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MEASUREMENT OF THE SPECTRUM OF OPTICAL PULSATIONS FROM HZ HERCULIS/HERCULES X-1

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also included tube noise from between scans, only the remaining 255 channels will be considered below.) In addition, high resolution spectra (20 minute integrations) using all 2048 scanner channels ($\sim$ 1 Å in width) were independently recorded. With the 4" slit used, the IDS had a resolution (FWHM) of 8 Å.

The high resolution spectrum for the entire run is shown in Fig. 1. Since the sky was not photometric for the entire run and the transparency was not monitored continuously, the normalization, particularly below 4000 Å, may not be precise. For reference, the shapes of representative blackbody curves are also shown. HZ Her is not isothermal at this binary phase, so detailed comparisons are not meaningful, but it is useful to note that the spectrum can be roughly characterized as a blackbody spectrum with $T \sim 14000\ ^\circ K$. The emission features λ 4640 and λ 4686 are apparent, with equivalent widths of $\sim$ 2.0 Å and $\sim$ 1.4 Å respectively, and these lines are essentially constant in strength throughout the run. (It is possible that the feature N III $\lambda\lambda$ 4634 - 4641 is blended with C III λ 4650 (see Crampton and Hutchings 1974); we do not have sufficient resolution to distinguish these lines.) The prominent absorption features Hβ and Hγ have equivalent widths of $\sim$ 6.8 Å and $\sim$ 5.6 Å respectively, and also persist throughout the run.

The time-resolved (255 channel) spectra were analyzed for optical pulsations. To determine the phase and frequency of the broadband signal, the photons in each 10 ms spectrum were summed over wavelength to give the total number of counts in successive 10 ms intervals. The resulting data string ($\sim 2^{20}$ points) was Fourier transformed and analyzed as described in Paper I. The (linear) change in the frequency with time was determined to be small ($< 10^{-8}$ Hz s^{-1}) and will not be considered further. The results of this broadband analysis are summarized in table 1 and are consistent with the data and model described in Paper I. Pulsed fraction (pulsed flux divided by average total flux) is shown as a function of time in Fig. 2. The low level of pulsations detected in the 6th point is unexpected. Although we have not found any instrumental effect which could account for this, we do not feel that a discussion of possible causes within the binary system is appropriate here.

Once the precise pulsation frequency was determined from the broadband Fourier transform, the data strings for each of the 255 wavelength channels were individually signal averaged at this frequency. Before we present the results of this procedure, however, a brief discussion of the analysis is in order. The complex Fourier amplitude $A(\omega)$ is defined in the usual way as

$$A(\omega) = \sum_{j=0}^{N-1} n_j e^{-i\omega j\tau} \tag{1}$$

where ω is the (angular) frequency and the n_j ($j = 0, 1, \ldots, N-1$) are the numbers of photons arriving in N contiguous time bins of duration τ. For N large, the $A(\omega)$ have two important properties:

(i). If the n_j describe a sine wave of frequency $\omega_0 << 2\pi/\tau$, i. e., $n_j = \alpha[1 + \cos(\omega_0 j\tau + \phi)]$, then

$$A(\omega_0) = \tfrac{1}{2} N \alpha e^{i\phi} \tag{2}$$

(ii). If the data is dominated by noise, the power $p(\omega) = |A(\omega)|^2$ will be distributed with an exponential probability density $\mathcal{P}$ (cf. Paper I):

$$\mathcal{P}(p/\bar{p})\, d(p/\bar{p}) = e^{-(p/\bar{p})} d(p/\bar{p}) \qquad (3)$$

where $\bar{p}$ is the average value of the power at frequencies close to but excluding the frequency of interest.

It is convenient to define the normalized Fourier amplitude $A'(\omega)$ as

$$A'(\omega) = A(\omega)\, \bar{p}^{\,-\frac{1}{2}} \qquad (4)$$

One can show under the same assumptions which lead to equation (3) that the real and imaginary parts of $A'(\omega)$ will have Gaussian distributions with $\sigma^2 = \frac{1}{2}$, centered at the origin. Thus, for the frequency of interest, $A'(\omega_0)$ contains both amplitude and phase information about the signal, and the errors on these quantities are determined by the $\pm \frac{1}{\sqrt{2}}$ statistical errors on the real and imaginary parts of $A'(\omega_0)$. In the following, the phase of the broadband signal has been arbitrarily chosen to be 0°, so the broadband amplitude is real and positive.

A scatter plot of the normalized Fourier amplitudes $A'_k(\omega_0)$, $k = 1, 2, \ldots, 255$, corresponding to the 255 wavelength channels, now provides a convenient and direct representation of the wavelength distribution of the optical pulsations from HZ Her. To show this, let us first consider two extreme cases for this distribution and suppose, as a first approximation, that each wavelength channel contains an equal number of photons. If the entire broadband signal, $|A'|^2 = 63.5$, were to lie in a single wavelength channel k_o, then (since $\bar{p}$ scales as the variance of the input distribution and therefore roughly as the number of channels considered) we would have $A'_{k_o} \approx \sqrt{63.5 \times 255} \approx 127$, with the remaining amplitudes clustered about the origin. If, on the other hand, the signal were equally distributed amoung <u>all</u> wavelengths, then the entire distribution of normalized amplitudes should be clustered about the point $\sqrt{63.5/255} \approx 0.5$ on the real axis.

To establish the normalizing parameter $\bar{p}_k$ for the kth wavelength channel we assume that $\bar{p}_k = \beta\, Ns_k^2$, where s_k^2 is the mean squared deviation of the kth channel (found from the time domain data) and β is a wavelength independent parameter which equals unity for a Poisson distribution. We have determined β by analyzing the data at two nearby frequencies, above and below the frequency of interest. Since the off-frequency data contain no signal, the size of the statistical fluctuations seen there define $\beta(= 1.47)$. Figure 3a shows the distribution of the 255 normalized amplitudes at one such nearby frequency.

The normalized amplitudes at the correct pulsation frequency are shown in Fig. 3b. The most evident characteristic is a 0.6 unit displacement of the centroid of the distribution, suggestive of simple broadband pulsations of constant (wavelength independent) pulsed fraction; no excess of pulsations at any wavelength is apparent. To take account of the fact that the number of detected photons per wavelength interval varied substantially over the observed spectrum, we have subtracted the contribution of a constant pulsed fraction of 0.2% from each amplitude and the resulting distribution is shown in Fig. 3c. The close similarity between Fig. 3c and 3a shows that, at least qualititively, a fixed pulsed fraction, independent of wavelength, is a good description of the spectral distribution of the signal.

Because of their special interest, the amplitudes corresponding to the emission features λ 4640 and λ 4686 are shown separately (uncorrected for broadband contribution) in Fig. 3d. It is clear that these amplitudes do not have large components in the direction specified by the broadband pulse phase (positive real axis) and therefore the corresponding features do not contribute significantly to the observed pulsations. We have derived upper limits (90% confidence) of 0.055 and 0.07 for the pulsed fractions at any phase for the features λ 4640 and λ 4686 respectively. This corresponds to a total pulsed equivalent width of ∿ 0.2 Å, an order of magnitude smaller than that reported by DMM.

The foregoing analysis can be made more quantitative as follows. The 255 points on a graph of pulsed fraction versus wavelength were successfully fit with <u>no</u> assumed wavelength dependence ($\chi^2 = 254.4$, 254 degrees of freedom), yielding a mean pulsed fraction m of 1.99×10^{-3}. If 50 or more wavelength channels had no signal present, an unacceptably large χ^2 would have resulted; the signal must therefore be present in at least 200 of the wavelength channels. If we assume that a linear term is present, i.e., that the pulsed fraction varies linearly with wavelength from $m(1 + \delta)$ at 3500 Å to $m(1 - \delta)$ at 6000 Å, then we find $\delta = -0.13 \pm 0.17$ ($\chi^2 = 253.9$). If we now assume that δ is a measure of the temperature difference between the total and pulsed radiation (both assumed to have blackbody spectra) and $T = 14000\ ^{\circ}K$ for the total (unpulsed) radiation, then we find $T = 11000^{+4000}_{-2000}\ ^{\circ}K$ as the color temperature of the pulsation-emitting region. This similarity between the pulsed and unpulsed spectra suggests that the pulsations arise from the same mechanism that is responsible for most of the unpulsed light from HZ Her, presumably blackbody re-radiation of the incident X-ray energy.

DISCUSSION

Because of the strong disagreement between our results and those of DMM, some further discussion is warranted. We first note that we have attempted to reproduce these latter results using equipment and analysis programs identical to those of DMM, but without success. Out of 10 nights of observations in 1975, all at appropriate binary phases, no statistically significant signals were seen through the narrow band interference filter covering 4620 - 4720 Å, although broadband pulsations were detected during 4 of the runs.

Our results might seem to indicate that the reported pulsed emission lines of DMM were transient events, which, for example, could result from the occasional presence of strongly pulsed soft X-rays. However, this interpretation leaves unresolved the reported phase agreement between the broadband and emission line pulsations of DMM. This phase agreement (within the $\pm\ 20^{\circ}$ experimental errors) is difficult to understand if the broadband pulsations are in fact distributed throughout the continuum (as our data indicates) and not simply due to other pulsing emission features (for example, filled-in Balmer absorption lines, as

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