Colors and patterns of black hole X-ray binary GX 339−4

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ABSTRACT

Black hole X-ray binaries show signs of the non-thermal component in the optical/near-infrared range during outbursts. We analyse the optical/near-infrared data of GX 339−4 over the 2002–2011 period. Using the soft state data, we estimate the interstellar extinction towards the source and characteristic color temperatures of the accretion disk. We show that the regular outbursts follow the same track on the color-magnitude diagrams despite substantial differences in the observed light curves. We find that the failed outbursts cannot be easily distinguished from the regular ones at the early stages of the outburst. We subtract the contribution of the accretion disk and obtain the spectra of the non-thermal component, which have constant, nearly flat shape during the transitions between hard and soft states. We discuss the evolution of the non-thermal component and suggest an explanation of such behaviour in terms of the hot accretion flow model.

Key words. accretion, accretion disks – black hole physics – methods: data analysis – stars: black holes – stars: individual: GX 339−4 – X-rays: binaries

1. Introduction

GX 339−4 is a well-studied black hole (BH) low-mass X-ray binary (LMXB) that was discovered as a bright and variable X-ray source using MIT OSA−7 experiment (Markert et al. 1973). The source is known to undergo recurrent outbursts every 2–3 years and it became a standard target for multiwavelength campaigns (Homan et al. 2005; Belloni et al. 2005, 2006; Tomskill et al. 2008; Shidatsu et al. 2011; Cadolle Bel et al. 2011; Motta et al. 2011; Rahoui et al. 2012; Buxton et al. 2012; Corbel et al. 2013). During outbursts the source undergoes transition between different states that can be distinguished using a variety of criteria, including the X-ray hardness ratio, quasi-periodic oscillations and other timing properties (Homan & Belloni 2005; McClintock & Remillard 2006; Remillard & McClintock 2006; Belloni 2010).

The origin of these states is still not very well understood, but is generally associated with the changes in the accretion flow geometry (see, e.g., Esin et al. 1997; Poutanen et al. 1997; Zdziarski et al. 2004; Done et al. 2007). In the soft X-ray state, the spectrum consists of a thermal component associated with the standard cold accretion disk (Shakura & Sunyaev 1973) and an additional power-law-like tail from the non-thermal corona (Poutanen & Coppi 1998; Gierliński et al. 1999; Zdziarski et al. 2001). In the hard state, the emission from the cold disk is greatly reduced due to its truncation at a radius significantly larger than the radius of the innermost stable orbit; the emission instead is dominated by thermal Comptonization of some seed photons (cold disk and internal synchrotron) in an inner hot, geometrically thick accretion flow. The transitions between the spectral states happen due to a change in the truncation radius, which results in a variation of the relative contributions of the cold disk and the hot flow and also lead to corresponding changes in the timing properties (Done et al. 2007; Gilfanov 2010; Poutanen & Veledina 2014; Poutanen et al. 2018).

For many years it was obvious that the X-ray emitting region of accreting BHs is rather compact because of the observed fast variability. On the other hand, the optical/near-infrared (ONIR) emission was thought to originate mostly from the outer disk irradiated by the central X-ray source. The first evidence that the situation is not so simple came already in the beginning of 1980s, when the fast optical variability and quasi-periodic oscillations at 20 s were detected from GX 339−4 by Motch et al. (1982), which were interpreted as a signature of emission from the hot accretion flow or corona (Fabian et al. 1982). Soon after, Motch et al. (1983) carried out simultaneous optical/X-ray observations which demonstrated a complicated structure of the cross-correlation function (CCF) with a precognition dip. Recently, similar CCFs were found in three BHs: XTE J1118+480 (Kanbach et al. 2001; Hynes et al. 2003a), Swift J1753.5−0127 (Durant et al. 2008, 2009, 2011; Hynes et al. 2009) and in GX 339−4 (Gandhi et al. 2008, 2010). The shape of the CCF can be explained if the optical emission contains two components: synchrotron emission from the hot flow and the reprocessed radiation that are anti-correlated and correlated with the X-rays, respectively (Veledina et al. 2011a). However, the shape of the CCF seems to be wavelength-dependent. For instance, the infrared/X-ray CCF of GX 339−4 showed a single peak with no precognition dip (Casella et al. 2010), which was successfully explained by a jet model, where the emission is powered by internal shocks (Malzac et al. 2018). Thus it is clear that the ONIR emission is not completely dominated by the accretion disk, but has at least one additional (non-thermal) component, either from the hot flow, or the jet, or both.
Signatures of this component are seen in the long-term variability as bright ONIR flares, which appear in the hard state (Hynes et al. 2000; Jain et al. 2001; Buxton & Bailyn 2004; Kalemci et al. 2013). Spectral evolution of the flare in XTE J1550–564 is consistent with the hot accretion flow scenario (Veledina et al. 2013; Poutanen & Veledina 2014). In Swift J1755.5–0127 the jet emission is known to be weak in radio and its contribution to the ONIR band is likely small (Durant et al. 2009), while the ONIR-X-ray broad-band spectra can well be explained by the hot flow model (Kajava et al. 2016a). On the other hand, the soft ONIR spectra of 4U 1543–47 (Kalemci et al. 2013) and MAXI J1836–194 (Russell et al. 2013) argue in favor of the jet scenario.

Origin of this non-thermal component can give us a clue to understanding the nature of the accretion-ejection engine operating in the BH vicinity. This aim can be reached by studying the evolution of its spectral shape throughout the outburst and in particular during the transitions between the states. This requires measurements of the interstellar extinction and subtraction of the (irradiated) accretion disk contribution. From this perspective, GX 339–4 is an interesting source because it has served as a target for numerous multiwavelength campaigns. The aim of this work is to study the behavior of the source spectrum on the color-magnitude diagram (CMD) and the evolution of the non-thermal component using spectral decomposition.

The paper is structured as follows. In Sect. 2, we describe the data used for the analysis. Sect. 3 contains details of the analysis, determination of the interstellar extinction, comparison of different outbursts, and determination of the spectrum of the non-thermal component. In Sect. 4 we discuss the observed ONIR properties and their connection to the X-rays and interpret them in terms of the hot flow model. We conclude in Sect. 5.

2. Data

Monitoring of GX 339–4 in the ONIR has been conducted using the ANDICAM camera (DePoy et al. 2003) on the Small and Moderate Aperture Research Telescope System (SMARTS; Subasavage et al. 2010). We use the publicly available SMARTS data in V, I, J and H filters taken in 2002–2011 (Buxton et al. 2012). We split the ONIR light curves into 7 intervals, each covering one of the regular or failed outbursts (see Sect. 3.1). The light curves, corrected for interstellar extinction (see Sect. 3.2), are shown in Fig. 1.

The X-ray data are taken from the Rossi X-ray Timing Explorer All-Sky Monitor (ASM) (Bradt et al. 1993), which provides observations of GX 339–4 in three energy ranges (1.5–3, 3–5 and 5–12 keV). The count rates from different channels are different outbursts, and determination of the spectrum of the non-thermal component. In Sect. 4 we discuss the observed ONIR properties and their connection to the X-rays and interpret them in terms of the hot flow model. We conclude in Sect. 5.

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1 http://www.astro.yale.edu/smarts/xrb/home.php
2 The data mentioned with the original publication (Buxton et al. 2012) cover 2002–2010 period and the fluxes in I filter are computed using an incorrect extinction A_I. The corrected values and 2011 data can be found at http://www.astro.yale.edu/buxton/GX339/.
3 http://xte.mit.edu/ASM_lc.html
Table 1. Start and end dates, corresponding outburst years and start dates of each identified outburst phase. Letter f in the first column denotes failed outbursts.

<table>
<thead>
<tr>
<th>Outburst</th>
<th>Years</th>
<th>Start MJD</th>
<th>End MJD</th>
<th>RPh MJD</th>
<th>RHS MJD</th>
<th>Hts MJD</th>
<th>SS MJD</th>
<th>StH MJD</th>
<th>DHS MJD</th>
<th>DPh MJD</th>
<th>Q MJD</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2002–2003</td>
<td>52298</td>
<td>52294</td>
<td>52294</td>
<td>52374</td>
<td>52400</td>
<td>52405</td>
<td>52738</td>
<td>52756</td>
<td>52786</td>
<td>52834</td>
</tr>
<tr>
<td>2</td>
<td>2004–2005</td>
<td>53040</td>
<td>53661</td>
<td>53661</td>
<td>53221</td>
<td>53231</td>
<td>53473</td>
<td>53490</td>
<td>53513</td>
<td>53553</td>
<td></td>
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<tr>
<td>3f</td>
<td>2006</td>
<td>53792</td>
<td>54020</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>2007</td>
<td>54124</td>
<td>54376</td>
<td>54498</td>
<td>54137</td>
<td>54146</td>
<td>54236</td>
<td>54252</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>5f</td>
<td>2008</td>
<td>54498</td>
<td>54747</td>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>6f</td>
<td>2009</td>
<td>54872</td>
<td>55129</td>
<td>54885</td>
<td>54543</td>
<td>54580</td>
<td>54634</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>2010–2011</td>
<td>55217</td>
<td>55836</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>

Table 2. ONIR filter effective wavelengths $\lambda$ and zero-point fluxes $F_0$ adopted from Buxton et al. (2012). Extinction coefficients are calculated using interstellar extinction laws from Cardelli et al. (1989) and O’Donnell (1994). (*$^*$) indicates the extinction coefficient, to which an additional correction of 0.15 mag was applied.

<table>
<thead>
<tr>
<th>Filter</th>
<th>$\lambda$</th>
<th>$F_0$</th>
<th>$A_k$</th>
</tr>
</thead>
<tbody>
<tr>
<td>V</td>
<td>5450</td>
<td>3636</td>
<td>3.58</td>
</tr>
<tr>
<td>I</td>
<td>7980</td>
<td>2416</td>
<td>2.31*</td>
</tr>
<tr>
<td>J</td>
<td>12500</td>
<td>1670</td>
<td>1.00</td>
</tr>
<tr>
<td>H</td>
<td>16500</td>
<td>980</td>
<td>0.64</td>
</tr>
</tbody>
</table>

3. Light curve analysis and results

3.1. Outburst phase separation

We use ONIR light curves to split regular outbursts (when GX 339–4 reaches the soft state) into different phases: a rising phase (RPh), which happens before the first ONIR flare, hard state at the rising phase (RHS), transition from the hard to the soft state (Hts), soft state (SS), transition from the soft to the hard state (StH), hard state at the decaying phase (DPh), decaying phase (DPh) and quiescence (Q). A preliminary separation into different states was done using the X-ray data (see e.g. Motta et al. 2009). We then fit an S-shape curve to the ONIR light curves in the RPh, Hts and StH phases and determine the transition dates. Further, we fit the broken power law to the DPh and Q data and obtain the start dates of quiescence. The details of the described procedure are explained in Appendix A and the start dates of each outburst phase (if this phase was observed) are presented in Table 1.

We also extend the fitting procedure to the failed outbursts, for which we identify ONIR states with colors, similar to the states of the regular outbursts. For the 2006 and 2009 outbursts we fit the model to the final transition to quiescence and use the obtained parameters to determine the start and end dates of the transition, similar to the Hts case. We then classify the 2008 outburst data based on the ONIR brightness, because during this event GX 339–4 shows extremely erratic behaviour, which resembles neither regular nor failed outburst.

We compare the transition dates obtained using our fitting procedure to the dates used in other works. According to Kalameci et al. (2013), the StH transitions of the regular outbursts occur 2 to 6 days later than ours (see our Table 1 and table 2 in Kalameci et al. 2013). The Hts transition of the 2002–2003 outburst, reported in Homan et al. (2005), starts 2 days earlier and lasts 6 days longer than ours. Finally, our start dates of the RHS and Hts of the 2007 outburst agree within errors with the transition dates computed using the X-ray data by Motta et al. (2009).

4 https://swift.gsfc.nasa.gov/results/transients/weak/GX339-4/
\( R_{\odot} = 3.1, \) Cardelli et al. (1989). Other known values of \( A_V \) include \( A_V = 3.5 \pm 0.5 \) (Gandhi et al. 2010) and \( A_V = 3.25 \pm 0.5 \) (Gandhi et al. 2011), which are derived from the color excess obtained in Zdziarski et al. (1998) and Buxton & Vennes (2003). We conclude that our estimate of \( A_V \) is well within the range of previously used values.

The normalization \( N \) provides information on the characteristic size of the part of the accretion disk emitting in ONIR. Using parameters of the binary system given in Table 3, we obtain \( R_{\text{surf}} = (2.8 \pm 1.1) \ R_{\odot} \). We then estimate the binary separation \( a/R_{\odot} = 4.17(M_i/M_\odot)^{1/3}(1 + q)^{1/3} P_{\text{orb}}^{2/3} \) day (see e.g. Frank et al. 2002), size of the primary Roche lobe \( R_{L,i}/a = 0.49/[0.6 + q^{2/3} \log(1 + e^{1/3})] \) (Eggleton 1983) and the maximum disk size due to the tidal instability \( R_{\text{tidal}}/a = 0.60/(1 + q) \) (Paczynski 1977; Warner 1995), which are shown in Table 3. This allows us to compare the parameters of GX 339–4 to its “twin” system XTE J1550–564 (Muñoz-Darias et al. 2008).

Analysis of the ONIR light curves of the 2000 outburst of XTE J1550–564 (Poutanen et al. 2014) showed that the effective radius of the irradiated disk of XTE J1550–564, \( R = 4.1 \ R_{\odot} \), is 40\% of the maximum disk size of 6.9 \( R_{\odot} \). Although GX 339–4 and XTE J1550–564 have similar sizes (Orosz et al. 2011; Hynes et al. 2003b; Heida et al. 2017), the major difference is the binary mass ratio \( q \), which is of order of 0.033 in case of XTE J1550–564 and 0.18 in case of GX 339–4 (see Table 3). Larger mass ratio leads to a smaller primary Roche lobe size, limiting the maximum size of the accretion disk.

### 3.3. Outburst template

Following the approach introduced in Maitra & Bailyn (2008), we study the \( V - (V - H) \) CMDs of the outbursts. We use regular outbursts to construct the outburst template. We use data from the same spectral state of different regular outbursts to compute the 90 per cent density contours for the RPh, RHS, DHS and DPH phases (with the exception of the 2004–2005 outburst, which RHS we omit because it is systematically fainter than that of the other regular outbursts). The template and state contours are shown in Fig. 3. We then use the obtained template to study the similarities between regular outbursts and the differences between regular and failed ones.

In order to estimate the shape of the ONIR spectra, we compute the intrinsic spectral slopes \( \alpha_{ij} \), correcting observed colors for the interstellar extinction:

\[
\alpha_{ij} = \frac{m_i - m_j - (A_i - A_j)}{2.5 \log \left( \frac{F_i}{F_j} \right)},
\]

where \( i, j \) correspond to one of the ONIR filters \( (V, I, J \text{ or } H) \), \( m_i - m_j \) is the observed color, \( A_i \) and \( A_j \) are the interstellar extinctions, \( \lambda_i \) and \( \lambda_j \) are the effective wavelengths, and \( F_i \) and \( F_j \) are the zero-point fluxes in \( i \) and \( j \) filters, respectively. We adopt the extinction law of Cardelli et al. (1989) and O’Donnell (1994) with \( R_V = 3.1 \) (for a detailed discussion, see Poutanen et al. 2014) and use filter parameters from Table 2. Equation (3) for \( V \) and \( H \) filters can be simplified to

\[
\alpha_{VH} = -0.84(V - H) + 0.69A_V + 1.16.
\]

Based on the RPh data of the 2002–2003 outburst, during the initial stage of the outburst GX 339–4 has a blackbody spectrum with temperature of \( T \approx 14 \) kK (for \( A_V = 3.58 \)) and \( V - H \approx 2.8 \). The spectrum then reddens towards the peak of the first flare (RHS), reaching \( V - H \approx 4 \). Then, during the rapid HtS transition, the spectrum becomes blue, which is typically attributed to the quenching of the non-thermal component. The SS evolution proceeds along the blackbody track (see Fig. 3, solid orange line). The GX 339–4 spectra evolve towards upper-left part of the CMD, indicating a substantial increase of the temperature from roughly 30 up to \( 50 \) kK. In \( 30–70 \) d ONIR fluxes of GX 339–4 decrease and the color temperatures drop substantially. This marks the end of the SS and the beginning of the rapid transition to the the DHS, which occurs at \( T \approx 20 \) kK.

During the SH transition, GX 339–4 moves almost horizontally on the \( V - (V - H) \) CMD, indicating a dramatic change in \( H \) filter fluxes, and almost no changes in \( V \). The spectrum reddens as the source approaches the DHS. GX 339–4 spends \( 20–30 \) d in this phase, approximately a half of the total duration of an ONIR flare, and after that it enters the decaying phase (DPH). During the next \( 50 \) d, the observed ONIR fluxes drop dramatically and the spectra become blue. The quiescence plateau, unlike other systems (see Kalemci et al. 2013; Poutanen et al. 2014), does not

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**Table 3. Parameters of the system (Heida et al. 2017).**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass ratio</td>
<td>( q = 0.18 \pm 0.05 )</td>
</tr>
<tr>
<td>Orbital period</td>
<td>( P = 1.76 \pm 0.01 ) d</td>
</tr>
<tr>
<td>Black hole mass</td>
<td>( M_1 = 5.9 \pm 3.4 \ M_\odot )</td>
</tr>
<tr>
<td>Inclination</td>
<td>( i = 58 \pm 21 ) deg</td>
</tr>
<tr>
<td>Distance</td>
<td>( D = 7 \pm 2 ) kpc</td>
</tr>
<tr>
<td>Binary separation</td>
<td>( a = 11.6 \pm 5.1 ) R_{\odot}</td>
</tr>
<tr>
<td>Roche lobe size</td>
<td>( R_{\text{L,1}} = 6.1 \pm 3.2 ) R_{\odot}</td>
</tr>
<tr>
<td>Maximum disk size</td>
<td>( R_{\text{tidal}} = 5.9 \pm 2.6 ) R_{\odot}</td>
</tr>
<tr>
<td>Effective radius of irradiated disk</td>
<td>( R_{\text{eff}} = 2.8 \pm 1.1 ) R_{\odot}</td>
</tr>
</tbody>
</table>

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**Fig. 3.** The evolution of magnitudes and colors of GX 339–4 throughout the outburst. \( V \) and \( V - H \) are observed magnitudes and colors, \( F_V \) is corrected for the interstellar extinction flux and \( \alpha_{VH} \) is the spectral slope, computed assuming \( A_V = 3.58 \) (see Eq. 4). Dotted pink contour corresponds to the RPh, top-right solid blue contour – to the RHS, top solid green arrow – to the HtS transition, solid orange contour – to the SS, bottom solid green arrow – to the reverse StH transition, bottom solid blue contour – to the DHS, dashed pink contour – to the DPh. Solid orange line gives the model blackbody curve with \( \log N = -21.9 \), see Eq. (1). Filled blue diamonds denote temperatures. The quiescent state is marked with letter \( Q \) in the lower part of the diagram.

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\( F_0^i \) are the zero-point fluxes in \( i \) and \( j \) filters, respectively. We adopt the extinction law of Cardelli et al. (1989) and O’Donnell (1994) with \( R_V = 3.1 \) (for a detailed discussion, see Poutanen et al. 2014) and use filter parameters from Table 2. Equation (3) for \( V \) and \( H \) filters can be simplified to

\[
\alpha_{VH} = -0.84(V - H) + 0.69A_V + 1.16.
\]
Fig. 4. (a) $V$ versus $V - H$ color-magnitude diagram of the 2002–2003 outburst. Filled upward-facing pink triangles correspond to the RPh, filled blue circles - to the RHS, filled downward-facing green triangles - to the HtS transition, filled orange squares - to the SS, open upward-facing green triangles - to the StH transition, open blue circles - to the DHS, open downward-facing green triangles - to the DPh, black crosses - to the Q. Contours are the same as in Fig. 3. The typical 1σ errors are shown in the lower left corner: the top orange cross corresponds to the bright states and is comparable to the plot symbol size, the bottom black cross corresponds to the quiescent state data, where observational errors are substantial. (b) ONIR $H$ (top) and $V$ (bottom) light curves of the same outburst. Symbols are the same as in panel (a). Errors are 1σ and error bars are comparable to the symbols size. Solid black line represents the model, fitted to the part of the SS data. The grey area around the line denotes 1σ errors and also includes the contribution from the intrinsic scatter. (c) ASM A X-ray light curve.

Fig. 5. Same as Fig. 4, but for the 2004–2005 outburst. (c) The BAT data are shown with open grey squares starting from the second half of the 2004–2005 outburst. Errors are 1σ.

follow the blackbody track, and shows a substantial (up to 1.5 mag) variability in $V - H$ colors. Interestingly, the decay phase of the 2007 outburst shows a different pattern. After reaching DHS, GX 339−4 stays there for more than 100 d, and is never observed to reach the quiescent level fluxes in the ONIR.

We find that the colors and magnitudes of RHS are systematically different from those of DHS. The RPh is somewhat bluer than the DPh for the same $V$ magnitude (Fig. 3). The SS contour (solid orange line) is elongated along the blackbody model that is fitted to the data. It shows that there is some spread of data points around the model curve, which can be caused by the short-term variability of GX 339−4 during its soft states (Kosenkov & Veledina 2018) and uncertainties in the observed fluxes.

The quiescence data shows a number of peculiarities. The spread in colors cannot be explained by the measurement errors (see Fig. 4a, bottom left corner), as it exceeds a typical error by
Fig. 6. Same as Fig. 5, but for the 2007 outburst.

Fig. 7. Same as Fig. 5, but for the 2010–2011 outburst.

a factor of 10. Interestingly, most of the quiescent data points lie below the blackbody line, i.e. the colors are typically bluer than the blackbody spectrum of the same size. We also note that the pre-quiescent state temperatures lie well above the hydrogen ionization limit.

3.4. Regular outbursts

Below we describe the properties of each outburst. We stress the peculiarities and deviations from the common pattern discussed in the previous sections. The 2002–2003 (Fig. 4) is the only outburst with a significant number of observations of the initial RPh (filled pink upward-facing triangles). There are also a few observations available for the HiS transition (filled green downward-facing triangles). As a result, we can trace the evolution of the GX 339–4 before and after the RHS (filled blue circles) and compare it to the decay stages: SiH transition (open green triangles), DHS (open blue circles) and DPh (open pink triangles). The most unusual part of the 2002–2003 outburst is its soft state. Immediately after the transition, the flux in H filter continued to grow and showed no significant short-term variability (see Fig. 4b; also Homan et al. 2005). In about 20 d (MJD≈52480) the flux started to decrease, and the light curve demonstrated significant variability, which was previously attributed to superhumps (Kosenkov & Veledina 2018). At the time of the change, the ASM fluxes and ASM B/A hardness ratio had a local minimum (see Fig. 4b-d).

The 2004–2005 outburst was fainter, both in the X-rays and in ONIR, as compared to other regular outbursts (see Figs. 1 and 2). The duration of the RHS, ≈180 d, is longer than that in the
other outbursts (20–75 d). The same conclusion can be reached from Fig. 5a, where the RHS (filled blue circles) are located between the two RHS and DHS contours (blue solid lines) of the outburst pattern. Similar to the other outbursts, the $V$-filter flux increased after the transition to SS, and then decreased together with the decreasing ASM fluxes (Fig. 5b, c). The DHS points are located well within the template contour, and the corresponding fluxes are only marginally lower than those of the RHS, in contrast to other regular outbursts.

The 2007 outburst demonstrates unusually short SS and a long DHS. Both ASM and ONIR fluxes decayed after the HS transition (Fig. 6b,c), and the decay continued for ≈100 d, as compared to typical ≈250–300 d for other outbursts. On the contrary, the DHS lasted over 100 d, in contrast to typical ≈50 d for other outbursts. The Swift/BAT light-curve indicated low flux level after MJD 54400, suggesting the source went into quiescence around that date.

The 2010–2011 outburst shows peculiar trend discontinuity of the ONIR light-curves during the SS (around MJD 55360, see Fig. 7b). Nevertheless, all SS data points align well with the blackbody model on the CMD (Fig. 7a), hence the observed trend changes are caused by the sudden decrease of the color disk temperature.

### 3.5. Failed outbursts

There have been three failed outbursts in 2002–2011. During these events GX 339–4 shows dramatic changes in ONIR fluxes, however, it never enters the SS, in contrast to the regular outbursts. The ONIR peak fluxes are about an order of magnitude fainter than the RHS of regular outbursts, however, the colors are the same. The 2006 and 2009 failed outbursts have similar duration and peak magnitudes (see Figs. 8b,c and 9b,c). Their paths on the CMD go through the regular DHS and DPh contours, and duration of different stages is comparable to the regular outbursts.

The 2008 failed outburst peak is about 0.5 magnitude fainter than that of the other failed outbursts (and about 1.5 magnitude fainter than in regular outbursts). It consists of two peaks (Russell et al. 2008; Kong 2008), both of them demonstrate colors and magnitudes of DHS (see Fig. 10a). The second brightening is, on the other hand, considerably longer than the typical DHS. The two peaks are separated by the valley, which we tentatively divide into two sections, by analogy to the HS and SS. The colors of these stages are also similar to those of corresponding stages of regular outbursts, but the timescales are somewhat larger (40–50 d as opposed to 10–20 d, see Fig. 10b, Table 1).

Interestingly, the $V$–$H$ colors of GX 339–4 during this event show a significant spread, which exceeds typical spreads in data points corresponding to any of the typical outburst phase (Russell et al. 2008). We note that the 2008 failed outburst occurred right after the regular 2007 outburst, and to the best of our knowledge there have been no observations of the decay to the quiescence after the DHS. Though we consider the 2008 outburst as a separate one based on the low, comparable to quiescence, BAT count rate, there is a possibility that this segment of the ONIR light curve is, in fact, a continuation of the exceptionally long outburst which started in 2007 (Russell et al. 2008).

The 2009 failed outburst shows a double-peaked profile (both in ONIR and X-rays, see Fig. 9b,c) and the $V$–$H$ colors of both peaks are the same. Interestingly though, the brightest phase of the 2009 outburst resembles the RHS of the 2004–2005 regular one in terms of phase duration, typical ONIR magnitudes and colors (see Fig. 5b and Fig. 9b, blue dots). This similarity makes it harder to separate regular and failed outbursts at the early phases. Therefore, if the RHS of an outburst has $V < 16$, we expect to observe transition to the soft state. If the RHS is fainter than $V = 16$, an outburst can be either regular with GX 339–4 reaching the soft state (similar to the 2004–2005 outburst, see Fig. 5), or a failed one with GX 339–4 transitioning to quiescence after the RHS (similar to the 2009 failed outburst, see Fig. 9).
3.6. Evolution of the non-thermal component

It is known that the changes of ONIR colors during the HtS and ShH transitions are related to quenching/recovery of the red, non-thermal component (see e.g. Fender et al. 1999; Jain et al. 2001; Corbel & Fender 2002). Separation of the thermal (disk) and non-thermal components and extraction of the non-thermal component spectra is important for understanding its origin. The task is, however, complicated by the fact that the spectrum of the thermal component (disk temperature) is an unknown function of time, resulting in an uncertainty of the spectrum of the non-thermal component. The shape of this component and, in particular, the spectral index may allow us to distinguish between different models, such as the jet (Fender 2001; Gallo et al. 2007; Uttley & Casella 2014) or the hot flow (Veledina et al. 2013; Poutanen & Veledina 2014; Poutanen et al. 2018). Contribution of the disk can be estimated by fitting the SS light-curves in different filters, and extrapolating the obtained fit to the transitions and the hard state (see, e.g., Buxton et al. 2012; Dinçer et al. 2012; Poutanen et al. 2014). However, a freedom in the choice of the fitting function and the fitting interval lead to an uncertainty in the non-thermal component spectrum.

In general, the emission of the irradiated accretion disk is expected to follow the fast rise – exponential decay profile (and a constant level of emission in quiescence, see e.g. Chen et al. 1997). The exponential decay profile was fit to the 2000 outburst data of XTE J1550–564 (Poutanen et al. 2014). However, GX 339–4 during SS shows both decay and rise periods, which translate to the linear relations for the magnitudes. Therefore, we
Fig. 11. (a) A sample of soft state spectra before the second ONIR flare of the 2002–2003 outburst (orange squares), transition from soft to hard state (green triangles) and a sample of the hard state spectra (blue circles) of the same outburst. (b) Same states/phases as in (a), but after subtraction of the thermal component (see Fig. 4b, solid black line). (c, d) Same as (a, b), but for the 2007 outburst. Fluxes are corrected for the interstellar extinction, errors are $1\sigma$.

fit parts of the SS light curves using the following model:

$$m_j(t) = m^0_j + \mu_j \left( t - t^0 \right) + \epsilon_j,$$

where $m_j$ is the observed magnitude in the $j$-th ONIR filter, $m^0_j$ and $\mu_j$ are the constant and the slope, $t$ is the time and $t^0$ is either the beginning (if the fitted data set covers the first part of the SS) or the end time of the fitted data set (if it covers the last part of the SS), $\epsilon_j$ is the intrinsic scatter, which is partially caused by superhump variability (Dinçer et al. 2012; Kosenkov & Veledina 2018). We use Bayesian inference to estimate these parameters and list them in Table 4.

Once the fit to the SS is obtained, we extrapolate the model to the transitions and the hard-state data. The errors on the fluxes of the non-thermal component are mostly coming from the uncertainties in the parameters of the fitted model and they increase towards the hard state. On the other hand, the contribution of the disk also drops, and it falls down to about 5 per cent in the RHS.

The fitted models are shown in Figs. 4-7(b) with the solid black lines. The grey areas around the model denote $1\sigma$ uncertainties. The model curve spans over the soft state data used for fitting (orange boxes), the transition phase (if present, green triangles) up to the nearest hard state (blue circles). The total spectra and the spectra of the non-thermal component are shown in Figs. 11-13. The fluxes are corrected for the interstellar extinction assuming $A_V = 3.58$ (see Sect. 3.2).

In the majority of cases, both the hard state and the state transition spectra of the non-thermal component appear to be nearly flat ($\alpha_{nth} = 0.06 \pm 0.12$, the best examples are the 2010–2011 RHS and 2004–2005 DHS, see Figs. 12d and 13b). During the transitions, the spectral shape of the non-thermal component
tends to be preserved (within errors) and the fluxes increase or decrease quasi-simultaneously in all four filters. We also note that there is no apparent difference between spectral shapes of that component in SfH and HfS transitions.

The spectral slope $\alpha_{\text{ONIR}}$ is affected by the assumed value of $A_V$. The impact of $A_V$ can be estimated using Eq. (4). For a relatively low value of $A_V \approx 3.0$ (Kong et al. 2000; Homan et al. 2005), $\alpha_{\text{ONIR}} = -0.34$, while for a relatively high $A_V = 3.7$ (Zdziarski et al. 1998; Buxton et al. 2012) we get $\alpha_{\text{ONIR}} = 0.15$. The changes in $A_V$ are also reflected in the shape of the SS data and their departure from the blackbody model on the CMD (see discussion in Sect. 4.1).

4. Discussion

4.1. ONIR spectral properties

There are several ways to study the ONIR data of X-ray binaries available in multiple filters. The magnitude-magnitude diagrams adopted in Buxton et al. (2012) can be used to emphasize the difference between hard and soft states and highlight the state transition tracks. However, these diagrams do not provide sufficient information about the shape of the spectra in each of the observed states and make it harder to separate RHS and DHS data points as they roughly follow the same broken power-law track (together with the data from quiescence, see e.g. fig. 9 in Buxton et al. 2012). Another method relies on the color-magnitude diagrams (see e.g. Maitra & Bailyn 2008; Russell et al. 2011; Poutanen et al. 2014). CMD plots benefit from the fact that they highlight both changes in the observed fluxes and in the shape of the spectra. Recently, the CMD was used to study the spectral
evolution of the black hole X-ray binary XTE J1550–564 during its 2000 outburst (Russell et al. 2011; Poutanen et al. 2014; Poutanen & Veledina 2014), which was very similar to that of GX 339–4. The characteristic hysteresis pattern present in the CMDs of both sources can be related to the hysteresis observed in the X-ray data (Poutanen et al. 2014). In three out of four regular outbursts, GX 339–4 was observed to have nearly identical HtS and StH transitions (see Sect. 4.2 for a discussion; also fig. 1 in Corbel et al. 2013, fig. 1 in Muñoz-Darias et al. 2008), while during the HtS transition of the rising phase of the 2002–2003 outburst the X-ray fluxes were a few times smaller than the typical values (Figs. 1 and 5a,b). Interestingly, though the 2002–2003 HtS transition starts at lower ONIR fluxes, it arrives at the same SS flux with a color temperature of 30-35 kK.

Notably, the highest SS temperature reached by XTE J1550–564 of 16 kK (Poutanen et al. 2014) is substantially smaller than the highest SS temperature of GX 339–4 (50 kK, see Fig. 7). The inferred values of SS temperatures can be affected by the overestimated value of $A_V$. However, lower $A_V$ results in the deviation of the SS track from the theoretical prediction of the blackbody model on the CMD (Fig. 3, solid orange line and orange contour). Further UV observations of GX 339–4 carried out during the early phase of the 2010–2011 SS suggest that the peak of the blackbody component lies at wavelengths, shorter than $\approx 2000 \, \text{Å}$, beyond the near-UV (see fig. 7 in Cadolle Bel et al. 2011), which imposes a lower limit of $\approx 15 \, \text{kK}$ on the blackbody temperature at the beginning of the SS. Unlike XTE J1550–564, which shows a typical exponential decay of ONIR fluxes during its SS, ONIR fluxes of GX 339–4 increase shortly after the HtS transition in two out of four regular outbursts. As a result, the highest color temperatures of GX 339–4 are observed somewhere in the middle of the SS, while the highest blackbody temperature of XTE J1550–564 is found at the beginning of the SS.
The SS temperatures depend on the flux irradiating the outer parts of the disk. That flux in turn is defined by the disk geometry, luminosity of the central X-ray source and its emission pattern, which in turn depends on the black hole spin. First of all, from the geometrical perspective, accretion disk in GX 339–4 can be a factor of ~2 smaller than that of XTE J1550–564 (see Table 1; also Orosz et al. 2011). Geometrically thicker outer parts of the disk can also increase the amount of irradiation flux received. Secondly, light bending effects in the vicinity of a Kerr black hole substantially increase the intensity of the illuminating flux (Suleimanov et al. 2008). There is evidence that the black hole spin of GX 339–4 can be as large as $a \approx 0.935$ (Reis et al. 2008, Miller et al. 2008; a more conservative estimate is given in Kolehmainen & Done 2010), compared to $a \approx 0.5$ in XTE J1550–564 (Steiner et al. 2011). Finally, there appears to be no substantial difference between SS luminosities of GX 339–4 and XTE J1550–564 (see e.g. Muñoz-Darias et al. 2013). It is possible that a complex interplay of these factors is responsible for the high SS temperatures observed in GX 339–4.

The quiescent states of GX 339–4 appear to deviate from those observed in XTE J1550–564. While for XTE J1550–564 these points lie on the blackbody track, for GX 339–4 they lie below the blackbody curve. It is known that the contribution of the companion star is small even in quiescence (up to 50 per cent to the $J$ and $H$ filters, Heida et al. 2017), and the red spectrum of the K-type companion cannot explain the shift towards the blue part of the CMD as well as substantial variability in color of GX 339–4. The reason for such a behavior in quiescence remains unclear.

The CMDs plotted from the ONIR data can be used efficiently to identify spectral states of the source and uncover spectral properties of the non-thermal component. We find that the regular and failed outbursts occupy the same regions in the CMD. Though the regular outbursts tend to be more luminous during the RHS, the position of points of 2004–2005 outburst intersects with brightest parts of the analysed failed outbursts. We thus conclude that the peak ONIR brightness has no predictive power for the failed outbursts. The reason for the similarity of ONIR brightness of regular and failed outbursts is yet to be understood. If the failed outbursts differ from the regular ones by the mass transfer rate, then the similar brightness during the RHS can be explained by a weak dependence of the non-thermal component on the accretion rate. Because it dominates in the ONIR, the difference between regular and faint outbursts is minor.

### Table 4. Best-fit parameters for the light curves in the soft state (Eq. 5). Errors are 1σ.

<table>
<thead>
<tr>
<th>Filter</th>
<th>$r^0$</th>
<th>$m^0_{ji}$</th>
<th>$\mu_j$</th>
<th>$\epsilon_j$</th>
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</thead>
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<tr>
<td></td>
<td>day</td>
<td>mag</td>
<td>mag day$^{-1}$</td>
<td>mag</td>
</tr>
<tr>
<td>Decaying phase of the 2002–2003 outburst</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$V$</td>
<td>17.50 ± 0.06</td>
<td>0.009 ± 0.002</td>
<td>0.16 ± 0.02</td>
<td></td>
</tr>
<tr>
<td>$I$</td>
<td>16.29 ± 0.05</td>
<td>0.008 ± 0.002</td>
<td>0.14 ± 0.02</td>
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</tr>
<tr>
<td>$J$</td>
<td>15.32 ± 0.09</td>
<td>0.006 ± 0.003</td>
<td>0.20 ± 0.03</td>
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</tr>
<tr>
<td>$H$</td>
<td>14.80 ± 0.06</td>
<td>0.003 ± 0.002</td>
<td>0.13 ± 0.02</td>
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<tr>
<td>Rising phase of the 2004–2005 outburst</td>
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<td></td>
<td></td>
<td></td>
</tr>
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<td>0.11 ± 0.01</td>
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<td>$J$</td>
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<tr>
<td>$H$</td>
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<td>Decaying phase of the 2004–2005 outburst</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<tr>
<td>$J$</td>
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<td>$H$</td>
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<td>Decaying phase of the 2007 outburst</td>
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<tr>
<td>$I$</td>
<td>16.36 ± 0.06</td>
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</tr>
<tr>
<td>$J$</td>
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<td>0.14 ± 0.02</td>
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<tr>
<td>$H$</td>
<td>14.78 ± 0.09</td>
<td>0.002 ± 0.003</td>
<td>0.18 ± 0.03</td>
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<tr>
<td>Rising phase of the 2010–2011 outburst</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>$V$</td>
<td>16.53 ± 0.04</td>
<td>−0.009 ± 0.001</td>
<td>0.16 ± 0.01</td>
<td></td>
</tr>
<tr>
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<td>0.15 ± 0.01</td>
<td></td>
</tr>
<tr>
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<td>0.14 ± 0.01</td>
<td></td>
</tr>
<tr>
<td>$H$</td>
<td>14.20 ± 0.04</td>
<td>−0.007 ± 0.001</td>
<td>0.15 ± 0.01</td>
<td></td>
</tr>
<tr>
<td>Decaying phase of the 2010–2011 outburst</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$V$</td>
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<td>0.045 ± 0.010</td>
<td>0.21 ± 0.05</td>
<td></td>
</tr>
<tr>
<td>$I$</td>
<td>16.68 ± 0.11</td>
<td>0.038 ± 0.008</td>
<td>0.19 ± 0.04</td>
<td></td>
</tr>
<tr>
<td>$J$</td>
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<td>0.032 ± 0.007</td>
<td>0.18 ± 0.04</td>
<td></td>
</tr>
<tr>
<td>$H$</td>
<td>15.05 ± 0.16</td>
<td>0.022 ± 0.011</td>
<td>0.22 ± 0.06</td>
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</tr>
</tbody>
</table>
4.2. ONIR vs X-ray correlation

Black hole LMXBs show strong non-linear correlation between radio, ONIR and X-ray fluxes. The radio – X-ray correlation was originally observed in GX 339−4 and V404 Cyg (Gallo et al. 2003) and later was confirmed on a much larger sample of Galactic LMXBs (including GX 339−4 during multiple outbursts, see Corbel et al. 2013; Islam & Zdziarski 2018). The global ONIR – X-ray correlation, which naturally arises from the different emission mechanisms (van Paradijs & McClintock 1994; Gallo et al. 2003), was observed for a number of black hole LMXBs (Russell et al. 2006) and for the 2002–2003, 2004–2005 and 2007 outbursts of GX 339−4, in particular (see Homan et al. 2005; Coriat et al. 2009). Here we expand the sample to include the 2010–2011 outburst.

We use the RXTE/ASM flux as a proxy for the X-ray luminosity. The observed flux, however, cannot be simply transformed into the bolometric luminosity, as the latter depends on the spectral shape. The bolometric correction is large in the hard state and quiescence (as most of emission is radiated at higher energies). We use the observed $H$-band flux as a proxy for the luminosity of the non-thermal component. Fig. 14 shows relationship between the $H$-band and X-ray fluxes for the regular outbursts (see Sect. 2; also Zdziarski et al. 2002). The source moves in the clockwise direction on this diagram. A hysteresis pattern at high X-ray fluxes is similar to that found in Coriat et al. (2009).

In the beginning of SS, the $H$-band flux is nearly constant, with some evidence of anti-correlation with the X-ray flux in the last outburst (Fig. 14d), which is likely caused by the changing bolometric correction. Such anti-correlation between ONIR and X-ray fluxes is atypical for GX 339−4 and other LMXBs, for which HS and SS tracks have very similar slopes (Fig. 14a,b,c; also Russell et al. 2006, 2007; Coriat et al. 2009).

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**Fig. 14.** Quasi-simultaneous ONIR $\nu H F_H$ versus X-ray 1.5 – 12 keV flux diagram. The X-ray data are taken from all three ASM bands. The colors and symbols are the same as in Fig. 4 and errors are 1$\sigma$. (a) 2002–2003, (b) 2004–2005, (c) 2007, and (d) 2010–2011 outbursts.
Therefore the slope of the optical–X-ray correlation is $L \log \nu$ which can be rewritten as

$$v_t \propto B^{\frac{2}{\gamma+2}} \tau^{\frac{2}{\gamma+2}},$$

(10)

where $\rho$ is the power-law slope of the electron distribution. Assuming density scaling with the accretion rate $\rho \propto m$ (i.e., $\tau \propto m$ too) and equipartition magnetic field $B^2 \propto \rho$ (assuming constant temperature), we arrive at

$$v_t \propto m \tau^{\frac{\rho}{\gamma+1}}.$$  

(11)

The X-ray luminosity scales with the accretion rate as $m$ or as $m^2$ for the cases of hot, radiatively efficient (e.g. Bisnovatyi-Kogan & Lovelace 1997) or inefficient (advection-dominated) accretion flow (e.g. Narayan & Yi 1995), respectively. Thus for these two cases we get

$$\beta = \frac{p + 6}{2(p + 4)} \quad \text{or} \quad \beta = \frac{p + 6}{4(p + 4)}.$$  

(12)

Taking $p = 4$ to satisfy the slope of the MeV emission observed from Cyg X-1 (McConnell et al. 2002), we predict $\beta \approx 0.63$ and $\gamma \approx 0.56$, or $\beta \approx 0.31$ and $\gamma \approx 0.78$, for the two cases. This range of $\gamma$ thus covers well the observed slope of the optical–X-ray correlation $\gamma_{\text{obs}} \approx 0.6$ obtained by Russell et al. (2006) for a number of black hole LMXB sources. We observe $\gamma_{\text{obs}} \approx 0.4$ (similar to $\gamma_{\text{obs}} \approx 0.48$ in Coriat et al. 2009). Such slopes require $\beta \approx 0.8 - 0.9$, which is hard to achieve. However, the underestimated value of $\gamma$ can be caused by the variable bolometric correction. The bolometric correction, which decreases with the increasing $L_X$, brings $\gamma_{\text{obs}}$ closer to the predicted interval $[0.56, 0.78]$, in agreement with Russell et al. (2006).

4.3. Origin of the non-thermal component

The nature of the red non-thermal component seen in LMXBs during the ONIR flares is debated. Two main candidates are proposed: synchrotron emission from the jet or from the hybrid accretion flow (see reviews by Uttley & Casella 2014; Poutanen & Veledina 2014). In some cases its soft spectrum is consistent with the optically thin synchrotron emission, and has been modelled with the jet (e.g. MAXI J1836–194; Russell et al. 2014; Peault et al. 2019). In other cases, when the disk-subtracted non-thermal component had a hard spectrum (Poutanen et al. 2014), or when the extrapolation of the radio continuum significantly underestimated ONIR fluxes (e.g. SWIFT J1753.5–0127; Chiang et al. 2010; Kajava et al. 2016b), the excess ONIR emission has been attributed to the hard accretion flow. A way to discriminate between the two models is to track the behaviour of non-thermal component during the ONIR state transition. In the simple jet scenario, the spectrum from radio to optical wavelengths can be described by a broken power-law (Blandford & Königl 1979), with partially-absorbed and optically thin parts. During the HS transition the synchrotron break frequency is expected to decrease, as it scales inversely-proportional to the inner disk radius (Heinz & Sunyaev 2003). In the hot flow model, the spectrum from infrared to X-rays is expected to have two breaks: the lower-frequency break between the partially-absorbed and fully

Fig. 15. A schematic representation of the evolution of GX 339–4 spectra during the rising phase hard state and HS transition of an outburst. The dotted pink line is the RPh hard spectrum, the solid blue line is the RHS, and the dashed green line is HS transition. Vertical black arrows indicate the transition sequence. Characteristic turnover frequency of each spectrum and the V filter frequency are shown with the vertical dashed lines. Characteristic spectral slopes in the ONIR and X-ray ranges are shown with $\alpha_{\text{ONIR}}$ and $\alpha_X$.

The RHS of the 2010–2011 outburst (Fig. 14d) seems to have a slope, which is not as steep as observed in other outbursts ($\partial \log \nu / \partial \log F(\text{ASM}) \approx 0.3$, as compared to $\approx 0.4$ for the 2002–2003 and 2007 events).

The relationship between ONIR and X-ray fluxes can be used to put constraints on the models of spectral formation in accreting black holes. The scaling of the ONIR and X-ray fluxes with the mass accretion rate was used to predict the observed ONIR–X-ray correlation in the jet-dominated scenario (Russell et al. 2006). Here we suggest an interpretation of the HS data in the framework of the hot accretion flow model (see Veledina et al. 2013; Poutanen & Veledina 2014). The schematic representation of the spectrum in the ONIR–X-ray range is shown in Fig. 15. For a broken-power-law spectrum we can express the luminosities in ONIR ($L_\text{ONIR}$) and X-ray ($L_\text{X}$) using luminosity at the turnover frequency ($v_t$):

$$\frac{L_\text{ONIR}}{L_0} = \left( \frac{\nu_0}{\nu_1} \right)^{\alpha_{\text{ONIR}}}, \quad \frac{L_\text{X}}{L_0} = \left( \frac{\nu_X}{\nu_1} \right)^{\alpha_X},$$

where $\alpha_{\text{ONIR}}$ and $\alpha_X$ are spectral slopes and $\nu_0$ and $\nu_X$ are characteristic frequencies in the ONIR and X-ray ranges, respectively.

The ratio of X-ray to ONIR luminosities is then

$$\frac{L_\text{X}}{L_\text{ONIR}} = \left( \frac{\nu_X}{\nu_1} \right)^{\alpha_X} \left( \frac{\nu_0}{\nu_X} \right)^{-\alpha_{\text{ONIR}}} = \frac{\nu_X^{\alpha_X}}{\nu_0^{\alpha_{\text{ONIR}}}} \nu_0^{\alpha_{\text{ONIR}} - \alpha_X},$$

which can be rewritten as

$$\log L_\text{X} - \log L_0 = \alpha_X \log \nu_X - \alpha_{\text{ONIR}} \log \nu_0 + (\alpha_{\text{ONIR}} - \alpha_X) \log v_t.$$  

(8)

Therefore the slope of the optical–X-ray correlation is

$$\gamma = \frac{\partial \log L_0}{\partial \log L_\text{X}} = 1 - \beta (\alpha_{\text{ONIR}} - \alpha_X),$$

(9)

where $\beta = \partial \log v_t / \partial \log L_\text{X}$.

Here we adopt $\alpha_{\text{ONIR}} \approx -0.7$ (see e.g. Poutanen & Urrutia 2009; Malzac & Belmont 2009; Veledina et al. 2011b; Poutanen & Veledina 2014) and $\alpha_{\text{ONIR}} \approx 0$ (average of four regular outbursts, see Figs. 11b,d; 12b,d; 13b,d) for the non-thermal component. In a hot-flow scenario (Veledina et al. 2013), the turnover frequency scales with the magnetic field $B$ and the Thomson optical depth $\tau$ at some characteristic inner radius as

$$v_t \propto B^{\frac{2}{\gamma+2}} \tau^{\frac{2}{\gamma+2}},$$

(10)

where $\rho$ is the power-law slope of the electron distribution. Assuming density scaling with the accretion rate $\rho \propto m$ (i.e. $\tau \propto m$ too) and equipartition magnetic field $B^2 \propto \rho$ (assuming constant temperature), we arrive at

$$v_t \propto m \tau^{\frac{\rho}{\gamma+1}}.$$  

(11)

The X-ray luminosity scales with the accretion rate as $m$ or as $m^2$ for the cases of hot, radiatively efficient (e.g. Bisnovatyi-Kogan & Lovelace 1997) or inefficient (advection-dominated) accretion flow (e.g. Narayan & Yi 1995), respectively. Thus for these two cases we get

$$\beta = \frac{p + 6}{2(p + 4)} \quad \text{or} \quad \beta = \frac{p + 6}{4(p + 4)}.$$  

(12)
self-absorbed parts (it corresponds to the extent of the flow), and the higher-frequency break between the partially-absorbed and synchrotron Comptonization parts (Veledina et al. 2013). Under the simplest assumptions, the state transition is accompanied by the collapse of the flow outer parts, and so the lower-frequency break is expected to increase, while the rest of the spectrum is almost unchanged.

Unlike expected in these two simplest scenarios, we find that the non-thermal component has constant shape during the HS transition, and only its normalization decreases (see Figs. 12b and 13b). The aforementioned evolution can be understood in terms of the hot flow model, however, we need to account for the fact that both the energy release and the electron number density increase when the accretion rate increases. This causes both the increase of total luminosity, as well as the increase of the higher break frequency. As the accretion rate increases, the synchrotron emission produced at the same physical radius in the flow shifts to higher frequencies (as the frequency of self-absorption increases) and becomes brighter (see changes between dotted and solid lines and between turnover frequencies $\nu_1$ and $\nu_2$ in Fig 15). Hence, at the RHS, we expect to see the increase of ONIR luminosity with nearly constant spectral shape (as the latter is determined by the distribution of parameters over the radius, rather than by their absolute values), till a certain point close to the state transition, when the major increase of energy proceeds through the geometrically thin accretion disk, rather than through the hot accretion flow. So, if the deposited energy increase becomes smaller, while the number density increase remains the same, we expect the higher break frequency, but smaller overall ONIR luminosity (see changes between solid and dashed lines and between turnover frequencies $\nu_{1,2}$ and $\nu_{2,3}$ in Fig 15).

The proposed scenario is capable of explaining both (nearly) constant colors of non-thermal component during the RHS, as well as the constant spectral shape at decreasing ONIR luminosity during the HS state transition. It implies that the hot flow extent during the observed transitions has not decreased so that the emission in the $H$ filter appeared in the fully self-absorbed part, i.e. that we do not see the collapse of the outer parts of the flow, in contrast to the expectations of the original scenario. Instead, the survival of the synchrotron-emitting plasma with the inwards-moving inner edge of the disk can be seen as the transition from the hot flow (within the boundaries of the cold disk) to the corona atop of the accretion disk.

This scenario is supported by the STH transition and the DHS, where we observe the same evolution happening in reverse. During the STH the spectra are nearly flat and their shapes do not change (see Figs. 11b,d, 12d and 13d), indicating that the $H$ filter remains in the self-absorbed part and we observe a reverse process of transition from the hot corona atop of the disk to the hot flow, as the inner edge of the disk moves outward.

5. Conclusions

We analysed the 2002–2011 ONIR light curves of GX 339–4. We used the ONIR data to separate the states of the source and compared the estimated transition dates with those obtained from the X-ray spectra. Using the SS data from four outbursts, we determined the value of the interstellar extinction towards the source. We obtained the ONIR spectral slopes during different phases of the outbursts. In the color-magnitude diagram, we constructed a template that describes the evolution of the source throughout the outbursts.

During the SS, the object is found to follow the blackbody model with a constant normalization. During the HS, a red non-thermal component dominates in the $H$ band, with the flux being higher at the rising phase than at the decaying phase. We find the transitions to the SS to occur at 30–40 kK, while the start of the reverse transition corresponds to the blackbody of $\approx 20$ kK. In quiescence, the spectrum of GX 339–4 is bluer than the blackbody model with the same normalization, which can be explained either by the presence of strong spectral features (edges), or by the decrease of the apparent emitting area. The corresponding disk temperatures are well above the hydrogen ionization limit. The variability of the source in this state exceeds the measurements errors and its nature is uncertain.

We traced the evolutionary tracks of the failed outbursts on the CMD and found that their HS show the same colors as the HS of regular outbursts, but lower ONIR fluxes. The decay of a failed outburst follows the same track as the decaying phase of a regular outburst. These properties make it difficult to predict the failed outburst at early stages using ONIR data alone. We found that at later stages bright RHS ($V < 16$) is a sign of a regular outburst.

Finally, we investigated the behaviour of the non-thermal component, which dominates the ONIR fluxes during the HS and the state transitions. For this, we subtracted the contribution of the thermal component (disk) using the SS light curves. We found that the luminosity of the non-thermal component evolves with a constant power-law spectrum with energy spectral index $\alpha \approx 0$ (where $F_\nu \propto \nu^\alpha$). This evolution can be explained in the model where non-thermal component originates from the synchrotron emission of the hot accretion flow. The extent of the accretion flow does not decrease, and the hot flow transforms into the hot corona atop of the accretion disk as the inner disk radius moves inward during the hard to soft transition. As a result, the $H$ filter remains in the fully self-absorbed region and the spectrum shape does not change. The reverse process occurs during the soft to hard transition.

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References

Appendix A: Separation of the states

We employ a synthetic algorithm in order to distinguish between different states of the source. We distinguish 8 different phases of an outburst (including rapid transitions between states). Each state can be identified quite easily on either color-magnitude or light curve plots. However, it can be difficult to determine exact dates at which transitions occur. The simultaneous analysis of four different outbursts requires an objective method to determine transition dates in all of the outbursts in a similar manner without human intervention.

The algorithm is based on the fitting of models to the transition data. We subdivide transitions into two categories: HtS and StH transitions, which share the similar S-shaped profile, and the transitions to/from quiescence. The evolution of the ONIR fluxes of GX 339–4 in the vicinity of the HtS ans StH can be usually well approximated by an exponential rise or decay, which corresponds to the linear trends in magnitudes. We construct a simple analytical function that fits two different linear trends before and after the transition and matches the intermediate S-shaped evolution with a sigmoid function:

\[
S(t) = \frac{m_1 + \mu_1(t - t_0)}{1 + \exp\left(\frac{t - t_0}{T}\right)} + \frac{m_2 + \mu_2(t - t_0)}{1 + \exp\left(-\frac{t - t_0}{T}\right)},
\]

where \(m_1, \mu_1, m_2, \mu_2\) are components of linear trends, \(t_0\) is the turnover point at which \(S(t_0) = 1/(m_1 + m_2)\), and \(T\) is the characteristic timescale of the transition. We then fit this model to the HtS and StH transitions using the data from the \(H\) filter light curve. The reason we chose the \(H\) filter is that the non-thermal component contributes the most to this filter, making it easier to determine the turnover points.

As a result, the transition boundaries can be universally expressed in terms of \(t_0\) and \(T\). We define HtS start date as \(t_0 - 2T\) and end date as \(t_0 + 3T\). Similarly, for the StH transition the start date is \(t_0 - 3T\) and the end date is \(t_0 + 2T\). The choice of the offset factors is influenced by the slopes of the trends before and after the transition. For example, at \(t = t_0 - 3T\) the contributions of the first and second trends are 5 and 95%, respectively, while at \(t = t_0 - 2T\) the trends contribute 12 and 88%, respectively.

As a result of such choice, the duration of the StH or HtS transition is 5\(T\) and can be directly obtained from the fitted model parameters. An example of such outburst separation is shown in Fig. A.1(a).

The boundaries between the decaying phase and the quiescence were determined in a similar manner. Due to the differences in the quiescent state baseline fluxes between outbursts, there is no common lower limit applicable to all of the outbursts simultaneously, which can be used to determine the end of the decay. Therefore, we fit similar model to the decaying phase and quiescence data, for which we fix the parameter \(T\) at 1/3 d, corresponding to the very rapid change of the fitted model from one trend to another. We then use the turnover point \(t_0\) as a formal definition of the boundary between transition and quiescence (see Fig. A.1b, dotted blue line).

The algorithm was also extended to the failed outbursts. We fitted our model to the 2006 and 2009 events and adopted \(t_0 - 2T\) and \(t_0 + 2T\) as the transition boundaries. For the 2008 failed outburst, we used the turnover points \(t_0\) to subdivide the light curve into 4 parts. During this event GX 339–4 showed extremely erratic behaviour with no clear manifestations of the non-thermal component, therefore the phase separation can be arbitrary and is only required for comparison to the other failed outbursts.

In order to compare the decaying phase of the failed and regular outbursts, we split the interval between the end of the SS and the beginning of the quiescence in half and mark the second half as DPh (see Fig. A.1b, pink open triangles). We also apply the algorithm to the rising phase of the 2002–2003 outburst, obtaining the RPh.

The algorithm is similar to the one used in Buxton & Bailyn (2004) and is relatively insensitive to the data selection effects, as we eliminate the process of by-eye separation of data into groups prior to fitting (Kalenci et al. 2013). As a result, this method can be used to study and compare transition dates of the outbursts observed in other LMXB transients.