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Spectral and timing behaviour of GS 2023+338

T. Oosterbroek1, M. van der Klis1, J. van Paradijs1,2, B. Vaughan1, R. Rutledge3, W.H.G. Lewin3, Y. Tanaka4, F. Nagase4, T. Dotani5, K. Mitsuda5, and S. Miyamoto5

1 Astronomical Institute “Anton Pannekoek”, University of Amsterdam, and Center for High Energy Astrophysics, Kruislaan 403, 1098 SJ Amsterdam
2 Physics Department, University of Alabama, Huntsville, AL 35899, USA
3 Massachusetts Institute of Technology, 37-627, Cambridge, MA 02139, USA
4 Institute of Space and Astronautical Science, Yoshinodai 3-1-1, Sagamihara, 229 Kanagawa, Japan
5 Osaka University of Health and Sports Science, Noda 1558-1, Kumorituri-cho, Sennan-gun, Osaka 590-04, Japan

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Abstract. We have studied the spectral and rapid variations of GS 2023+338 using all Ginga (LAC) data available of this source. We used colour-colour and hardness-intensity diagrams to study the spectral behaviour and for the variability behaviour we used the FFT-technique to obtain power spectra, the energy dependence of the variability and the energy dependence of the phase delays. We find that the spectral behaviour is strongly influenced by changes in the local absorption. These changes also influence the variability at low photon energies and relatively long time scales (≈1 s). The global shape of the power spectra of GS 2023+338 is similar to that of other black hole candidates in the “low” (hard) state, however, small differences are present in the detailed power spectral shape between those sources.

Key words: accretion, accretion disks – X-rays: stars – stars: individual: GS 2023+338

1. Introduction

The X-ray transient GS 2023+338 was discovered with Ginga (Makino et al. 1989) during an outburst in 1989. The optical counterpart was identified as the old Nova Cygni 1938 (V404 Cygni, Wagner et al. 1989). From optical spectroscopy Casares, Charles & Taylor (1992) found that the mass function is 6.26±0.31 M⊙ which makes it the most convincing stellar-mass Black-Hole Candidate (BHC) currently known. Casares and Charles (1994) further refined the mass function to be: 6.08±0.06 M⊙. Modelling of the ellipsoidal variations of the source by Shahbaz et al. (1994) led to a most probable mass of the compact object of 12 M⊙ (see however, Hasswell 1992, who argued, for A 0620−00, that superhump variations with a period different from the orbital period may lead to distortions of the orbital lightcurve and incorrect parameter estimates)

Observations of GS 2023+338 with Ginga (All Sky Monitor and Large-Area Counters) have been reported by Kitamoto et al. (1989). Spectral variations were studied by In ’t Zand et al. (1992) using data from Kvant. Miyamoto et al. (1992, 1993a) studied the time variations of GS 2023+338 and compared it to the behaviour of other BHCs in the low-intensity state. Long-term variability was discussed by Terada et al. (1994). The source has also been detected at radio wavelengths (Hjellming & Han 1989), with a flux of 1.6 Jy, which is high for X-ray transients (see Hjellming 1995).

In this paper we investigate the relation between the spectral changes of GS 2023+338 and the rapid variability behaviour of its X-ray flux. Application of this kind of analysis to low-mass X-ray binaries (LMXB) in which the accretor is a neutron star has led to a distinction of two groups of accreting low magnetic field neutron stars in LMXBs: viz. atoll- and Z-sources (Hasinger & van der Klis 1989).

Analysis of the fast-timing behaviour has been applied to other sources such as pulsars (Takeshima 1992), BHC (Miyamoto et al. 1991, 1992, 1993a,b, 1994a,b) and Cir X-1 (Oosterbroek et al. 1995). The general expectation underlying these analyses is that the character of the compact object is reflected in the characteristics of the fast-timing behaviour and thus the fast-timing behaviour can be used as a tool to probe the character of the compact object (e.g., Miyamoto 1993, 1996).

From these analyses a global picture is emerging where the main parameters which determine the behaviour are the mass accretion rate (Ṁ) and the strength of the magnetic field of the compact object (see e.g. Van der Klis 1994a, 1994b, 1995a).

The character of the accreting object (black hole vs. neutron star) may play a smaller role in determining the fast variability behaviour, and also the spectral behaviour, than the magnetic

Send offprint requests to: T. Oosterbroek

1 The term “low-intensity” is historical and might be misleading: the total flux in this state may actually be higher than in the “high-state” due to the high-energy tail. This has, for example, been observed in GX339−4 (Grebenev et al. 1993)
field strength. A classical example of a source whose fast timing behaviour is reminiscent of "typical" black-hole behaviour is the neutron star accretor Cir X-1 (Oosterbroek et al. 1995). Cir X-1 also shows spectral characteristics which are resembling those of BHCs (e.g., a hard spectrum, see Dower, Hale & Morgan 1982).

In this paper we use Colour-Colour Diagrams (CDs) and Hardness-Intensity Diagrams (HIDs) to study spectral variations, and Fourier transformations to study the power spectra and phase delay spectra. We make a detailed comparison between the properties of this source and the data which are available of other BHCs and to a lesser extent neutron stars.

2. Observations

The data we used in this paper were obtained with the Large Area Counter (LAC, Turner et al. 1989) on board of the Ginga satellite (Makino et al. 1989). The first data were obtained on May 23, 1989 and the last data almost 160 days later on November 1. For a log of the observations we refer to Tables 1 and 2.

The observations can be divided into two parts: one with as high a time resolution as possible, uncorrected for dead time, background, and collimator response, which is used for the timing analysis, and another with a moderate time resolution (usually 4 seconds) with high spectral resolution and corrected for dead time, background, and collimator response, which is used for the spectral analysis.

The properties of the data we used are also summarized in Tables 1 and 2. It should be noted that these two data sets show overlap. Some data which have been obtained at high time resolution (especially MPC3 and MPC2 mode data) have also been corrected for background, aspect and dead-time and rebinned in time to make them suitable for inclusion in the CDs and HIDs.

The data can be further divided into a part taken on May 30, 1989 (1989 day 150) when the source was extremely bright, with dead time corrected count rates up to $6 \times 10^4$ cts/s, already described in some detail by Oosterbroek et al. (1995), and all other data, in which those extreme count rates are not reached. Those very high count rates require special precaution in the data analysis, and because the source behaviour on May 30 is different from that during the other observations, the May 30 data will be described mostly separately. During those early observations source variations are very dramatic and irregular. (Note that the peak rate in Fig. 1 of Tanaka, 1989, is about a factor 3 higher; this is caused by the higher time resolution employed in that figure, in combination with the extreme rapid variability of the source, and a different energy range (1–37 keV vs. 2.3–23 keV).)

3. Analysis

For the spectral analysis we made CDs and HIDs. The choice of the bands for the CDs and HIDs was dictated by three concerns: (i) we want approximately the same number of counts in each band to optimize the statistics, (ii) all energy boundaries should coincide with the energy channels of the MPC3 mode, since we do not want to interpolate in such broad channels, (iii) the highest energy bands should be high enough to be sensitive to a change in the power law tail in the spectrum, since this may be a good diagnostic tool for the analysis of BHCs. We find that a good balance between these considerations could be obtained with the following choice of the energy channels: 2.3–4.6 keV, 4.6–6.9 keV, 6.9–11.5 keV, and 11.5–23.0 keV.

For the timing analysis we made FFT's of data segments with a length of 256 seconds of data with a highest time resolution of 1 ms (PC data, other data have lower time resolution). This results in power spectra which have a range from ~0.004 to 512 Hz. For data with a lower time resolution (MPC3 and MPC2 data) the Nyquist frequency is accordingly lower. The lowest Nyquist-frequency we used was 8 Hz (for the MPC2 data in high bit rate mode). All power spectra were normalized to obtain the power density in units of (fractional rms)$^2$/Hz or (rms/mean)$^2$/Hz (see Van der Klis 1994c for a recipe how to obtain such a normalization, see also Belloni and Hasinger 1990, and Miyamoto et al. 1991). For the background count rate we used 68 counts/second (Turner et al. 1989). Variations in the background result in errors in the normalization of the order of 5%.

We fitted the power spectra with a model consisting of three components: (i) A Lorentzian component which is centered at zero frequency and which has a full width at half maximum (FWHM) of ~0.1 Hz; (ii) A Lorentzian component with a zero central frequency and a FWHM of a ~2–3 Hz and (iii) for the spectra which have a Nyquist frequency of 512 Hz, a Lorentzian component centered around ~30 Hz. This model gives a satisfactory description of the shape of the power spectra (Fig. 8 and 9) and follows the "wiggles" in the power spectrum. However, the values which are found for the $\chi^2$ are formally too high for the fits to be acceptable ($\chi^2 \sim 100$ for 81 d.o.f., and $\chi^2 \sim 70$ for 45 d.o.f.). We note that a similar $\chi^2$ can also be obtained with other fit models (e.g. a power law with different slopes in the various frequency intervals), but almost always more free parameters are needed. This is probably caused by the fact that the "bump" around 2–3 Hz is most easily fitted with a Lorentzian.

To obtain acceptable fits to power spectra which are obtained in the first 10 days of the outburst we found it necessary to include a power-law component in the fit-model. This power law is needed to obtain a good fit to the lowest frequency points and has indices of ~2.

The Poisson level was subtracted from each power spectrum before we made fits to it. The method we used to determine the Poisson level takes into account dead time, and has been described by Mitsuda & Dotani (1989). We find that the dead time calculation is sufficiently accurate to predict the Poisson level for the power spectra at the observed count rates.

We have checked that power introduced by changes in pointing of the instrument is negligible. We did this by making a power spectrum of the raw uncorrected data and a power spectrum of the data which had been corrected for aspect (and dead time and background). We found that the difference is very small (less than 0.001 (rms/mean)$^2$/Hz) at 0.005 Hz; this approxi-
Table 1. Log of the observations used for the corrected data.

<table>
<thead>
<tr>
<th>Observation time (UT) yr/day UT</th>
<th>MJD (-47000)</th>
<th>Time Res. (sec)</th>
<th>Obs. mode</th>
<th>Energy channels</th>
<th>Energy range (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>89/143 09:28:10 to 89/143 11:38:54</td>
<td>669.39456019-669.48534722</td>
<td>4</td>
<td>MPC3</td>
<td>12</td>
<td>1.2-36.8</td>
</tr>
<tr>
<td>89/150 05:08:41 to 89/150 07:47:49</td>
<td>676.21436343-676.32487269</td>
<td>4</td>
<td>MPC2</td>
<td>48</td>
<td>1.2-36.8</td>
</tr>
<tr>
<td>89/152 23:20:25 to 89/153 02:40:57</td>
<td>678.97251157-679.1177083</td>
<td>4</td>
<td>MPC2</td>
<td>48</td>
<td>1.2-36.8</td>
</tr>
<tr>
<td>89/153 02:46:25 to 89/153 06:03:45</td>
<td>679.11556713-679.25260417</td>
<td>4</td>
<td>MPC3</td>
<td>12</td>
<td>1.2-36.8</td>
</tr>
<tr>
<td>89/154 23:17:49 to 89/154 23:25:49</td>
<td>680.97593750-681.24857639</td>
<td>4</td>
<td>MPC2</td>
<td>48</td>
<td>1.2-36.8</td>
</tr>
<tr>
<td>89/155 21:31:53 to 89/156 02:40:57</td>
<td>681.98714120-682.17010417</td>
<td>4</td>
<td>MPC2</td>
<td>48</td>
<td>1.2-36.8</td>
</tr>
<tr>
<td>89/156 19:43:25 to 89/156 07:47:49</td>
<td>680.97593750-681.24857639</td>
<td>4</td>
<td>MPC2</td>
<td>48</td>
<td>1.2-36.8</td>
</tr>
<tr>
<td>89/154 23:17:49 to 89/156 04:04:57</td>
<td>681.97593750-681.24857639</td>
<td>4</td>
<td>MPC2</td>
<td>48</td>
<td>1.2-36.8</td>
</tr>
<tr>
<td>89/155 21:31:53 to 89/156 02:40:57</td>
<td>681.97593750-681.24857639</td>
<td>4</td>
<td>MPC2</td>
<td>48</td>
<td>1.2-36.8</td>
</tr>
<tr>
<td>89/156 19:43:25 to 89/156 07:47:49</td>
<td>680.97593750-681.24857639</td>
<td>4</td>
<td>MPC2</td>
<td>48</td>
<td>1.2-36.8</td>
</tr>
</tbody>
</table>

Table 2. Log of the observations used for the high time resolution data.

<table>
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<tr>
<th>Observation time (UT) yr/day UT</th>
<th>MJD (-47000)</th>
<th>Time Res. (sec)</th>
<th>Obs. mode</th>
<th>Energy channels</th>
<th>Energy range (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>89/143 09:28:10 to 89/143 11:38:54</td>
<td>669.39456019-669.48534722</td>
<td>0.00781</td>
<td>MPC3</td>
<td>10</td>
<td>1.2-36.8</td>
</tr>
<tr>
<td>89/150 01:17:09 to 89/150 02:46:57</td>
<td>676.05357639-676.11577083</td>
<td>0.00098</td>
<td>PC</td>
<td>2</td>
<td>1.2-36.8</td>
</tr>
<tr>
<td>89/150 04:31:17 to 89/150 07:47:53</td>
<td>676.18839120-676.32491898</td>
<td>0.06250</td>
<td>MPC2</td>
<td>48</td>
<td>1.2-36.8</td>
</tr>
<tr>
<td>89/152 23:20:21 to 89/153 02:40:57</td>
<td>678.97246528-679.11177083</td>
<td>0.06250</td>
<td>MPC2</td>
<td>48</td>
<td>1.2-36.8</td>
</tr>
<tr>
<td>89/153 02:46:25 to 89/153 05:59:19</td>
<td>679.11556713-679.24952546</td>
<td>0.00781</td>
<td>MPC3</td>
<td>10</td>
<td>1.2-36.8</td>
</tr>
<tr>
<td>89/154 23:17:49 to 89/156 04:04:57</td>
<td>680.97070602-682.17010417</td>
<td>0.06250</td>
<td>MPC2</td>
<td>48</td>
<td>1.2-36.8</td>
</tr>
<tr>
<td>89/155 21:36:01 to 89/155 23:09:49</td>
<td>681.90001157-681.96515046</td>
<td>0.00098</td>
<td>PC</td>
<td>2</td>
<td>1.2-36.8</td>
</tr>
<tr>
<td>89/160 19:43:25 to 89/163 02:14:29</td>
<td>687.62181713-687.74345185</td>
<td>0.00098</td>
<td>PC</td>
<td>2</td>
<td>1.2-36.8</td>
</tr>
<tr>
<td>89/169 17:33:28 to 89/169 19:09:44</td>
<td>695.73157407-695.79842593</td>
<td>0.50000</td>
<td>MPC1</td>
<td>48</td>
<td>1.2-59.7</td>
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<tr>
<td>89/169 19:15:48 to 89/169 22:36:02</td>
<td>695.80263889-695.94847222</td>
<td>0.00098</td>
<td>PC</td>
<td>2</td>
<td>1.2-36.8</td>
</tr>
<tr>
<td>89/169 22:36:08 to 89/169 22:45:52</td>
<td>695.94175926-695.94851852</td>
<td>0.06250</td>
<td>MPC2</td>
<td>48</td>
<td>1.2-36.8</td>
</tr>
<tr>
<td>89/170 15:44:52 to 89/170 15:47:24</td>
<td>696.65625000-696.6578037</td>
<td>0.06250</td>
<td>MPC2</td>
<td>48</td>
<td>1.2-36.8</td>
</tr>
<tr>
<td>89/171 14:39:32 to 89/171 20:59:04</td>
<td>697.61078704-697.74345185</td>
<td>0.00098</td>
<td>PC</td>
<td>2</td>
<td>1.2-36.8</td>
</tr>
<tr>
<td>89/187 09:46:28 to 89/187 13:17:36</td>
<td>713.40726852-713.55388889</td>
<td>0.4</td>
<td>MPC2</td>
<td>48</td>
<td>1.2-36.8</td>
</tr>
<tr>
<td>89/201 05:38:23 to 89/201 06:42:19</td>
<td>727.23498843-727.27938657</td>
<td>0.00098</td>
<td>PC</td>
<td>2</td>
<td>1.2-36.8</td>
</tr>
</tbody>
</table>

We also made FFT's of 256 second long data segments of the energy resolved data (PC, MPC2, and MPC3 data). We used these FFT's of data obtained at different energies to study the coherence and phase delays of the variability between different energy bands (see Vaughan, 1994). We used the technique ($\chi^2$-technique) in which all FFT's at all energies are used simultaneously to extract the phase delays between these energy bands. These FFT's were also used to construct power spectra in different energy bands. From these power spectra we constructed rms spectra, which give the fractional variability of the various spectra components as a function of energy.

We found that in some data sets occasional spikes were present which greatly increased the variability in one energy channel (or a few non-neighbouring channels) only. These spikes can not be astrophysical in origin, since they occur in a narrower energy band than the detector energy resolution ($\sim20\%$ at 6 keV). We also find that these spikes are only present above $\sim10$ keV and occur more often at higher energies. When
we made the final rms spectra (and phase delay spectra) we filtered the data which were used to make the power spectra. This was done by calculating the local mean of a few points (for the MPC2 data with 61.5 msec resolution we used 9 points, i.e., an average over \( \sim 0.5 \) s), and then calculated the level which has a very low probability to be exceeded (we took \( 1.10^{-10} \)) based on Poisson statistics. All data points above this level were substituted with the mean level. Per FFT only a few (less than 10) spikes were generally found, and due to filtering them out the power was only slightly diminished (normally less than 1 percent); we concluded this from a comparison to the neighbouring energy channels. From a comparison of rms-spectra made with the original (unfiltered) data and rms-spectra made from the filtered data, we conclude that spikes are removed very well, while real source variations are not or only very slightly affected.

Another analysis we performed on the data is the calculation of high-to-low flux X-ray spectral ratios. In order to do this we calculated the running mean of the dead time and background corrected data (over 64 s) and accepted the spectra when the instantaneous flux was above a certain flux level (we find that 1.1 times the running mean works well) to make PHA-spectra of the high-intensity data. This was done with data obtained in the MPC2 and MPC1 mode, resulting in 48 channels spectral resolution. We also made PHA-spectra of the low intensity data by taking the instantaneous count rates below 0.9 times the running mean. In this way we obtained dead time and background corrected PHA-spectra at high count rates, which contained about 20–30% of the total data, and PHA-spectra at low count rates, which contained about the same amount of data. The PHA-ratio spectrum was then calculated as the ratio of the spectrum obtained at the peaks to the spectrum obtained at the valleys. These PHA-ratios give us an additional way to look at the energy dependence of the flux variations.

4. Results

In the following sections we describe the CDs, HIDs and lightcurves we obtained for GS 2023+338 (Sect. 4.1), and the large changes in the low-energy absorption (Sect. 4.2). In Sect. 4.3 we will present the power spectra we have obtained, and in Sect. 4.4 we describe in some more detail the spectral changes which take place in the source spectrum on relatively short time scales. Finally we present the rms-spectra and phase-delay spectra we obtained in Sect. 4.5 and Sect. 4.6, respectively.

4.1. Light curve, CDs, and HIDs

The light curve of GS 2023+338 cannot be characterized by a simple smooth curve. In Fig. 1, which shows the sum of the count rates over the 4 energy bands (i.e., 2.3–23 keV), as a function of time, we see that the only trend visible is a long term decline as function of time. However, as we can see from Fig. 2, the variations on time scales shorter than a day are almost of the same order as the changes on time scales of a month. As we will discuss below this is largely due to large variations in the \( N_H \) column density.

![Fig. 1. The 2.3–23 keV light curve of all the corrected (see text) data of GS 2023+338. One point corresponds to 4s (occasionally 16 or 64s) of data; error bars are smaller than the size of the points. Note the large range of intrinsic variations within each observation. Data have been corrected for dead time, background, and collimator response.](image)

The soft colour (SC) as a function of time (which is, as we will show in Sect. 4.2 a good measure of the \( N_H \)), is very variable in the first month of the outburst, whereas the variations are substantially less in the later phases.

In the colour-colour diagram (Fig. 3) the following signatures are visible: there is a track which extends from SC \( \sim 3 \) to SC \( \sim 0.7 \), with a sharp bend at those low SC values. The observations which lies around the bend are obtained in the last stages of the outburst. There is another collection of points which lie above and partly to the left of the main track. Those points were obtained in the very early stages of the outburst (May 23 and 30, day 143 and 150), when the source was very bright. The CD seems more or less repeatable: the last (low intensity) observation falls on top of the observations obtained \( \sim 3 \) months earlier, at around the bend of the left-most tip of the extended branch. The width of the track gives an indication of the errors in the individual points; the errors in the points which lie above and to the left of this main track are smaller; real variations are thus present here (errors in both the soft and hard colour range from \( \sim 0.01 \) to 0.3).

In the soft colour vs. intensity diagram (Fig. 4) several tracks are visible. They represent the data obtained during different observations. The errors can be estimated from the widths of these tracks. The data points at high count rates have been obtained early in the outburst. The errors in the points which lie above and to the left of this main track are smaller; real variations are thus present here (errors in both the soft and hard colour range from \( \sim 0.01 \) to 0.3).

Furthermore we can discern in the SC vs. intensity diagram that a track seems to be visible which is embedded in a cloud of points. The scatter in this cloud of points (which
is roughly delimited by a triangle with coordinates: \((I, \text{SC}) = (1000, 0.6), (6000, 0.6), (2000, 1.8)\) is not statistical. The statistical scatter can be roughly estimated from the width of the tracks, which are visible in the CD. The extra scatter is a result of real changes in \(N_{\text{H}}\). The regions where the statistical scatter is substantial are the left-most cloud of points \((I, \text{SC}) = (70, 0.8)\) and the cloud of points around \((I, \text{SC}) = (500, 2)\). In the first region the count rate is low, which increases the scatter. In the second region the count rate is relatively low, and more important, a lot of low-energy absorption is present, which decreases the count rate in the lowest energy band significantly, and thus the statistical scatter is increased.

The errors in the hard colour (HC) vs. intensity diagram (Fig. 5) are around \(\sim 0.01-0.05\) in the hard colours (the errors in the count rates are very small), with the exception of the cloud of points around HC \(\sim 0.5\) and a count rate of \(\sim 60\) and around HC 0.7 and count rates of \(\sim 800\), where the errors are up to a factor of five higher. This diagram is somewhat simpler than the CD and Soft-colour vs. Intensity diagram. The hard colour is mainly sensitive to changes in the intrinsic spectrum: i.e., a harder spectrum gives a higher value for the HC.

4.2. Synthetic CDs and HIDs

In a first attempt to understand the complex behaviour of the source in the CDs and HIDs we made synthetic spectra, which
we folded through the *Ginga* detector response. We then calculated the fluxes that would have been observed in the four energy bands that we used in our analysis. This enabled us to make CDs and HIDs for these simulated data. Varying one parameter of the model (which consisted of various combinations of a power law, blackbody component, Gaussian line and absorption) enabled us to see how a change in one parameter affected the position in the CD. We found from this that, almost independently of the assumed spectral shape, the effect of increasing $N_{\text{H}}$ is to move a point along a line parallel to the main track we observe in the CD. We therefore conclude that the main determinant of the position in the CD is the value of the column density $N_{\text{H}}$. This column density has to be produced mainly locally, because of its large changes. This procedure we applied is functionally equivalent to the determination of the so-called “reddening line” (see Schulz et al. 1988).

To investigate the $N_{\text{H}}$ variation in some more detail we have determined the location of points in the CD for an assumed power-law spectrum (photon index $-1.35$) and $N_{\text{H}}$ between $5 \times 10^{21}$ and $2 \times 10^{23}$ cm$^{-2}$, in steps of $5 \times 10^{21}$ (Fig. 6). We find that the density of the points decreases to the right in the CD, in a similar way as is observed in the real data for GS 2023+338. This suggests that the distribution of the $N_{\text{H}}$ values is more or less uniform between the two extremes. In order to test this we estimated the $N_{\text{H}}$ from the soft colour in the following way: we selected points above soft colour 1.0 and belonging to the branch in the CD (i.e. hard colour below the line through $(SC, HC) = (1.0,0.7)$ and $(2.0,0.8)$). We calculated the soft colours for an artificial spectrum with $N_{\text{H}}$ ranging from 0.5 to 20 (10$^{22}$ cm$^{-2}$), with steps of 0.5. We then converted the measured soft colour to

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**Fig. 4.** The soft-colour vs. intensity diagram of GS 2023+338. Soft colour is the same as in Fig. 3, intensity is the count rate in the 2.3−23 keV band. Data have been corrected for dead time and collimator response.

**Fig. 5.** The hard-colour vs. intensity diagram of GS 2023+338. Hard colour is the same as in Fig. 3, intensity is the count rate in the 2.3−23 keV band.

**Fig. 6.** The observed colour-colour diagram of GS 2023+338 (small dots), and the synthetic points (large dots) calculated from a power law spectrum (photon-index $-1.35$) absorbed by different amounts of column density. The column density ($N_{\text{H}}$) ranges from $5 \times 10^{21}$ and $2 \times 10^{23}$ cm$^{-2}$, in steps of $5 \times 10^{21}$. Column density increases from the left to the right.

**Fig. 7.** The number distribution of the obtained $N_{\text{H}}$-values (see text). From this figure we conclude that $N_{\text{H}}$-values between roughly 500 and 1600 (10$^{20}$ cm$^{-2}$) are distributed approximately uniformly.
Fig. 8. The power spectra data with a Nyquist frequency of 64 Hz or greater (MPC3 and PC data). The approximate start times (MJD - 47000) at which the power spectra are obtained are plotted in the top-right corners of the panels. For the power spectra which have been fitted with a model consisting of three Lorentzians the fit (drawn line, mostly invisible), and the individual Lorentzian components (dashed, dot-dashed, and dotted for resp. Lorentzian 1, 2, 3) have been drawn in order to show their relative contribution in the different frequency regimes.

Fig. 11 shows the power spectrum obtained when the source was very bright (MJD=47676.25). In this power spectrum additional power is visible around frequencies of 0.05 Hz. We have fitted all power spectra with a model consisting of Lorentzians (see Sect. 3). We note that the inclusion of a third Lorentzian decreases the $\chi^2$ by $\sim$40 (from $\sim$ 140 to $\sim$ 100) for different. Here there is clearly less power above $\sim$0.1 Hz. The spectrum is much steeper than the other power spectra. From the fits to the power spectrum it can be concluded that in our power spectral decomposition (see Sect. 3), the difference is mainly caused by the absence of the component with a FWHM of 2–3 Hz. While these power spectra were obtained the source occupied a different region in the CD. We concluded this from data with high-energy resolution, which were obtained just before and after (but not simultaneously with) the high-time resolution data. In Fig. 10 we can see which region in the CD was approximately occupied by the source when the power spectra were obtained.

The NH-value by a linear interpolation. In Fig. 7 we have plotted a histogram of these obtained NH estimates. From this figure we see that between $5 \times 10^{22}$ and $1.6 \times 10^{23}$ the distribution is more or less uniform and starts to drop off above $1.6 \times 10^{23}$.

Only in the parts of the CD where the source gets very bright (i.e., points above and to the left of the main track) and the left most tip (i.e., the bend around (SC,HC)=0.7,0.5) the intrinsic source spectrum has to change. In the other parts of the CD the behaviour in this diagram can be reasonably well described by a fixed underlying spectrum, that is only modified by variable absorption.

4.3. Power spectra

In Fig. 8 we present the power spectra as obtained with the PC-data. From this figure it is clear that the power spectra are remarkably similar to each other during most of the outburst. Only the power spectra obtained on May 30 (day 150, 1A) are
Fig. 9. The power spectra for the MPC2 data. Approximate start times (MJD - 47000) for the power spectra are plotted in the top-right corners of the panels.

Fig. 10. In this figure the (approximate) regions are plotted where the power-spectra are obtained. In the left panel the place where the power spectra with the high Nyquist frequencies (MPC3 and PC data) are plotted. In the right panel the positions where the power spectra with low Nyquist frequency (MPC2 data) are obtained have been plotted. The horizontal line labelled with 3A indicates where (at the main branch) the power spectra have been obtained. The regions indicated in the left panel for the PC data are only very approximate, since no spectral data are available when PC data is obtained.
The power spectrum obtained when the source is very bright. This spectrum has been obtained between MJD = 47676.2139004630 and 47676.314519676

Table 3. In this table the times can be read at which the different power spectra and rms spectra are obtained. The labels mentioned in the first column are also used in the figures.

<table>
<thead>
<tr>
<th>label</th>
<th>Start time (MJD - 47000)</th>
<th>End time (MJD - 47000)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MPC2 1A</td>
<td>676.1875</td>
<td>676.31640625</td>
</tr>
<tr>
<td>MPC2 1B</td>
<td>678.96875</td>
<td>679.1015625</td>
</tr>
<tr>
<td>MPC2 1C</td>
<td>680.96875</td>
<td>680.9717130</td>
</tr>
<tr>
<td>MPC2 2A</td>
<td>680.97265625</td>
<td>681.23046875</td>
</tr>
<tr>
<td>MPC2 2B</td>
<td>681.89453125</td>
<td>682.15625</td>
</tr>
<tr>
<td>MPC2 3A</td>
<td>686.8203125</td>
<td>686.96484375</td>
</tr>
<tr>
<td>MPC2 3B</td>
<td>687.0078125</td>
<td>687.078125</td>
</tr>
<tr>
<td>MPC2 4A</td>
<td>695.94140625</td>
<td>696.65234375</td>
</tr>
<tr>
<td>MPC2 4B</td>
<td>697.609375</td>
<td>697.8671875</td>
</tr>
<tr>
<td>MPC2 4C</td>
<td>713.40625</td>
<td>713.546875</td>
</tr>
<tr>
<td>MPC2 4D</td>
<td>729.1015625</td>
<td>729.203125</td>
</tr>
<tr>
<td>PC 1A</td>
<td>676.05078125</td>
<td>676.1015625</td>
</tr>
<tr>
<td>PC 1B</td>
<td>681.89453125</td>
<td>681.9717130</td>
</tr>
<tr>
<td>PC 2</td>
<td>695.80078125</td>
<td>695.9375</td>
</tr>
<tr>
<td>PC 3</td>
<td>697.72265625</td>
<td>697.79296875</td>
</tr>
<tr>
<td>PC 4</td>
<td>713.3359375</td>
<td>713.3515625</td>
</tr>
<tr>
<td>PC 5A</td>
<td>727.234375</td>
<td>727.27734375</td>
</tr>
<tr>
<td>PC 5B</td>
<td>728.9453125</td>
<td>729.08203125</td>
</tr>
<tr>
<td>MPC3 A</td>
<td>669.39453125</td>
<td>669.484375</td>
</tr>
<tr>
<td>MPC3 B</td>
<td>679.11328125</td>
<td>679.23046875</td>
</tr>
</tbody>
</table>

~80 degrees of freedom and is therefore statistically significant. However, the shape of the additional component is not well constrained.

We conclude from our fits (see Table 4) that the changes in the shape of the power spectrum over a period of 60 days are very small. The only systematic change which might be present is a shift toward lower frequencies of the Lorentzian component with a full width at half maximum (FWHM) of ~3 Hz, although it is a relatively small change (see Table 4). This width changes from ~3.4 Hz on MJD 47676 to ~2.5 on MJD 47728. There are some additional significant, seemingly random, changes in the power spectra, which are reflected in the obtained fit parameters. The overall shape, however, remains fairly constant.

A problem in the interpretation of the obtained fit parameters is the correlation between the parameters. Especially the obtained width of the first Lorentzian is strongly correlated with the obtained width of the second Lorentzian. This is evident from Table 5 in which we see that whenever a small value for the width of the first Lorentzian is obtained also a small value for the width of the second Lorentzian is obtained.

Additionally we also have tried to estimate an upper limit for Lorentzian shaped peaks in the power spectrum between 2 and 10 Hz. This is relevant, because in other BHCs QPOs with these frequencies have been observed. We only tried to fit the spectra where the count rates are high (PC1A, PC1B, MPC3A) to determine this upper limit. We included a Lorentzian component in our fit model in which the frequency was allowed to vary between 2 and 10 Hz, and the FWHM was constrained to be smaller than ~0.5 times the frequency of this component. We note that the results of the procedure depend on the assumed underlying spectral shape and the results are therefore only approximate. However, from a visual inspection of the power spectra no indications of the presence of QPO are obtained, while in other BHCs in the “very-high” state, these QPO peaks are immediately obvious. We can set a firm (1σ) upper limit of 4% to the strength of the QPO in this frequency region.

4.4. X-ray spectral changes

From our analysis of the X-ray spectral changes we draw the following conclusions: (i) The influence of changes in $N_H$ on the spectral shape (and thus the colours) is very large. To first order the behaviour in the colour-colour diagram for a large fraction of the data can be described reasonably well by changes in the (local) column density ($N_{\text{H}}$). We find that in the later observations the inferred column density is less, and also less variable, which suggests that the source is getting clear of matter which is local to the source. (ii) A different type of change in the colours occurs near the peak of the outburst. This tells us that the intrinsic spectrum is then changing. When this happens also a different power spectrum is obtained.

The results of the analysis of the ratios of spectra obtained at the intensity peaks and valleys are summarized in Fig. 12, from which we learn that there is large difference in the energy-dependent variability. Especially during the maximum of the outburst (the panels marked with a 1 I− V) we see that there is a large variation of shapes. In the first panel we see a lot of variability around 5 keV and a signature of an iron line with less variability (see Oosterbroek et al. 1995). In the second and third panel we see the presence of a soft component which is relatively invariable.

The later ratio plots (2, 3, 4 I) show differences caused by the variation in cold-matter absorption. If the $N_H$-value is high (and thus the variatons in $N_{\text{H}}$), we see this as increased variability towards the lowest energies. Since the spectra are obtained using
Table 4. Fits to the power spectra obtained from the PC and MPC3 data.

<table>
<thead>
<tr>
<th>Obs.</th>
<th>rms L. 1 (%)</th>
<th>FWHM L. 1 (Hz)</th>
<th>rms L. 2 (%)</th>
<th>FWHM L. 2 (Hz)</th>
<th>rms L. 3 (%)</th>
<th>FWHM L. 3 (Hz)</th>
<th>L. 3 freq</th>
<th>( \chi^2/\text{dof} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1B</td>
<td>26.5 ± 1.7</td>
<td>0.115 ± 0.04</td>
<td>26.6 ± 0.5</td>
<td>3.4 ± 0.2</td>
<td>2.5 ± 0.7</td>
<td>73 ± 115</td>
<td>41 ± 0.6</td>
<td>30 ± 0.12</td>
</tr>
<tr>
<td>2</td>
<td>29.4 ± 0.5</td>
<td>0.20 ± 0.01</td>
<td>25.9 ± 0.2</td>
<td>3.49 ± 0.07</td>
<td>4.3 ± 0.6</td>
<td>61 ± 20</td>
<td>44 ± 0.9</td>
<td>34 ± 0.4</td>
</tr>
<tr>
<td>3</td>
<td>26.4 ± 0.7</td>
<td>0.22 ± 0.02</td>
<td>26.0 ± 0.6</td>
<td>3.38 ± 0.11</td>
<td>5.4 ± 0.7</td>
<td>20 ± 8</td>
<td>30 ± 3</td>
<td>106 ± 8</td>
</tr>
<tr>
<td>4</td>
<td>28.5 ± 1.0</td>
<td>0.18 ± 0.02</td>
<td>25.6 ± 0.4</td>
<td>3.14 ± 0.14</td>
<td>4.9 ± 0.7</td>
<td>14 ± 11</td>
<td>25 ± 4</td>
<td>103 ± 8</td>
</tr>
<tr>
<td>5A</td>
<td>25.9 ± 1.0</td>
<td>0.14 ± 0.02</td>
<td>26.5 ± 0.5</td>
<td>2.55 ± 0.13</td>
<td>4.6 ± 1.0</td>
<td>21 ± 9</td>
<td>30 ± 3</td>
<td>93.6 ± 81</td>
</tr>
<tr>
<td>5B</td>
<td>29.9 ± 0.7</td>
<td>0.094 ± 0.007</td>
<td>26.6 ± 0.2</td>
<td>2.53 ± 0.07</td>
<td>5.0 ± 0.7</td>
<td>21 ± 9</td>
<td>30 ± 3</td>
<td>93.6 ± 81</td>
</tr>
</tbody>
</table>

Table 5. Fits to the power spectra obtained from the MPC2 data.

<table>
<thead>
<tr>
<th>Obs.</th>
<th>rms L. 1 (%)</th>
<th>FWHM L. 1 (Hz)</th>
<th>rms L. 2 (%)</th>
<th>FWHM L. 2 (Hz)</th>
<th>rms L. 3 (%)</th>
<th>FWHM L. 3 (Hz)</th>
<th>L. 3 freq</th>
<th>( \chi^2/\text{dof} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1B</td>
<td>18.6 ± 0.6</td>
<td>0.15 ± 0.02</td>
<td>17.9 ± 0.3</td>
<td>2.70 ± 0.15</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>77.2/48</td>
</tr>
<tr>
<td>1C</td>
<td>9.4 ± 0.4</td>
<td>0.017 ± 0.01</td>
<td>22.1 ± 1.2</td>
<td>0.95 ± 0.2</td>
<td>12.5 ± 3</td>
<td>3.6 ± 0.8</td>
<td>2.3 ± 0.5</td>
<td>41.6/45</td>
</tr>
<tr>
<td>2A</td>
<td>18.6 ± 0.8</td>
<td>0.034 ± 0.006</td>
<td>20.2 ± 0.5</td>
<td>0.42 ± 0.03</td>
<td>18.4 ± 0.4</td>
<td>3.54 ± 0.05</td>
<td>1.01 ± 0.7</td>
<td>67/45</td>
</tr>
<tr>
<td>2B</td>
<td>16.9 ± 0.9</td>
<td>0.058 ± 0.006</td>
<td>18.4 ± 0.6</td>
<td>0.65 ± 0.08</td>
<td>17.0 ± 0.8</td>
<td>3.67 ± 0.09</td>
<td>1.18 ± 0.12</td>
<td>68.8/45</td>
</tr>
<tr>
<td>3</td>
<td>14.3 ± 0.6</td>
<td>0.08 ± 0.01</td>
<td>21.4 ± 0.3</td>
<td>0.82 ± 0.04</td>
<td>14.1 ± 0.5</td>
<td>4.24 ± 0.08</td>
<td>1.74 ± 0.12</td>
<td>95.1/45</td>
</tr>
<tr>
<td>4A</td>
<td>22.1 ± 1.2</td>
<td>0.33 ± 0.06</td>
<td>19.3 ± 1.3</td>
<td>3.1 ± 0.4</td>
<td>5.71/2</td>
<td>1.3 ± 0.6</td>
<td>2.5 ± 0.3</td>
<td>37.8/45</td>
</tr>
<tr>
<td>4B</td>
<td>23.8 ± 1.0</td>
<td>0.17 ± 0.02</td>
<td>14.3 ± 1.5</td>
<td>1.15 ± 0.15</td>
<td>17.0 ± 2.0</td>
<td>3.28 ± 0.06</td>
<td>1.30 ± 0.09</td>
<td>52.4/45</td>
</tr>
<tr>
<td>4C</td>
<td>24.1 ± 0.8</td>
<td>0.12 ± 0.01</td>
<td>21.7 ± 1.3</td>
<td>1.96 ± 0.16</td>
<td>8.8 ± 0.27</td>
<td>2.56 ± 0.20</td>
<td>2.30 ± 0.31</td>
<td>78.0/45</td>
</tr>
<tr>
<td>4D</td>
<td>26.3 ± 0.7</td>
<td>0.075 ± 0.007</td>
<td>23.2 ± 0.3</td>
<td>1.73 ± 0.09</td>
<td>6.9 ± 1.4</td>
<td>1.91 ± 0.26</td>
<td>2.30 ± 0.15</td>
<td>41.3/45</td>
</tr>
</tbody>
</table>

Table 6. Fits to the power spectra observed during the first 8 days of the observations.

<table>
<thead>
<tr>
<th>Obs.</th>
<th>rms L. 1 (%)</th>
<th>FWHM L. 1 (Hz)</th>
<th>rms L. 2 (%)</th>
<th>FWHM L. 2 (Hz)</th>
<th>FWHM L. 3 (%)</th>
<th>L. 3 freq</th>
<th>( \chi^2/\text{dof} )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.001 – 1 Hz</td>
<td>–</td>
<td>0.001 – 100 Hz</td>
<td>–</td>
<td>0.001 – 100 Hz</td>
<td>0.001 – 100 Hz</td>
<td>0.001 – 100 Hz</td>
</tr>
<tr>
<td>I</td>
<td>34 ± 3</td>
<td>2.15 ± 0.04</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>147/86</td>
<td></td>
</tr>
<tr>
<td>MPC3A</td>
<td>34 ± 11</td>
<td>1.98 ± 0.04</td>
<td>10.8 ± 3.8</td>
<td>3.6 ± 3.1</td>
<td>51/66</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MPC3B</td>
<td>71 ± 16</td>
<td>2.17 ± 0.18</td>
<td>16.2 ± 0.5</td>
<td>1.92 ± 0.18</td>
<td>80/66</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a moving average over 64 seconds, which effectively filters out all the faster variations, this confirms that there are large changes in the column-density on long time scales.

4.5. Rms-spectra

The rms-spectra we obtained during the observations with enough time- and spectral resolution are plotted in Fig. 13. A remarkable rms spectrum in Fig. 13 is that presented in panel “1 B+C”; a decrease is visible below ~7 keV. This is probably associated with the presence of a soft-component in the spectrum which is not (or less) variable and dilutes the variability (see Tanaka, 1991).

In the other rms spectra we see that the average 0.01–8 Hz rms-variability is ~30%, while in some rms-spectra an increase towards lower photon energies below ~4 keV is visible (rms-spectra 2 and 3). In the panels labeled 4A+B, 4C, 4D this increase at low photon energies is much less prominent. This favours an interpretation where an underlying ~30% variability that is roughly constant with photon energy is, at low photon energies, increased by additional changes in the \( N_H \) column density. The changes in the column density introduce additional variability in the flux only below ~4 keV. The additional variability below ~4 keV is not present in the last observation (rms-spectra 4A+B, 4C, 4D), which is consistent with a lower \( N_H \)-value (and changes of this value) as derived from the CD at that time. In Fig. 14 we have plotted the rms-spectra as obtained from integrating the variability between 0.01–0.1, 0.1–1, and 1–8 Hz, and from 0.01 to 8 Hz. From this figure we can conclude that the changes in the \( N_H \) column density only occur on time scales longer than 1 second, since the variability in the 1–8 Hz band is almost constant with photon energy.

The result from the analysis of the rms spectra and the spectral ratios are consistent; on time scales longer than 1 s variations in the absorbing column play an important role in the variability of GS 2023+338.

4.6. Phase delays

The phase delays as a function of photon energy are plotted in Fig. 15. We have plotted the phase delays (for certain frequency bands) as a function of energy, because we are interested in possible dependencies on photon energy. We see that phase changes occur, but that they are generally modest: no phase delays with an amplitude larger than 0.1 radians are detected. In general, the phase delay increases monotonically with photon energy. Be-
between 0 and 1 Hz a delay is present at energies below $\sim 4$ keV (panel 3). It should be noted that this occurs when the increase towards low energies in the rms-spectrum (interpreted as the effect of changes in $N_{\text{H}}$) is most prominent.

From the phase delays plotted in panels labeled 2 and 3 it seems that the phase delays are somewhat larger in the $1−2$ Hz band than in the $0−1$ Hz band. This is also present in the data presented by Miyamoto et al. (1992) for Cyg X-1. However, it is difficult to compare our results with those of Miyamoto et al. (1992) since we have plotted the phase delays in two selected frequency bands against photon energy, while Miyamoto et al. (1992) have plotted the phase delays between two energy bands against frequency. A comparison of our results with the results of Miyamoto et al. (1992) for GX339−4 show that the phase delays might be similar.

We conclude from this is that only small phase-differences are present in the variations at different energies of the X-ray flux; those phase delays seem to be roughly comparable to those found in Cyg X-1 (and possibly GX339−4), however the quite large statistical errors inherent to the determination of small phase delays make a accurate comparison difficult.

5. Discussion

In this section we will make a comparison between the behaviour as found for GS 2023+338 with the behaviour found in other BHCs.

5.1. Comparison of the power spectra with those of other Black Hole Candidates

The overall power spectral shape of GS 2023+338 (see Fig. 8 and 9) is somewhat like that of Cyg X-1, GX 339−4, and GS1124−68 in the low (hard) state (see Miyamoto et al. 1992). It can be described by an (almost) flat part below frequencies of $\sim 0.05$ Hz, while above this frequency the power drops off
In two sources, the part of the spectrum above this frequency has been observed to stay approximately the same, while the part below this cut-off frequency changes. This has been observed in Cyg X-1 (Belloni & Hasinger 1990) and GX 339–4 (Miyamoto et al. 1991). The part above the cut-off frequency has been described in different ways by different authors: as a power law with different indices in three different frequency regimes (Belloni and Hasinger 1990), or as composed of different Lorentzians (Miyamoto et al. 1991).

However, there are some differences: GS 2023+338 does not show the above-described Belloni-Hasinger effect as seen in data from Cyg X-1. There is no clear change visible in the power spectra of GS 2023+338 with respect to the level or cut-off frequency of the flat top, although the intensities are different by a large factor (see also Miyamoto et al. 1993a). Another difference with respect to Cyg X-1 is that the power spectrum is steeper at higher frequencies (above $\sim 5$ Hz). In Cyg X-1 the power spectrum above these frequencies can be described with a power law with index 2. It should, however, be noted that the steepness of the spectrum of Cyg X-1 above a few Hz can be described with a power law with an index changing between 1.4–2 (Belloni and Hasinger 1990). In 4U 1705–44 (a burst source, Berger and Van der Klis, 1996) the steepness of the power spectrum at frequencies just above the flat part can be described with a power law with an index of $\sim 0.9$. A possible relation between the mass of the compact object and the steepness of the power spectrum might exist, but currently not enough data on different sources are available to draw conclusions.

From Belloni and Hasinger (1990) it appears that in the power spectrum of Cyg X-1 a bump around $\sim 4$ Hz is present. A similar component is also visible in the power spectra of GX 339–4 presented by Miyamoto et al. (1992) at around 2 Hz. In GS 2023+338 this bump is also present and we modelled it with the zero-centered Lorentzian component with a FWHM of $\sim 3$ Hz, and its frequency thus is $\sim 1.5$ Hz. In atoll sources, which show similar behaviour to black holes in their low states when

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**Fig. 13.** The 0.01–8 Hz rms variability spectra for four data sets. Labels refer to the same data as were used for the power spectra in Fig. 9. Note the increase towards lower energies of the variability which is present in rms-spectra 2 and 3, but much less in rms-spectrum 4.
they are dim (e.g. 4U 1705-44) additional power is present at
frequencies of \( \sim 3 \) Hz (Berger and Van der Klis 1996).

Summarizing we can say that we are beginning to see small
differences (e.g. the frequency of the “bumps” or the steepness
of the spectra) in the power spectra of different BHCs. It will
be interesting to study those subtle differences between these
sources in more detail.

The power spectra observed during the early stages of the
outburst (and thus at high count rates) (PC spectrum 1A, and
both MPC3 spectra) differ from the power spectra observed
in other black-hole candidates. They contain a large amount
of variability (\( \sim 35\% \) between 0.001 and 1 Hz) and can be
described as a steep (\( \alpha \sim -2 \)) power law. They do not resemble the
power spectra of other BHCs in their high or very high state (see
for this additional steep component in the power spectra of GS 2023+338 is the effect of the variations in \( N_q \) which occur below \( \sim 1 \) Hz (see Sect. 4.5).

The power spectrum observed at the highest peak of the
outburst (May 30 data), shows an additional component near
0.04 Hz (Fig. 11). This power spectrum looks similar to that of
Cyg X-1 as obtained with Sigma data (Vikhlinin et al. 1994).
This power spectrum of Cyg X-1 has been obtained in its low
state and shows a peak around 0.05 Hz. This peak can either be
labeled broad low-frequency QPO or “peaked” low-state noise.
Since in GS 2023+338 the peak is only observed once we can not study its behaviour in more detail.

It is clear that around maximum intensities the shape of the
power spectrum changes, but it does not develop into a very-
high-state spectrum (which is characterized by very strong band
limited noise with a cut-off frequency in the range from 1 to 10
Hz and QPO with a frequency between 2–10 Hz and sometimes
harmonics), since no evidence for 2–10 Hz QPO is present
(we estimate an upper-limit of 4\% in the 2–10 Hz range). The
upper limit is not very strict since a lot of variability is present
in this source and small deviations from the global shape of the
power spectrum have to be fitted with a relatively strong
QPO component. This upper limit is not very different from the
observed strength of the QPO in e.g., GX 339−4: 4–5\% (Miyamoto et al. 1991).

It is remarkable that although GS 2023+338 reaches very
high count rates and high luminosities (Tanaka (1989) con
cluded from the saturation of the light curve near the peak that the
Eddington luminosity was reached) the power spectrum is
remarkably similar to that of other BHCs in the low-state (spectrally hard). Only when the source is at its peak the power spect
(um and also the energy spectrum) changes, but certainly does
not resemble a power spectrum of other BHCs in either the high
(soft) or very-high state. Tanaka (1989) reached a similar con
clusion from a spectral analysis which showed that the intrinsic
spectrum of GS 2023+338 was always a power law, and did not show the ultra-soft component usually seen in the high and
very-high states of BHCs. There are two possible differences
with other sources which could explain this behaviour. The first
is that GS 2023+338 is known to have a very massive compact
object (>6 \( M_\odot \), and probably \( \sim 12 \) \( M_\odot \), see Shahbaz et al.,
1994), possibly more massive than that of other BHCs. How
ever, it is not clear how the high mass of the compact object
(which is after all probably of the same order of the masses of
other BHCs) could prevent the source from exhibiting high-
very-high state behaviour, especially since the main determin
ant of the behaviour would likely be the fraction of the Ed
dington luminosity at which the source is radiating. The source
may reach the Eddington limit for a \( \sim 10 \) \( M_\odot \) compact object
(Tanaka 1989).

The other possibility is at different inclination of the source. It
could well be that a different viewing geometry is present, and
therefore a different part of the region around the comp
act object is observed. However, although there are sugge
ctions (see Van der Klis 1995b), little is known about the effects
of inclination on the observed variability behaviour. An incl
ation of \( \sim 42–80\% \) is allowed from optical observations (Casares
& Charles 1994); from modelling of the ellipsoidal variations
Shahbaz et al. (1994) find a lower limit of \( \sim 50\% \).

5.2. Energy dependence of the variability

From Fig. 13 (panel “1 non-high”) we conclude that during
the early stages of the outburst the variability below 7 keV di

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{rms_spectra.png}
\caption{The frequency dependence of the rms spectra. From top to bottom the rms-spectra in the frequency range 0.01−8, 0.01−0.1, 0.1−1, and 1−8 Hz are plotted. The data used in this figure are the same as used for panel 2A and 2B in Fig. 13.}
\end{figure}
The phase delay spectra. Both the delays in the 0−1 Hz, and the 1−2 Hz band have been plotted (indicated in top right of the panels). The channel with an energy of ∼6 keV has been chosen as a reference channel and has therefore by definition a phase delay of zero. Typical errors are 0.02 to 0.05 radians (in observation 1 the errors are 2 to 3 times larger). The observed scatter in the plots is smaller due to correlations between the points.

minishes (see also Oosterbroek et al. 1995), which is explained by Tanaka (1991) as caused by the presence of a diluting soft component which is not variable itself.

From the rms spectra (Fig. 13 and 14) we conclude that changes in N_H affect the fast variability behaviour of GS 2023+338. At low variability frequencies the contribution of changes in N_H is evident. At frequencies above 1 Hz there is almost no extra variability below ∼5 keV. This suggest that changes in N_H take place on a time scale of >1 s.

Since we find that the N_H-changes play an important role on time scales longer than 1 s, we consider here a model where clumps of cold gas move in front of the compact object on a Keplerian time scale. Whenever such a cloud (or any other geometry, e.g. filaments) passes through the line of sight it introduces an additional N_H and a temporal variation in the flux. The clouds which cause the absorption should not be completely ionized. In the next part we make an estimation at which radii, partially ionized clouds could be present. Below we denote the time scale of the variability with τ, and the characteristic size of the clouds with l. The clouds are at a distance a from the compact object.

\[ l = \frac{2\pi a}{P_{\text{Kepler}}} \]  
(1)

Where \( P_{\text{Kepler}} \) is the orbital period at a distance a. For a 12 solar mass black hole this can be written as:

\[ l = 2.3 \cdot 10^8 a^{-\frac{1}{2}} \tau \quad (a \text{ in light seconds}) \]  
(2)

If we take as the change in N_H 10^{22} cm^{-2} (which is high for variation on a time scale of 1 s, but reasonable for the slower variations), then \( nl = 10^{22} \) where n is the density of hydrogen atoms (in cm^{-3}) and thus:

\[ n = \frac{4 \cdot 10^{13} \sqrt{a}}{\tau} \]  
(3)

The ionization parameter ξ is defined as: \( \xi = \frac{L}{na^2} \) (Hatchett, Buff & McCray 1975), where L is the luminosity of the central
source (we take $L$ as 10% of the Eddington luminosity for a 12 $M_\odot$ compact object). This can be written as:

$$\xi = \frac{5 \cdot 10^3 \tau}{a^2}$$

(4)

Low-energy absorption takes place for $\xi \lesssim 50$ (Hatchett et al. 1975), which leads to:

$$a \gtrsim \theta^{0.4}$$

(5)

this leads to a radius of 6–40 light seconds, as the minimal radius where enough absorbing material can be orbiting the compact object. This is well inside the system since the semi-major axis equals $\sim$90 light seconds. A site where this orbiting material can be naturally found is the rim of the accretion disk. At the high accretion rates present in GS 2023+338 we expect that the accretion disk is thick, and together with the inclination of $\sim$42–80$^\circ$ it could be that we are just looking through the edge of the accretion disk and, if the disk is slightly irregular, see the observed variations in the column density. The large N$_H$-values in the large changes in this value could result from a special viewing geometry (i.e., just through the rim of the disk).

If the above is a correct interpretation of the rapid changes of the column-density, then the opening angle of the disk must be at least 10$^\circ$, but less than $\sim$50$^\circ$.

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