Detection of a large Be circumstellar disk during X-ray quiescence of XTE J1946+274

M. Özbey Arabacı1, A. Camero-Arranz2, C. Zurita3,4, J. Gutiérrez-R-Soto5,6, E. Nespoli7, J. Suso7, F. Kiaeeread8,9, J. García-Rojas3,4, and Ü. Kızılolları1

1 Department of Physics, Middle East Technical University, Ankara, 06531, Turkey.
2 Institut de Ciències de l’Espai, (IEEC-CSIC), Campus UAB, Fac. de Ciències, Torre C5 pa., 08193, Barcelona, Spain.
3 Instituto de Astrofísica de Canarias, E-38200, La Laguna, Tenerife, Spain.
4 Universidad de La Laguna, Dept. Astrofísica, E-38206, La Laguna, Tenerife, Spain.
5 Universidad de Valencia, Dept. Didáctica de las Matemática, Avda. Tarongers, 4, 46022, Valencia, Spain.
6 Instituto de Astrofísica de Canarias, E-38286, La Laguna, Tenerife, Spain.
7 Observatorio Astronómico de la Univ. de Valencia, C/Catedrático Jose Beltran, 2, 46980 Paterna (Valencia), Spain.
8 Nordic Optical Telescope, Apartado 474, 38700 Santa Cruz de La Palma, Spain.
9 Department of Astronomy, Oscar Klein Center, Stockholm University, AlbaNova, Stockholm SE-10691, Sweden.

Received ; accepted

ABSTRACT

Aims. We present a multiwavelength study of the Be/X-ray binary system XTE J1946+274 with the main goal of better characterizing its behavior during X-ray quiescence. We also aim to shed light on the mechanism/s which trigger the X-ray activity for this source.

Methods. XTE J1946+274 was observed by Chandra-ACIS during quiescence in 2013 March 12. In addition, this source has been monitored from the ground-based astronomical observatories of El Teide (Tenerife, Spain), Roque de los Muchachos (La Palma, Spain) and Sierra Nevada (Granada, Spain) since 2011 September, and from the TÜBITAK National Observatory (Antalya, Turkey) since 2005 April. We have performed spectral and photometric temporal analyses in order to investigate the quiescent state and transient behavior of this binary system.

Results. Our optical study revealed that a long mass ejection event from the Be star took place in 2006, lasting for about seven years, and another one is currently ongoing. We also found that a large Be circumstellar disk is present during quiescence, although major X-ray activity is not observed. We made an attempt to explain this scenario by assuming the permanently presence of a tilted (sometimes warped) Be decretion disk. The 0.3–10 keV X-ray spectrum of the neutron star during quiescence was well fitted with either an absorbed black-body or absorbed power-law models. The main parameters obtained for these models were kT = 1.43±0.17 and Γ = 0.9±0.4 (with NH = 2×1024 cm−2). The 0.3–10 keV flux of the source was ∼0.8–1×10−11 erg cm−2s−1. Pulsations were found with Ppuls = 15.757(1) s (epoch MJD 56365.115) and an rms pulse fraction of 32.1(3)%.

Conclusions.

Key words. X–rays: binaries - stars: HMXRB - stars: individual: XTE J1946+274

1. Introduction

The hard X-ray transient XTE J1946+274 is one of the poorly-understood sources among Be/X-ray binaries (BeXRB), although its X-ray behavior have been studied in detail since its discovery with All Sky Monitor (ASM) on board the Rossi X-Ray Timing Explorer (RXTE) in 1998 (Smith & Takeshima1998). The system showed two main transient X-ray active phases detected with different X-ray satellites between 1998 and 2011. The first and the longest X-ray activity lasted about ~3 years (between September 1998–August 2001) including 13 consecutive outbursts (Wilson et al. 2003). During the initial outburst of these series, having the peak X-ray flux of ~110 mCrab in 2–60 keV band, it was revealed that the system had an X-ray pulsat with a spin period of 15.83±0.02 s (Smith & Takeshima1998; Wilson et al.1998) orbiting around its Be companion with a period of 169.2 days in an 0.33 eccentric orbit (Campana et al.1999; Wilson et al.2003). In addition the existence of a cyclotron resonance scattering feature (CRSF) or a cyclotron line at ~35 keV was reported by Heindl et al. (2001) using the 1998 outburst observations of High Energy X-Ray Timing Experiment (HETE) and Proportional Counter Ray (PCA) on RXTE.

After a ~9 years quiescence in X-rays, the system underwent a new outburst phase starting on 2010 June 4, reaching a value of 140 mCrab in the 15–50 keV energy band within ~22 days on the Swift/Burst Alert Telescope (BAT) hard X-ray transient monitor (Krimm et al.2010; Müller et al.2012). Similar to the previous active phase of the source, the second outburst period was again in a series including an initial giant outburst followed by four fainter outbursts (Camero-Arranz et al.2010; Caballero et al.2010; Nakajima et al.2010; Müller et al.2010). The presence of another CRSF feature at ~25 keV was discovered indicating the variation of cyclotron lines between the different outbursts (Müller et al.2012).
The optical spectroscopic observations come from OSN (purple), NOT (yellow) and RTT150 (light red) (see also Table 2).

Table 2. Hα equivalent width (EW) measurements of optical counterpart to XTE J1946+274.

| DATE      | MJD     | EW (Å) | FWHM (Å) | Telescope |
|-----------|---------|--------|----------|-----------|
| 2007-Jul-18 | 54299.816 | -37.35±1.39 | 9.88±0.27 | RTT150    |
| 2012-Mar-27 | 56013.148 | -17.73±0.76 | 11.09±0.46 | OSN       |
| 2012-Apr-18 | 56035.132 | -28.49±1.20 | 11.57±0.30 | OSN       |
| 2012-May-22 | 56069.014 | -41.65±1.31 | 10.19±0.46 | OSN       |
| 2012-May-22 | 56069.039 | -40.70±1.39 | 9.87±0.15  | OSN       |
| 2012-May-28 | 56075.024 | -45.16±1.36 | 10.40±0.78 | NOT       |
| 2012-Jun-19 | 56097.997 | -39.87±1.52 | 10.30±0.11 | OSN       |
| 2012-Jul-4  | 56112.963 | -45.07±1.01 | 9.69±0.74  | OSN       |
| 2012-Jul-5  | 56113.030 | -47.62±0.95 | 10.21±0.94 | OSN       |
| 2012-Jul-9  | 56137.922 | -39.12±0.86 | 10.12±0.32 | RTT150    |
| 2012-Aug-11 | 56150.981 | -44.46±1.18 | 10.62±0.44 | OSN       |
| 2012-Aug-24 | 56163.847 | -41.64±1.74 | 10.14±0.31 | RTT150    |
| 2012-Sep-16 | 56186.734 | -39.65±1.15 | 9.76±0.31  | RTT150    |
| 2012-Oct-9  | 56209.917 | -42.18±1.11 | 11.66±0.26 | OSN       |
| 2012-Dec-11 | 56272.669 | -42.58±2.04 | 10.35±0.31 | RTT150    |
| 2013-Sep-8  | 56543.815 | -40.11±1.35 | 9.88±0.31  | RTT150    |
| 2013-Nov-8  | 56604.714 | -36.11±0.58 | 13.33±0.13 | RTT150    |
| 2013-Dec-26 | 56652.890 | -38.68±1.79 | 14.09±0.88 | RTT150    |
| 2014-Jun-19 | 56827.041 | -39.60±0.97 | 9.07±0.49  | RTT150    |
| 2014-Jul-17 | 56855.813 | -42.79±1.10 | 9.95±0.60  | RTT150    |
| 2014-Aug-03 | 56872.859 | -41.06±0.80 | 9.85±0.43  | RTT150    |
| 2014-Oct-20 | 56950.753 | -43.14±1.28 | 9.83±0.49  | RTT150    |
| 2014-Oct-21 | 56951.774 | -42.37±1.15 | 9.99±0.45  | RTT150    |

2. Observations and data reduction

2.1. Optical spectroscopic observations

Optical spectroscopic observations of the companion were performed during 2011 April – 2014 October with four different telescopes: the Russian-Turkish 1.5-m telescope (RTT150) at the TÜBİTAK National Observatory in Antalya (Turkey), the 2.56-m Nordic Optical Telescope (NOT) located at the Observatorio del Roque de los Muchachos (La Palma, Spain), and the 1.5-m Telescope at the Observatorio de Sierra Nevada (OSN-CSIC) in Granada (Spain). In addition to this long-term observation set we include a spectrum of the source taken in June 2007 with RTT150.

The spectroscopic data from RTT150 were obtained with the TÜBİTAK Faint Object Spectrometer and Camera (TOSC). It is equipped with a 2048×2048, 15μm pixel Fairchild 447BI CCD whose FOV is 13.3′ × 13.3′. We used slit 67′′ (1′′:24) with Grism 8 having an average dispersion of 1.1 Å/pixel and providing a 5800–8300 Å wavelength coverage. The reduction of RTT150 spectra was done using the Long-Slit package of MIDAS. Bias correction, flat-fielding and removal of cosmic-ray hits were carried out with standard MIGAS routines.

The low-resolution OSN spectra (R≈1400) were acquired using Albireo spectrograph centred on Hα wavelength (6562.8 Å) whereas NOT spectrum was obtained with the Andalucía Faint Object Spectrograph and Camera (ALFOSC) using Grism 7, with a dispersion of 1.5 Å/pixel, and 0′′5–1″ slits. The reduction of this data set was performed using standard proce-

1 http://www.eso.org/projects/esomidas
2 The data presented here were obtained [in part] with ALFOSC, which is provided by the Instituto de Astrofísica de Andalucía (IAA) under a joint agreement with the University of Copenhagen and NOTSA.
dures within IRAF\(^4\) including bias subtraction, removal of pixel-to-pixel sensitivity variations, optimal spectral extraction, and wavelength calibration based on arc-lamp spectra.

All spectroscopic data were normalized with a spline fit to continuum and corrected to the barycenter after the wavelength calibration. The full width at half maximum (FWHM) and equivalent width (EW) measurements of H\(_\alpha\) lines were acquired by fitting Gaussian functions to the emission profiles using the ALICE subroutine of MIDAS.

### 2.2. Optical/IR photometric observations

As a part of our monitoring campaign the optical counterpart to XTE J1946+274 has been observed in the optical and infrared bands during the period of 2011 September – 2014 November (see Table 3) with the 80-cm IAC80 and the 1.5-m TCS telescopes at the Observatorio del Teide on Tenerife (Spain) respectively. We obtained the optical photometric CCD images using B and V filters with integration time of 120 s. In infrared, J, H and K\(_s\) simultaneous observations were performed using the CAIN camera with integration times of 150 s. The reduction of the data was done by using the pipelines of both telescopes based on the standard aperture photometry (Camero et al. 2014, for more details on reduction). The main part of the long-term optical CCD observations of the source include the 0.45-m reflecting ROTSEIIId telescope data achieved from 2005 April to 2012 November (MJD 53465–56215). ROTSEIIId telescope, located at the TÜBİTAK National Observatory (Antalya, Turkey), operates without filters and a pipeline immediately after the pointing. Instrumental magnitudes with IRAF\(^4\) including bias subtraction, removal of pixel-to-pixel sensitivity variations, optimal spectral extraction, and wavelength calibration based on arc-lamp spectra. We obtained the optical photometric CCD images using B and V filters with integration time of 120 s. In infrared, J, H and K\(_s\) simultaneous observations were performed using the CAIN camera with integration times of 150 s. The reduction of the data was done by using the pipelines of both telescopes based on the standard aperture photometry (Camero et al. 2014, for more details on reduction).

The main part of the long-term optical CCD observations of the source include the 0.45-m reflecting ROTSEIIId telescope data achieved from 2005 April to 2012 November (MJD 53465–56215). ROTSEIIId telescope, located at the TÜBİTAK National Observatory (Antalya, Turkey), operates without filters and a pipeline immediately after the pointing. Instrumental magnitudes within IRAF\(^4\) including bias subtraction, removal of pixel-to-pixel sensitivity variations, optimal spectral extraction, and wavelength calibration based on arc-lamp spectra. All spectroscopic data were normalized with a spline fit to continuum and corrected to the barycenter after the wavelength calibration. The full width at half maximum (FWHM) and equivalent width (EW) measurements of H\(_\alpha\) lines were acquired by fitting Gaussian functions to the emission profiles using the ALICE subroutine of MIDAS.

| DATE       | MJD   | B     | V     | J     | H     | K\(_s\) |
|------------|-------|-------|-------|-------|-------|--------|
| 2011-Sep-11| 55815.029| 12.450±0.028 | — | — | — | — |
| 2011-Sep-23| 55827.959| 12.694±0.059 | 11.727±0.048 | — | — | — |
| 2011-Sep-24| 55828.962| — | — | — | — | — |
| 2011-Oct-15| 55849.970| 11.402±0.066 | — | — | — | — |
| 2011-Dec-05| 55900.815| 11.260±0.042 | 11.899±0.152 | — | — | — |
| 2012-Mar-30| 56016.195| 15.784±0.050 | 11.240±0.105 | — | — | — |
| 2012-Apr-10| 56027.140| 18.737±0.056 | 11.282±0.009 | — | — | — |
| 2012-Apr-15| 56032.192| 15.89±0.051 | — | — | — | — |
| 2012-Apr-22| 56039.195| 15.898±0.051 | — | — | — | — |
| 2012-May-07| 56054.179| 12.734±0.083 | 11.856±0.019 | — | — | — |
| 2012-Jun-02| 56080.183| 15.835±0.050 | — | — | — | — |
| 2012-Jun-04| 56082.206| 15.784±0.051 | — | — | — | — |
| 2012-Jun-11| 56089.214| 15.793±0.050 | — | — | — | — |
| 2012-Jun-14| 56092.957| 15.841±0.051 | — | — | — | — |
| 2010-Jul-01| 56109.913| 15.773±0.054 | — | — | — | — |
| 2012-Jul-07| 56115.892| 15.777±0.056 | — | — | — | — |
| 2012-Jul-10| 56118.885| 15.795±0.051 | — | — | — | — |
| 2013-Mar-13| 56364.225| 12.504±0.015 | 11.897±0.025 | — | — | — |
| 2013-Apr-21| 56403.164| 15.666±0.026 | — | — | — | — |
| 2013-Apr-22| 56404.145| 15.615±0.007 | 11.278±0.060 | — | — | — |
| 2013-May-03| 56415.075| 12.464±0.057 | 11.202±0.084 | — | — | — |
| 2013-Jun-30| 56473.074| 12.329±0.006 | 11.227±0.059 | — | — | — |
| 2013-Jul-12| 56485.011| 12.464±0.016 | — | — | — | — |
| 2013-Aug-11| 56515.996| 12.493±0.022 | 11.262±0.068 | — | — | — |
| 2013-Aug-28| 56532.892| 12.517±0.020 | 11.817±0.009 | — | — | — |
| 2013-Sep-09| 56544.937| 12.424±0.006 | 11.688±0.005 | — | — | — |
| 2013-Sep-11| 56546.022| 12.324±0.049 | 11.745±0.009 | — | — | — |
| 2013-Sep-11| 56546.942| 12.463±0.031 | 11.845±0.009 | — | — | — |
| 2013-Oct-09| 56574.887| 12.493±0.035 | 11.797±0.007 | — | — | — |
| 2013-Nov-01| 56597.927| 12.455±0.070 | 11.826±0.090 | — | — | — |
| 2013-Nov-10| 56606.872| 15.646±0.051 | — | — | — | — |

\(^3\) IRAF is distributed by the National Optical Astronomy Observatory, optical images which is operated by the Association of Universities for Research in Astronomy (AURA) under cooperative agreement with the National Science Foundation.

\(^4\) The Robotic Optical Transient Search Experiment, ROTSE, is a collaboration of Lawrence Livermore National Lab, Los Alamos National Lab, and the University of Michigan (http://www.ROTSE.net)
Fig. 2. In this figure the optical/IR photometry of all the corrected images were obtained using an aperture of 3 pixels (10 arcsec) in diameter by SExtractor Package (Bertin & Arnouts 1996). By comparing all the stars in each frames with USNO-A2.0 catalog R-band magnitudes, calibrated ROTSEIIId magnitudes were acquired. For the timing analysis the time series were corrected to the barycenter by using JPL DE200 ephemerides (Kaźmiołkowska et al. 2005 for the details of ROTSEIIId data reduction).

2.3. X-ray observations
The Chandra X-ray Observatory observed XTE J1946+274 with the Advanced CCD Imaging Spectrometer (ACIS) instrument in FAINT mode in 2013 March 12 (MJD 56363.115) for a total exposure time of 4.6 ks. Figure 1 and Table 1 provide the log of this observation. We used a 1/8 subarray, which provides a time resolution of 0.4 s, and the typical ACIS-S imaging and spectral configurations. The source was positioned in the back-illuminated ACIS-S3 CCD at the nominal target position. Standard processing of the data was performed by the Chandra X-ray Center (CXC) to Level 1 and Level 2 (processing software DS ver. 8.5.1.1). In this work we have used CIAO software (ver. 4.6) for the reprocessing and the analysis of the data. Since 2008, the Gamma-ray Burst Monitor (GBM) on board the Fermi satellite, has been monitoring XTEJ1946+274. In this study we used timing products provided by the GBM Pulsar Team (see e.g. Finger et al. 2009, Camero-Arranz et al. 2010a for a detailed description of the timing technique). We also used quick-look X-ray results provided by the RXTE All Sky Monitor team5 and Swift/BAT transient monitor results provided by the Swift/BAT team (Krimm et al. 2013).

3. Analysis and results
3.1. Optical/IR photometry
The results of our multiwavelength campaign are shown in Figure 2. In this figure the optical/IR behavior of the Be star is displayed, together with the X-ray activity observed from the neutron star (see Tab. 3). The ROTSE magnitude (fourth panel, from top to bottom) steadily varied from 2005 to 2013, with a minimum in 2006 and a maximum around mid 2010. A main X-ray outburst was then detected in 2010 lasting ∼270 days. In contrast to the other BeXRB systems showing recurrent series of normal outbursts, they did not coincide with the time of periastron passage of the neutron star (NS). After the 2010/2011 X-ray outburst series, the Be/X-ray binary XTE J1946+274 did not show any transient activity. The quiescent phase has been ongoing for ∼3 years, although since 2012 the optical/IR magnitudes have been showing an increasing trend (see second and third panels of the same Figure).

In order to search for periodic variability in the daily ROTSE light curve we used the Lomb-Scargle (Scargle 1982) and Clean (Roberts et al. 1987) algorithms. The frequency analysis was applied to all photometric data, including 1747 points, over a range from 0 to 17.49 d−1 (Nyquist frequency). We did not find any periodic variation in the original data, except for the power at the frequency of 1 d−1, as a result of the daily observing schedule. We then rebinned the light curve in 30 days bins. Figure 3 reveals a quasi-sinusoidal pattern in the data, with a minimum at the beginning of 2006 (MJD ∼53700). This seems to indicate that a brightening phase in the Be star occurred for almost five years, followed by a quick decline in about 2 years. To clarify this point we used the Fourier analysis module included in the Period04 software package6 (Lenz & Breger 2005), which is based on a discrete Fourier transform algorithm. We thus fitted a sinusoid to a combination of the observed frequency 3.3(8)×10−4 d−1 (∼3050 d), found by Period04, together with its first and second harmonics. The uncertainties in the frequency determinations were computed from Monte Carlo simulations. The resulted fitted curve (see also Figure 3) shows the probable evolution of the Be star brightening episode, probably a mass ejection event.

3.2. Hα line
In Figure 4 we present the spectroscopic tracing of the Hα line profiles observed between 2012–2014. The Hα line was always seen in a single-peaked emission (as the one in 2007 July 18) and even its EW and FWHM measurements showed significant variations (see top panel of Figure 4). The first spectroscopic observation of this period had the lowest value of Hα emission line, ∼18 Å, observed for XTE J1946+274. The weakness of this emission comparing to the typical values of XTE J1946+274 might be interpreted as variations in the decretion disk of the Be star.

http://xte.mit.edu/ASM/lc.html

5 http://xte.mit.edu/ASM/lc.html

6 http://www.astro.univie.ac.at/dsn/dsn/Period04
Fig. 3. Complete ROTSE IIId light curve binned using 30 days bins. Overplotted is the fitted sinusoid to the data (see Sect. 3 for more details).

Fig. 4. Hα line profile evolution during the X-ray quiescence. The presence of any remarkable variation is not detected.

star. Assuming that the EW measurement of Hα line emission was also related to the amount of the material in the emitting region of the disk, the weakness of the EW would be the result of the mass loss either through the accretion of the NS or the truncation of its size despite the lack of an X-ray activity. It is also possible that the weakest value we caught does not represent the lowest one, instead it can be a part of the refilling process of the disk after a disk-loss episode. In fact, a sharp increasing trend of the EW right after this value confirms the suggested idea. The decrease in EW lasted about three months reaching its peak value of ∼48 Å. It is also important to note that the EW and FWHM values of the source show an inverse relation despite the expected positive relation (Hanuschik 1989).

In addition, we computed the rotational velocity of the Be star. First we estimated its projected rotational velocity of XTE J1946+274 as vsini ∼323 km s⁻¹ via the average values of EW and FWHM parameters (Hanuschik 1989). Then using the inclination angle of the system given by Wilson et al. (2003), the true rotational velocity, vrot, of the Be star was measured as 323–449 km s⁻¹. Taking the mass of the star as 16 M⊙ and 8 R⊙ as the limit radius for a B type star, then the critical break-up velocity, vcrit, was found to be ∼618 km s⁻¹. Thus, we find the critical fraction, defined as the ratio of the equatorial rotational velocity to the break-up velocity, of XTE J1946+274 as w ∼0.5–0.72. This result indicates that the Be star in XTE J1946+274 is rotating at 50–70% of its break-up velocity, typical to the stars for the same type.

4. Chandra/ACIS-S X-ray analysis during quiescence

4.1. Imaging

We extracted an image in the 0.3–10 keV energy range, using the Chandra pointing observation from 2013 as described in Sect. 2.3. We then applied the CIAO wavdetect tool to the 4.6 ks ACIS-S cleaned image and found XTE J1946+274 at α = 19°45′39.346122 and δ = 27°21′54.942243 (J2000) with a signal-to-noise ratio of 11.025, and a statistical error of 0′.0018 radius.

4.2. Spectral study

To obtain the 0.3–10 keV phase-averaged spectrum for the Chandra ACIS-S observation we used source and background photons extracted as described in Section 2. We used the specextract script, which uses a combination of CIAO tools, to extract source and background spectra for XTE J1946+274. To extract only the photons from the point source a circular region with 2″.5 radius and a circular background region of radii

FWHM value of ∼10.5 Å. It is also important to note that the EW and FWHM values of the source show an inverse relation despite the expected positive relation (Hanuschik 1989).
Table 4. Spectral parameters from an absorbed PL model and absorbed BB. Errors are given at the 90% confidence level.

| Parameter | PL | BB |
|-----------|----|----|
| $N_a^a$ | 0.7(4) | 0.21(15) |
| $\Gamma^b$ | 0.9(4) | - |
| $\Gamma_{norm}^c$ | 1.03(3) | - |
| $kT$(keV) | - | 1.43(17) |
| $kT_{norm}$ | - | 0.020(8) |
| abs.Flux$^d$ | 1.0(3) | 0.81(16) |
| unabs.Flux$^d$ | 1.2(4) | 0.84(18) |
| C-stat (d.o.f.) | $108.32(148)$ | $109.15(148)$ |

$^a \times 10^{-4}$ photons keV$^{-1}$ cm$^{-2}$ s$^{-1}$ at 1 keV.

$^b \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ in the 0.3–10 keV energy band.

Fig. 5. Background subtracted X-ray pulse profile (in counts s$^{-1}$) for XTE J1946+274 during quiescence in the 0.3–10 keV energy band.

18″ (far from the source) were used. For the present analysis we used the XSPEC package (version 12.8.1g) (Arnaud 1996).

Two models provided the best fit to the data, an absorbed power law (PL) and blackbody (BB) models. For the photoelectric absorption we used the cross-sections from Balucinska-Church & McCammon (1992) and the Solar abundance from Anders & Grevesse (1989). The best-fit parameters for these models can be seen in Tab. 4. The main parameters for both models are $\Gamma=0.9 \pm 0.4$ (C-stat=108.32 for 148 d.o.f.), and $kT=1.43 \pm 0.17$ keV (C-stat=109.15 for 148 d.o.f.), with $N_a=2.7 \times 10^{22}$ cm$^{-2}$. The 2–10 keV observed flux was $F_X=7.5(3) \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ for the BB and PL models, respectively. The photon index is similar to the value found for XTE J1946 in the 0.3–10 keV band.

Regarding the evolution of the PF$_{rms}$, with energy we obtained values of 51.02(12)%, 18.52(2)%, 54.27(13)%, and 37.23(15)% in the 0.3–1.5 keV, 1.5–3 keV, 3–4.5 keV, and 4.5–10 keV energy bands, respectively (see Fig. 6). We would like to note that for the profiles at different energy bands the phase binning was reduced to 8, since the PF$_{rms}$ formulation did not yield real solutions in some of the bands.

4.3. Timing

For the timing analysis, we first referred the arrival time of each photon to the barycenter of the solar system using the CIAO tool axbary. Then, we used the dmextract tool to create background-subtracted lightcurves, using the time resolution of the data (~0.4 s). For this, we extracted the source photons on each individual observation from a circular region with 2.5′′ radius, and another one for the background, far from the source.

We searched for pulsations using the Xronos package obtaining a PF$_{rms}=15.757(1)$ s (epoch: MJD 56 363.115; $\nu=0.063464(4)$ Hz). Figure 5 shows the pulse profile obtained by folding the X-ray data set using the former period. Despite the low luminosity level of the source in this observation, we can observe a profile with two almost identical smooth peaks separated by a dip at phases $\sim 0.4$. Wilson et al. (2003) found that the profile consisted of an asymmetric structure with the main peak near phase $\sim 0.2$ in a RXTE/PCA observation of this source at its lowest intensity level during the 2001 outbursts. We note, however, that this profile was obtained in the 2–30 keV energy range. In our Chandra/ACIS-S observation the dip in the pulse profile was more prominent at low energies in the 0.3–1.5 keV band, vanishing as the energy increases (see Fig. 6), and with the pulse profile evolving to single-peaked. The shape of the profile at 3–4.5 keV was narrower and quite symmetric comparing to the asymmetric single peaks found at 1.5–3.5 keV and 4.5–10 keV, with all peaking at different phases of $\sim 0.2$, $\sim 0.4$, and $\sim 0.6$ for each energy band.

The modulation amplitude of the 0.3–10 keV pulse displayed in Fig. 5 (12 phase bins) can be measured using a pulse fraction defined $PF_{rms}=1/y [1/n \sum (y_i-\bar{y})^2-\sigma^2]^{1/2}$, where $n$ is the number of phase bins per cycle, $y_i$ is the number of counts in the $i$th phase bin, $\bar{y}$ is the mean of $y_i$, and $\sigma$ the mean number of counts in the cycle. We obtained a $PF_{rms}$ value of 32.1(3)%.

Using the standard definition $PF_{rms}=F_{max}-F_{min}$, we obtained the value we expected, being 36(20)%. Regarding the evolution of the PF$_{rms}$, with energy we obtained values of 51.02(12)% in the 0.3–1.5 keV, 1.5–3 keV, 3–4.5 keV, and 4.5–10 keV energy bands, respectively (see Fig. 6). We would like to note that for the profiles at different energy bands the phase binning was reduced to 8, since the PF$_{rms}$ formulation did not yield real solutions in some of the bands.

5. Discussion

5.1. Be/NS interaction

XTE J1946+274 is one of the BeXRB that spends most of its time in an X-ray quiescent phase. The uniqueness of the sys-
tem comes from its X-ray outburst behavior that is not connected to the orbital passages of the NS. The shifts in the outburst phases with respect to the periastron/apastron passages of the NS is thought to be result of the global perturbations triggered by the truncation of the disk radius. During quiescent state we have not seen any trace of such density wave in the decretion disk that shows itself as the variation of the emission profiles in the spectroscopic data. Wilson et al. (2003) attributed the variations in the Hα emission profile to the existence of the perturbations in the disk and added the difficulties of detection of the density perturbations in XTE J1946+274 since the relatively small viewing angle restricts the size of the projected area to be observed. According to that, only the large-scaled perturbations can be seen in the disk of XTE J1946+274. In contrast to this idea, Silaj et al. (2010) suggested that emission line profile shapes could not be used to estimate the inclination angle of the system since for a given inclination angle different types of profile shapes might be produced as a result of the density changes in the disk-thermal structure. This means that, conversely the suggested picture of Wilson et al. (2003) for XTE J1946+274, we should have seen the profile changes if there had occurred any density variations in the decretion disk, despite the small inclination angle of the system.

Be stars are variable on all time scales. Short-term variability is commonly associated with either the rotation of the star and/or non-radial pulsations (see e.g. Kızıloğlu et al. 2007; Gutiérrez-Soto et al. 2011), while the long-term is believed to be originated by structural changes in the Be decretion disk. The typical time scale for the formation and disintegration of the disk has been found to coincide with the observed time scales of the largest amplitude variations (Lyuty & Zaitseva 2006; Camero et al. 2014). The observed long optical brightening experienced by XTE J1946+274 may be interpreted as a slow mass ejection event which started in 2006, peaked in 2010, and rapidly decreased afterwards, reaching quiescence probably at the beginning of 2013.

The high values obtained for the Hα EW, with the line always seen in emission, may indicate that a large Be circumstellar disk is permanently present in this system. It is worth noting that although renewed X-ray activity was not observed until 2010, already in 2007 July the EW of the Hα line had a value of –37.35 Å (see Table 2). One possible explanation is that the disk is tilted with respect to the orbital motion of the NS. Despite the lack of spectroscopic data at earlier phases, we visualize a scenario in which the 2006 optical enhancement originated, besides a steady increase of the Be circumstellar disk, the appearance of global perturbations and the warping of a differentially rotating disk. This eventually triggered the X-ray activity when the NS contacted the warped area (see Okazaki et al. 2013) in 2010. The X-ray outbursts series emptied the pile and the disk dramatically decreased around 2011 (see bottom panel of Fig 7). Although the recovery of the decretion disk was fast, our data point out that the disk reached its maximum size by the time the mass ejection event was over. In such a stable environment the disk did not get warped and therefore no X-rays were detected. This seems to be confirmed by the absence of any variations in our Hα line profiles during the same period.

The ongoing optical/IR brightening resembles so far the previous mass ejection event from 2006–2012. Probably initiated around mid 2012, it appears to be propitiating the refilling of the disk. If the phenomenon repeats we foresee that approximately in two years XTE J1946+274 will manifest in X-rays.
5.2 NS behavior

XTE J1946+274 displayed an extended period of activity from 1998 September to 2001 July. Wilson et al. (2003) noted that this period of activity resembled a series of normal outbursts (thirteen) more than a single giant outburst. After approximately 8 years in quiescence, XTE J1946+274 reawakened in X-rays with a series of five outbursts between 2010 and 2011 (but less intense than in 1998). Once again, two outbursts were observed per orbital period, which did not clearly coincide with the times of periastron and apastron passages of the NS. Fermi/GBM detected pulsations from XTE J1946+274 between 2010 and 2011 (see top panel of Fig. 7). The initial and larger outburst did not show a large spin-up rate as in 1998, retaining $\dot{\nu} \sim 0.8 \times 10^{-11}$ Hz s$^{-1}$ during the first 50 days ($P \sim 2 \times 10^{-9}$ Hz s$^{-1}$). In the following normal outburst the NS spun up at a similar rate of $0.7 \times 10^{-11}$ Hz s$^{-1}$ ($P \sim 1.6 \times 10^{-9}$ Hz s$^{-1}$). Then a spin down period overcame with $\dot{\nu} \sim -0.3 \times 10^{-11}$ Hz s$^{-1}$ ($P \sim 7 \times 10^{-10}$ Hz s$^{-1}$) in 20 days. In the final three outbursts series the spin up rate was similar during each event, that is $\dot{\nu} \sim 0.5 \times 10^{-11}$ Hz s$^{-1}$ ($P \sim 1 \times 10^{-9}$ Hz s$^{-1}$).

The last frequency measurement reported by GBM was $0.0635228(3)$ Hz ($P_{\text{spin}} = 15.74238(2)$ s) in 2011. Considering our frequency determination of 2013, the source spun down at a rate $\dot{\nu} \sim -0.98 \times 10^{-11}$ Hz s$^{-1}$ ($P \sim 2.4 \times 10^{-10}$ Hz s$^{-1}$). Spin-up torque/flux correlations for this source were found by Wilson et al. (2003), suggesting the presence of an accretion disk around the NS during XTE J1946 active periods. This scenario is corroborated by Fermi/GBM during the 2010/2011 X-ray outbursts (see Fig. 7).

To determine whether or not the observed X-ray turn-off was due to centrifugal inhibition of accretion (Stella et al. 1988), Wilson et al. (2003) estimated the flux at the onset of this effect by equating the magnetospheric radius and the corotation radius, obtaining a threshold flux for the onset of centrifugal inhibition of accretion in the range of $0.6-6.0 \times 10^{-11}$ ergs cm$^{-2}$ s$^{-1}$. Our observed flux during quiescence in 2013 was well below this range ($\sim 0.1 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$), corresponding to a X-ray luminosity of $\sim 1.2 \times 10^{34}$ erg s$^{-1}$ in the 0.3-10 keV range.

The problem we face now is to explain the origin of the detected X-ray activity while the centrifugal inhibition of accretion was operating. Accretion from the stellar wind of the companion may be the origin of the observed luminosity, or the equatorial low-velocity high-density wind characteristic of Be/X-ray binaries. In addition, it has been suggested that the propeller mechanism switches off when the angular velocity of the NS is smaller than the Keplerian velocity at the Alfven radius (Illarionov & Kompaneets 1990). There is, instead, accretion to the NS over the other parts of the total cross-section, and outflow of a Compton-heated wind over the other parts, providing an extra spindown torque component.

Based on our observation of XTE J1946+274 during quiescence in 2013, and assuming that this source enters the supersonic propeller regime (see e.g. Davies & Pringle 1981, Henrichs 1983), it is expected to spin down at a rate of $\dot{\nu}_{\text{superc}} = -4\pi \mu^2 (GM)^{-1} (c_i / \mu r_\text{a})$, where $\mu$ is the NS magnetic moment, $M$ the mass of the NS, $I$ the moment of inertia, $c_i$ is the sound speed at the magnetospheric radius (which we take here of the order of the free-fall velocity), and $r_\text{a}$ is the Alfven radius (Henrichs 1983). With this $\dot{\nu}_{\text{superc}} \approx 0.13 \times 10^{-12}$ Hz s$^{-1}$, which has the same order of magnitude than the observed measurement, although $\sim 7.5$ times smaller. We note, however, that there is no general consensus on the estimate of the propeller efficiency, and the difference on the estimate of the torque during supersonic propeller state may be as large as $\approx 10^2$ under certain conditions (see discussion for LS 1+61°303 in Papitto et al. 2012). It is also possible that other types of torques might be operating simultaneously with the propeller-type torque, e.g. the “frictional” torque (Ghosh 1993, and references therein), with the effect of increasing the observed spindown torque on the NS. On the other hand, the X-ray luminosity in supersonic propeller regimen is given by $L_X \approx 8M v_{\text{rel}}^2$ (Henrichs 1982), where $M$ is the mass accretion rate, and $v_{\text{rel}}$ is the relative velocity which is typically of the order of $\sim 1000$ km/s. For XTE J1946+274 this yields $L_X \approx 1.13 \times 10^{34}$ erg s$^{-1}$, which reproduces what was observed in 2013 ($\sim 1.19 \times 10^{33}$ erg s$^{-1}$). Moreover, we found that this is also true for the long quiescence period between 2001 and 2010. The observed spindown rate from MJD 55353.01 to 52115.70, computed using the last frequency determination by Wilson et al. (2003) in 2001 ($\sim 0.0635$ Hz), and the first one detected by GBM ($\sim 0.063421$ Hz) in 2010, gives $\dot{\nu}_{\text{obs}} \approx 0.18 \times 10^{-12}$ Hz s$^{-1}$. This result nicely agrees with the source being in supersonic propeller regimen.

6. Summary and conclusions

We have performed a long-term multiwavelength study of the Be/X-ray binary system XTE J1946+274, a source which spends almost all its time in quiescence. Our findings include the detection of a large Be circumstellar disk during that phase. We address the absence of major X-ray activity by discussing our results in terms of the neutron star Be-disk interaction.

- A long mass ejection event from the Be-star commenced in 2006, attained its maximum intensity in 2010, and reached quiescence presumably in 2012.
- The high values obtained for the $H_n$ EW (always in emission) point to the permanently presence of a large Be circumstellar disk, probably tilted with respect to the orbital motion of the NS.
- We proposed that the optical enhancement possibly originated, besides a steady increase of the Be circumstellar disk, the appearance of global perturbations and the warping of a differentially rotating disk.
- Therefore, the mechanism that might be triggering the X-ray activity is the contact of the NS with the warped area of the Be disk. After the series of X-ray episodes, the pile emptied and the disk dramatically decreased.
- There was an absence of variations in the $H_n$ line profiles during the posterior fast recovery of the disk. This took place in parallel to the decay of the optical mass ejection event. In a much more stable environment the disk did not get warped and therefore no X-rays were detected.
- On the other hand, the pulsations from the NS have been detected during X-ray quiescence in 2013, with $P_{\text{pulse}} = 15.757(1)$ s and an rms pulse fraction of 32.1(3)%. The 0.3–10 keV X-ray spectrum of the NS was well fitted with either an absorbed black-body or absorbed power-law models ($K = 1.43 \pm 0.17$ and $\Gamma = 0.9 \pm 0.4$).
- The observed X-ray luminosity during quiescence may be well explained by the NS being in supersonic propeller regimen.
- The ongoing optical/IR brightening resembles so far the previous mass ejection event. If the proposed scenario from above is valid we predict that approximately in two years XTE J1946+274 will show major X-ray activity.

Acknowledgments. This article is partially based on service observations made with the IAC80 and TCS telescopes oper-
ated on the island of Tenerife by the Instituto de Astrofísica de Canarias (IAC) in the Spanish Observatorio del Teide. The present work is also based on observations made with the Nordic Optical Telescope, operated by the Nordic Optical Telescope Scientific Association at the Observatorio del Roque de los Muchachos (IAC), La Palma, Spain. The Albireo spectrograph at the 1.5-m telescope is operated by the Instituto de Astrofísica de Andalucía at the Sierra Nevada Observatory. We thank TÜBITAK and ROTSE collaboration for partial support in using the RTT 150 and ROTSEIIIId Telescopes with project numbers TUG-RTT150.08.45, 12ARTT150-264-1 and ROTSE-40. The scientific results reported in this article are based in part on data obtained from the Chandra Data Archive. The work of J.G.S. is supported by the Spanish Programa Nacional de Astronomía y Astrofísica under contract AYA2012-39246-C02-01. E. N. acknowledges a VALi+d postdoctoral grant from the Generalitat Valenciana and was supported by the Spanish Ministry of Economy and Competitiveness under contract AYA 2010-18352. A. C. was supported by the AYA2012-39303, SGR2009-811 and iLINK2011-0303 grants. M.O. A. acknowledges support from TÜBITAK, The Scientific and Technological Research Council of Turkey, through the research project 106T040.

References

Akerlof, C. W., Kehoe, R. L., McKay, T. A., et al. 2003, PASP, 115, 132
Anders, E. & Grevesse, N. 1989, Geochim. Cosmochim. Acta, 53, 197
Arnaud, K. A. 1996, in Astronomical Society of the Pacific Conference Series, Vol. 101, Astronomical Data Analysis Software and Systems V, ed. G. H. Jacoby & J. Barnes, 17
Balcicinska-Church, M. & McCammon, D. 1992, ApJ, 400, 699
Berin, E. & Arons, S. 1996, A&AS, 117, 393
Caballero, I., Potschmidt, K., Bozzo, E., et al. 2010, The Astronomer's Telegram, 2692, 1
Camero, A., Zurita, C., Gutierrez Soto, J., et al. 2014, ArXiv e-prints
Camero-Arranz, A., Finger, M. H., Ilksenov, N. R., Wilson-Hodge, C. A., & Beklen, E. 2010a, ApJ, 708, 1500
Camero-Arranz, A., Finger, M. H., Wilson-Hodge, C., & Jenke, P. 2010b, The Astronomer's Telegram, 2677, 1
Campana, S., Israel, G., & Stella, L. 1999, A&A, 352, L91
Davies, R. E. & Pringle, J. E. 1981, MNRAS, 196, 209
Finger, M. H., Beklen, E., Narayana Bhat, P., et al. 2009, ArXiv e-prints
Ghosh, P. 1995, Journal of Astrophysics and Astronomy, 16, 289
Gutiérrez-Soto, J., Reig, P., Fabregat, J., & Fox-Machado, L. 2011, in IAU Symposium, Vol. 272, IAU Symposium, ed. C. Neiner, G. Wade, G. Meynet, & G. Peters, 505–506
Hanuschik, R. W. 1989, Ap&SS, 161, 61
Heindl, W. A., Coburn, W., Gruber, D. E., et al. 2001, ApJ, 563, L35
Henrichs, H. F. 1982, PhD thesis, University of Amsterdam
Henrichs, H. F. 1983, in Accretion-Driven Stellar X-ray Sources, ed. W. H. G. Lewin & E. P. J. van den Heuvel, 393–429
IIarionov, A. F. & Kompaneets, D. A. 1990, MNRAS, 247, 219
Kızıloğlu, Ü., Kızıloğlu, N., & Baykal, A. 2005, AJ, 130, 2766
Kızıloğlu, Ü., Kızıloğlu, N., Baykal, A., Yerli, S. K., & Özbey, M. 2007, A&A, 470, 1023
Krimm, H. A., Barthelmy, S. D., Baumgartner, W., et al. 2010, The Astronomer's Telegram, 2663, 1
Krimm, H. A., Holland, S. T., Corbet, R. H. D., et al. 2013, ApJS, 209, 14
Lenz, P. & Berger, M. 2005, Communications in Asteroseismology, 146, 53
Lyuty, V. M. & Zaitseva, G. V. 2000, VizieR Online Data Catalog, 902, 60013
Müller, S., Kühlmehl, M., Caballero, L., et al. 2012, A&A, 546, A125
Müller, S., Kühlmehl, M., Potschmidt, K., et al. 2010, The Astronomer's Telegram, 3077, 1
Nakajima, M., Mihara, T., Nakagawa, Y. E., et al. 2010, The Astronomer's Telegram, 3048, 1
Okazaki, A. T., Hayasaki, K., & Moritani, Y. 2013, PASJ, 65, 41
Papitto, A., Torres, D. F., & Rea, N. 2012, ApJ, 756, 188
Priedhorsky, W. C. & Holt, S. S. 1987, Space Sci. Rev., 45, 291
Robert, D. H., Lehar, J., & Dreher, J. W. 1987, AJ, 93, 968
Scargle, J. D. 1982, ApJ, 263, 835
Silaj, J., Jones, C. E., Tycner, C., Sigut, T. A. A., & Smith, A. D. 2010, ApJS, 187, 228
Smith, D. A. & Takeshima, T. 1998, The Astronomer's Telegram, 36, 1
Stella, L., White, N. E., & Rosner, R. 1986, ApJ, 308, 669
Verrecchia, F., Israel, G. L., Negueruela, I., et al. 2002, A&A, 393, 983
Wilson, C. A., Finger, M. H., Coe, M. J., & Negueruela, I. 2003, ApJ, 584, 996
Wilson, C. A., Finger, M. H., Wilson, R. B., & Scott, D. M. 1998, IAU Circ., 7014, 2