The reawakening of the sleeping X-ray pulsar XTE J1946+274

Sebastian Müller1, Matthias Kühnel1, Isabel Caballero2, Katja Potschmidt3, Felix Fürst1, Ingo Kreykenbohm1, Macarena Sagredo1,4, Maria Obst1, Jörn Wilms1, Carlo Ferrigno3, Richard E. Rothschild5, and Rüdiger Staubert7

1 Dr. Karl Remeis-Observatory & ECAP, Universität Erlangen Nürnberg, Sternwartstr. 7, 96049 Bamberg, Germany
2 CEA Saclay, DSM/IJF/SAp-UMR AIM (7158) CNRS/CEA/Université Paris 7, Diderot, 91191 Gif sur Yvette, France
3 CRESST and NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA and Center for Space Science and Technology, UMBC, Baltimore, MD 21250, USA
4 Department of Physics, Florida International University, Miami, FL 33199, USA
5 ISDC Data Center for Astrophysics, University of Geneva, 16 Chemin d’Écogia, 1290 Versoix, Switzerland
6 Center for Astronomy and Space Sciences, University of California, San Diego, La Jolla, CA 92933, USA
7 Institut für Astronomie und Astrophysik, Universität Tübingen, Sand 1, 72076 Tübingen, Germany

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1. Introduction

Due to the ~10¹² G strong magnetic field at the magnetic poles of many accreting neutron stars in high-mass X-ray binaries, cyclotron resonance scattering features (CRSFs or cyclotron lines) are observable in the X-ray spectra of these sources. These lines originate from photons generated in the accretion column of a magnetized neutron star interacting with electrons in the column, since their motion perpendicular to the B-field is quantized into Landau-levels with energy differences

$$\Delta E \approx 12 \text{keV} \left( \frac{B}{10^{12} \text{G}} \right)^{1.5}$$

To date CRSFs have been reported for about 20 X-ray pulsars (Caballero & Wilms 2011).

The 15.8 s pulsar XTE J1946+274 was first detected in 1998 (Smith & Takahama 1998; Wilson et al. 1998). It is a transient X-ray source with a Be-type companion (Vercelli et al. 2000). This kind of main-sequence B stars shows Balmer emission lines of a quasi-Keplerian equatorial disk near the Be star (see, e.g., Hanashchik 1996; Slettebak 1988). Interaction between this disk and the orbiting neutron star can lead to violent X-ray outbursts resulting in the appearance of a bright X-ray sources in the sky.

The initial outburst of XTE J1946+274 in 1998 lasted about three months. Heindl et al. (2001) reported on the discovery of a CRSF at an energy near 35 keV during this outburst, which was followed by several fainter outbursts separated by ~80 d (Campana et al. 1999). This separation was later established by Wilson et al. (2003) as half of the ~170 d orbital period. The occurrence of two outbursts per orbit could be related to the misalignment of the Be star's angular momentum and the orbital plane of the neutron star. While we look nearly onto the pole of the Be star, the orbital inclination is ~46° (Wilson et al. 2003).

After a phase of nearly periodic flaring between 1998 and 2001, XTE J1946+274 went into quiescence until 2010 June, when a new sequence of outbursts started (see, e.g., Müller et al. 2010). The principal outburst behavior in 2010 was the same as that observed in the 1990s, with two outbursts per orbit. As shown in Fig. 1, however, the five outbursts seen during 2010 are not clearly connected to the times of periastron and apastron passages (based on the orbital ephemeris from Wilson et al. 2003), nor to any other specific orbital phase. This new outburst episode ended in 2011 June and the source was back in quiescence at the time of writing.

In this paper, we report on INTEGRAL, Swift, and RXTE observations of the first and the third outburst of this series in 2010 June/July and 2010 November/December, respectively. In Sect. 2 we give a summary of the observations. In Sect. 3 we describe the continuum model and study the time and pulse phase resolved behavior of the spectra. Summary and conclusions are given in Sect. 4.

2. Observations and data reduction

The 2010/2011 outburst series started on 2010 June 4, when Swift/BAT detected an increase of the X-ray flux of XTE J1946+274, rising up to 40 mCrab (15-50 keV) within three days (Krimm et al. 2010). This first outburst lasted about 60 d and reached a flux of ~140 mCrab (see Fig. 1). The subsequent four outbursts lasted between 30 and 50 d, each, reaching almost the same maximum flux level between 40 and 60 mCrab. The separation of the outbursts is between 60 and 90 d. A pecu-
liar behavior was observed during the third outburst where the primary maximum was followed by another brightening, reaching again luminosities up to ~50 mCrab (Fig. 1, inset).

We present data from the Proportional Counter Array (PCA, Jahoda et al. 2006) on board the Rossi X-ray Timing Explorer (RXTE), Bradt et al. 1993), the INTEGRAL Soft Gamma-Ray Imager (ISGRI, Lebrun et al. 2003) on board the International Gamma-Ray Astrophysics Laboratory (INTEGRAL, Winkler et al. 2003), and the X-ray Telescope (XRT, Burrows et al. 2005) on board the Swift Gamma-Ray Burst Explorer (Gehrels 2004). Data were reduced with the standard analysis pipelines, based on heasoft (v. 6.10 and 6.11) and INTEGRAL OSA v. 9.0. XTE J1946+274 was monitored by RXTE regularly during the first and the third outburst. The source was also sporadically in the field of view of INTEGRAL during the first and the third outburst. Swift pointings were available only during the main and secondary peak of the third outburst. Table 1 contains a log of the observations with these satellites, which are also indicated in Fig. 1.

PCA consisted of five proportional counter units (PCUs) with a field of view of ~1°, sensitive between 2 and 90 keV. Since PCU2 is known to be the best calibrated one (Jahoda et al. 2006), only data from the top layer of this PCU are used. We obtained 2–60 keV light curves with 0.125 s resolution, spectra in the standard2f mode, and pulse phase resolved spectra using GoodXenon data. The light curves were corrected to the barycenter of the solar system using faxbary. The PCA background model SkyVLE was used for PCA background subtraction. Due to large uncertainties in the orbital parameters (Wilson et al. 2003) no correction could be performed for the neutron star’s orbital motion. The lack of sufficient statistics prevented us from improving the existing orbital solution. Data from the High Energy X-ray Timing Experiment (HEXTE, Rothschild et al. 1998) on board RXTE were excluded from our analysis since both HEXTE clusters were not rocking at the time of the observations. The resulting uncertainties in the background determination are too large for the purposes of this paper.

The CdTe detector of INTEGRAL/ISGRI covers the energy range from ~18 keV to 1 MeV (Lebrun et al. 2003). Thanks to the large field of view of INTEGRAL, XTE J1946+274 was detected several times during its recent outbursts between 2010 June and 2011 April in observations pointed at Cyg X-1. We extracted ISGRI pulse phase averaged spectra for all obser-

![Fig. 1. 15–50 keV Swift/BAT light curve of the 2010/2011 outburst series. The times of periastron and apastron passages are marked by P and A, respectively. These epochs and the corresponding uncertainties were calculated using the orbital solution from Wilson et al. (2003). The insets provide a closer view on the first (Jun/Jul) and the third (Nov/Dec) outburst. The blue, red, and green arrows in these insets indicate the observations times for PCA, ISGRI, and XRT, respectively. Epochs over which data were summed for the time resolved spectral analysis are indicated with 1 to VI.](image)

### Table 1. Summary of all observations used.

<table>
<thead>
<tr>
<th>ID</th>
<th>start date</th>
<th>MJD</th>
<th>$\tau_{\text{pc}}$</th>
<th>$c^2$</th>
<th>$e^2$</th>
</tr>
</thead>
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<tr>
<td>PCA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>01-00</td>
<td>Jun 20</td>
<td>55367.14–55367.18</td>
<td>2.92</td>
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<tr>
<td>01-01</td>
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<td>55367.18–55367.20</td>
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<td>1</td>
<td></td>
</tr>
<tr>
<td>01-02</td>
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<td>5.09</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>01-03</td>
<td>Jun 24</td>
<td>55371.74–55371.78</td>
<td>1.57</td>
<td>1</td>
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</tr>
<tr>
<td>01-04</td>
<td>Jun 26</td>
<td>55373.50–55373.61</td>
<td>10.51</td>
<td>1</td>
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<tr>
<td>01-05</td>
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<td>5.04</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>01-06</td>
<td>Jun 28</td>
<td>55375.68–55375.70</td>
<td>5.62</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>01-07</td>
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<td>55377.65–55377.66</td>
<td>5.26</td>
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<td></td>
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<tr>
<td>03-00</td>
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<td>55380.09–55380.92</td>
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</tr>
<tr>
<td>03-01</td>
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<td>4.61</td>
<td>1</td>
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<tr>
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<td>8.96</td>
<td>1</td>
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<tr>
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<td>7.82</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>04-00</td>
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<td>1</td>
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</tr>
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<td>1</td>
<td></td>
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<tr>
<td>07-00</td>
<td>Nov 26</td>
<td>55526.54–55526.56</td>
<td>1.76</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>07-01</td>
<td>Nov 28</td>
<td>55528.36–55528.39</td>
<td>2.35</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>07-02</td>
<td>Nov 30</td>
<td>55530.58–55530.62</td>
<td>2.29</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>08-01</td>
<td>Dec 03</td>
<td>55533.26–55533.30</td>
<td>3.16</td>
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<tr>
<td>08-01</td>
<td>Dec 03</td>
<td>55535.28–55535.31</td>
<td>1.64</td>
<td>1</td>
<td></td>
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<tr>
<td>08-02</td>
<td>Dec 05</td>
<td>55537.51–55537.57</td>
<td>1.60</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>08-02</td>
<td>Dec 07</td>
<td>55537.71–55537.74</td>
<td>2.62</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

### Notes.
- For PCA, the first column contains the number of the ObsID after 95032-12- and for XRT after 0031888. For ISGRI the revolution number is listed.
- Total background corrected counts. Negative count rates are due to uncertainties in the background determination.
- Epoch for data grouping, see text for details. ObsIDs without assignment in this column are different enough to other spectra during the same epoch that they cannot be combined with the other data or they were recorded without simultaneous low-energy measurements.
- We therefore exclude these data from our analysis.

1 http://heasarc.gsfc.nasa.gov/lheasoft/lftools/fhelp/faxbary.txt
Timing mode. For the source region we have chosen a circle 600 for a discussion of the statistical significances of the Galactic extracted using circles of the same radius at two off-source posi­
cations around the source with a radius of

and $h$: residuals after adding the Galactic ridge emission to the result obtained from epochs $I$ and $IV$. $i$ and $j$: resid­
uals after adding the Fe Kα line to the model. Since in the model fit of epoch $IV$ the depth of the CRSF results to zero, panel $j$ displays the final result for epoch $IV$. In panel $k$, the CRSF has been added to the data for epoch $I$. See also text for a discussion of the statistical significances of the Galactic ridge emission, the 10 keV feature, and the CRSF.

The background was defined in Table 2 and shown in Fig. 1. The spectra in epochs $I$ and $II$ cover the first outburst at the maximum and the fading phase of the first outburst. The last set of observations is summarized in epoch $V$. These XRT data cover the fading phase of the flare right after the third outburst. Before defining these epochs we confirmed that the spectral variability during these epochs is negligible.

3. Spectral analysis

We performed all fits using the Interactive Spectral Interpretation System (ISIS, Huckle & Denicola 2000). In order to improve the signal to noise ratio of individual spectra we averaged the data over six data blocks in time taking into account the flux level and instrument availability. These epochs I–VI are defined in Table 2 and shown in Fig. 1. The spectra in epochs $I$ and $II$ cover the first outburst at the maximum and fading phase, respectively. Epochs $III$–$V$ follow the maximum and the fading phase of the third outburst. The flux in the maximum level of this outburst (epoch $III$) is comparable to the fading phase of the first outburst (epoch $II$). The last set of observations is summarized in epoch $VI$. These XRT data cover the fading phase of the flare right after the third outburst. Before defining these epochs we confirmed that the spectral variability during these epochs is negligible.

3.1. Spectral model

As shown, e.g., by Becker & Wolff (2007), the X-ray spectra of accretion-powered X-ray pulsars can be roughly described by a powerlaw with a high energy cutoff. In practical data modelling, this continuum has been approximated by several different con­tinuum models (see, e.g., Kreykenbohm et al. 2002, for a summary). Here we describe the data using the so called Fermi-Dirac cutoff ($FDCO$, Tanaka 1986), given by

$$ FDCO(E) \propto E^{-\gamma} \times \left[ 1 + \exp \left( \frac{E - E_{c}}{E_{c0}} \right) \right]^{-\delta}, $$

which has been successfully applied to other accreting X-ray pulsars such as Vela X-1 (Kreykenbohm et al. 2008). This continuum is modified by the CRSF, modeled as a line with a
I I I

perfectly well known and the source might also slightly change including XTEJ1946+274, also contain an absorption or emission Gaussian optical depth profile

centroid energy has been fixed to this so-called version of TBabs 3, using abundances by Wilms et al.

we fooled this feature as a broad Gaussian absorption feature, as we also did for the CRSF (Eq. 3) with the centroid energy, appears always at about the same energy, it is probably not re-

of view. In our modelling of the PeA data we therefore intro-

sion that is picked up by the PCA only, due to its larger field of view. In our modelling of the PeA data we therefore intro-

duced a model for the Galactic ridge emission based on that of Ebisawa et al. (2007), who described the ridge emission as the sum of two bremsstrahlung components and an iron line

complex modelled by three Gaussian lines at 6.4keV, 6.67keV, and 7.0keV, with equivalent width ratios of 85:45:8:129, respectively. Since we used the PCA data down to 4.5keV only, we did not account for the two soft bremsstrahlung components and modelled the Galactic ridge emission as the sum of three narrow Gaussians, with fixed energies and equivalent width ratios according to Ebisawa et al. (2007). This component was applied only to the PCA data and absorbed by the interstellar medium using the Galactic N H as determined from the Leiden/Argentine/Bonn (LAB) Survey of Galactic H I, N H = 9.4·10 21 cm -2 (Kalberla et al. 2005). We determined the flux of the Galactic ridge emission from simultaneous fits to the XRT and PCA data from epochs III and IV. In epoch IV, residuals around 6–7keV are only visible in PCA, while in XRT neither residuals from this emission, nor from a source intrinsic iron Kα line are detected. Thus, the residuals in the epoch IV PCA spectrum must be caused by Galactic ridge emission. In epoch III, on the other hand, we find weak evidence for the presence of a source intrinsic iron Kα line in the XRT spectrum. The unabsorbed flux of the 6.4keV iron line of the Galactic ridge emission in both spectra is consistent with each other (7.2±2.0)·10 -5 photons s -1 cm -2, and (6.6±2.0)·10 -5 photons s -1 cm -2 for epoch III and IV, respectively). While these values are slightly higher than the 1.22±10 -5 photons s -1 cm -2 reported by Ebisawa et al. (2007), the difference is still within the typical variation of the Galactic ridge emission over the Galactic plane (Yamauchi et al. 2009). Since the flux of the Galactic ridge emission is constant over time, we added this model component with parameters fixed to the mean value as obtained from epochs III and IV to the PCA spectra of all epochs. We find that for the late part of the outburst, the ridge contributes 1.5% of the 3–10keV flux and 8% in the Fe band (6–7keV). To estimate the significance of the Galactic ridge emission, we performed Monte Carlo simulations of the best fit model without this feature to create a set of 1000 synthetic spectra. We then performed the fit allowing all model parameters, including the Galactic ridge emission, to vary. For both epochs III and IV none of these simulations led to a fake spectrum for which the improvement in χ 2 was as large as in the real data, i.e., the probability that the

Table 2. Results of the time resolved spectral analysis.

<table>
<thead>
<tr>
<th>Epoch</th>
<th>Start</th>
<th>Stop</th>
<th>CTS</th>
<th>F 1</th>
<th>F 2</th>
<th>N H</th>
<th>ΔE</th>
<th>ECEF</th>
<th>WCRSF</th>
<th>χ 2 /dof</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>367</td>
<td>378</td>
<td>17.2</td>
<td>6.9(2)</td>
<td>8.4(2)</td>
<td>2.1±24</td>
<td>0.75±0.06</td>
<td>7.25±0.21</td>
<td>16.7±24</td>
<td>10±4</td>
</tr>
<tr>
<td>II</td>
<td>380</td>
<td>394</td>
<td>16.46</td>
<td>4.71(3)</td>
<td>5.72(2)</td>
<td>2.6±24</td>
<td>0.82±0.06</td>
<td>6.1±0.14</td>
<td>19.4±24</td>
<td>9.5±2.5</td>
</tr>
<tr>
<td>III</td>
<td>424</td>
<td>529</td>
<td>2.93</td>
<td>3.0(3)</td>
<td>3.79(16)</td>
<td>1.77±24</td>
<td>0.77±0.06</td>
<td>8.0±0.14</td>
<td>16.5±1.5</td>
<td>1.5±0.1</td>
</tr>
<tr>
<td>IV</td>
<td>530</td>
<td>534</td>
<td>1.68</td>
<td>2.56(4)</td>
<td>3.17(2)</td>
<td>1.84±24</td>
<td>0.74±0.06</td>
<td>8.18±0.14</td>
<td>14.4±4</td>
<td>0.4±0.02</td>
</tr>
<tr>
<td>V</td>
<td>533</td>
<td>538</td>
<td>1.12</td>
<td>1.88(2)</td>
<td>2.46(2)</td>
<td>5.1±24</td>
<td>1.04±0.06</td>
<td>6.0±0.14</td>
<td>19.0±1.5</td>
<td>≤1.5</td>
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<tr>
<td>VI</td>
<td>552</td>
<td>559</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>1.69(10)</td>
<td>2.14±24</td>
<td>0.84±0.06</td>
<td>7.25</td>
<td>16.7±1.0</td>
</tr>
</tbody>
</table>

Notes. Uncertainties and upper limits are at the 90% confidence level. Numbers without error bars were held fixed at the values listed.

9 Epoch for data grouping. 10 Total background corrected PCA counts between 7 and 15keV, in multiples of 10 8.

10 Absorbed flux, in units of 10 -2 photons s -1 cm -2 . F 1 and F 2 cover the energy bands 10–20 keV and 7–15 keV, respectively. In epoch VI, the 10–20 keV band is not fully covered by the data and no flux value can be listed. 11 In units of 10 -2 cm -2 . 12 In units of keV. 13 In units of 10 -4 photons s -1 cm -2 . The centroid energy has been fixed to 6.4keV, and the width to 10 -4 keV. 14 In units of eV. 15 CPCA, CISGRI and CXT are defined as the cross calibration and normalization constants for PCA, ISGRI, and XRT, respectively. 16 In multiples of 10 -5 .

Gaussian optical depth profile

exp(−τ(E)), with τ(E) = τ CSR SF × exp _1 _2 (E − E CSR SF σ CSR SF ) 2 . (3)

The equivalent width of this feature will be denoted with W CSR SF in the following. The spectra of some X-ray pulsars, including XTEJ1946+274, also contain an absorption or emission like feature in the range 8–12 keV (Coburn 2001). The origin of this so-called 10 keV feature is still unclear, however, since it appears always at about the same energy, it is probably not related to the magnetic field strength of the neutron star. We modelled this feature as a broad Gaussian absorption feature, as we also did for the CRSF (Eq. 3) with the centroid energy, E 0 , the width, σ E , optical depth, τ 0 , and equivalent width, W 0 . Finally, intrinsic absorption was modelled with an updated version of TBabs 3 , using abundances by Wilms et al. (2000) and cross sections by Verner & Yakovlev (1995).

In modelling the data, we have to take into account that the cross-normalization of the different instruments used is not perfectly well known and the source might also slightly change in flux between the different observations. These effects were taken into account by cross calibration constants c CSR SF and c ISGRI, using the PCA as the reference instrument. Furthermore, the PCA background was allowed to vary slightly in count rate. To account for these imperfections in the modelling of the background, we introduced the constant c 0 .

Finally, the data modelling is affected by the proximity of the source to the plane of the Galaxy. Galactic ridge emission (GREG, see, e.g., Worrall et al. 1982; Warwick et al. 1985) manifests itself through the presence of an emission feature at ≈6–7keV in the PCA spectrum caused by unresolved Fe Kα fluorescence lines. These lines are not present in the XRT data in epochs III and IV and therefore must be due to diffuse emission that is picked up by the PCA only, due to its larger field of view. In our modelling of the PCA data we therefore introduced a model for the Galactic ridge emission based on that of Ebisawa et al. (2007), who described the ridge emission as the sum of two bremsstrahlung components and an iron line

3 see http://pulsar.sternwarte.uni-erlangen.de/wilms/research/pulsrs/
Galactic ridge emission is real is greater than 99.9 % (>3.3σ). The remaining residuals at 6.4 keV can be explained by a narrow source intrinsic Kα fluorescence line. We model this feature by a thin Gaussian emission line with fixed centroid energy $E_{\text{Kα}} = 6.4$ keV and width $\sigma_{\text{Kα}} = 10^{-4}$ keV. The flux, $A_{\text{Kα}}$, (and thus equivalent width, $W_{\text{Kα}}$) were allowed to vary.

In summary, the model used can be written as

$$M = \text{THabs} \times (\text{FDCO} + \text{Fe_{6.4keV}}) \times G_{10keV} \times G_{\text{CRSF}} \times \text{GRE}. \quad (4)$$

3.2. Time resolved spectroscopy

In this section we describe the time resolved behavior of the spectral parameters. For each of the six epochs we fitted the respective spectra separately, including the Galactic ridge emission as a constant component as discussed above. Example spectra of two epochs together with the best model fit are shown in Fig. 2. The free fit parameters are summarized in Table 2 and displayed in Fig. 3. We calculated fluxes in the energy band 10–20 keV for the epochs I–V. In order to be able to compare the source fluxes of all epochs, but avoid excessive extrapolation of the models, we also derived the fluxes in the energy band 7–15 keV. We excluded the contribution from the Galactic ridge emission from this flux.

The resulting $\chi^2_{\text{red}}$ for all fits does not exceed 1.3 (see Table 2). For epoch I, the value of $\chi^2_{\text{red}}$ is rather high. Here, the greatest contribution to $\chi^2_{\text{red}}$ originates from residuals of the ISGRI data which are caused by calibration problems, so we accept this fit. Note that not all model components are necessary to describe the data in the spectra with low statistics, e.g., epoch V provides an statistically too low $\chi^2_{\text{red}}$ of 0.78. The reason for including these components in these fits as well, even though the components overdetermine the fit model, is that this way it can be shown that these spectra are at least consistent with the full model. In addition, we note that an overestimation of the systematic error would also yield a $\chi^2_{\text{red}}$ that is too low. In epoch VI only XRT data are available and the continuum parameters are badly constrained from these data alone. We therefore fixed $E_{\text{fold}}$ and $E_{\text{cut}}$ to the value obtained from epoch I because a change of these parameters affects mainly energies not covered by XRT. However, possible influences of these fixed parameters to the free fit parameters $N_{\text{H}}$ and $\Gamma$ might affect the results.

The behavior of the photon index, $\Gamma$, the cutoff energy, $E_{\text{cut}}$, and the folding energy, $E_{\text{fold}}$, yields information about the evolution of the spectral continuum. In most cases there are no or only slight variations of these parameters apparent. However, we know from previous observations that these parameters can also be significantly correlated to each other. We therefore also derived a model independent illustration of the spectral changes by dividing the background subtracted PCA spectra from epochs I–V by the spectrum from epoch I (see Fig. 4). The ratios II/I, III/I, and IV/I appear to be mainly constants, meaning that the variations of the continuum parameters in epochs I–IV are probably artificial and due to cross correlations. In contrast to this, ratio V/I shows a spectral softening for epoch V, caused by a real change of the continuum parameters.

Except for epochs covered by XRT, the hydrogen column density $N_{\text{H}}$ is not well determined and the best-fit parameters are consistent with constant $N_{\text{H}}$. In addition to the line caused by Galactic ridge emission, an Fe Kα fluorescence line at 6.4 keV is required during the first outburst and the maximum phase of the third outburst (epochs I–III). The flux of this line is correlated with the X-ray flux of the source, as expected for a fluorescent line. Furthermore, for these epochs at highest luminosities (I–III), the equivalent width $W_{\text{Kα}}$ stays roughly constant. In the fading phase of the third outburst and its subsequent flare (epochs IV–VI), this feature is consistent with zero, meaning that the additional emission at these energies can be explained by the Galactic ridge emission. To estimate the significance of the Fe Kα line, we performed similar Monte Carlo simulations as those done for the Galactic ridge emission. For epochs I and II, the probability that there is a source intrinsic Fe Kα line is greater than 99.9 % (>3.3σ). During epochs III and IV, where the source was much fainter, these simulations show that the probability for Fe line emission from the source is 98.5% (2.4σ) and 62.0% (0.9σ), i.e., here the Fe line region is dominated by Galactic ridge emission.

![Fig. 4. a: PCA spectra of time bins I–V (shifted in y-direction for better visibility). b: Ratio of the background corrected time resolved spectra.](image-url)
We find no evidence for the centroid energy, the width, and the optical depth of the 10 keV feature to be variable over time. Due to the lack of statistics, the width of the feature, $\sigma_{\text{CO}}$, in epoch III and IV cannot be constrained and is therefore fixed to the mean value obtained from epochs I and II, i.e., $\sigma_{\text{CO}} = 2.0$ keV. In epoch V, also due to the lack of statistics, this feature is not required to describe the data. We therefore omit it from our model in this epoch, and also from epoch VI, where our coverage exists only below 7 keV.

One of the most interesting questions is whether there is a cyclotron line present as in the 1998 outburst (Heindl et al. 2001). We find a possible CRSF at $\sim$25 keV during epochs I–IV, i.e., those epochs where good coverage exists above 10 keV. The statistics during the maximum of the first outburst (epoch I) are good enough to obtain CRSF parameters that are well constrained. As is fairly common for CRSF fits (Coburn 2001), the width and depth of the line are strongly correlated. We therefore set a lower limit of 0.5 keV for the width, which is comparable to the resolution of the PCA at these energies. Monte Carlo simulations as described above lead to a 93% (1.81$\sigma$) probability that the CRSF found in epoch I is real.

The dependence of the CRSF's parameters to the choice of the approach of modeling the continuum is an important point which also has to be discussed. The results presented here were obtained by first adding the 10 keV feature to the model, and then accounting for the CRSF. Doing this vice versa for epoch I, we find another minimum of $x^2_{\text{red}}$ leading to different cyclotron line parameters, i.e., $E_{\text{CRSF}} = 29.6^{+4.6}_{-3.5}$ keV, $\tau_{\text{CRSF}} = 0.3^{+0.3}_{-0.1}$, and $\sigma_{\text{CRSF}} = 6.8^{+1.1}_{-0.7}$ keV. The main problem for this alternative approach is the need of fixing parameters to certain values for the final fit. For example, allowing $\sigma_{\text{CRSF}}$ for the final fit to vary leads to an unrealistically broad CRSF which effectively models part of the exponential rollover and not the line. Furthermore, the quality of this fit is slightly worse ($x^2 = 97$ vs. $x^2 = 86$). We note that there is a third solution in which the centroid energy of the CRSF is in agreement with Heindl et al. (2001). However, contrary to Heindl et al. (2001), this third solution has an unphysically broad and shallow shape and is thus not physically meaningful. All results presented in this paper are based on the approach first adding the 10 keV feature, and then the CRSF.

Finally, we note that there are two further solutions, where the CRSF is located at 30 keV and 40 keV and a line width of less than 1 keV. These two solutions are indeed physically meaningful, however, a Monte Carlo estimation of the significances of these features yields probabilities of 85% (1.44$\sigma$) and 86% (1.48$\sigma$), respectively, much lower than for the solution with the CRSF at 25 keV. Furthermore, these two solutions are supported only by about three data bins per instrument (the 40 keV solution even only by INSGR1), while the 20 keV solution is based on a much larger number of spectral bins.

Including a CRSF in the fainter observations in epochs II–IV does not significantly improve the fits. All observations are in principle consistent with the presence of a weak line as that seen in epoch I. Including for consistency such a feature in the spectral modeling, fixing the centroid energy and width and leaving the optical depth respectively the equivalent width of the line as a free parameter effectively gives an upper limit for the depth of the line in these observations. Not unexpectedly, the limit for $\tau_{\text{CRSF}}$ becomes larger for the fainter phases of the outburst (Table 2). We find no evidence for the equivalent width $W_{\text{CRSF}}$ to be variable over time.

### Table 3. Results of the pulse phase resolved spectral analysis.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>MP</th>
<th>SP</th>
<th>Off</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\psi$</td>
<td>0.50±0.01</td>
<td>0.13±0.04</td>
<td>0.34±0.50 &amp; 0.91±0.13</td>
</tr>
<tr>
<td>$\Gamma$</td>
<td>0.87±0.05</td>
<td>0.49±0.10</td>
<td>0.71±0.07</td>
</tr>
<tr>
<td>$E_{\text{ain}}$ [keV]</td>
<td>6.7±0.4</td>
<td>7.9±0.1</td>
<td>7.8±0.5</td>
</tr>
<tr>
<td>$E_{\text{CRSF}}$ [keV]</td>
<td>19.2±1.3</td>
<td>11.2±1.3</td>
<td>15.0±2.3</td>
</tr>
<tr>
<td>$A_{\text{IV}}$ [10^{-4}]</td>
<td>11.9±2.5</td>
<td>8.7±2.8</td>
<td>9.3±2.2</td>
</tr>
<tr>
<td>$W_{\text{IV}}$ [keV]</td>
<td>56±15</td>
<td>46±15</td>
<td>54±14</td>
</tr>
<tr>
<td>$E_{\text{IV}}$ [keV]</td>
<td>9.7±0.7</td>
<td>9.5±0.3</td>
<td>9.9±0.2</td>
</tr>
<tr>
<td>$\tau_{\text{CRSF}}$</td>
<td>0.12±0.08</td>
<td>0.04±0.06</td>
<td>0.13±0.09</td>
</tr>
<tr>
<td>$W_{\text{CRSF}}$ [keV]</td>
<td>-180±90</td>
<td>-60±60</td>
<td>-210±130</td>
</tr>
<tr>
<td>$\chi^2_{\text{red}}$</td>
<td>1.09±56</td>
<td>1.10±55</td>
<td>0.93±56</td>
</tr>
</tbody>
</table>

Notes: Uncertainties and upper limits correspond to the 90% confidence level for one parameter of interest.

*In units of photons s^{-1} cm^{-2}. The centroid energy has been fixed to 6.4 keV, and the width to 10^{-4} keV.
From the individual pulse phases is too low to allow us to study and HEXTE data from 1998, outburst, and the diamond to the average spectrum of the 1998 outburst, obtained by reextracting and analyzing the old PCA and HXTE data from 1998. This constant ratio is in agreement with the spectral parameters to large unconstraints in NH and the width of the ground scaling factor for PCA.

Figure 7 shows the ratios of background corrected pulse phase resolved spectra. The ratio MP/SP is assumed to be equal to the result from the pulse averaged analysis and was therefore frozen to this value. Initial fits of the pulse phase resolved spectra lead to large uncertainties in $N_H$ and the width of the 10 keV feature $\sigma_E$. These values were therefore frozen to the results from the phase averaged analysis. The signal to noise ratio in the spectra from the individual pulse phases is too low to allow us to study the behavior of the CRSF. Similar to the flux dependent analysis, we freeze the CRSF centroid energy and width to the result from the pulse averaged analysis and allow only the optical depth respectively the equivalent width to vary (due to the marginal significance of the CRSF no further attempt was made to study a phase dependence of the cyclotron line).

Figure 6 shows the ratios of background corrected pulse phase resolved spectra. The ratio MP/off appears mainly as a constant, while the other two ratios reveal more complex shapes. This constant ratio is in agreement with the spectral parameters of the main peak and the off state. These parameters show almost no or only slight differences to each other. The ratio MP/SP, a falling line, can be explained by a change in photon index. This explanation is confirmed from the spectral analysis. While $E_{\text{out}}$ and $E_{\text{off}}$ show only small differences, the photon index $\Gamma$ is significantly lower in the secondary peak, i.e., the spectrum in this phase bin is harder than in the other phase bins. The centroid energy of the 10 keV feature does not vary with pulse phase while its depth weakens during the main peak. The equivalent width remains constant in the main and the secondary peak, while it shows a larger value in the off state. Finally, we note that there is neither evidence for changes of the Fe line flux nor for the equivalent width over the pulse phase.

4. Results and conclusions

4.1. Outburst series

In this paper we analyzed quasi-simultaneous XRT, ISGRI, and PCA observations of two outbursts of XTE J1946+274 during a series in the second half of 2010.
Before the onset of this outburst series, XTE J1946+274 was in a state of quiescence for almost one decade, i.e., about 20 orbits of the neutron star. Even though the formation, structure, and dynamics of Be disks are even today far from being completely understood (see, e.g., Draper et al., 2011, and references therein), the missing mass accretion onto the neutron star during that time is probably due to the absence of a sufficiently large Be disk during that time. A new outburst was only possible once the disk had been replenished and accretion could be triggered.

This series shows similar behavior as the one observed in 1998, e.g., two outbursts are observed per orbital period. The outbursts of XTE J1946+274 could also be similar to those seen in GX 301–2, which have been extensively modeled by Leahy (2002). These authors posit that an additionally stream of matter is flowing from the primary, and that a second outburst per orbit could be caused by the passage of the neutron star through this stream. These flux peaks of GX 301–2 occur near the apsides of this system.

However, the outbursts of XTE J1946+274 do not clearly coincide with the times of periastron and apastron passages of the neutron star (Fig. 1). This could be explained by 3-dimensional simulations, which show that the disturbance of the Be disk by the gravitational field of the neutron star could lead to a strong asymmetric structure of the circumstellar material, which could also lead to multiple X-ray outbursts during one orbital period (see, e.g., Okazaki et al., 2011).

Alternatively, the outbursts can be triggered by the neutron star passing through the Be disk due to a misalignment of the orbit and the Be star’s equatorial plane (Wilson et al., 2003).

Another possible explanation for the irregularity of the outbursts is that they are triggered by density variations in the Be disk and not by orbital effects alone. This assumption could be verified by regular optical monitoring of the Balmer Hα line, which is an indicator for the presence of such a disk (see, e.g., Grundstrom et al., 2007, and references therein).

4.2. Spectroscopic results

An absorbed Fermi-Dirac cutoff powerlaw together with an iron Kα fluorescence line, an iron line complex between 6 and 7 keV caused by Galactic ridge emission, a Gaussian like absorption feature around 10 keV, and a cyclotron line at ~25 keV reproduce the observations well in terms of χ². We find time as well as pulse phase dependent variability of the continuum parameters of XTE J1946+274. In the time resolved case, these changes might be caused by different accreting mechanisms depending on the mass transfer onto the neutron star. The periodically changing line of sight with respect to the X-ray emitting region, caused by the rotation of the neutron star, is likely responsible for the variabilities observed in the pulse phase resolved analysis. Furthermore, this rotation together with differences in the accretion geometries at the two magnetic poles of the neutron star might lead to the asymmetric pulse profile of the X-ray pulsar (see Fig. 5).

Studying the behavior of the spectral shape is problematic, because the spectral parameters photon index Γ, folding energy E₉₀ₐₖ, as well as the cutoff energy E₉₅ₐₖ, which describe the broad-band shape of the X-ray spectrum, show strong cross correlations to each other. To account for this, we calculated ratios of the spectra for both, the time resolved and the pulse phase resolved studies. In the time resolved case, we find clear deviations from a constant ratio for epoch V. During epochs I–IV, the overall spectral shape seems to remain relatively constant. In the pulse phase resolved analysis, the spectrum of the secondary peak turns out to be significant harder than these from the main peak and the off state. Such properties of X-ray spectra are due to, e.g., the temperature of the visible part of the X-ray emitting region, in particular the accretion column.

Another feature required to get a good fit is a source intrinsic Gaussian iron Kα emission line at 6.4 keV. The disagreement in the strength of the required emission in this energy range between PCA and XRT in initial fits can be solved by inducing the emission of the Galactic ridge. The strength of the Galactic ridge emission is about four times larger than found in other regions of the Galaxy (Ebisawa et al., 2007). Such a difference is consistent, however, with the typical spatial variations of the ridge emission (Yamauchi et al., 2009). Furthermore, Kühnel et al. (2012) found an emission strength consistent with our result for GRO J1008–57.

After taking into account the contribution due to Galactic ridge emission, the flux of the source intrinsic Fe Kα emission line is correlated with the X-ray flux Fₓ (see Fig. 7), as also observed in other X-ray transients (see, e.g., Inoue 1985). The Fe Kα line is significantly detected at source fluxes >7–15 keV greater than about 0.035 photons−1 cm−2. At fluxes below this value, the source intrinsic line is consistent with zero. The equivalent width Wₑ₉ₒ₅ is constant for high luminosities, i.e., epochs I–III. Reanalyzing the earlier RXTE data (Heindl et al., 2001) with the continuum model employed here yields an equivalent width which is also in agreement with the result from the 1998 outburst (Wₑ₉ₒ₅ = 59 ± 10 eV). The different values for Wₑ₉ₒ₅ for the fainter observations, where the Fe Kα line is only marginally detected, can be caused by the uncertainties of the Galactic ridge emission, which significantly contributes to the data at these energies. In the pulse phase resolved analysis we find no evidence for variability of the line flux. This result indicates that it is emitted in a region large compared to the distance travelled by light during one pulse period. The equivalent width also shows no variation, which we would actually expect for a constant model component at varying flux levels. However, this can be explained by the quite large relative uncertainty of Wₑ₉ₒ₅, which is on the same order of magnitude as the respective variations.

The 10 keV feature is present during all epochs and pulse phases. It shows relatively constant results for line energy, width, and depth in the time resolved case. The reanalysis of the 1998 data yields an equivalent width of Wₑ₉ₒ₅ = 250 ± 100 eV, which also equals the results for the current outburst. While we find almost no connection of the parameters of this feature with the luminosity, its optical depth and equivalent width varies with pulse phase. Wₑ₉ₒ₅ is constant during the main and the secondary peak, but it strongly increases during the off state. This behavior indicates that the fractional amount of absorbed flux related to the continuum level is constant for the main and the secondary peak and changes in the off state. This behavior of the 10 keV feature could give rise to speculations about possible physical processes e.g., pulse phase dependent absorbing processes, producing such a feature. On the other hand, the residuals around 10 keV could also be due to the failing of the spectral broad-band continuum models resulting in a wrong description of the data around these energies. More quantitative analyses of this feature, also from other sources where it occurs in emission, are urgently needed to reveal the true nature of this enigmatic feature.
4.3. Cyclotron resonance scattering feature

We find weak evidence for the presence of the CRSF, first discovered by Heindl et al. (2001) during the 1998 outburst series. The cyclotron line improved the model fit for the high signal to noise epoch 1 spectrum, where PCA and ISGRI data are available. Later spectra are consistent with the presence of a CRSF with unchanged parameters, however, the line is not formally detected in these observations because of their lower signal to noise ratio. We stress that due to its relative weakness, the inclusion of the CRSF in our fits does not affect our results for the continuum parameters or for the pulse phase resolved analysis.

The cyclotron line was emitted from the neutron star's surface was confirmed by the analysis of the X-ray flux of the 1998 observation (\(F_{\text{X-ray}} = 10^{-2} \text{ photonss}^{-1} \text{ cm}^{-2} \)). However, fits to the data analyzed here. CRSF values in the 1998 data is due to the fact that, while the exponential decrease of the CRSF must have varied between the data sets. Reanalyzing the earlier RXTE data with an overall positive correlation between the X-ray flux of the 1998 observation is significantly lower than that measured in the 2010 CRSF values (\(E_{\text{F}} = 25.3 \pm 1.0 \text{ keV} \)). Heindl et al. (2001). Furthermore, the equivalent width in 1998 was also significantly larger than that measured in the 1998 outburst (\(E_{\text{C}} = 0.05 \pm 0.07 \text{ vs. } E_{\text{C}} = 0.31 \pm 0.07 \text{ keV} \)).

The cyclotron line energies around 30 keV Coulomb braking is the dominating braking process in the luminosity range of the accretion column is dominated by Coulomb braking. For cyclotron line energies around 30 keV Coulomb braking is the dominating braking process in the luminosity range of 1-5 \(10^{37} \text{ erg s}^{-1} \). For higher luminosities, radiation braking dominates. XTE J1946+274's peak outburst luminosity of 4.5 \(10^{37} \text{ erg s}^{-1} \) is barely consistent with this range, however, given that the source seems to be located at the transition between Coulomb and radiation braking and was brighter in 1998, the very large change in CRSF energy seems unlikely to be due to a pure mass accretion rate effect.

The conclusion, while the possibility of a luminosity dependent CRSF is intriguing, the poor signal to noise ratio of the 2010 data does not allow a definitive answer concerning the luminosity dependence of the CRSF. Further, longer, monitoring observations of XTE J1946+274 during its next outburst episode are urgently needed to resolve this question.

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