

The implications of this study can be extended to the entire class of X-ray pulsars: while cyclotron lines have been claimed for only nine sources, power-law to exponential breaks are a general feature of the spectra of X-ray pulsars. If this identification of the cutoff energy as a magnetic feature is accepted, then this feature provides a measure of the magnetic field strength in all x-ray pulsars in which it can be observed, and the more certain knowledge of the magnetic field may positively affect the study of the evolution and formation of neutron stars.

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