POSSIBLE DETECTION OF A CYCLOTRON RESONANCE SCATTERING FEATURE IN THE X-RAY PULSAR 4U 1909+07

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ABSTRACT

We present timing and broad band spectral studies of the high-mass X-ray binary pulsar 4U 1909+07 using data from Suzaku observations during 2010 November 2–3. The pulse period of the pulsar is estimated to be 604.11 ± 0.14 s. Pulssations are seen in the X-ray light curve up to ~70 keV. The pulse profile is found to be strongly energy-dependent: a complex, multi-peaked structure at low energy becomes a simple single peak at higher energy. We found that the 1–70 keV pulse-averaged continuum can be fit by the sum of a blackbody and a partial covering Negative and Positive power law with Exponential cutoff model. A weak iron fluorescence emission line at 6.4 keV was detected in the spectrum. An absorption-like feature at ~44 keV was clearly seen in the residuals of the spectral fitting, independent of the continuum model adopted. To check the possible presence of a cyclotron resonance scattering feature (CRSF) in the spectrum, we normalized the pulsar spectrum with the spectrum of the Crab Nebula. The resulting Crab ratio also showed a clear dip centered at ~44 keV. We performed statistical tests on the residuals of the spectral fitting and also on the Crab spectral ratio to determine the significance of the absorption-like feature and identified it as a CRSF of the pulsar. We estimated the corresponding surface magnetic field of the pulsar to be 3.8 × 1012 G.

Key words: pulsars: general -- stars: individual (4U 1909+07) -- stars: neutron -- X-rays: stars

1. INTRODUCTION

Accretion-powered X-ray binary pulsars, which were discovered in the early 1970s (Giacconi et al. 1971), are among the brightest X-ray sources in the sky. These binary systems consist of a neutron star with a strong magnetic field (B ~ 10^{12} G) and a supergiant or a Be star as an optical companion. Mass transfer from the companion star to the neutron star takes place through Roche lobe overflow (in the case of low-mass X-ray transfer from the companion star to the neutron star takes place and a supergiant or a Be star as an optical companion. Mass

Ea = 11.6B_{12}(1 + zg)^{-1} (keV), where zg is the gravitational redshift and B_{12} is the magnetic field strength in units of 10^{12} G. Detection of a cyclotron scattering resonance feature (CRSF) in the spectrum, therefore, provides the direct measurement of the strength of the pulsar magnetic field. The CRSFs have been detected in the spectrum of about 19 X-ray pulsars (Coburn et al. 1999; Naik et al. 2011, and references therein). This model consists of two power-law continua with a common photon index but with different hydrogen-absorbing column densities. Several emission lines due to fluorescence from ions at different ionization levels and broad absorption-like features due to cyclotron resonance scattering are often seen in the pulsar spectrum. The magnetic field strength B and the cyclotron resonance energy Ea are related through the relation Ea = 11.6B_{12}(1 + zg)^{-1} (keV), where zg is the gravitational redshift and B_{12} is the magnetic field strength in units of 10^{12} G. Detection of a cyclotron scattering resonance feature (CRSF) in the spectrum, therefore, provides the direct measurement of the strength of the pulsar magnetic field. The CRSFs have been detected in the spectrum of about 19 X-ray pulsars (Coburn et al. 2002; Staubert 2003; Pottschmidt et al. 2012) using data from several X-ray observatories. The harmonics of fundamental cyclotron absorption lines are also detected in some pulsars (Nakajima et al. 2006; Orlandini et al. 2012).

The HMXB pulsar 4U 1909+07 was discovered with the Uhuru satellite and referenced as 3U 1912+07 in third Uhuru catalog (Giacconi et al. 1974). The position of the pulsar was refined and the source was renamed 4U 1909+07 in the fourth catalog (Forman et al. 1978). The presence of many other sources in the intensity range of 2–12 mCrab and the 2–10 keV energy range was reported at nearby coordinates of 4U 1909+07 through observations with different missions such as OSO7, ArielS, HEAO - 1, and EXOSAT. Wen et al. (2000) recognized that all the sources such as 4U 1909+07, 3A 1907+074, 1H 1907+074, GPS 1908+075, 1E 1908.4+0730,
and X1908+075 reported through various surveys are consistent to within an uncertainty of 1'. The orbital period of the binary system was reported to be 4.4 days using *Rossi X-Ray Timing Explorer (RXTE)* All-Sky Monitor data (Wen et al. 2000). Using *RXTE* Proportional Counter Array observations of 4U 1909+07, pulsations with a 605 s period were detected in the X-ray flux (Levine et al. 2004). The orbital inclination, orbital separation, and mass of the companion star were estimated to be in the range of 38°–72°, 60–80 h, and 9–31 M⊙, respectively (Levine et al. 2004). The detection of an OB star in the near-infrared within the X-ray error box of the pulsar confirmed the system to be an OB supergiant-neutron star HMXB (Morel & Grosdidier 2005). The distance of the binary system was estimated to be ~7 kpc (Morel & Grosdidier 2005). *RXTE* and *HET E INTEGRAL* observations of the pulsar showed that the 605 s pulsation in the X-ray flux is not stable; it changes erratically on time scales of years (Fürst et al. 2011). The pulse profile was found to be strongly energy-dependent. The phase-averaged spectrum, obtained from the above observations, was well described by a power law with a high-energy cutoff continuum model along with a blackbody component (Fürst et al. 2011). Fürst et al. (2012) also analyzed data from *Suzaku* observations of the pulsar and described the spectrum using the same model as was used in their earlier work. In both cases, there was no detection of CRSF in the pulsar spectrum. Data from *Suzaku* observation were used in later case and the high energy data were truncated at 40 keV in the spectral fitting. However, using the same data set up to high energy ranges, we detected an absorption-like feature at ~44 keV and interpreted it as possible CRSF in the pulsar spectrum. The details of analysis and results we obtained are described in the following sections.

2. OBSERVATION AND ANALYSIS

The HMXB pulsar 4U 1909+07 was observed with *Suzaku* on 2010 November 2–3. We used the publicly available archival data of processing version 2.5.16.28 in the present work to investigate the timing and spectral properties of the pulsar. The observations were carried out at the “XIS nominal” pointing position for effective exposures of ~30 ks and ~22 ks for the X-ray Imaging Spectrometer (XIS) and the Hard X-ray Detector (HXD), respectively. *Suzaku* was operated with “normal” clock mode in the “1/4 window” option. In this operational mode, the time resolution and field of view (FoV) of XIS are 2 s and 17.8 × 4.4, respectively.

*Suzaku*, the fifth Japanese X-ray astronomy satellite, was launched by the Japan Aerospace Exploration Agency (JAXA) on 2005 July 10 (Mitsuda et al. 2007). The instruments on board *Suzaku* cover the 0.2–600 keV energy range through two sets of instruments, XIS (Koyama et al. 2007) and HXD (Takahashi et al. 2007). XIS consists of imaging CCD cameras that are located at the focal plane of the X-Ray Telescope (XRT). Among the four XISs, XIS-0, XIS-2, and XIS-3 are front illuminated (FI), whereas XIS-1 is back illuminated (BI). In full-window mode, the effective area of XIS is 340 cm² for front illumination and 390 cm² for back illumination at 1.5 keV. Due to large charge leakage in the imaging region, XIS-2 has not longer been operational since 2007 September. The non-imaging detector HXD consists of two types of instruments such as silicon PIN diodes covering the 10–70 keV energy range and the GSO crystal scintillator covering the 30–600 keV energy range. The effective area of PIN is 145 cm² at 15 keV and for the effective area of GSO is 315 cm² at 100 keV. The FoVs of XIS and PIN are 18' × 18' and 34' × 34' in open window mode, respectively. GSO has same FoV as PIN up to 100 keV. As XIS-2 is no longer operational, the data from the other 3 XISs, PIN, and GSO are used in the present analysis.

For analysis, we used HEASoft software package (version 6.12). The calibration database (CALDB) files, released in 2012 February 10 (for XIS) and 2011 September 13 (for HXD) by the instrument teams are used for data reduction. The unfiltered event files are reprocessed using the “aepipeline” package of FTOOLS. These reprocessed cleaned event files are used for further analysis. The arrival times of X-ray photons were converted to arrival times at the solar system barycenter by applying the “aebarycen” task of FTOOLS on the reprocessed cleaned event files of XIS, PIN, and GSO. Source light curves and spectra were accumulated from XIS reprocessed cleaned event data by selecting a circular region with a 3' diameter around the central X-ray source. The XIS background spectra were extracted from the same event files by selecting circular regions away from the source position. By using the “xissimfgen” and “xissimarfgen” tasks of FTOOLS, the response files and effective area files for each XIS were generated for spectral fitting. Using reprocessed and cleaned HXD data, light curves and spectra were accumulated by using the task “XSELECT” of FTOOLS. Simulated background event data (provided by the instrument teams) were used to estimate the HXD/PIN and HXD/GSO backgrounds for 4U 1909+07 observations. The response files released in 2010 July (for HXD/PIN) and 2010 May (for HXD/GSO) were used for spectral analysis. An additional effective area file, released in 2010 May, was used for HXD/GSO.

3. RESULTS AND DISCUSSION

3.1. Timing Analysis

As described above, source light curves with time resolutions of 2 s, 1 s, and 1 s were extracted from barycenter-corrected XIS, HXD/PIN, and HXD/GSO reprocessed event data. The orbital period of the binary system is short (4.4 days) and *Suzaku* observations of the pulsar spanned a significant part of the binary orbit, so it is possible that the X-ray pulsations got smeared. To neutralize the effect of orbital motion on the X-ray pulsations, the photon arrival times in each of the light curves were corrected for the binary motion using the ephemeris given by Levine et al. (2004). The orbital motion and barycenter-corrected light curves were used for timing studies of the pulsar. By applying pulse folding and the χ² maximization technique, the pulse period of the pulsar was estimated to be 604.11 ± 0.14 s for XIS-0 and 604.08 ± 0.13 s for HXD/PIN. The pulse period of 604.11 s estimated from the XIS light curve was used to generate pulse profiles of the pulsar in the 0.4–12 keV, 10–70 keV, and 40–200 keV energy ranges using background-subtracted XIS, HXD/PIN, and HXD/GSO light curves, respectively. The corresponding pulse profiles are shown in Figure 1. From this figure, it is seen that the pulse profiles are strongly energy-dependent. In soft X-rays (top panel of the figure), the shape of the profile is found to be complex because of the presence of dip-like features, whereas it becomes a single peaked profile in the 10–70 keV (HXD/PIN) energy range (middle panel). The pulsations are either absent or marginal in the 40–200 keV (HXD/GSO) energy range (bottom panel). To investigate the evolution of pulse profile with energy, several energy-resolved light curves were extracted from the barycenter-corrected XIS, HXD/PIN, and HXD/GSO event data. An orbital correction was applied to all the light curves before generating the pulse.
profiles. The corresponding energy-resolved pulse profiles are shown in Figure 2. The evolution of pulse profile from a complex shape at soft X-rays to a single-peaked profile up to ∼70 keV can be clearly seen in Figure 2. It can be seen that the 604.11 s pulsation is present in GSO light curves up to 70 keV energy range, beyond which it is absent.

The pulse profiles of the HMXB pulsar 4U 1909+07 strongly depend on energy. At low energies (<10 keV), the shape of the profile is found to be complex because of the presence of several dip-like structures. These structures disappear at high energies, making the pulse profile single-peaked in the 10–70 keV energy range, beyond which the pulsations are absent in the pulsar. Energy-dependent dips or dip-like features in the pulse profile are seen in many accretion-powered X-ray pulsars such as 4U 0115+63 (Tsygankov et al. 2007), A 0535+262 (Naik et al. 2008), 1A 1118–61 (Maitra et al. 2012, and references therein), GRO J1008–57 (Naik et al. 2011), EXO 2030+375 (Naik et al. 2013), etc. Detailed pulse-phase resolved spectral analysis of many HMXB pulsars such as GRO J1008–57 (Naik et al. 2011), 1A 1118–61 (Devasia et al. 2011a; Maitra et al. 2012), GX 304-1 (Devasia et al. 2011b), EXO 2030+375 (Naik et al. 2013), etc. showed complex pulse profile structure, which was interpreted as being due to the presence of an additional stream of matter at certain pulse phases, which are phase locked to the neutron star. Absorption of soft X-ray photons by the additional matter in narrow streams causes dips or dip-like features in the pulse profiles.

3.2. Spectral Analysis

A pulse-phase averaged spectral analysis of 4U 1909+07 was performed using spectra accumulated from the XIS-0, XIS-1, XIS-3, PIN, and GSO detectors. The corresponding background spectra and response files were obtained as described above. Spectra from both FI CCDs (XIS-0 and XIS-3) and corresponding background spectra and response files were merged together by applying the task “addascaspec.” Simultaneous spectral fitting was carried out by using the spectrum, background, and response data files of merged FI CCDs (0.8–10 keV), XIS-1 (0.8–10 keV), HXD/PIN (12–70 keV), and HXD/GSO (40–100 keV) with the software package XSPEC v12.7. Because of the presence of known artificial structures in XIS energy spectra around the Si and Au edge, data in the 1.7–1.9 keV and 2.2–2.4 keV energy ranges were ignored in the spectral fitting. XIS spectra were re-binned by a factor of 8 from 0.8 keV to 2 keV and by a factor of 6 from 2 keV to 10 keV. The HXD/PIN spectrum was re-binned by a factor of 2 from 25 keV to 40 keV and by a factor of 6 from 40 keV to 70 keV. The binning of GSO spectrum was suggested by the instrument team. All spectral model parameters except for the relative instrument normalizations were tied together in the spectral fitting. We attempted to fit the broadband continuum

Figure 1. Pulse profiles of the HMXB pulsar 4U 1909+07 in 0.4–12 keV (XIS-0), 10–70 keV (HXD/PIN), and 40–200 keV (HXD/GSO) energy ranges are shown. The profiles are obtained from corresponding light curves by estimated 604.11 s pulse period of the pulsar. The errors shown in the figure are estimated for 1σ confidence level. Two pulses are shown for clarity.

Figure 2. Energy-resolved pulse profile of 4U 1909+07 at different energy bands obtained from XIS-0, HXD/PIN, and HXD/GSO data. The evolution of the pulse profile from a complex shape in soft X-ray energy ranges to a single-peaked profile up to ∼40 keV can be clearly seen. The pulsation in GSO can be seen up to ∼70 keV.
To obtain a suitable model that described the broadband spectrum, we noted anomalous residuals were noted in the spectral fitting. We tried to describe the continuum spectrum. All of these models proposed a blackbody component for soft X-ray excesses were needed. A partial-covering absorption component (Sunyaev & Titarchuk 1985). A partial-covering, high-energy cutoff power-law model with blackbody and Gaussian components and a cyclotron line. Model 5: partial-covering NPEX model with blackbody and Gaussian components. Model 6: partial-covering NPEX model with blackbody and Gaussian components and a cyclotron line.

| Parameter                   | Value          | Value          | Value          | Value          | Value          | Value          |
|-----------------------------|----------------|----------------|----------------|----------------|----------------|----------------|
| $N_{H_1}$ ($10^{22}$ atoms cm$^{-2}$) | 6.16 ± 0.17 | 5.95 ± 0.19    | 7.50 ± 0.21    | 7.53 ± 0.25    | 7.09 ± 0.20    | 7.05 ± 0.19    |
| $N_{H_2}$ ($10^{22}$ atoms cm$^{-2}$) | 9.71 ± 0.95 | 8.20 ± 1.28    | 32.19 ± 8.20   | 34.01 ± 7.82   | 38.78 ± 7.89   | 39.71 ± 7.90   |
| Covering fraction           | 0.52 ± 0.03   | 0.47 ± 0.05    | 0.18 ± 0.04    | 0.18 ± 0.03    | 0.19 ± 0.03    | 0.20 ± 0.03    |
| $kT_{BB}$ (eV)              | 3.38 ± 0.21   | 2.71 ± 0.23    | 0.19 ± 0.01    | 0.19 ± 0.01    | 0.20 ± 0.01    | 0.20 ± 0.01    |
| Normalization of $kT_{BB}$ ($10^{-3}$) | 1.50 ± 0.14 | 1.18 ± 0.18    | 10.59 ± 3.25   | 11.07 ± 3.10   | 5.65 ± 1.70    | 5.27 ± 1.82    |
| Iron line energy (eV)       | 6.39 ± 0.01   | 6.39 ± 0.01    | 6.39 ± 0.01    | 6.39 ± 0.01    | 6.39 ± 0.01    | 6.39 ± 0.01    |
| Iron line width (eV)        | 0.01 ± 0.01   | 0.01 ± 0.01    | 0.01 ± 0.01    | 0.01 ± 0.01    | 0.01 ± 0.01    | 0.01 ± 0.01    |
| Iron line eq. width (eV)    | 73 ± 3        | 72 ± 3         | 68 ± 3         | 68 ± 3         | 69 ± 3         | 68 ± 3         |
| Power-law index             | 1.91 ± 0.03   | 1.77 ± 0.05    | 1.43 ± 0.05    | 1.44 ± 0.04    | 1.05 ± 0.06    | 1.01 ± 0.07    |
| Normalization of power law ($10^{-2}$) | 7.40 ± 0.51 | 5.36 ± 0.71    | 4.16 ± 0.50    | 4.26 ± 0.52    | 4.37 ± 2.16    | 13.98 ± 1.77   |
| High energy cutoff (eV)     | 3.34 ± 0.28   | 7.37 ± 0.16    | 12.78 ± 1.58   | 12.78 ± 1.58   | 12.78 ± 1.58   | 12.78 ± 1.58   |
| Folding energy (eV)         | 23.42 ± 1.51  | 24.23 ± 1.10   | 24.23 ± 1.10   | 24.23 ± 1.10   | 24.23 ± 1.10   | 24.23 ± 1.10   |
| Cyclotron line $E_C$ (eV)   | 43.75 ± 1.51  | 43.10 ± 2.09   | 43.85 ± 1.58   | 43.85 ± 1.58   | 43.85 ± 1.58   | 43.85 ± 1.58   |
| Width of cyclotron line (eV) | 4.72 ± 2.58   | 1.03 ± 2.35    | 2.04 ± 2.02    | 2.04 ± 2.02    | 2.04 ± 2.02    | 2.04 ± 2.02    |
| Depth of cyclotron line     | 1.25 ± 0.50   | 1.01 ± 0.83    | 1.57 ± 0.89    | 1.57 ± 0.89    | 1.57 ± 0.89    | 1.57 ± 0.89    |
| Flux$^c$ (in the 1–10 keV range) | 1.51 ± 0.10 | 1.51 ± 0.03    | 1.51 ± 0.18    | 1.51 ± 0.16    | 1.51 ± 0.15    | 1.51 ± 0.14    |
| Flux$^c$ (in the 10–70 keV range) | 4.22 ± 0.29 | 4.14 ± 0.40    | 3.76 ± 0.42    | 3.76 ± 0.38    | 3.94 ± 0.69    | 4.01 ± 0.75    |
| $C_{XSIS-10}/C_{XSIS-1}/C_{PIN}$ | 1.0/0.94/1.1 | 1.0/0.94/1.22 | 1.0/0.94/1.18 | 1.0/0.94/1.17 | 1.0/0.94/1.13 | 1.0/0.94/1.13 |
| $kT_{BB}$ (degrees of freedom) | 600 (489) | 587 (486)      | 576 (487)      | 573 (484)      | 578 (487)      | 570 (484)      |

Notes. Model 1: partial-covering, power-law model with blackbody and Gaussian components. Model 2: partial-covering power-law model with blackbody and Gaussian components and a cyclotron line. Model 3: partial-covering, high-energy cutoff power-law model with blackbody and Gaussian components. Model 4: partial-covering, high-energy cutoff power-law model with blackbody and Gaussian components and a cyclotron line. Model 5: partial-covering NPEX model with blackbody and Gaussian components. Model 6: partial-covering NPEX model with blackbody and Gaussian components and a cyclotron line.

$N_{H_1}$, equivalent hydrogen column density; $N_{H_2}$, additional hydrogen column density.
$^c$ In units of $10^{39}$ erg s$^{-1}$ (d/10 kpc)$^{-2}$, where d is the distance to the source.
$^d$ Photons keV$^{-1}$ cm$^{-2}$ s$^{-1}$ at 1 keV.
$^e$ Absorption uncorrected flux (in units of $10^{-10}$ erg cm$^{-2}$ s$^{-1}$).

The parameters obtained by fitting the partial-covering, high-energy cutoff power-law model to the spectrum are in good agreement with Table 2 of Fürst et al. (2012). However, the partial-covering NPEX continuum model with iron lines and a blackbody component described the spectrum better, yielding an acceptable blackbody temperature of 0.2 keV. An absorption-like feature was seen in the pulsar spectrum and in the residuals at ~44 keV that allowed us to add a CRSF component in the spectral model. The addition of a CRSF component to the above continuum models improved the $\chi^2$ values for each model (as given in Table 1). The count rate spectra of the pulsar 4U 1909+07 are shown in Figure 3 (for partial covering the partial-covering, power-law model), Figure 4 (for the partial-covering, high-energy cutoff power-law model), and Figure 5 (for the partial-covering NPEX model) along with the model components (top panels). The middle panels in the above three figures show the residuals to the fitted models without the CRSF whereas the bottom panels show the residuals to the best-fitting model using the CRSF component in the spectral models. The presence of an absorption feature at ~44 keV can be clearly seen in the middle panels of all figures.

To test the statistical significance of the $\chi^2$ improvement due to the addition of the CRSF component, we performed an $F$-test. In the case of emission line features (additive components in XSPEC), the $F$-test routine incorporated in the XSPEC package should be the best suited to perform the

~3 keV fit the pulsar spectrum well. A blackbody component with a high temperature as high as ~3 keV is unusual in the case of accretion-powered X-ray pulsars. The addition of a high-energy cutoff to the partial covering power-law model fit the data well with a blackbody temperature of ~0.2 keV. The parameters obtained by fitting the partial-covering, high-energy cutoff power-law model to the spectrum are in good agreement with Table 2 of Fürst et al. (2012). However, the partial-covering NPEX continuum model with iron lines and a blackbody component described the spectrum better, yielding an acceptable blackbody temperature of 0.2 keV. An absorption-like feature was seen in the pulsar spectrum and in the residuals at ~44 keV that allowed us to add a CRSF component in the spectral model. The addition of a CRSF component to the above continuum models improved the $\chi^2$ values for each model (as given in Table 1). The count rate spectra of the pulsar 4U 1909+07 are shown in Figure 3 (for partial covering the partial-covering, power-law model), Figure 4 (for the partial-covering, high-energy cutoff power-law model), and Figure 5 (for the partial-covering NPEX model) along with the model components (top panels). The middle panels in the above three figures show the residuals to the fitted models without the CRSF whereas the bottom panels show the residuals to the best-fitting model using the CRSF component in the spectral models. The presence of an absorption feature at ~44 keV can be clearly seen in the middle panels of all figures.
significance test (although care should be taken while using this; see Protassov et al. 2002). However, in the case of multiplicative components such as CRSF, the $F$-test in XSPEC is inappropriate for performing the null hypothesis test. The $F$-test in XSPEC is based on the assumption that the inclusion of the new component does not alter the continuum. This is true if the component is added to the continuum model, whereas this is not correct if the component is multiplied by the continuum. Therefore, we used a different $F$-test, as described in Press et al. (2007), to test the statistical significance of the CRSF component in the spectrum of 4U 1909+07 (see, e.g., Orlandini et al. 2012). The $F$-test routine is available in the IDL package (named mpfTest) and was used for significance tests of multiplicative components such as CRSF or Gaussian absorption features (Decesar et al. 2013). The probability of chance improvement (PCI) is evaluated for each of the three models used to fit the pulsar spectrum without and with the CRSF component. The estimated PCI values after the addition of the CRSF component to the (1) partial-covering, power-law model with black-body a blackbody, (2) the partial-covering, high-energy cutoff power-law model with a blackbody, and (3) the partial-covering NPEX model with a blackbody are found to be 37%, 51%, and 47%, respectively. Considering the high value of PCI for all three models, the CRSF is found to not be statistically significant. But the residuals shown in the middle panels of Figures 3–5 clearly show an absorption-like feature at $\sim 44$ keV. It may be noted that the goodness-of-fit estimator chosen here to assess the statistical significance of the CRSF ($\chi^2$) is not the best suited as it does not take into account the “shape” of the residuals. Considering the identical distribution of residuals around 40 keV (the middle panels of Figures 3–5), we applied the run-test (also called the Wald-Wolfowitz test) on the residuals obtained from the spectral fitting by using above three continuum models. The IDL routine for the run-test was used to derive the null hypothesis of the randomness in the residuals of spectral fitting in the 37–65 keV energy range. It was found that the number of data points used for the run test in the 37–65 keV energy range is 12 (6 points below zero and 6 points above zero), 13 (4 points below zero and 9 points above zero), and 13 (6 points below zero and 7 points above zero) for partial covering the partial-covering power-law, partial-covering, high-energy cutoff, and partial-covering NPEX continuum models, respectively. The probability of getting 3 runs in above the energy range was estimated to be 0.8%, 0.7%, and 0.5%, respectively. The marginal difference in the probability values is because of the use of different continuum models that can affect the residuals in the spectral fitting. The computed probability of $\leq 1\%$ for all three continuum models rejects the hypothesis of random sampling of the detected absorption feature in the pulsar spectrum. Among the three continuum models, it is found

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3 http://www.physics.wisc.edu/~craigm/idl/down/mpftest.pro

4 http://www.astro.washington.edu/docs/idl/cgi-bin/getpro/library07.html?R_TEST
that the NPEX continuum model with a blackbody, a Gaussian function, and a CRSF feature at ∼44 keV yields the best fit to the 0.8–70 keV data. The presence of an absorption feature at ∼44 keV in the residuals of all the models suggests that the CRSF is indeed required in the spectral fitting. The best-fit spectral parameters obtained by using three different continuum models along with additional components are given in Table 1. It can be seen from the table that the addition of a CRSF at ∼44 keV improved the spectral fitting in all cases.

The same Suzaku observations were analyzed, although with the ISIS package, by Fürst et al. (2012). These authors did not use HXD/GSO data because of possible contamination from the nearby source GRS 1915+105 and therefore performed their spectral analysis in the 1–40 keV energy range. Considering the earlier result, the possible CRSF feature at ∼44 keV was carefully examined by different approaches. As the pulsar is weak in hard X-ray energy ranges, we tried to establish that the observed photons in the spectrum beyond ∼40 keV are not affected by detector energy response uncertainties. We extracted pulsar light curves in 10–40 keV, 40–50 keV, and 50–70 keV energy ranges from HXD/PIN and HXD/GSO reprocessed event data. The corresponding background light curves were also extracted from the simulated background event data (as described in the previous section). The background-subtracted and orbital-corrected light curves in the above energy ranges were used to generate power density spectra. The energy-resolved power density spectra of 4U 1909+07, as shown in Figure 6, show additional power (peaks) at ∼1.65 mHz (the spin frequency of the pulsar) in the 10–40 keV (top panel), 40–50 keV (second panel), and 50–70 keV (third and fourth panels) energy ranges. The power density spectra shown in the top three panels were extracted from the corresponding light curves obtained from HXD/PIN data whereas the spectrum shown in the bottom panel was extracted from HXD/GSO data.

The presence of additional power at ∼1.65 mHz in the power density spectra at 40–50 keV and 50–70 keV confirms that photons beyond 40 keV in the spectrum are not associated with any energy response uncertainties.

To establish the absorption-like feature seen at ∼44 keV in the pulsar spectrum as CRSF, we evaluated the energy spectra of the pulsar 4U 1909+07 in a model-independent manner. We attempted to normalize the pulsar spectrum with that of the Crab Nebula, the spectrum of which is a featureless power law with a photon index of ∼2.1. The normalization (Crab ratio) has the advantage of minimizing the effects due to the detector response and the uncertainties in the energy response. To generate the Crab ratio, we used a Crab observation with Suzaku (on 2010 April 5) that is nearest to the observation of the pulsar 4U 1909+07. Data reduction and background estimation for the Crab HXD/PIN data were done as described above and the Crab ratio was obtained to investigate the presence of the absorption feature in the pulsar spectrum. The resulting Crab ratio in the 12–70 keV energy range is shown in Figure 7. The presence of the absorption feature at ∼44 keV, as was seen in the spectral fitting (middle panels of Figures 3–5), can be clearly seen in the figure. It should be noted here that the shape of this CRSF-like feature in the Crab ratio is very similar to that seen in the middle panels of the above figures. In order to evaluate the statistical significance of the absorption feature, we performed a run test on the Crab ratio data. It was found that in the 37–65 keV energy range in the Crab ratio, there are 13 data points with 3 runs in which 7 points are above zero and 6 points are below zero. The probability of obtaining 3 runs is only ∼1%. This result, together with the results obtained from the analysis on the spectral residuals, strongly supports the genuine presence of an absorption feature in the Crab ratio at ∼44 keV. It confirms the presence of CRSF at ∼44 keV in the HMXB pulsar 4U 1909+07.

4. CONCLUSIONS

In this work, we have studied the timing and spectral properties of the HMXB pulsar 4U 1909+07 using data from Suzaku observations. The pulse profiles strongly depend on energy and evolve from a complex shape at lower energy to a single-peaked profile at higher energy. Broadband spectroscopy of the HMXB pulsar 4U 1909+07 in the 1–70 keV energy range is reported here for the first time. Although the pulsar is very weak in hard X-rays, the high sensitivity of the HXD on board Suzaku helped in performing phase-averaged spectroscopy at
energies up to 70 keV. The energy spectrum of the X-ray pulsar is well described by a partial-covering NPEX model with a blackbody component. For the first time, we report the possible detection of CRSF at \( \sim 44 \) keV in this pulsar. Based on this detection, the magnetic field strength at the neutron star surface is estimated to be \( \sim 3.8 \times 10^{12} \) G. It is seen that the values of CRSF detected in accretion-powered X-ray pulsars follow a continuum distribution starting from as low as \( \sim 11 \) keV for 4U 0115+634 (Nakajima et al. 2006) to as high as \( \sim 76 \) keV for GRO J1008−57 (Yamamoto et al. 2013). Nevertheless, a CRSF at \( \sim 100 \) keV is reported in LMC X-4 (La Barbera et al. 2001), but it is yet to be confirmed. Considering the confirmed values of CRSF in X-ray pulsars, the CRSF detected in the pulsar 4U 1909+07 in the present work falls in the higher side. It is to be noted that we report the detection of CRSF at \( \sim 44 \) keV in the spectrum of 4U 1909+07, obtained from a \( \sim 22 \) ks of exposure with HXD. *Suzaku* observations with long exposures are required to confirm the presence of the absorption feature in this pulsar. The LAXPC instrument on the upcoming *Astrosat* mission will also provide a very good opportunity to establish the CRSF feature in the slow HMXB pulsar 4U 1909+07.

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