EVOLUTION OF THE X-RAY PROFILE OF THE CRAB PULSAR

M. Y. Ge\(^1\), L. L. Yan\(^1\), F. J. Lu\(^1\), S. J. Zheng\(^1\), J. P. Yuan\(^2\), H. Tong\(^2\), S. N. Zhang\(^1\), and Y. Lu\(^1\)

\(^1\) Key Laboratory for Particle Astrophysics, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China; gemy@mail.ihep.ac.cn
\(^2\) Xinjiang Astronomical Observatory, Chinese Academy of Sciences, Urumqi, Xinjiang 830011, China

Received 2015 June 28; accepted 2015 December 24; published 2016 February 8

ABSTRACT

Using the archival data from the Rossi X-ray Timing Explorer, we study the evolution of the Crab pulsar’s X-ray profile in a time span of 11 years. The X-ray profiles, as characterized by a few parameters, changed slightly, but with high statistical significance in these years: the separation of the two peaks increased with a rate of \(0^\circ.088 \pm 0^\circ.020\) per century, the flux ratio of the second pulse to the first pulse decreased by \((3.64 \pm 0.86) \times 10^{-2}\) per century, and the pulse widths of the two pulses represented by their full widths at half maxima decreased by \(1^\circ.44 \pm 0^\circ.15\) and \(1^\circ.09 \pm 0^\circ.73\) per century, respectively. The evolutionary trends of the X-ray profile are similar to that observed in radio, but with quantitative differences. Finally, we briefly discuss the constraints of these X-ray properties on the geometry of the emission region of this pulsar.

Key words: pulsars: individual (PSR B0531+21) – stars: neutron – X-rays: stars

1. INTRODUCTION

The Crab pulsar is one of the most widely studied celestial objects. It was born in 1054, has a spin period of 33 ms, and is bright over the full electromagnetic spectrum from radio to high energy γ-rays. At all wavelengths, this pulsar shows a double-pulse structure, with the main pulse (MP) and the interpulse (IP) separated by a phase of \(\sim 0.4\), and the exact pulse morphology varies as a function of photon energy (Eikenberry & Fazio 1997; Rots et al. 1998; Kuiper et al. 2001; Molkov et al. 2010; Ge et al. 2012). Compared to the radio profile, the X-ray profile has broader pulses and bridge emission that is missing in the radio band (Eikenberry & Fazio 1997; Massaro et al. 2006). The two X-ray pulses are called P1 and P2 (Kuiper et al. 2001), which correspond to the MP and IP in radio (Lyne et al. 2013), although the X-ray P1 and the radio MP are not exactly aligned, and the X-ray phase lag also varies with energy with a maximum of \(-0.01\) at 5–9 keV (Rots et al. 2004; Molkov et al. 2010; Ge et al. 2012).

In comparison with the phase-resolved spectrum, the long-term change of the pulse profile of the Crab pulsar is relatively less studied, but it is equally important. The pulse profile is related to the shape of the emission beams that are determined by the magnetic field structure (Gold 1968). The long-term change of the pulse profile thus reflects the evolution of the pulsar’s magnetosphere or its projected geometry along the line of sight. Given the fact that the rotation powered pulsars are very stable and produce data with high statistics, frequent and long time span coverage is needed in order to reveal the very small profile evolution. The Crab pulsar is the best source for this kind of study because it is bright at multi-wavelengths, and, as a calibration source for essentially all instruments involved, it is observed very frequently. Previous studies suggested that the separation of the X-ray P2 and P1 increased with a rate of \(0^\circ.71 \pm 0^\circ.24\) per century (Ge et al. 2012). Significant radio profile evolution was discovered by Lyne et al. (2013) with the high precision daily observations at Jodrell Banks Observatory. The separation of the two radio pulses showed a steady increase with \(0^\circ.62 \pm 0^\circ.03\) per century in the past 22 years (Lyne et al. 2013), while the relative integrated flux densities of the two pulses decreased with \(-0.172 \pm 0.008\) per century. Since the evolution of the pulse separation in the X-ray band and radio band are similar, though the former was only marginally detected, the possible X-ray profile evolution may be due to the same mechanism. Progressive change of the magnetic inclination was used to explain the radio results (Lyne et al. 2013; Arzamasskiy et al. 2015; Zanazzi & Lai 2015), which could also explain the X-ray properties.

A study of the X-ray profile evolution can add more constraints to pulsar physics. In pulsar emission models, the radio emission region of a pulsar is thought to be located over the two magnetic poles, while the high energy emission comes from two high-altitude gaps that are close to the light cylinder in the magnetosphere (Cheng et al. 1986a, 1986b; Sturmer & Dermer 1994; Daugherty & Harding 1996). If the magnetic inclination changes, the X-ray profile should exhibit simultaneous variation with the radio profile. However, the changing rates at the two wavelengths might not be the same because of the different projection effects along the line of sight. The evolution of the X-ray and radio profiles of the Crab pulsar, therefore, presents the three-dimensional information of the magnetosphere structure with different viewing angles.

A time related evolution of the pulsar X-ray profile has not yet been firmly detected, though several studies have been carried out. Patt et al. (1999) reported that the flux densities of Crab’s two pulses are steady at the level of 7% with one hour data from the Rossi X-ray Timing Explorer (RXTE). Rots et al. (2004) and Chetana & Biswajit (2011) also studied the X-ray profile evolution by fitting the profiles and comparing the fitted parameters, and no evolution was found. As mentioned previously, Ge et al. (2012) found that the separation of the X-ray P1 and P2 increased at the 3σ level, which is the only evidence for X-ray profile evolution so far. In this paper, we study the X-ray profile evolution of the Crab pulsar in detail, by analyzing its pulse shape and shape parameters such as pulse separation, pulse flux ratio, and pulse widths, using all of the available archival data from RXTE. In order to make sure that the obtained profile evolution is genuine, we also investigate the variation of the observed profile induced by the instrumental aging effect.
2. OBSERVATIONS AND DATA REDUCTION

The RXTE data analyzed in this study were obtained by both the Proportional Counter Array (PCA) and the High Energy X-ray Timing Experiment (HEXTE). The total exposure time of these observations is about 230 ks for PCA and 237 ks for HEXTE, as listed in Table 1. The data reduction is done using flools from the High Energy Astrophysics Software (HEASoft, version v6.15).

### 2.1. PCA Data Reduction

PCA is composed of five Proportional Counter Units (PCUs, named PCU0, PCU1, PCU2, PCU3, PCU4), which have an effective energy coverage of 2–60 keV, a total collection area of 6500 cm², and the best ever time resolution of up to 1 μs (in Good Xenon mode; Jahoda et al. 2006). However, the data of PCU1 have not been used in this study because of its propane loss around 2006 December 25 (Garcia et al. 2014), which resulted in a big change of the effective area response and such a change could distort the evolution of the pulse profile that varies with energy. Observations with the data mode E_250us_128M_0_1s (E_250us; Table 1, MJD 51956–55927) are selected for the final analysis, because most of the observations were done in this data mode. The time resolution of E_250us data is about 250 μs with all absolute channels, which are merged to 128 relative channels. Compared to the data set used in Ge et al. (2012), about three more years of data are added in this analysis, including ObsIDs P95802, P96382, and P96802, as listed in Table 1.

To get the pulse profile from an observation, we first select the good events and then fold them by using the flools command FASEBIN and FBSSUM. The procedure for event selection is described as follows: (1) create the filter file for this observation with XTEFILT; (2) generate the Good Time Interval (GTI) file by MAKETIME using the filter file; (3) use the GTI file to create the “good” events file with GROSSTIMEFILT; (4) remove the clock events and select the events of the four PCUs, from the event mode data by SFIT and FSELECT. This procedure is the same as in Ge et al. (2012). From the prepared data, the phase-resolved spectrum is first created by FASEBIN of flools with 1000 bins and the JPL ephemeris DE-200 (Standish 1990). This spectrum contains the information of photon count numbers in each energy channel within the corresponding phase bin. As there are precise radio ephemerides (including periods and phases) for the Crab pulsar from Jodrell Bank (Lyne et al. 1993), they are used in the process to produce the phase-resolved spectrum. The pulse profile of each observation is obtained from the phase-resolved spectrum by FBSSUM, which sums up the photon count numbers in all of the energy channels.

The integrated profile in a period is obtained by adding all of the individual profiles from the observations included. Phase 0 of a profile is obtained by a cross-correlation analysis between this profile and the reference one. When we produce the total profile from all of the observations over the 11 years, the reference profile is the one generated from the first observation. However, when we produce the integrated profile in a time period, the total profile is used as the reference one.

### 2.2. HEXTE Data Reduction

The HEXTE instrument consists of two independent detector clusters A and B, each containing four Na(TI)/Cs(t)Na scintillation detectors (Rothchild & Blanco 1998). The HEXTE detectors are mechanically collimated to a 1° field of view and cover the 15–250 keV energy range with a detection area of 1400 cm². In its default operation mode, when one cluster points to the target, the other one is off from the source.

---

Table 1

| Obs ID   | Start Date | End Date | Offset(′) | PCA Exposure (s) | HEXTE Exposure (s) |
|----------|------------|----------|-----------|------------------|--------------------|
| 40093    | 1999 Mar 08| 1999 Mar 22| 0.03      | ...              | 13724              |
| 50098    | 2000 Jul 17| 2000 Jul 21| 0.03      | ...              | 5474               |
| 50099    | 2001 Aug 27| 2001 Aug 27| 0.03      | 7504             | 15466              |
| 60079    | 2002 Oct 22| 2002 Oct 22| 0.03      | 20240            | 18632              |
| 60080    | 2001 Jul 18| 2001 Jul 20| 0.03      | 3776             | 3701               |
| 60420    | 2001 Sep 07| 2001 Sep 09| 0.03      | 1824             | 1718               |
| 70018    | 2002 May 09| 2003 May 14| 0.03      | 9616             | 7024               |
| 70802    | 2002 Feb 26| 2003 Feb 26| 0.03      | 7888             | 7263               |
| 80802    | 2003 Feb 15| 2004 Feb 15| 0.03      | 17552            | 17221              |
| 90129    | 2004 Nov 15| 2004 Nov 18| 0.03      | ...              | 5946               |
| 90802    | 2004 Feb 29| 2005 Feb 25| 0.03      | 18032            | 16086              |
| 91802    | 2005 Mar 13| 2006 Feb 10| 0.03      | 17088            | 13971              |
| 92018    | 2006 May 10| 2006 Dec 21| 0.03      | ...              | 9774               |
| 92802    | 2006 Mar 11| 2006 Sep 24| 0.03      | 23536            | 25704              |
| 93802    | 2007 Jul 17| 2008 Dec 17| 0.03      | 28768            | 30164              |
| 94802    | 2008 Dec 31| 2009 Nov 07| 0.03      | 16768            | 13922              |
| 95802    | 2010 Jan 03| 2010 Dec 08| 0.03      | 29028            | 162291             |
| 96382    | 2011 Oct 17| 2011 Dec 11| 0.03      | 8211             |                    |
| 96802    | 2011 Dec 17| 2012 Jan 01| 0.03      | 19920            | 153011             |

Total Exposure(s) 229751 237321

Note.

Only cluster A data of HEXTE were used in our analyses.

---

http://heasarc.gsfc.nasa.gov/docs/xte/pca_history.html

http://www.jb.man.ac.uk/pulsar/crab.html
to provide instantaneous background measurements. Because of the co-alignment of the HEXT and the PCA, the two instruments observe the same target simultaneously. In this analysis, data from both Cluster A and B are used before 2009 December 14, and after that only Cluster A data are available because cluster B ceased modulation and started off-source position thereafter. 7

The data mode selected for the pulse profile study is E_8us_256_DX0F with a time resolution of 8 μs. The standard data reduction is performed and the data were extracted from clusters A and B separately. Pulse profiles are obtained using FASEBIN and FBSSUM of ftools, with the same timing parameters and procedure as done for the PCA profiles.

3. EVOLUTION OF THE X-RAY PROFILE

In this section, the evolution of the X-ray profile is studied in two ways, using the profile ratio curve and the profile parameters respectively. The profile ratio is the ratio between two normalized profiles in different epochs, which can exhibit the profile variation directly if the profile changes with time. On the other hand, in order to investigate the profile evolution in a more quantitative way, we use four parameters to characterize the X-ray profiles in different epochs.

3.1. Profile Ratio from PCA

If the X-ray profile of the Crab pulsar shows detectable secular changes, the ratio between the normalized profiles in different epochs should deviate from a uniform distribution. The total profiles obtained from the 11-year observations of PCA and HEXT are shown in Figure 1, in which the PCA profile shows a much higher statistics than the HEXT one. Therefore, two groups of profiles obtained from PCA data in time ranges of MJD 51955(2001 February 15)–52500/2002 August 14) and MJD 55254(2010 February 27)–55927(2012 January 01), are created, and then merged into two integrated profiles to produce the ratio as a function of its pulse phase. In order to eliminate the effect of the different background levels in these two ranges, the two integrated profiles are re-generated as follows: (1) subtract the background level that is determined by the mean flux per bin in phase 0.63–0.83 as Ge et al. (2012); (2) normalize the pulse profile to make the integrated flux, which is the sum of the flux per bin times the phase bin size; (3) add 9.0 to the value in each bin, because the total background count rate is about nine times as high as the count rate of the pulses; and (4) normalize the pulse profile again. After these steps, the two profiles (Profile1 and Profile2) are used to produced the ratio as shown in Figure 2(b).

As can be seen clearly in Figure 2(b), the distribution of the ratio is not uniform, with the χ^2 of 63.2 for 17 points. The ratio at P1 (phase: ~0.02 to 0.02) is higher than 1.0 with a mean of 1.0016, and lower than 1.0 with a mean of 0.9994 at the bridge (0.14–0.25, as defined in Kuiper et al. 2001). Compared to P1, P2 shows different behaviors that the ratio is around 1.0 at the leading edge (phase: 0.35–0.40) and is higher than 1.0 at the trailing edge (phase: 0.40–0.439). The deviation of the ratio from a uniform distribution implies that the X-ray profile evolved with time: after a few years, P1 becomes sharper and the distance between P1 and P2 had increases slightly.

3.2. Parameterization of the X-Ray Profile

Since the X-ray profile of the Crab pulsar has a typical double-peak structure, we used four parameters, including separation (Φ), flux ratio (R_f), and widths (W_1 and W_2) of P1 and P2, to quantify the X-ray profile. Φ is the relative phase distance between the two maxima of the pulses. W_1 and W_2 are defined as the full widths at half maxima (FWHM) of P1 and P2 after subtracting the pulse background (phase 0.63–0.83). R_f is the ratio between the integrated fluxes of P1 (~0.034 to 0.007) and P2 (0.344–0.426), i.e., the integrated flux within the FWHM of the two pulses.
The fluxes of P1 and P2 (as well as their errors) could be obtained directly, but more calculations are needed for \( \Phi, W_1, \) and \( W_2 \) to have accuracies finer than the bin size. To obtain the accurate peak position and the width of a pulse, we fit it using the empirical formula proposed by Nelson et al. (1970):

\[
L(\phi - \phi_0) = N \left( 1 + a(\phi - \phi_0) + b(\phi - \phi_0)^2 \right)
\times e^{-\int_0^l (\phi - \phi_0)^2} + I,
\]

where \( L \) is the intensity at phase \( \phi \), \( l \) is the baseline of the pulse profile, \( \phi_0 \) is the phase shift, \( N \) is the pulse height of the profile, and \( a, b, c, d, f \) are the shape coefficients. In the fitting, P1 is chosen in the phase range of \(-0.075\) to \(0.0355\) and P2 in \(0.305\)–\(0.465\).

The peak separation \( \Phi \) is calculated with the following steps similar to Ge et al. (2012): (1) fit the two pulses of the total profile with Nelson’s formula and obtain their shape coefficients \( a, b, c, d, f \) as well as \( N, l, \) and \( \phi_0 \), which are listed in Table 2; (2) for the integrated profile in a time period from which we want to get \( \Phi \), fit its two pulses using the Nelson formula with \( N, \phi_0, \) and \( I \) free and the other shape coefficients fixed to the values in Table 2; (3) use the positions of the two maxima of the fitted profiles to get their separation. \( W_1 \) and \( W_2 \) are obtained in a similar way. We fit the observed profile with Nelson’s formula with all of the coefficients free, and then the FWHMs of the fitted profiles are taken as the widths of P1 and P2.

We estimate the errors of \( \Phi, W_1, \) and \( W_2 \) with a Monte-Carlo method. 100 simulated profiles are created by sampling from the original profile under the assumption that the photon counts in every phase bin follow Poisson distribution. Then these simulated profiles are fitted with Nelson’s formula and 100 groups of \( \Phi, W_1, \) and \( W_2 \) values are obtained. The distribution widths of these values represent their statistical errors, and the 1σ width of the Gaussian function, fit to the distribution of a parameter, is taken as its 1σ error.

### 3.3. Profile Evolution with Time

To study the evolution of \( \Phi, R_f, W_1, \) and \( W_2 \), we divide the PCA observations into six groups with roughly equal time spans of about 660 days. In each group, an integrated profile is produced and a set of \( \Phi, R_f, W_1, \) and \( W_2 \) are derived, so we have six data points for every parameter from the PCA observations. Because the source photons collected by HEXTE are much less than that by PCA, two profiles and thus two sets of data points from HEXTE data are obtained in time ranges of MJD 51302 (1999 March 08)–54789 (2008 November 19) and MJD 52570 (2002 October 23)–55927 (2012 January 01), respectively.

Figure 3 displays \( \Phi, R_f, W_1, \) and \( W_2 \) of the Crab pulsar measured from PCA and HEXTE. The parameters of the PCA profiles show large differences from the HEXTE ones, because the X-ray profile varies with energy (Mineo et al. 1997; Massaro et al. 2006). However, the variation trends of the parameters from these two instruments are similar. The peak separation \( \Phi \) increases with time and the other parameters decrease with time.

#### 3.3.1. Profile Evolution Results from the PCA Data

First, we only choose the PCA data to study the profile evolution using the four parameters defined above. The values of these parameters in different epochs are fitted with linear functions to derive their changing rates. As listed in Table 3, the evolutions of \( R_f \) and \( W_1 \) are detected with a high significance: the changing rate of \( R_f \) is \(-3.52 \pm 0.64 \times 10^{-2} \) per century, and that of \( W_1 \) is \(1.745 \pm 0.19\) per century. The evolutions of \( \Phi \) and \( W_2 \) are less significant, with \(0.89 \pm 0.26\) and \(-1.09 \pm 0.95\) per century, respectively. The changing rate of the peak separation is consistent with the result from (Ge et al. 2012) within 1σ, and the new result has a slightly higher significance. These quantitative results for the peak separation and flux ratio are consistent with the qualitative results deduced from the profile ratio.

The flux ratio of the two pulses should be different if the fluxes are integrated in different phase ranges. In order to get more information of the profile evolution, two more flux ratios are calculated with different phase ranges as shown in Figure 1. \( R_{f1} \) represents the integrated flux ratio of P1 (\(-0.06\) to \(0.04\))

### Table 2

|               | \( a \)  | \( b \)  | \( c \)  | \( d \)  | \( f \)  | \( \chi^2_{\nu} \) | dof |
|---------------|---------|---------|---------|---------|---------|----------------|-----|
| PCA P1        | -30.79  | 1550.04 | -55.03  | 4521.40 | 568.32  | 2.0           | 92  |
| PCA P2        | -29.84  | 372.30  | -42.00  | 1265.97 | 138.09  | 2.4           | 128 |
| HEXT P1       | -34.26  | 2351.16 | -49.04  | 5971.22 | 667.86  | 2.0           | 92  |
| HEXT P2       | -26.94  | 209.19  | -45.95  | 887.59  | 131.46  | 1.7           | 128 |

Figure 3. Profile parameters of the Crab pulsar from PCA (squares) and HEXTE (triangles) observations. Panels a–d show the peak separation (\( \Phi \)), flux ratio \( R_f \), and widths \( W_1 \) and \( W_2 \) of P1 and P2, respectively. The data points of \( R_f, W_1, \) and \( W_2 \) from HEXTE data are shifted vertically by \(-0.273, -0.0014, \) and \(-0.002, \) respectively.
and P2 (0.32–0.43) (as defined in Kuiper et al. 2001). The mean value of $R_f^1$ is 0.936(5), which is consistent with the result of Kuiper et al. (2001). $R_f^1$ is the peak flux ratio of P1 and P2, which has a mean value of 0.619(1). As shown in Figure 4, the changing rates of $R_f^1$ and $R_f^3$ are $(-0.1 \pm 0.8) \times 10^{-2}$ per century and $(-2.8 \pm 1.5) \times 10^{-2}$ per century, respectively. Apparently, no evolution is detected for $R_f^3$, while the changing rate of $R_f^1$ is close to $R_f^1$ but with a much lower significance. In any case, the changing rates of these two flux ratios are also significantly smaller than that observed in radio.

### 3.3.2. Joint Study of the Profile Evolution with PCA and HEXTE

Figure 3 shows that the parameters inferred from the HEXTE data, which show an evolution similar to the PCA results, even though the parameters from two kinds of instruments have different mean values. With the assumption that the secular changes of the profile measured by PCA and HEXTE follow the same trends, the PCA and HEXTE parameters are shifted to around zero so that the $\chi^2$ of the linear fitting, which is defined by Equation (2), reaches the minimum.

$$\chi^2 = \frac{1}{N-3} \sum_{ij} \left( \frac{k(t_{ij} - t_0) + b_i - \Phi_{ij}}{\sigma_y} \right)^2$$

where $N$ is the number of points, $k$ is the changing rate, $i$ is 0 or 1 to represent the data from PCA or HEXTE, $j$ denotes the data points from each instrument, $\Phi_{ij}$ is the peak separation, and $\sigma_y$ is the error of the peak separation obtained with the Monte Carlo method described in Section 3.1. The intercept $b_i$ corresponds to the values at $t_0 = 54,000$ in MJD format. The best estimation for $b_i$ is obtained when $\chi^2$ reaches the minimum. Then, the corrected peak separation $\Phi'$ is obtained with $b_0 = 0.40028$ and $b_1 = 0.39994$ subtracted. As presented in Figure 5, $\Phi'$ increases linearly with time. $R_f$, $W_1$, and $W_2$ are processed with the same method, and the shifted intercepts for all of these parameters are listed in Table 4.

![Figure 4. Pulse flux ratios of the Crab pulsar calculated in different phase ranges for PCA. The square points represent the ratios of the fluxes integrated in the FWHM of the two pulses ($R_f$, shifted by $-0.292$), the cross points represent the ratios of the fluxes integrated in $-0.06$ to $0.04$ (for P1) and $0.32$ to $0.43$ (for P2) ($R_f^i$), and the triangle points represent the ratios of the fluxes at the two peaks ($R_f^3$, shifted by $0.312$). The dashed, dotted--dashed, and solid thick lines are the fitted results for $R_f$, $R_f^i$, and $R_f^3$, respectively. The thin lines and points represent the effect of the instrument aging on the above parameters as described in Section 4.1. The phase ranges for the flux ratio calculation are shown in Figure 1.](image)

Table 3

| Instrument | $\Phi$ (°/century) | $R_f^1$ ($10^{-2}$) | $W_1$ (°/century) | $W_2$ (°/century) |
|------------|-------------------|---------------------|------------------|------------------|
| PCA        | 0.89 ± 0.26       | $-3.52 \pm 0.64$    | $-1.45 \pm 0.19$ | $-1.09 \pm 0.95$ |
| All$^a$    | 0.88 ± 0.20       | $-3.54 \pm 0.86$    | $-1.44 \pm 0.15$ | $-1.09 \pm 0.73$ |
| Resp$^b$   | $-0.004 \pm 0.001$| 0.56 ± 0.01         | $0.026 \pm 0.001$| $-0.046 \pm 0.001$|
| Radio$^c$  | 0.62 ± 0.03       | $-17.2 \pm 0.8$     | ...              | ...              |

Notes.

$^a$ The changing rates of the parameters from the joint PCA and HEXTE data.

$^b$ The changing rates of the parameters from the faded profiles that represent the aging effect of PCA.

$^c$ The radio results by Lyne et al. (2013).

$W_2$ decrease with slopes of $1°.44 \pm 0°.15$ and $1°.09 \pm 0°.73$ per century, respectively.

### 4. DISCUSSION

In this section, we first study whether the observed profile evolution is due to the aging of the instruments, and then discuss the possible constraints of our results on the geometry of the pulsar’s magnetosphere.

#### 4.1. Profile Changes Induced by the Aging of PCA

Previous studies have shown that the X-ray profile of the Crab pulsar varies with photon energy (Eikenberry & Fazio 1997; Rots et al. 1998; Massaro et al. 2000; Willingale 2001; Molkov et al. 2010; Ge et al. 2012), which can also be described quantitatively by the phase-resolved spectrum, as studied in detail by Ge et al. (2012) using the PCA observations (from 2001 February 15 to 2009 November 07). Because the X-ray profiles we studied in this paper are integrated over the entire energy bands of the instruments, if the effective area of the instrument at different energies had gradual changes in the ~11 years of operation (Garcia...
et al. 2014), it could also result in artificial changes of the X-ray profiles. In order to study the influence of the instrument aging on the observed profile evolution, we use the phase-resolved spectrum \( F(\phi, E) \) measured from PCA (Ge et al. 2012) as input and convolve it with the effective area curves of these four PCUs in different epochs to fake the profiles from which the shape parameters in those epochs can be further derived. Comparison of the shape parameters of the faked profiles and those of the observed ones can verify whether the profile evolution we found is intrinsic or not. The detailed process and results are given below.

The input profile \( F(\phi, E) \) can be expressed as

\[
F(\phi, E) = \beta(\phi)(E/E_0)^{-\alpha(\phi)}\exp[-N_H\sigma(E)],
\]

where the normalized flux \( \beta(\phi) \) and photon index \( \alpha(\phi) \) are inferred from Ge et al. (2012), \( E \) is the photon energy in units of keV and \( E_0 = 1 \) keV, the absorption column density \( N_H \) is \( 0.36 \times 10^{22} \) cm\(^{-2}\) (Ge et al. 2012), and \( \sigma(E) \) is the photo-electric cross-section (Morrison & McCammon 1983). Since the phase bin sizes in Table 5 of Ge et al. (2012) are not fine enough to get a smooth pulsed profile, the normalized fluxes are fitted with two combined Nelson formula (Nelson et al. 1970), which are mainly used to fit the two pulses and four Gaussian functions mainly for the bridge region; finally, the flux in each phase bin is obtained from the interpolation of the fitted functions. Similarly, the photon indices of the pulsed emission in (Ge et al. 2012) are first smoothed with a Gaussian function with 1-sigma width of 0.01, and the smoothed photon indices are further fitted with an 18 order polynomial to get the photon index for the phase bin used in this paper. Because there were only observed photon indices available in the phase range greater than \(-0.135\) and smaller than \(0.545\) (Ge et al. 2012), the polynomial function cannot be constrained outside of this phase range. Therefore, the photon indices (of the pulsed emission) for bins with phases smaller than \(-0.135\) are fixed as 1.72, the value at \(-0.135\); for bins with phases greater than \(0.545\), the photon indices are fixed as 2.17. The pulse profile \( F_p(\phi) \), which is the phase-resolved spectra (of the pulsar plus nebula) convolved with the response matrix, is obtained as follows.

\[
F_p(\phi) = \sum_{E_i} F(\phi, E)RSP(E, i)\Delta E,
\]

where \( RSP(E, i) \) is the average response matrix of the four PCUs, and \( \Delta E \) the input energy width at energy \( E \).

The dead time of the instrument could also change the pulse profile because the photon fluxes at different phases are not the same. We therefore calculated the dead time correction DCOR using the formulae

\[
DCOR = \frac{T}{T - DTF},
\]

and

\[
DTF = C \times T \times dt,
\]

where \( T \) is the length for one phase bin, \( C \) is the photon flux of both the pulsar (Ge et al. 2012) and the nebula (Garcia et al. 2014), and \( dt \) is the time for RXTE/PCA to process the information of one event (Jahoda et al. 2006), which is also called the dead time. \( T \) is 33.6 \( \mu s \) because the profile is divided into 1000 phase bins in the calculation. The background events are also considered when we calculated DTF.\(^6\) The response profile is divided by DCOR when we produce the “final” faked profiles.

Similar to what we did previously, using the faked profiles, we can obtain the ratio and parameter changes induced by the instrument aging. The dashed line in the lower panel of Figure 2(b) represents the ratio of the faked profiles in MJD 51956–52500 (Profile3) and MJD 55254–55927 (Profile4). It is very different from the observed one and has a much smaller amplitude. The variations of \( \Phi_1, R_1, W_1 \), and \( W_2 \) induced by the aging of PCA are presented in Figure 6, while the linear fitting results are listed in Table 3. It can be found that the changing rates are about one to two orders of magnitude lower than the observed ones. We also checked the effect of instrument aging on \( R_2 \) and \( R_3 \). The changing rates of \( R_2 \) and \( R_3 \) resulted from instrument aging are \((0.29 \pm 0.01) \times 10^{-2}\) and \((0.45 \pm 0.01) \times 10^{-2}\) per century, which are opposite of the observed ones. Therefore, the contribution of the instrument aging to the observed pulse profile evolution is negligible.

4.2. Constraints on the Geometry of the Magnetosphere

The X-ray profile of the Crab pulsar shows secular changes: the peak separation of the profiles increases while the flux ratio and widths of the two pulses decreases with time. The evolutionary trends of the X-ray profile are similar to that observed in radio, which means that the magnetosphere evolution has a similar effect on emission regions of the X-ray and radio pulses.

For a simple magnetic dipole, the evolution of the magnetosphere axis is expected toward alignment rather than orthogonality (Lyne et al. 2013; Philippov & Spitkovsky 2014; Arzamasskiy et al. 2015). However, the secular increases of \(\beta(\phi) \) are 2.17, the value at \(-0.135\); for bins with phases greater than \(0.545\), the photon indices are fixed as 2.17. The pulse profile \( F_p(\phi) \), which is the phase-resolved spectra (of the pulsar plus nebula) convolved with the response matrix, is obtained as follows.

\[
F_p(\phi) = \sum_{E_i} F(\phi, E)RSP(E, i)\Delta E,
\]

where \( RSP(E, i) \) is the average response matrix of the four PCUs, and \( \Delta E \) the input energy width at energy \( E \).

The dead time of the instrument could also change the pulse profile because the photon fluxes at different phases are not the same. We therefore calculated the dead time correction DCOR using the formulae

\[
DCOR = \frac{T}{T - DTF},
\]

and

\[
DTF = C \times T \times dt,
\]

where \( T \) is the length for one phase bin, \( C \) is the photon flux of both the pulsar (Ge et al. 2012) and the nebula (Garcia et al. 2014), and \( dt \) is the time for RXTE/PCA to process the information of one event (Jahoda et al. 2006), which is also called the dead time. \( T \) is 33.6 \( \mu s \) because the profile is divided into 1000 phase bins in the calculation. The background events are also considered when we calculated DTF.\(^6\) The response profile is divided by DCOR when we produce the “final” faked profiles.

Similar to what we did previously, using the faked profiles, we can obtain the ratio and parameter changes induced by the instrument aging. The dashed line in the lower panel of Figure 2(b) represents the ratio of the faked profiles in MJD 51956–52500 (Profile3) and MJD 55254–55927 (Profile4). It is very different from the observed one and has a much smaller amplitude. The variations of \( \Phi_1, R_1, W_1 \), and \( W_2 \) induced by the aging of PCA are presented in Figure 6, while the linear fitting results are listed in Table 3. It can be found that the changing rates are about one to two orders of magnitude lower than the observed ones. We also checked the effect of instrument aging on \( R_2 \) and \( R_3 \). The changing rates of \( R_2 \) and \( R_3 \) resulted from instrument aging are \((0.29 \pm 0.01) \times 10^{-2}\) and \((0.45 \pm 0.01) \times 10^{-2}\) per century, which are opposite of the observed ones. Therefore, the contribution of the instrument aging to the observed pulse profile evolution is negligible.

4.2. Constraints on the Geometry of the Magnetosphere

The X-ray profile of the Crab pulsar shows secular changes: the peak separation of the profiles increases while the flux ratio and widths of the two pulses decreases with time. The evolutionary trends of the X-ray profile are similar to that observed in radio, which means that the magnetosphere evolution has a similar effect on emission regions of the X-ray and radio pulses.

For a simple magnetic dipole, the evolution of the magnetosphere axis is expected toward alignment rather than orthogonality (Lyne et al. 2013; Philippov & Spitkovsky 2014; Arzamasskiy et al. 2015). However, the secular increases of

\(^6\) http://heasarc.gsfc.nasa.gov/docs/xte/recipes/pca_deadtime.html
the peak separations in the radio and X-ray bands are inconsistent with this expectation. Lyne et al. (2013) explained the evolution with a geometrical model, showing that the inclination of the magnetic axis increases with time as the torque develops through the return current in the neutron star surface (Beskin & Nokhrina 2007). Based on the magnetohydrodynamic simulations, Philippov & Spitkovsky (2014) and Arzamasskiy et al. (2015) pointed out that the secular increases of the peak separation are the magnetic dipole precession behavior with a characteristic time of 100 years. The similar evolutionary rates of the X-ray and radio peak separations imply that the two kinds of emission are located at similar latitudes.

The evolution in the relative flux densities of the radio components are explained as highly coherent. Narrow beam and small structural magnetospheric changes might have large effects on the component flux densities (Lyne et al. 2013). However, the changing rate of $R_f$ $(3.64 \pm 0.86) \times 10^{-2}$ per century, is significantly lower than the radio result, $(17.2 \pm 0.8) \times 10^{-2}$ per century. The difference becomes even larger if wider phase intervals are chosen to integrate the flux. This means that the X-ray emitting region is much larger than the radio emitting region, consistent with those represented by the widths of the radio and X-ray pulses. Therefore, a more complicated model is needed to explain the overall evolutionary behaviors of the radio and X-ray profiles, combined with the effects of the propagation time and relativity (Morini 1983).

5. SUMMARY

In this paper, we found that the X-ray profile of the Crab pulsar experiences secular changes with time. The ratio of the two profiles in different epochs showed that, after a few years, P1 becomes sharper and the distance between P1 and P2 increases slightly. Quantitatively, the peak separation of the two pulses increases by $0.38 \pm 0.20$ per century, the ratio of the flux integrated within the FWHM of P1 to that of P2 decreases by $(3.64 \pm 0.86) \times 10^{-2}$ per century, and the FWHMs of P1 and P2 changes with $-1.44 \pm 0.15$ per century and $-1.09 \pm 0.73$ per century, respectively. These evolutionary trends are similar to the radio trends, though the values are different. A more complicated model of pulsar emission geometry is needed to explain the radio and X-ray results simultaneously.

Drs. Michael Smith, Lorenzo Natalucci, Craig Markwardt, Yuanyue Pan, Liming Song, and Jinping Qu are appreciated for their useful suggestions. We thank the High Energy Astrophysics Science Archive Research Center (HEASARC) at the NASA/Goddard Space Flight Center for maintaining its online archive service that provided the data used in this research. This work is supported by the National Science Foundation of China (11233001 and 11503027) and the Strategic Priority Research Program on Space Science, the Chinese Academy of Sciences, grant No. XDA04010300.

REFERENCES

Arzamasskiy, L., Philippov, A., & Tchekhovskoy, A. 2015, MNRAS, 453, 3540
Beskin, V. S., & Nokhrina, E. E. 2007, Ap&SS, 308, 569
Cheng, K. S., Ho, C., & Ruderman, M. 1986a, ApJ, 300, 500
Cheng, K. S., Ho, C., & Ruderman, M. 1986b, ApJ, 300, 522
Chetana, J., & Biswajit, P. 2011, RAA, 11, 1134
Daugherty, J. K., & Harding, A. K. 1996, A&AS, 120, 107
Eikenberry, S. S., & Fazio, G. G. 1997, ApJ, 476, 281
Garcia, J. A., McClintock, J. E., Steiner, J. F., Remillard, R. A., & Grinberg, V. 2014, ApJ, 794, 73
Ge, M. Y., Lu, F. J., Qu, J. L., et al. 2012, ApJS, 199, 32
Gold, T. 1968, Nature, 218, 731
Jahoda, K., Markwardt, C. B., Radeva, Y., et al. 2006, ApJ, 163, 401
Kuiper, L., Hermsen, W., Casusamo, G., et al. 2001, A&A, 378, 918
Lyne, A. G., Graham-Smith, F., Weltevrede, P., et al. 2013, Sci, 342, 598
Lyne, A. G., Pritchard, R. S., & Graham-Smith, F. 1993, MNRAS, 265, 1003
Massaro, E., Campana, R., Casusamo, G., & Mineo, T. 2006, ApJ, 459, 859
Massaro, E., Casusamo, G., Lietto, M., & Mineo, T. 2000, A&A, 361, 695
Mineo, T., Casusamo, G., Segreto, A., et al. 1997, A&A, 327L, 21
Molkov, S., Jourdain, E., & Roques, J. P. 2010, ApJ, 708, 403
Morini, M. 1983, MNRAS, 202, 495
Morrison, R., & McCammon, D. 2002, ApJ, 207, 119
Nelson, J., Hills, R., Cutaback, D., & Wampler, J. 1970, ApJ, 161, 235
Patt, B. L., Ulmer, M. P., Zhang, W., et al. 1999, ApJ, 522, 440
Philippov, A. A., & Spitkovsky, A. 2014, ApJL, 785, L33
Rothschild, R. E., Blanco, P. R., Gruber, D. E., et al. 1998, A&A, 496, 538
Rot, A. H., Jahoda, K., & Lyne, A. G. 2004, ApJL, 605, L129
Rot, A. H., Jahoda, K., Macomb, D. J., et al. 1998, ApJ, 501, 749
Standish, E. M., Jr. 1990, A&A, 234, 252
Sturman, S. J., & Dermer, C. D. 1994, ApJL, 420, L79
Willingale, R., Achenbach, B., Griffiths, R. G., et al. 2001, A&A, 365, 212
Zanazzi, J. J., & Lai, D. 2015, MNRAS, 451, 695

The Astrophysical Journal, 818:48 (7pp), 2016 February 10

| Instrument | $\Phi$ | $R_f$ | $W_1$ | $W_2$ |
|------------|--------|--------|--------|--------|
| PCA        | 0.40028 $\pm$ 0.00017 | 1.2330 $\pm$ 0.0012 | 0.03989 $\pm$ 0.00014 | 0.08056 $\pm$ 0.00033 |
| HEXTE      | 0.39994 $\pm$ 0.00022 | 1.5058 $\pm$ 0.0038 | 0.04125 $\pm$ 0.00028 | 0.08228 $\pm$ 0.00056 |

Figure 6. Parameters derived from the faked PCA profiles representing the influence of the aging of PCA. The solid lines are the linear fits to these parameters. The mean values of these parameters are subtracted because we are only interested in their variations.