PHASE-RESOLVED SPECTRAL ANALYSIS OF 4U 1901+03 DURING ITS OUTBURST

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ABSTRACT

The high-mass X-ray binary 4U 1901+03 is reported to have a pulse profile evolving with the X-ray luminosity and energy during its outburst in 2003 February–July: the pulse peak changed from double to single along with the decreasing luminosity. We have carried out a detailed analysis on the contemporary phase-resolved energy spectrum of 4U 1901+03 as observed by the Rossi X-ray Timing Explorer. We find that the spectra are phase dependent. At the beginning of the outburst, the maximum of the optical depth for Compton scattering is near the major phase peak. During the decay of the outburst, the optical depth has the maximum away from the main peak of the pulse profile. For each observation, Fe Kα emission line is detected in the phase-resolved spectra, and its flux is constant across the pulse phases. This suggests that the origin of the Fe emission is from the accretion disk, not the surface of the neutron star.

Key words: pulsars: individual (4U 1901+03) – stars: neutron – X-rays: stars

1. INTRODUCTION

Most of the known X-ray binary pulsars are the so-called high-mass X-ray binaries (HMXBs). They are usually Be/X-ray binaries characterized by a transient nature. The Be star is an early-type non-supergiant star with observable emission lines from the material in its circumstellar disk (see Slettebak 1988 for a review). Be/X-ray binaries usually show two types of outburst behavior: normal outburst with low X-ray luminosity lasting for days–weeks, and giant outbursts with higher X-ray luminosity ($L_X \gtrsim 10^{37}$ erg s$^{-1}$) occurring irregularly every several years. Giant outbursts are thought to be driven by a dramatic expansion of the disk surrounding the Be star, which leads to the formation of an accretion disk around the compact object. During the giant outburst, the neutron star is detected with a pulsed emission. The spectra of a Be/X-ray binary are usually represented by a cutoff power-law shape (e.g., Coburn et al. 2002; Corbet et al. 2009; Crawford et al. 2009). The Fe Kα feature between 6 and 7 keV and low-energy absorption due to the cool material are observable as well (White et al. 1983; Wilson et al. 2008).

4U 1901+03 was detected as a Be/X-ray binary pulsar (Liu et al. 2006). The orbital period and eccentricity of the system are measured as 22.58 days and 0.035, respectively. The period of X-ray pulsation is about 2.73 s (Galloway et al. 2005). The location of the source, R.A. $= 19^\mathrm{h} 04^\mathrm{m} 13^\mathrm{s}$ and decl. $= +3^\circ 09' 26''$, is (J2000.0) obtained by the observation with Uhuru (Forman et al. 1978; Priedhorsky & Terrell 1984). With the observation of the Rossi X-ray Timing Explorer (RXTE) Proportional Counter Array (PCA), Galloway et al. (2003a) obtained precise coordinates of R.A. $= 19^\mathrm{h} 03^\mathrm{m} 37^\mathrm{s}$, decl. $= +3^\circ 11' 31''$.

There are two giant outbursts in the history of 4U 1901+03 observations. The first one was detected with Uhuru and Vela 5B in 1970–1971 (Forman et al. 1976; Priedhorsky & Terrell 1984). The second giant outburst took place in 2003 February and was first detected by the All-Sky Monitor on RXTE, followed by a series of pointed RXTE observations over the next five months (Galloway et al. 2003b). At the hard X-ray, contemporary observations from the INTEGRAL satellite are also available. During the second giant outburst, the X-ray flux of the source reached a value of $F_{2.5–25\,\text{keV}} \sim 8 \times 10^{-9}$ erg cm$^{-2}$ s$^{-1}$.

Based on the RXTE observations, Galloway et al. (2005) made a thorough study on the orbital parameters, preliminary X-ray spectral analysis, and pulse profiles from several observations for 4U 1901+03 during the 2003 giant outburst. Chen et al. (2008) carried out the detailed analysis of the energy dependence of the pulse profile during the outburst and found that the pulse profile is correlated with both the X-ray luminosity and photon energy (Wang & Welte 1981; White et al. 1983; Nagase 1989; Mukerjee et al. 2000). Phase-resolved spectral analysis is needed to study the emission configuration of a Be/X-ray binary pulsar. We present here for the first time the phase-resolved spectra of 4U 1901+03 using all available RXTE data taken during the 2003 giant outburst. The paper is organized as follows. Description of observations and spectral model is given in Section 2, results are given in Section 3, and finally the discussion of the results is in Section 4.

2. OBSERVATION AND DATA REDUCTION

The observations analyzed in this paper are from the PCA and the High Energy X-Ray Timing Experiment (HEXTE) onboard the RXTE satellite from 2003 February 10 to July 16. The PCA consists of five non-imaging, co-aligned Xe multiwire Proportional Counter Units (PCUs) covering a nominal energy range from 2 to 60 keV. Only PCU0 and PCU2 data are adopted in this work, which were on time the whole 4U 1901+03 was observed. The HEXTE instrument consists of two independent clusters (Clusters A and B) covering an energy range from 15 to 250 keV. Because detector 2 of Cluster B of HEXTE lost its spectral capability and automatic gain control, only Cluster A data are analyzed in this work. We extract light curves and spectra from PCA and HEXTE during the intervals when the source has the offset angle of less than 0.02 and the limb of the earth is more than 10° with respect to the source direction. All HEXTE data products are dead-time corrected using the HEASOFT ftool hxtdead.

The data of Standard-2 and GoodXenon modes of the PCA and the Archive and Science Event modes of the HEXTE are used to perform the spectra and timing analysis. The total light curve is extracted with Standard-2 mode data, and pulse-averaged X-ray spectra are extracted with Standard-2 and
Science Event mode data. The pulse profiles of the chosen observations are extracted with GoodXenon, and the phase-resolved spectra are extracted with the GoodXenon and Science Event data modes, using the software fasebin. Figure 1 shows the light curve of 2.0–21.0 keV and the soft and hard colors that are defined as the count rate ratios 4.5–6.1 keV/2.0–4.5 keV and 9.8–21.0 keV/6.1–9.8 keV, respectively.

The PCA background subtraction is carried out using the latest versions of the appropriate background models, and a 1\% systematic error is added to the spectra to account for the calibration uncertainties. Events in energy range of \(\sim 2.5–20\) keV of the PCA and 17–80 keV of the HEXTE (17–50 keV for the late observations of the outburst) are selected for the spectral analysis with the software XSPEC, version 12.3.0p (Arnaud 1996; Dorman & Arnaud 2001).

2.1. Spectral Model

According to the characteristic of the light curve (Figure 1), we study the phase-averaged spectra of 10 typical observations, carried out on February 10, 15, 22, and 23; March 27 and 30; April 30; May 25; and June 14 and 28, respectively, covering the outburst profile of the beginning, the peaking, the stepping down at the middle of decaying, and the ending tail. Various spectral models are used to fit the phase-averaged spectra of these observations, e.g., cutoffpl, powerlaw, bknpower, compTT, and a combination of each with a blackbody component. A Gaussian component centered at 6–7 keV, which represents fluorescent Fe line emission, shows up as well in all spectra. A model consisting of compTT with a spherical geometry (Titarchuk 1994) and a Gaussian component is statistically acceptable (\(\chi^2_{\text{red}} \sim 1\)) to fit the spectra (also see Galloway et al. 2005). Due to the low effective area of the PCA below 3 keV, the column density \(n_H\) of neutral absorption cannot be constrained well. Therefore, for all spectral fits, we fix \(n_H\) at \(1.2 \times 10^{22}\) cm\(^{-2}\) (Galloway et al. 2005). Such a model fits the data well until April 30. For the observations near the end of the outburst (May 25, June 14 and 28), an additional component of a blackbody has to be introduced in order to have a reasonable \(\chi^2_{\text{red}}\). The temperature of the blackbody is \(kT_{\text{bb}} \sim 1\) keV. As an example, Figure 2 shows the fitting results with various models to the data of the April 30 observation.

We choose three typical observations on February 10, March 27, and April 30 to analyze the evolvement of the phase-resolved spectra. The phase-resolved spectra are extracted with eight phase bins. Figure 3 shows the spectra from the data of the April 30 observation, for phase bin no. 5 (0.4375–0.5625). The fitting results of the spectra show that the Gaussian component is needed in the spectrum.
removed.

A rapid decrease. The soft color and the hard color suggest an ent evolutions: the soft color evolves similar to the light curve, decay of the outburst, the hard and the soft colors have differ-

spectrum (Galloway et al. 2005; Chen et al. 2008). During the Diagnosis of the pulse profile revealed a change from double peaking, near the stepping down, and near the ending. The

Notes.

the temperature of blackbody and normbb is the normalization of blackbody.

3. RESULTS

3.1. Variation of Soft and Hard Colors

Figure 1 shows a stepping down feature of the light curve that occurred around April 30, during the decay of the outburst. Diagnosis of the pulse profile revealed a change from double peaks to single peak at this time (Chen et al. 2008). Accompanying this as well are modifications to the fit model of the spectrum (Galloway et al. 2005; Chen et al. 2008). During the decay of the outburst, the hard and the soft colors have different evolutions: the soft color evolves similar to the light curve, while the hard color shows the opposite trend and ends up with a rapid decrease. The soft color and the hard color suggest an overall trend that the spectrum softens at the beginning, hardens with the decay of the outburst, and turns to soft at the end.

3.2. Phase-averaged Spectra

Table 1 shows the results of the fit models on 10 typical observations described in Section 2, i.e., the beginning, the peaking, near the stepping down, and near the ending. The

results show that the temperature of the seed photons ($T_0$) in the Comptonization model is about 1 keV and decreases slightly during the decay of the outburst. The temperature of the hot electron population ($kT$) remained at about 5 keV. The optical depths of the observations from February 10 to April 30 are consistent with a flat distribution within the error bars, and the average is derived as $\sim 5$. At the end of the outburst, the optical depths are obtained as $7\sim 8$. We note that the Fe Kα line emission with equal width $\sim 100$ eV is present at around 6.5 keV in the energy spectrum, and its flux varies between $\sim 1 \times 10^{-11}$ and $10 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$, showing a trend of increasing with the intensity. At the end of the outburst, an additional spectral component of a blackbody is needed for spectral fittings.

3.3. Phase-resolved Spectra

To study the evolution of the phase-resolved spectra, we choose the three observations with high signal-to-noise ratios, i.e., on February 10, March 27, and April 30. The spin light curve of each observation is subdivided into eight phases—for each one the energy spectrum is extracted—and the flux is shown in

![Figure 3](image-url)
Figure 4. Phase-resolved spectral parameters as a function of pulse phases. From top to bottom: the pulse profiles of 32 phase bins obtained from all PCA channels (2–60 keV); the flux of 3–30 keV of eight phase bins in units of $10^{-9}$ ergs cm$^{-2}$ s$^{-1}$; optical depth for Compton scattering; the temperature of the scattering electron cloud; the central energy and flux of the Fe emission line. The central energies of the Fe line are fixed for phases 4 and 5 of March 27 and phases 3 and 4 of April 30.

Figure 5. Fitting result of the spectrum of phase 2 of the April 30 observation. The left panel shows the fitting result and residual, and the right panel shows the model components of (compTT+gaus).

Figure 4. The figure shows the phase dependence of the spectra of the three observations. The pulse profiles of the three observations, each with 32 phase bins, are presented in the top panels of Figure 4. At the beginning of the outburst (February 10), the optical depth reaches maximum near the major phase peak. However, during the decay of the outburst, the maximum moves toward the second one, and the temperature of the scattering electron has a trend of anti-correlation with the optical depth. The center energy of the Fe line is almost around 6.5 keV. For each observation, the fluxes of the Fe line are approximately constant across the pulse phases. The spectra from the phases of the lowest intensity (one for February 10, two for March 27, and two for April 30) present the obvious Fe feature.

An example from phase 2 of the data of April 30 is shown in Figure 5.

3.4. Spectral Ratios

The detailed phase-to-phase variation is best illustrated by the ratios of the phase-resolved spectra to the spectrum of the phase with minimum count rate (Leahy & Matsuoka 1990). We show the phase-resolved spectral ratios of the three observations. The minimum count rate spectra are from phase 1 of the February 10 observation and phase 2 for the March 27 and April 30 observations. The phase ratios are then presented separately in Figures 6–8. There are dips in the pulse-height channel ratios (PHA) plots at ~6.5 keV (as marked by the ar-
row in the first panel of Figure 6). The dip is due to the flux of the Fe emission line that only occurs in the non-pulse component; this is consistent with the results of the phase-resolved spectra.

For phase 2 of the February 10 observation, at the beginning of the main pulse, the ratios increase with energy. The ratio increases rapidly with energy at phase 3 where the main pulse is peaking, but slowly at the phases (4 and 5) beyond. This is the case as well at the end of the main pulse (phase 6) until the energy is around 10 keV, beyond which the ratio remains almost constant. Such a trend holds more or less in phases 7 and 8, corresponding to the second pulse, but with a turnover of the ratio at energies larger than 10 keV. For the March 27 observation, the properties of the PHA ratios are similar to those for the February 10 observation. For the April 30 observation, phases 3–5 correspond to the main pulse peak. The PHA ratios of these phases increase with energy, but are constant above 10 keV. Phases 1 and 6–8 are around the second pulse, and their
PHA ratios increase at low energy (<10 keV) and decrease at 10–20 keV. The overall spectral ratio of the April 30 observation is different from those of February 10 and March 27.

The PHA ratios of the phase-resolved increase to the phase with minimum count rate with energy, illuminating that the spectra of the pulsed emission are generally harder. The stronger the flux of the pulsed emission, the harder the spectrum. At phases around the second pulse, the spectrum decreases abruptly at higher energies.

4. DISCUSSION

The X-ray radiation modes of a Be/X-ray binary pulsar are generally thought to have a tight relationship with the luminosity (Parmar et al. 1989). At high luminosity ($\gtrsim 10^{37}$ erg s$^{-1}$), the accretion flow onto the magnetic pole can be decelerated via the radiative shock formed near the neutron star surface (Wang & Frank 1981). The emitting plasma will be compressed under the shocked region, where the photons can only escape from the sides of the column (fan-beam mode). Under some circumstances, a pencil beam may still emerge (Nagel 1981). At lower luminosity ($\lesssim 10^{37}$ erg s$^{-1}$), the infalling material may be decelerated in a collisionless shock above the neutron star surface (Basko & Sunyaev 1975; Kirk & Galloway 1981). In such a case, either a thin emitting region or the effects of the strong magnetic field can cause the formation of a pencil beam of emission (e.g., Mészáros et al. 1983). Various models could be verified by the observational properties of X-ray pulsars.

We have analyzed the phase-resolved spectra of 4U 1901+03 and found that the optical depth and the temperature of the scattering electron are related to the pulse phases, which are common features of X-ray pulse binaries (e.g., La Barbera et al. 2003). Spectral ratios indicate that the main pulse peak has the hardest spectrum, which is the common property of accreting pulsars (Hickox & Vrtilek 2005; Tsygankov et al. 2007). Our results show that at the beginning of the outburst (February 10), where the luminosity $\gtrsim 10^{37}$ erg s$^{-1}$, the emission of the main pulse has the possible origins of a fan beam. The main pulse has a large optical depth, which could be due to the fact that, during the main peak, the angle between the column axis and the observer’s line of sight has the highest value so that the observer is looking almost along the beam (Klochkov et al. 2008). During the decay of the outburst, our results are consistent with the emission configuration of the main peak from the fan beam and the second peak from the pencil beam (Chen et al. 2008). The main peak that has the hard spectrum is due to the fact that high energy photons are more likely to escape in a fan beam from a hot region close to the footstep and perpendicular to the accretion column (Basko & Sunyaev 1976; White et al. 1983; Klochkov et al. 2008). This is consistent with the low optical depth and high temperature of the scattering electron of the main peak.

The second peak is produced by low-energy photons escaping in a pencil beam along the direction of the accretion column where the optical depth is larger and the electron temperature is lower. These results are in accordance with those of Chen et al. (2008) who analyzed energy-resolved pulse profiles in detail. They concluded that the fan beam contributes to the main pulse peak and the pencil beam to the second pulse peak. In addition, in some energy bands, the flux varies by almost a factor of 2 between different pulse phases (Chen et al. 2008), which could be due to the fact that both of the angles of the spin-axis from the viewing direction and between the magnetic pole and the spin-axis are substantial. Therefore, it is likely that emission from both magnetic poles contributes to the pulse profile.

We note that the evolution of the hard color is similar to that of the pulse fraction (see Chen et al. 2008), and spectral ratios show that the spectra of the pulsed emission are harder than those of the non-pulsed under larger pulsed fluxes. This indicates that the high-energy photons contribute mostly to the pulsed emission, which is consistent with the evolution of the pulse fraction shown in Figure 4 of Chen et al. (2008). Perhaps
the lower energy radiation is dominated by photons from the accretion column walls that hit the neutron star surface and are reprocessed, which would lead to a lower pulse fraction.

Fe Kα emission line with equivalent widths of several hundred eV is usually detected in an X-ray pulsar, and may be caused by the illumination of neutral or partially ionized material in the accretion disk, the stellar wind of the high-mass companion, or material in the line of sight or in the accretion column (Pravdo et al. 1977; Basko 1980; Nagase 1985; Paul et al. 2002; Naik et al. 2005). Our results show that prominent Fe emission with equivalent width ∼100 eV is detected in the spectra of 4U 1901+03. The flux of the Fe emission line increases with the X-ray luminosity throughout the outburst (Figure 1 and Table 1), is proportional to that of the continuum intensity, and increases with increasing accretion rate (Suchy et al. 2008). For each observation, Fe line is detected in the spectra of 4U 1901+03. The flux of the Fe emission line originates from the accretion column of the magnetic polar cap. Furthermore, the spectral fit of the phase-resolved spectrum shows that the center energy of Fe neither changes among the pulse phases nor evolves along the outburst of 4U 1901+03. We therefore believe that, during the outburst of 4U 1901+03, Fe emissions come from a region in the accretion disk but not the surface of the neutron star.

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