Suzaku observation of the transient X-ray pulsar GRO J1008–57

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ABSTRACT

We report the timing and broad-band spectral properties of the Be transient high-mass X-ray binary pulsar GRO J1008–57 using a Suzaku observation in the declining phase of its 2007 November and December outbursts. Pulsations with a period of 93.737 s were clearly detected in the light curves of the pulsar up to the 80–100 keV energy band. The pulse profile was found to be strongly energy dependent, a double-peaked profile at soft X-ray energy bands (<8 keV) and a single-peaked smooth profile at hard X-rays. The broad-band energy spectrum of the pulsar, reported for the first instance in this paper, is well described with three different continuum models, namely (i) a high energy cut-off power law, (ii) a Negative and Positive power law with EXponential (NPEX) cut-off and (iii) a partial covering power law with high energy cut-off. In spite of large value of absorption column density in the direction of the pulsar, a blackbody component of temperature ~0.17 keV for the soft excess was required for the first two continuum models. A narrow iron Kα emission line was detected in the pulsar spectrum. The partial covering model, however, is found to explain the phase-averaged and phase-resolved spectra well. The dip-like feature in the pulse profile can be explained by the presence of an additional absorption component with high column density and covering fraction at the same pulse phase. The details of the results are described in the paper.

Key words: stars: neutron – pulsars: individual: GRO J1008–57 – X-rays: stars.

1 INTRODUCTION

High-mass X-ray binary (HMXB) systems are strong X-ray emitters via the accretion of matter from the OB companion. The majority of the HMXBs are known to be Be X-ray binaries. The mass donor in the Be binary systems is generally a B star that is still on the main sequence and lying well inside the Roche surface. In these Be binary systems, the compact object (a neutron star) is typically in a wide orbit with moderate eccentricity with orbital period in the range of 16–400 d (Coe 2000). The neutron star in these Be systems spends most of the time far away from the circumstellar disc surrounding the Be companion. Mass transfer from the Be companion to the neutron star takes place through the circumstellar disc. Strong X-ray outbursts are normally seen when the neutron star (pulsar) passes through the circumstellar disc or during the periastron passage (Okazaki & Negueruela 2001). The outbursts in the Be/X-ray binaries are also theoretically explained by invoking the truncation of the circumstellar disc (Okazaki et al. 2002). According to the model, the neutron star exerts a negative torque outside some critical radius resulting in the truncation of the Be disc. The disc matter then accumulates in the outer rings of the disc until the truncation is overcome by the effects of global one-armed oscillations, disc warping, etc. The subsequent sudden infall of the high-density disc matter on to the neutron star causes X-ray outbursts in these systems.

With the exception of a very few peculiar cases like LS I+61303 (Massi et al. 2004 and references therein), all of the Be/X-ray binary systems appear to be accretion-powered X-ray pulsars. The pulse period of the X-ray pulsars in Be binary systems is in the wide range of seconds to hundreds of seconds. There is a strong correlation between the pulse period and the orbital period (Corbet 1986) suggesting effective transfer of angular momentum from the accreted material. On the longer time-scale (months to years), the variability is observed in optical and infrared bands that are attributed to the structural changes in the circumstellar disc (Reig et al. 2001 and references therein). The X-ray spectra of Be/X-ray binary pulsars are usually hard. A fluorescent iron emission line at 6.4 keV is observed in the spectrum of most of the X-ray pulsars. It is possible that most of these systems have a soft X-ray excess above the power-law continuum component. However, detection of the soft excess depends on the value of absorption column density (Paul et al. 2002; Naik & Paul 2004a,b and references therein).

The transient X-ray pulsar GRO J1008–57 was discovered on 1993 July 14 by the BATSE experiment on board the Compton
\textit{Gamma Ray Observatory} (CGRO; Stollberg et al. 1993). X-ray pulsations of 93.587 s were detected in the 20–120 keV energy range of BATSE. From ASCA observation, the X-ray pulse profile of the pulsar was found to have a double-peak structure with a well-defined, sharp intensity minimum and a less prominent secondary minimum (Tanaka 1993). The BATSE spectrum was described by an optically thin thermal bremsstrahlung model with $kT = 25$ keV. Following the discovery, the optical and infrared observations of the optical counterpart to GRO J1008–57 revealed the presence of strong Balmer emission lines and infrared excess (Coe et al. 1994). Based on these results, the system was classified as a massive binary system consisting of a neutron star as the compact object and a Be or a supergiant primary. After 260 d of this outburst, a second outburst was detected by BATSE (Finger et al. 1994). Assuming this 260 d as the orbital period of the pulsar, Finger et al. (1994) estimated the mass of the binary companion to be $3–8 M_\odot$ indicating the system as a HMXB. The ROSAT Position Sensitive Proportional Counter (PSPC) observation of the pulsar, in the declining phase of the discovery outburst by BATSE in 1993, clearly detected the 93.4-s pulsation with a double-peaked pulse profile in 0.1–2.4 keV light curve (Petré & Gehrels 1994). A search in the archive of EXOSAT/Medium-Energy Experiment (ME) observation, centred on HD 88661, revealed the presence of the pulsed emission at the same period during the 1993 outburst (Macomb, Shrader & Schultz 1994). The X-ray spectrum (0.8–10 keV range) was found to be well approximated ($N_H = 0.7 \times 10^{22} \text{atoms cm}^{-2}$) and described by a hard power law with a photon index of $\sim 1.2$. A combined analysis of data from the CGRO and ASCA observations, though non-simultaneous, shortly after the peak of the discovery outburst, reported that the broad-band spectrum of the pulsar can be well approximated by a power law with an exponential cut-off and a 6.4-keV iron emission line (Shrader et al. 1999). The pulse profile was also found to be energy dependent, a double-peaked profile detected by ASCA that evolved into a single-peaked profile as detected by BATSE. Analysing the BATSE and Rossi X-ray Timing Explorer (RXTE)/All-sky Monitor (ASM) flux histories, Shrader et al. (1999) suggested the orbital period of the system to be $\sim 135 \text{d}$. However, Levine & Corbet (2006) detected a 248.9-d periodicity in the RXTE ASM X-ray light curve by analysing data accumulated over nearly 10 yr. This periodicity was found by visual identification of periodically occurring outbursts in the ASM light curve. An independent analysis of pulse-period variations during outbursts, using BATSE data, estimated the orbital period to be precisely 247.8 d (Coe et al. 2007) which is a good agreement with the orbital period determined from the recurrence of the X-ray outbursts in ASM light curve.

Following the detection of an intense outburst from GRO J1008–57 with the Burst Alert Telescope (BAT) on Swift on 2007 November 17 (Krimm et al. 2007), the accreting X-ray pulsar was observed with various X-ray observatories. The RXTE observations detected the pulsar up to $\sim 70$ keV along with the regular $\sim 93.75$-s pulsations (Wilms et al. 2007). Suzaku performed a Target of Opportunity (TOO) observation of the pulsar on 2007 November 30. The results obtained from the analysis of the Suzaku observation are presented in this paper.

\section*{2 OBSERVATION}

The transient pulsar GRO J1008–57 was observed with the Suzaku during the declining phase of the 2007 November outburst. We used public data (ver-2.1.6.16) for the Suzaku TOO observation of the pulsar in the present work. The RXTE/ASM monitoring of the pulsar showed that the outburst lasted for $\sim 20 \text{d}$. During this outburst, the peak luminosity was about $\sim 90 \text{mCrab}$ ($\sim 7 \text{ASM counts s}^{-1}$). During this outburst, the pulsar was observed with the RXTE and Suzaku observatories. The RXTE/ASM (1.5–12 keV) and Swift/BAT (15–50 keV) one-day-averaged light curves of GRO J1008–57 between 2007 September 29 and 2008 January 20 are shown in the top and bottom panels of Fig. 1, respectively. The region between the vertical lines shows the duration of the Suzaku observation of the source.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure1.png}
\caption{The RXTE ASM and Swift/BAT light curves of GRO J1008–57 in 1.5–12 and 15–50 keV energy bands from 2007 September 29 (MJD 54372) to 2008 January 20 (MJD 54485). The region between the vertical lines shows the duration of the Suzaku observation of the source.}
\end{figure}

\textit{Suzaku}, the fifth Japanese X-ray astronomy satellite (Mitsuda et al. 2007), was launched on 2005 July 10. It covers the 0.2–600 keV energy range with the two sets of instruments, XIS (Koyama et al. 2007) covering the 0.2–12 keV energy range and the Hard X-ray Detector (HXD; Takahashi et al. 2007) which covers the 10–70 keV with PIN diodes and 30–600 keV with GSO scintillators. Among the four sets of XISs, one is back illuminated (BI) whereas the other three are front illuminated (FI). The field of view of the XIS is $18 \times 18 \text{arcmin}^2$ in a full window mode with an effective area of 340 cm$^2$ (FI) and 390 cm$^2$ (BI) at 1.5 keV. The energy resolution was 130 eV (full width at half-maximum) at 6 keV just after the launch. The HXD is a non-imaging instrument that is designed to detect high-energy X-rays. The HXD has 16 identical units made up of two types of detectors, silicon PIN diodes ($< 70$ keV) and GSO crystal scintillator ($> 30$ keV). The effective areas of PIN and GSO detectors are $\sim 145 \text{cm}^2$ at 15 keV and $315 \text{cm}^2$ at 100 keV, respectively. For a detailed description of the XIS and HXD detectors, refer to Koyama et al. (2007) and Takahashi et al. (2007). As XIS-2 is no more operational, data from other three XISs are used in the present analysis. The GSO data are used for timing analysis here in this paper. As the pulsar is very faint at energies above 50 keV, we did not use the GSO spectrum in the spectral fitting.
3 ANALYSIS AND RESULTS

For XIS and HXD/PIN data reduction, we used the cleaned event data and obtained the XIS and PIN light curves and source spectra. The simulated background events, as suggested by the instrument team, were used to estimate the HXD/PIN background for the GRO J1008−57 observation. The response file released in 2007 September was used for HXD/PIN spectrum. The accumulated events of the XIS data were discarded when the telemetry was saturated, the data rate was low, the satellite was in the South Atlantic Anomaly and the source elevation above the Earth’s limb was below 5° for night-Earth and below 20° for day-Earth. Applying these conditions, the source spectra were accumulated from the XIS cleaned event data by selecting a circular region of 4.3 arcmin around the image centroid. Because this extraction circle is larger than the optional window, the effective extraction region is the intersection of the window and this circle. The XIS background spectra were accumulated from the same observation by selecting rectangular regions away from the source. The response files and effective area files for XIS were generated by using the ‘xismarfgen’ and ‘xisrmfgen’ tasks of ftools (ver-6.3.1). The HXD/GSO data were reprocessed to extract the source light curves for various energy ranges. X-ray light curves of 2-, 1-, and 8-s time resolutions were extracted from the XIS, PIN and GSO event data, respectively.

3.1 Timing analysis

For the timing analysis, a barycentric correction was applied to the arrival times of the X-ray photons using the ‘aebarycen’ task of ftools. As described above, light curves with time resolutions of 2, 1 and 8 s were extracted from XIS (0.2–12 keV), HXD/PIN (10–70 keV) and HXD/GSO (50–200 keV) event data. Pulse folding and a χ² maximization method was applied to all the light curves yielding the pulse period of the pulsar to be 93.737(1) s. The pulse profiles obtained from the background-subtracted XIS, HXD/PIN and HXD/GSO light curves of the Suzaku observation of the pulsar are shown in Fig. 2. The epoch was adjusted to obtain the minimum in the profile at phase zero. From the figure, it is observed that the shape of the pulse profiles obtained from the three XIS light curves are identical, whereas it is different to that obtained from the PIN and GSO data. The dip in the pulse profile in pulse-phase range 0.95–1.05, hereafter referred to as a primary dip, is narrow at soft X-rays (XIS energy band) and broad in the hard X-ray energy bands. Apart from the variable width of the dip, another dip-like structure is present in the soft X-ray pulse profile in the 0.35–0.45 pulse-phase range which is absent in the hard X-ray profiles. To investigate the energy dependence of the pulse profile of GRO J1008−57, we generated light curves in different energy bands from XIS, PIN and GSO event data. The background-subtracted light curves are folded with the pulse period of the pulsar and the corresponding pulse profiles are shown in Fig. 3. To determine up to what energy pulsations are detected in GSO, we have searched for pulsations in narrow energy bands of 10 and 20 keV within the entire GSO energy range. The pulsations are clearly detected in the 80–100 keV band, with a detection significance of 7.7σ. The background-subtracted light curves do not show any excess above 100 keV, and as expected, no pulsations are detected beyond this energy. The dip-like structure in pulse-phase range 0.35–0.45 is found to be very prominent up to ∼4 keV. The width and depth of this structure decrease gradually with energy up to ∼10 keV, beyond which it becomes indistinguishable in the pulse profile, making the hard X-ray pulse profiles smooth and single peaked. Pulse-phase-resolved spectroscopy would help in understanding the nature of the energy dependence of the dip-like structure in the pulse profile of GRO J1008−57.

3.2 Spectral analysis

3.2.1 Pulse-phase-averaged spectroscopy

The broad-band spectrum of accretion-powered X-ray pulsars is generally described by a power law, broken power law or power law with high energy cut-off continuum models. In some cases, the pulsar spectrum has also been described by the Negative and Positive power law with E XPonential (NP EX) continuum model (Mihara 1995; Makishima et al. 1999; Terada et al. 2006; Naik et al. 2008 and references therein). In case of a few X-ray pulsars, it has been reported that the absorption has two different components (Endo, Nagase & Mihara 2000; Mukherjee & Paul 2004). In this model, one absorption component absorbs the entire spectrum, whereas the other component absorbs the spectrum partially. This model is known as partial absorption model. The choice of appropriate continuum model, therefore, is very much important to understand the properties of the pulsars. We tried to find a suitable continuum model to fit the broad-band spectrum of GRO J1008−57. In the process, we attempted to fit the pulsar spectra with different continuum models with additional spectral components such as blackbody radiation, iron emission line, etc. The models giving statistically acceptable parameters are described here in this section.

The source spectrum was extracted from the events selected in the energy ranges of 0.3–10.0 keV for the BI CCD (XIS-1),...
0.5–10 keV for the FI CCDs (XISs-0 and 3) and 10–70 keV for the HXD/PIN detectors. After appropriate background subtraction, simultaneous spectral fitting was done using the XIS and PIN spectra with \textsc{xspec} v12. All the spectral parameters, other than the relative normalization, were tied together for all the detectors. Because an artificial structure is known to exist in the XIS spectra around the Si edge, we ignored energy bins between 1.75 and 1.85 keV in the spectral analysis. Apart from the Si edge, large fit residuals due to calibration uncertainties are often observed near the edge structures of the XIS/XRT instrumental responses. Therefore, additional model components for possible fluorescence lines at energies below \(\sim 3.5\) keV are not considered during the spectral fitting.

### 3.2.3 The NPEX continuum model

We found that, as in case of A0535+262 (Terada et al. 2006, Naik et al. 2008), the NPEX continuum model also describes the broad-band spectrum of GRO J1008–57, as well as the previous model. The NPEX continuum model is an approximation of the unsaturated thermal Comptonization in hot plasma (Makishima et al. 1999).
Table 1. Best-fitting parameters of the phase-averaged spectra for GRO J1008–57 during the 2007 Suzaku TOO observation with 1σ errors. Model 1: high energy cut-off power-law model with blackbody and Gaussian components. Model 2: NPEX model with blackbody and Gaussian components. Model 3: partial covering high energy cut-off power-law model with Gaussian component.

| Parameter  | Model 1     | Value      | Model 2 | Value      | Model 3 | Value      |
|------------|-------------|------------|---------|------------|---------|------------|
| $N_{H1}$ (10$^{22}$ atoms cm$^{-2}$) | 1.75 ± 0.02 | 1.49 ± 0.01 | 1.29 ± 0.01 |
| $N_{H2}$ (10$^{22}$ atoms cm$^{-2}$) | 0.17 ± 0.01 | 0.21 ± 0.01 | 0.36 ± 0.01 |
| Covering fraction | 5.76 ± 0.01 | 6.46 ± 0.01 | 6.39 ± 0.01 |
| $kT$ (keV) | 0.27 ± 0.01 | 0.25 ± 0.01 | 0.7 ± 0.02 |
| Iron line energy (keV) | 61 ± 7 | 59 ± 6 | 21 ± 4 |
| Iron line width (keV) | 8.9 ± 0.1 | 8.8 ± 0.3 | 3.2 ± 0.4 |
| Iron line equivalent width (eV) | 5.38 ± 0.06 | 6.8 ± 0.1 | 6.5 ± 0.1 |
| Iron line flux$^a$ | 17.3 ± 0.1 | 20.4 ± 0.2 |
| Power-law index ($\alpha_1$) | 5.76 ± 0.35 | 7.2 ± 0.4 |
| High energy cut-off (keV) | 9.5 ± 0.5 | 5.7 ± 0.4 |
| E-fold energy (keV) | 1.47 (1589) | 1.49 (1589) | 1.35 (1589) |

$N_{H1}$ is equivalent hydrogen column density, $N_{H2}$ is additional hydrogen column density. Quoted source flux is not corrected for interstellar absorption.

This continuum model reduces to a simple power law with negative slope at low energies that is used to describe the spectra of accretion-powered X-ray pulsars at low energies. The analytical forms of the NPEX model is

\[ \text{NPEX}(E) = (N_1 E^{-\alpha_1} + N_2 E^{-\alpha_2}) \exp \left( -\frac{E}{kT} \right), \]

where $E$ is the X-ray energy (in keV), $N_1$ and $\alpha_1$ are the normalization and photon index of the negative power law, respectively, $N_2$ and $\alpha_2$ are those of the positive power law and $kT$ is the cut-off energy in units of keV. All five parameters of the NPEX continuum component were kept free. As in the case of the Suzaku observation of the Be transient X-ray pulsar A0535+262 (Naik et al. 2008), we could not constrain the positive power-law index $\alpha_2$ at 2 and fixed it at 3 in the subsequent analysis. The reduced instrument normalizations of the three XISs and PIN detectors were kept free and the values are found to be 1.00:1.03:0.99:1.00 for XIS3:XIS0:XIS1:PIN with a clear agreement with the previous values. It is found that, unlike the previous two continuum models, the blackbody component for soft excess in the pulsar was not required to fit the 0.8–70 keV spectrum. The values of the equivalent column densities $N_{H1}$ and $N_{H2}$ are found to be $\sim 1.3 \times 10^{22}$ and $4.96 \times 10^{22}$ atoms cm$^{-2}$, respectively. The covering fraction of the more absorbed power law $[= \text{Norm}_2/(\text{Norm}_1 + \text{Norm}_2)] = S_2/(S_1 + S_2)$ is found to be $\sim 0.36$. The partial covering model showed improvement in the spectral fitting compared to the previous two continuum models with reduced $\chi^2$ of 1.35 (for 1589 dof).

The parameters of the three different continuum models obtained from the simultaneous spectral fitting to the XIS and PIN data of the Suzaku observations of GRO J1008–57 are given in Table 1. The count rate spectra of the pulsar GRO J1008–57 are shown in Fig. 4 (for high energy cut-off power-law model), Fig. 5 (for NPEX model) and Fig. 6 (for partial covering model) along with the model components (top panels) and residuals to the best-fitting model (bottom panels).

The spectral fitting of the non-simultaneous OSSE and BATSE observations of the pulsar showed a marginal cyclotron absorption feature centred at ~88 keV (Shrader et al. 1999). The corresponding magnetic field of the pulsar is estimated to be ~10$^{13}$ G which is at the higher end of the magnetic field strengths of the neutron stars in the accreting X-ray binary pulsars, suggesting the detection at ~88 keV could be the second harmonics. However, in our spectral fitting, no such absorption feature was present at ~44 keV. Therefore, we did not add any additional cyclotron absorption component to the spectral fitting at ~44 keV.

\[ N(E) = \Gamma N_{H1} e^{-\Gamma E} I(E), \]

where $I(E) = 1$ for $E < E_c$, and $I(E) = e^{-\frac{E}{E_c}}$ for $E > E_c$.\[ \]

\[ \frac{E}{E_c} \]

\[ \frac{E}{E_c} \]
Figure 4. Energy spectrum of GRO J1008−57 obtained with the XIS and PIN detectors of the Suzaku TOO observation, along with the best-fitting model comprising a blackbody component, high energy cut-off power-law continuum model and a narrow iron line emission. The bottom panel shows the contributions of the residuals to the $\chi^2$ for each energy bin for the best-fitting model.

Figure 5. Energy spectrum of GRO J1008−57 obtained with the XIS and PIN detectors of the Suzaku TOO observation, along with the best-fitting model comprising a blackbody (BB) component, NPEX continuum model and a narrow iron line (Fe line) emission. The negative and positive power laws are marked by PL1 and PL2, respectively. The bottom panel shows the contributions of the residuals to the $\chi^2$ for each energy bin for the best-fitting NPEX continuum model.

Figure 6. Energy spectrum of GRO J1008−57 obtained with the XIS and PIN detectors of the Suzaku TOO observation, along with the best-fitting model comprising a partially absorbed high energy cut-off power-law continuum model and a narrow iron line emission. The bottom panel shows the contributions of the residuals to the $\chi^2$ for each energy bin for the best-fitting model.

3.2.5 Pulse-phase resolved spectroscopy

The presence of energy-dependent dips in the pulse profile of GRO J1008−57 prompted us to make a detailed study of the spectral properties at different pulse phases of the transient pulsar. To investigate the changes in the spectral parameters at different pulse phases, we used data from the XIS (both BI and FI) and HXD/PIN detectors. The XIS and PIN spectra were accumulated into 20 pulse-phase bins by applying phase filtering in the FTOOLS task XSELECT. The XIS and PIN background spectra and response matrices used for the phase-averaged spectroscopy were also used for the phase-resolved spectroscopy. Simultaneous spectral fitting was done in the 1.0–70.0 keV energy band. The phase-resolved spectra were fitted with all the three continuum models used to describe the phase-averaged spectrum, separately. We fixed some of the parameters such as the values of blackbody temperature (in case of Models 1 and 2, as given in Table 1), absorption column density, iron line energy and line at the phase-averaged values. The relative instrument normalizations were fixed at the values obtained from the phase-averaged spectroscopy. It was found that Models 1 and 2, when used to fit the phase-resolved spectra, did not provide good fit for some of the pulse phases. It was also found that the blackbody flux (i.e. the soft excess) was significantly high during the dip-like feature in the pulse profile. It is difficult to explain a significant increase in the blackbody flux during a narrow pulse phase (during the dip-like feature in the pulse profile). This is our main basis to reject the first two models and use the partial covering model (Model 3 – as given in Table 1) for pulse-phase-resolved spectroscopy. All the 20 pulse-phase-resolved spectra were fitted well with this model.

The parameters obtained from the simultaneous spectral fitting to the XIS and PIN phase-resolved spectra with Model 3 are shown in Fig. 7. The top panels of the figure show the pulse profiles of the pulsar obtained from XIS (left-hand panel) and PIN data (right-hand panel). The second panels show estimated source flux in 1–10 keV (left-hand panel) and 10–70 keV (right-hand panel). It can be seen that the shape of the pulse profiles and the estimated source flux over the pulse phases follow exactly the same pattern. It can be seen that the value of $N_{\text{H2}}$ is significantly high in the 0.9–1.05 pulse-phase range (the primary dip in the pulse profile). Very large value of $N_{\text{H2}}$ in the above pulse-phase range most probably due to the presence of accretion column or accretion stream in the pulsar. The high values of $N_{\text{H2}}$ with high values of covering fraction at the pulse phase of dip-like feature in the pulse profile (0.4–0.5 phase range) suggest that the dip-like feature is caused by the absorption due to additional matter at that pulse-phase range. The indifferent values of the iron emission-line flux suggest that the matter emitting the iron fluorescence line is probably distributed symmetrically around the pulsar. The values of the power-law photon index, cut-off energy and e-folding energy are found to be maximum in the 0.9–1.1 pulse-phase range, i.e. at the main dip in the pulse profile. There is no remarkable change in the values of the above three parameters during the short dip in the pulse profile (in the 0.4–0.5 pulse-phase range).
Figure 7. Spectral parameters obtained from the pulse-phase-resolved spectroscopy of Suzaku observation of GRO J1008−57. The errors shown in the figure are estimated for 1σ confidence level. In the figure, the iron line flux (Fe Flux), power-law flux (PO Flux) and \( N_H^2 \) are plotted in the units of \( 10^{-12} \), \( 10^{-10} \) erg cm\(^{-2}\) s\(^{-1}\) and \( 10^{22} \) atoms cm\(^{-2}\), respectively. The power-law flux is not corrected for low-energy absorption. The XIS and PIN pulse profiles are shown in the top left-hand and top right-hand panels, respectively.

4 DISCUSSION

4.1 Pulse profile

The temporal and spectral properties of the Be transient X-ray pulsar GRO J1008−57 have been reported only in a couple of occasions since its discovery. We detected X-ray pulsations in GRO J1008−57 as high as the 80–100 keV energy band, which has not been reported earlier. The pulse profile of GRO J1008−57 is found to be strongly energy dependent, i.e. a double-peaked profile in the soft X-ray energy band (<10 keV) and a single-peaked smooth profile in hard X-rays. The double-peaked profile at soft X-rays, as shown here in this paper, is found to be different from that of the single-peaked profile (in the 1–4 keV energy range) obtained from the EXOSAT observation of GRO J1008−57 in 1985 (Macomb et al. 1994). Similar changes in the shape of pulse profiles are also seen in the Be transient X-ray pulsar A0535+262 (Naik et al. 2008), a single-peaked profile in the quiescence (Mukherjee & Paul 2005) and a double-peaked profile during outbursts (at high luminosity). The double-peaked pulse profiles seen in GRO J1008−57 agrees with the luminosity dependence of the pulse profiles as seen in other pulsars. The presence of dip-like structures in the pulse profiles of these X-ray pulsars is described as due to the obscuration of matter to the radiation. As we showed here, the dip-like feature in the pulse profile of GRO J1008−57 is probably due to the additional absorption (other than the Galactic column density) at the pulse phase.

4.2 Spectroscopy

The broad-band X-ray spectrum of GRO J1008−57 has been described here for the first time in detail. Shrader et al. (1999) tried to explain the pulsar spectrum obtained from the OSSE data by a thermal bremsstrahlung model with a characteristic temperature \( kT = 19 \) keV. However, when the spectral fitting was extended towards the low energy (ASCA energy range), the fitting was inconsistent. The statistics was improved marginally because of the addition of an absorption component at \( \sim 88 \) keV for the possible cyclotron features. Shrader et al. (1999), when the ASCA, BATSE and OSSE observations of the pulsar were fitted simultaneously, found that the broad-band spectrum can be described by an absorbed power law with high energy cut-off and a Gaussian component for the iron emission line. However, the ASCA, BATSE and OSSE observations of the pulsar were not simultaneous. The mid-points of ASCA and OSSE observations used were separated by 4 d during which time the source intensity was halved. As the spectrum of Be transient pulsars can differ at different luminosity states, the broad-band spectral analysis of the Suzaku observations of the pulsar can give better information on the properties.

Selection of an appropriate continuum model is important to investigate the presence of several features in the pulsar spectrum, such as the soft excess represented by a blackbody component, emission lines, cyclotron absorption features, etc. Most of the transient Be X-ray binary pulsars undergo periodic outbursts due to the enhanced mass accretion when the neutron star passes through...
the dense regions of the circumstellar disc or periastron passage when the outer edge of the disc is stripped off resulting in sudden accretion of matter on to the neutron star. During the passage, the value of the absorption column density increases compared to the value of the Galactic column density in the source direction. The spectral fitting to the data obtained from ASCA, BATSE and OSSE observations of the transient pulsar GRO J1008−57 during the 1993 August outburst yielded the value of \( N_{\text{H}} \) in the range of 0.8−1.73 \( \times 10^{22} \) atoms cm\(^{-2} \) (Table 1; Shrader et al. 1999). In case of data obtained from the Suzaku observation of the pulsar, it is found that the 0.8−70.0 keV broad-band spectra can be well described by three different continuum models with similar statistical parameters. The high energy cut-off power-law model and NPEX continuum model yielded higher value of \( N_{\text{H}} \) than that of the Galactic value in the direction of the pulsar. It is interesting to note that, in spite of a high value of column density, a blackbody component of temperature \( kT \sim 0.2 \) keV was also required for these two continuum models to describe the broad-band spectrum of the pulsar. In these two models, it is estimated that the absorption-corrected flux of the soft X-ray excess (blackbody) in GRO J1008−57 is about 2 per cent of the unabsorbed source flux in the 0.8−70 keV energy range.

The third model, i.e. the partial covering model, however, fits the pulsar spectrum comparatively better than the previous two continuum models. Based on our results from the phase-resolved spectroscopy, the earlier two continuum models were not preferred to describe the properties of the pulsar. In the partial covering model, \( N_{\text{H}} \) is considered as the Galactic hydrogen column density, and \( N_{\text{H2}} \) is interpreted as the column density of the material that is local to the neutron star. The value of \( N_{\text{H2}} \) is maximum during the primary dip that is interpreted as due to the accretion column. The high value of \( N_{\text{H2}} \) and the covering fraction at 0.4−0.5 pulse-phase explain the dip-like feature in the pulse profile. The broad-band spectroscopy of GRO J1008−57 also shows the presence of a narrow iron K\( \alpha \) emission line at 6.4 keV. The iron emission line is generally interpreted as due to the fluorescent line from the cold matter in the surrounding region of the neutron star.

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