Long-term X-ray variability characteristics of the narrow-line Seyfert 1 galaxy RE J1034+396

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ABSTRACT
We present the results of our study of the long-term X-ray variability characteristics of the narrow-line Seyfert 1 galaxy RE J1034+396. We use data obtained from the AstroSat satellite along with light curves obtained from XMM–Newton and Swift–XRT. We use the 0.3–7.0 keV and 3–20 keV data, respectively, from the SXT and the LAXPC of AstroSat. The X-ray spectra in the 0.3–20 keV region are well fitted with a model consisting of a power law and a soft excess described by a thermal Compton emission with a large optical depth, consistent with the earlier reported results. We have examined the X-ray light curves in the soft and hard X-ray bands of the SXT and LAXPC, respectively, and find that the variability is slightly larger in the hard band. To investigate the variability characteristics of this source at different time-scales, we have used X-ray light curves obtained from XMM–Newton data (200 s to 100 ks range) and Swift–XRT data (1 to 100 d range) and find that there is evidence to suggest that the variability increases sharply at longer time-scales. We argue that the mass of the black hole in RE J1034+396 is likely to be \( \sim 3 \times 10^6 \) \( M_{\odot} \), based on the similarity of the observed quasi-periodic oscillation (QPO) to the high-frequency QPO seen in the galactic black hole binary GRS 1915+105.

Key words: accretion, accretion discs – galaxies: active – galaxies: individual: RE J1034+396 – galaxies: Seyfert – X-rays: galaxies.

1 INTRODUCTION
The active galactic nucleus (AGN) RE J1034+396 (also known as Zw212.025) at redshift \( z = 0.042 \) is a narrow-line Seyfert 1-galaxy (NLS1) (Pounds, Done, & Osborne 1995; Mason, Puchnarewicz, & Jones 1996; Breeveld & Puchnarewicz 1998; Puchnarewicz, Mason, & Siemiginowska 1998). It was first observed during the ROSAT WFC All-Sky Survey in 1990 (Pounds et al. 1993). It has since been observed on many occasions at different wavelengths, from radio to X-rays (Puchnarewicz et al. 1995, 2001; Pounds et al. 1995; Breeveld & Puchnarewicz 1998). Further observations were made in X-rays by ASCA (GIS & SIS) in 1994 (Serlemitsos et al. 1995), the Deep Survey Spectrometer onboard EUVE in 1997, the BeppoSAX narrow-field instrument in 1997 (Puchnarewicz et al. 2001), and XMM–Newton in 2007 (Middleton et al. 2009), and in the optical with the twin-armed ISIS spectrograph on the William Herschel Telescope in La Palma.

The 0.1–2.4 keV spectrum observed with the ROSAT Position Sensitive Proportional Counter (PSPC, Pfeffermann et al. 1986) showed an unusual ‘big blue bump’ (BBB) with a high temperature whose high energy turnover is observed at around 0.4 keV in the soft X-ray band (Puchnarewicz et al. 1995, 1998). The BBB has a very high temperature (\( kT \sim 100 \) eV), dominating the extreme-ultraviolet (EUV) and soft X-ray emission and leaving a bare power-law like continuum component in the optical (Puchnarewicz et al. 1995, 1997). The lack of BBB emission in the UV as suggested by IUE data implies a very hot accretion disc around a relatively low-mass
black hole ($\sim 10^6 M_\odot$) (Puchnarewicz et al. 1995). The strong and variable ultrasoft X-ray excess could be explained by a high mass accretion rate onto a relatively low-mass black hole (Pounds et al. 1995). Examining a wide-band spectral energy distribution (SED) of this source, Done et al. (2012) suggest that the spectrum consists of three components: a black body from the disc (representing the BBB), a hard coronal component (power law at high energies), and a low-temperature high-optical-depth Comptonization of the disc emission in the soft X-ray region.

The data from a long XMM–Newton observation (91 ks) showed a significant quasi-periodic oscillation (QPO) signal ($\nu = 2.7 \times 10^{-4}$ Hz, corresponding to a period of about 1 h) in the X-ray power spectrum for RE J1034+396 (Gierliński et al. 2008), similar to the QPOs seen in the X-ray power spectrum of black hole binaries (BHBs) (Middleton et al. 2009; Bian & Huang 2010). As AGNs and quasars are thought to be scaled-up versions of galactic BHBs, powered by accretion onto supermassive black holes with masses of $10^6$–$10^9 M_\odot$ (Gierliński et al. 2008), the QPOs seen in this source signify that accretion properties of AGNs are similar to the accretion flow around the BHBs (Middleton et al. 2009).

In this paper, we present the results from our investigation of the long-term X-ray variability characteristics of RE J1034+396 using AstroSat data along with archival XMM–Newton and Swift–XRT data. In the next section, we present the AstroSat observations and in Section 3, we present the variability study using archival data from XMM–Newton and Swift–XRT. In the last section, we discuss the results in the context of the mass of the black hole in this source.

2 ASTROSAT OBSERVATIONS

AstroSat, the first Indian multiwavelength space observatory successfully launched on 2015 September 28, has five scientific instruments onboard (Singh et al. 2014). These are the Soft X-ray focusing Telescope (SXT), the Large Area X-ray Proportional Counters (LAXPC), the Cadmium Zinc Telluride Imager (CZTI), the Scanning Sky Monitor (SSM), and the UltraViolet Imaging Telescope (UVIT). RE J1034+396 was observed by AstroSat on 2016 April 21–22 (Observation ID : G05_238T03_9000000424). In this work, data from the SXT and LAXPC are used.

2.1 SXT observations

The SXT onboard AstroSat is a grazing incidence X-ray telescope with a focal length of 2 m with a thermoelectrically cooled CCD in the focal plane. The effective area of the SXT is $\sim 65$ cm$^2$ at 1.5 keV. It covers the energy range of 0.3–8 keV, with an energy resolution of 5–6 per cent at 1.5 keV. It has a field of view of $\sim 40$ arcmin diameter and its angular resolution is 2 arcmin full width at half-maximum (FWHM). The point spread function is described by a double King function with FWHM of 40 arcsec for the inner core (Singh et al. 2016, 2017). RE J1034+396 was observed with the SXT in the photon-counting (PC) mode.

SXT observations are carried out with a Sun-avoidance angle $\geq 45$ deg and RAM angle (the angle between the payload axis and the velocity vector direction of the spacecraft) $> 12$ deg to ensure the safety of the instrument. The level 1 data from individual orbits are received at the SXT Payload Operation Centre (POC) from the Indian Space Science Data Center (ISSDC). These are then processed using the sxtpipeline at the POC. The sxtpipeline does the event extraction, the time tagging of events, the coordinate transformation from raw (detector) to sky coordinates, bias subtraction and adjustment, flagging of bad pixels and calibration source events, event grading (grade definition similar to Swift–XRTI; see Romano et al. 2005), the pulse height amplitude (PHA) construction for each event, the conversion from the event PHA to pulse invariant (PI), and a search for hot and flickering pixels. Further screening criteria such as selecting events with a bright Earth-avoidance angle of $\geq 110$ deg and removing data taken during the passage through the South Atlantic Anomaly (SAA) using the condition that the Charged Particle Monitor (CPM) rate is below 12 counts s$^{-1}$ are applied. Events with grades $> 12$ are also removed. Good time interval (GTI) files and level 2 quick-look products such as an image, spectrum, and light curve are produced for the entire field of view for each orbit (Singh et al. 2016, 2017). Using a PYTHON script developed by the SXT team, GTIs during each orbit were selected, time overlaps between consecutive orbit data files were removed, and a merged event file of all cleaned events was generated. This resulted in an exposure of 42.8 ks.

Using the cleaned event file an image was created (Fig. 1), and source and background regions were chosen. For this, xselect was used to extract light curves for 40 circles centred on the source with radii increasing in steps of 0.5 arcmin. Average count rates in the 0.3–7 keV energy range were estimated and surface brightness (counts per sec per unit sky area) values were calculated for the 40 annular regions. The variation of these photon fluxes with radius is shown in Fig. 2. The variation of the photon flux with radius obtained from a source-free sky image analysed in the same way is also shown. Error bars shown in the figure correspond to 1$\sigma$. It can be seen from the figure that beyond 10 arcmin, the source and the background count rates are similar to each other. The total count rates in the annular regions with inner and outer radii of 13 and 19 arcmin are estimated to be $(1.26 \pm 0.10) \times 10^{-4}$ counts s$^{-1}$ arcmin$^{-2}$ and $(1.12 \pm 0.09) \times 10^{-4}$ counts s$^{-1}$ arcmin$^{-2}$ respectively for the source and background runs. Here, the errors are estimated as the rms variation in the data. Hence, we have used a region with a radius of 10 arcmin around the RE J1034+396 location as the source region and an annular region with an inner radius of 13 arcmin and an outer radius of 19 arcmin as the background.
average variance from measurements for data with $\text{err}^2_2$.

LAXPC LX20. Time in seconds starts from 2016 April 21 03:00 (UTC), i.e. light curve of RE J1034+396 in the 3–20 keV band from the top layer of energy range 0.3–7 keV from SXT observations. Lower panel: orbit-wise light curve of RE J1034+396 in the Figure 3.

Suitable background files, based on a model built from the observed source-free sky regions, are also generated. Data from source-free sky regions observed within a few days of the source observation are used and appropriate scaling is performed depending on the orbit. A fit to the variation of background counts as a function of latitude and longitude is used. In the case of a difference in the gain between the source and background spectral files, an appropriate gain shift is applied to the background file.

To generate the light curve, source and background spectra are produced for each orbit. To improve the statistics, data from only the top layers are used. Data from the three LAXPC units (called LX10, LX20, and LX30) are analysed separately. LX30 was suspected to have undergone a gas leakage resulting in a continuous gain shift (Antia et al. 2017) and hence these data were not used in the present analysis. Orbit-wise source and background spectra are compared in the 35–80 keV region. In the top layer, no source counts are expected in this energy range. For the LAXPC unit LX20, the ratios of source to background counts in various pulse height (pha) channels were found to be consistent with a constant. Hence, the ratio of total counts from source to background spectra was used as the normalization factor for each orbit. It was found to vary from 0.94 to 1.02. For LX10, the channel-wise ratio showed a linear trend making the procedure for correction difficult. We therefore have not used data from LX10 for further analysis.

Using a total of 67.3 ks of useful data from the top layer of LX20 (LX20-L1), the light curve for the 3–20 keV band shown in the lower panel of Fig. 3 was generated. For each orbit (with an average source exposure of ~3 ks), the normalized average background rate has been subtracted from the source count rate. For this LAXPC time-series, an FVA of 0.278 ± 0.053 is found.

We note that the data from each satellite orbit (shown in Fig. 3) are not strictly simultaneous for the SXT and the LAXPC instruments, primarily because the Earth elevation-angle data-selection criterion is more stringent for the SXT. The LAXPC light curve, however, has a significantly higher fractional variability than that for the SXT.

2.3 Spectral analysis

X-ray spectra for the source and background regions for the entire SXT dataset were extracted (as described in Section 2.1). Data from

1. http://astrosat-ssc.iucaa.in/?q=documents
the LX20 top layer were used to generate orbit-wise on-source and background spectra using the prescription given in Section 2.2. These were combined using appropriate scaling factors. Further, these merged source and background spectra were compared in 35–80 keV region and normalized.

XSPEC-compatible RMF and ARF files for the SXT and LAXPC were obtained from the AstroSat Science Support Cell. These were sxt.spc.psi.x01v03.arf, sxt.spc.mat.g00t12.rmf for the SXT and lx20.scm.sh08l1v01.rmf for the LAXPC unit LX20. SXT spectra were binned to a minimum of 20 counts per energy bin using GRPPHA to facilitate $\chi^2$ fitting. XSPEC (version 12.9.0) (Arnaud 1996) was used. Energy ranges of 0.3–7 keV and 3–20 keV were used for the SXT and LX20, respectively. The SXT and LX20 data were fit simultaneously with a model including components for the line-of-sight absorption, a soft excess, and a power-law tail similar to that used by Middleton et al. (2009). Solar abundances were set to the most recent aspl model (Asplund et al. 2009); photoelectric absorption cross-sections were set to vern, and the default Lambda cold dark matter cosmology ($H_0 = 70$, $q_0 = 0.0$, $\Omega_\Lambda = 0.73$) was used. Line-of-sight absorption was modelled with the Tuebingen–Boulder ISM absorption model (Tbls) with the N_H value fixed at the galactic value of 1.47 $\times$ 10^{20} cm$^{-2}$ (Middleton, Uttley, & Done 2011). The soft excess was modelled using the compt model (Titarchuk 1994), for the Comptonization of soft photons in a hot plasma. A power law was used to model continuum emission over the 0.3–20 keV range. To account for the relative normalization between the SXT and LX20, constant multiplicative factors for the two instruments were incorporated. The constant factor was fixed to 1 for the SXT and was allowed to vary and fitted for LX20. The auxiliary response file sxt.spc.psi.x01v03.arf used for the SXT excludes a circular region with a 1 arcmin radius centred on the source, leading to an overestimation of the source flux. A correction factor for this effect has been estimated using SXT data from a bright source (1ES1959+650). It is found to be about 0.92 and this correction is applied to the SXT flux estimate.

A difference in the SXT gain function compared to that used in the response matrix revealed by residuals near the gold absorption edge at $\sim$2 keV was corrected by using the gain-fit command. While executing this command, the slope was fixed to 1 and the offset was varied. A positive gain offset of 33 eV was seen and for the best fit a $\chi^2$/degrees of freedom = 212/146 was obtained with a null hypothesis probability of 3.08 $\times$ 10^{-4}. The best-fitting model parameters and their 90 per cent confidence errors are given in Table 1. The relative normalization between LX20 and the SXT is 1.37 $\pm$ 0.17. The fitted spectra are shown in Fig. 4 along with the spectral energy distribution and residuals in terms of $\chi^2$.

Middleton et al. (2009) made a detailed spectral analysis of RE J1034+396 using the XMM–Newton data when the high-frequency QPO (HFQPO) was detected and concluded that the soft excess

<table>
<thead>
<tr>
<th>$\Gamma^a$</th>
<th>$T_0$ (keV)</th>
<th>$kT_e$ (keV)</th>
<th>$\tau$</th>
<th>const</th>
<th>$\chi^2$/dof</th>
<th>$F^b$ (1–10 keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.80 $\pm$ 0.09</td>
<td>$0.03^{+0.02}_{-0.01}$</td>
<td>$0.14^{+0.025}_{-0.021}$</td>
<td>21.157$^{4.10}_{-3.40}$</td>
<td>$1.37^{+0.17}_{-0.15}$</td>
<td>212/146</td>
<td>4.05</td>
</tr>
</tbody>
</table>

Notes: $^a$ Photon index, $n_H \propto E^{-\Gamma} \, \, (\text{ph cm}^{-2} \, \, \text{s}^{-1} \, \, \text{keV}^{-1})$. $^b$Flux in units of 10^{-12} erg cm$^{-2}$ s$^{-1}$.

3 SWIFT AND XMM–NEWTON OBSERVATIONS

To understand the source variability behaviour at different time-scales, we have analysed the data from Swift (spanning time-scales of days to months) and XMM–Newton (covering the shorter time-scales). Here, for consistency, we only use low-energy data ($\sim$0.5–8 keV) for an analysis of variability and power spectral density (PSD) generation at a variety of time-scales.

3.1 Swift observations

RE J1034+396 has been observed with the Swift–XRT (Burrows et al. 2004) on several occasions. In this work, we have used the data taken between 2016-01-30 00:14:24 and 2017-04-10 16:04:48, when the sampling was quite dense, obtained from the Swift public archive. All the data sets were processed using the XRTDAS (version 2) http://astrosat.ssc.iucaa.in/?q=data_and_analysis 3 https://swift.gsfc.nasa.gov/archive/
Table 2. FVA for RE J1034+396 at different time-scales obtained from different instruments.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Energy range (keV)</th>
<th>Observation dates</th>
<th>Duration</th>
<th>Bin Size</th>
<th>Variability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swift–XRT</td>
<td>0.3–8.0</td>
<td>2016 January 30–2017 April 10</td>
<td>436 d</td>
<td>4 d</td>
<td>0.119 ± 0.012</td>
</tr>
<tr>
<td>SXT</td>
<td>0.3–7.0</td>
<td>21 April 2016</td>
<td>42.7 ks</td>
<td>97 m</td>
<td>0.123 ± 0.031</td>
</tr>
<tr>
<td></td>
<td>0.3–1.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.0–7.0</td>
<td></td>
<td></td>
<td></td>
<td>0.123 ± 0.033</td>
</tr>
<tr>
<td>LAXPC (LX20-L1)</td>
<td>3.0–20.0</td>
<td>21 April 2016</td>
<td>67.3 ks</td>
<td>97 m</td>
<td>0.278 ± 0.053</td>
</tr>
<tr>
<td>XMM–Newton</td>
<td>0.3–10.0</td>
<td>May 31–2007 June 1</td>
<td>93 ks</td>
<td>200 s</td>
<td>0.088 ± 0.003</td>
</tr>
<tr>
<td></td>
<td>0.3–1.0</td>
<td></td>
<td></td>
<td></td>
<td>0.084 ± 0.003</td>
</tr>
<tr>
<td></td>
<td>1.0–10.0</td>
<td></td>
<td></td>
<td></td>
<td>0.157 ± 0.0084</td>
</tr>
</tbody>
</table>

Figure 5. Light curve of RE J1034+396 obtained from Swift–XRT observations during 2016-01-30 to 2017-04-10 in the 0.3–8 keV band. Count rates are average values for each observation. 0 corresponds to MJD 57400.

3.3.0) software package available under HEASOFT (version 6.21). The standard procedure involving XRTPIPELINE (version 0.13.3) was used for cleaning and calibrating event files. Data taken in the PC mode were used and the standard grade selection of 1–12 was applied in the analysis. A circular region with a radius of 90 arcsec centred at the location of RE J1034+396 was used to extract source counts. A 180 arcsec circular region offset from the source region was used for background estimation. Source and background light curves with bin sizes of 10 s and over the energy range of 0.3–8 keV were extracted using the tool XRTPRODUCTS (version 0.4.2). The source light curves were corrected for telescope vignetting as well as for PSF losses using the tool XRTLCCORR (version 0.3.8). Background-subtracted source light curves were then obtained. For each observation, an average rate was calculated. The observation-wise light curve is shown in Fig. 5. Typically there is one observation ∼1 ks every 3–4 days.

The fractional variability estimated for this light curve is 0.119 ± 0.012, very similar to that found with the SXT.

3.2 XMM–Newton observations

RE J1034+396 was observed with the XMM–Newton satellite (Jansen et al. 2001) on several occasions. We have analysed the data from observations carried out on 2007 May 31, which is one of the longest data stretches available with a duration of 93 ks (Gierliński et al. 2008). The XMM–Newton satellite has two X-ray instruments: (i) the European Photon Imaging Cameras (EPIC) and (ii) the Reflection Grating Spectrometers (RGS). There are three EPIC cameras, MOS1, MOS2, and PN. We use only the data from the EPIC-PN (Strüder et al. 2001). Data reduction was accomplished using the XMM–Newton SCIENCE ANALYSIS SYSTEM (SAS v:15.0.0) along with the recent calibration files. Unflagged events (flag = 0) with PATTERN ≤ 4 for the PN camera were used. Intervals during soft proton flares were excluded by generating a GTI file above 10 keV for the full field with RATE ≤ 0.85 counts s⁻¹, which gives the maximum signal-to-noise ratio. The filtered event file was extracted using evselect (SAS tool) for the energy range 0.2–10 keV. An image was extracted using xselect. Circular regions with a radius of 20 arcsec centred on the source and with a radius of 40 arcsec offset from the source were used to extract source and background counts, respectively. Light curves for source and background regions over the energy range of 0.3–10 keV with a bin size of 200 s were generated. The background-subtracted light curve shown in Fig. 6 has an FVA of 0.088 ± 0.003.

The variability amplitudes measured on different time-scales from the various instruments are shown in Table 2. For the SXT and XMM–Newton data, we also give the variability in two different energy ranges: below 1 keV (where the soft excess is dominant) and above 1 keV (dominated by the power law). The AstroSat results for the variability are consistent with the strong energy dependence pointed out by Middleton et al. (2009) and Middleton et al. (2011). The XMM–Newton 1–10 keV variability result is intermediate to the low-energy (SXT, Swift, and XMM) results and the higher-energy LAXPC band is also consistent.
high-frequency QPO seen at days, and scaling to supermassive black holes of mass $\sim 10^6 M_\odot$ in galactic black hole sources occur on a time-scale of several thousand years considering the fact that typical spectral state changes take place on such a time-scale. To quantify this, we have generated the PSD for RE J1034+396 (Alston et al. 2014). Even then, properties of the source behaviour such that the QPOs are seen only at certain states and the PSD remains unchanged. In Table 2, we have shown the variability amplitude at different time-scales and there is an indication of the variability increasing at longer time-scales. To quantify this, we have generated the PSD for RE J1034+396 (using the powspec tool in ftools) and shown in Fig. 7. In this figure, the combined PSD using the Swift–XRT, AstroSat SXT, and XMM–Newton EPIC-PN data is shown. The $F_{\text{rms}}$ (Equation 1) points for these three data sets are also included, by converting them to the units of $(\text{rms/mean})^2$ Hz$^{-1}$, by taking the average frequency from the bin size and data length (the Swift–XRT and XMM–Newton data are split into two bin sizes). These points are consistent with the PSD points and clearly show an increase of power at longer time-scales. This type of behaviour was seen in several AGNs in the past (see e.g. Uttley, McHardy, & Papadakis 2002).

### 4 DISCUSSION

RE J1034+396 is one of the rare AGNs showing a clear X-ray QPO signal (Gierliński et al. 2008). The detection of this QPO was facilitated by the fact that the observed QPO period ($\sim 1$ h) is quite short. Comparing to GRS 1915+105, which has a mass of $\sim 12.9 \pm 2.4 M_\odot$ (Hurley et al. 2013), this period could be the regular C-type QPO seen at a few Hz in the hard state of low-mass black hole sources (Reig et al. 2000), and would imply a black hole mass of $\sim 10^6 M_\odot$ in RE J1034+396. Alternatively, using the high-frequency QPO seen at $\sim 65$–$67$ Hz (Altamirano & Belloni 2012) would imply a black hole mass of $\sim 10^6 M_\odot$. One way to distinguish between these two possibilities is to examine the PSD on a wider frequency range and compare it with that seen from GRS 1915+105. The AstroSat data, combined with the other observations on diverse time-scales, provides this opportunity as shown below.

We assume that the general shape of the PSD does not change significantly on the time-scale of a few years – a reasonable assumption considering the fact that typical spectral state changes in galactic black hole sources occur on a time-scale of several days, and scaling to supermassive black holes of mass $\sim 10^6$–$10^9 M_\odot$, the spectral state change in RE J1034+396 should occur in $\sim 100$–$1000$ yr. We, however, note here that even in the state where high-frequency QPOs are produced, there could be subtle variations in the source behaviour such that the QPOs are seen only at certain ranges of hardness ratios (Altamirano & Belloni 2012). Similar state-dependent QPO observations have also been reported for RE J1034+396 (Alston et al. 2014). Even then, properties of the source such as the spectrum and PSD remain unchanged.

In Table 2, we have shown the variability amplitude at different time-scales and there is an indication of the variability increasing at longer time-scales. To quantify this, we have generated the PSD for RE J1034+396 (using the powspec tool in ftools) and shown in Fig. 7. In this figure, the combined PSD using the Swift–XRT, AstroSat SXT, and XMM–Newton EPIC-PN data is shown. The $F_{\text{rms}}$ (Equation 1) points for these three data sets are also included, by converting them to the units of $(\text{rms/mean})^2$ Hz$^{-1}$, by taking the average frequency from the bin size and data length (the Swift–XRT and XMM–Newton data are split into two bin sizes). These points are consistent with the PSD points and clearly show an increase of power at longer time-scales. This type of behaviour was seen in several AGNs in the past (see e.g. Uttley, McHardy, & Papadakis 2002). We have fitted the PSD with a model consisting of a zero-centred Lorentzian describing the flat-top noise and another Lorentzian for the narrow QPO component.

### Figure 7
Power spectrum of GRS1915+105 for high-frequency (cyan), C-type lower-frequency (red), and C-type higher-frequency (violet) QPOs, respectively, along with the corresponding best-fitting models (Reig et al. 2000).

### Figure 8
Power spectrum of RE J1034+396 obtained using Swift–XRT (green), AstroSat SXT (red) and XMM–Newton EPIC-PN (yellow) data. The brown points are calculated from the fractional variability amplitude $F_{\text{rms}}$ (Equation 1) for these three data sets, which show a clear increase of power at longer time-scales.

**Figure 7.** The PSD of RE J1034+396 obtained using Swift–XRT (green), AstroSat SXT (red) and XMM–Newton EPIC-PN (yellow) data. The brown points are calculated from the fractional variability amplitude $F_{\text{rms}}$ (Equation 1) for these three data sets, which show a clear increase of power at longer time-scales. To quantify this, we have generated the PSD for RE J1034+396 (using the powspec tool in ftools) and shown in Fig. 7. In this figure, the combined PSD using the Swift–XRT, AstroSat SXT, and XMM–Newton EPIC-PN data is shown. The $F_{\text{rms}}$ (Equation 1) points for these three data sets are also included, by converting them to the units of $(\text{rms/mean})^2$ Hz$^{-1}$, by taking the average frequency from the bin size and data length (the Swift–XRT and XMM–Newton data are split into two bin sizes). These points are consistent with the PSD points and clearly show an increase of power at longer time-scales. This type of behaviour was seen in several AGNs in the past (see e.g. Uttley, McHardy, & Papadakis 2002). We have fitted the PSD with a model consisting of a zero-centred Lorentzian describing the flat-top noise and another Lorentzian for the narrow QPO component. The reduced $\chi^2$ for this fit is 0.81 for 41 degrees of freedom and the best-fitting QPO frequency is $2.53^{+0.13}_{-0.08} \times 10^{-4}$ Hz. This is close to the value reported by Gierliński et al. (2008) and others. Note that, while the flat-top noise description of the Swift–XRT points appears to be reasonable, future availability of PSD points in the frequency range of $\sim 10^{-6}$ to $10^{-5}$ Hz might be required to verify this description.

For comparison, we have shown the PSDs of GRS 1915+105 in Fig. 8. These PSDs are generated using data from the Proportional Counter Array (PCA) onboard the Rossi X-ray Timing Explorer (RXTE). GRS 1915+105 was observed on many occasions with RXTE. We have chosen the data sets corresponding to high-frequency QPO (observation ID: 80701-01-28-01 on 2003 October 21), C-type QPO with lower frequency (observation ID: 10408-01-27-00 on 1996 July 26), and C-type QPO with higher frequency (observation ID: 10408-01-30-00 on 1996 August 18; Reig et al. 2000). The data were analysed using the standard procedure, light curves generated using the tool SPECTRUM under HEASOFT version 6.21 and the PSD determined using the powspec tool in FTOOLS.

In Fig. 9, we compare the three GRS 1915+105 PSD best-fitting model curves from Fig. 8 with the above-mentioned RE J1034+396 best-fitting model curve from Fig. 7 in the following way. The frequencies of each GRS 1915+105 PSD curve are scaled (divided) by a factor $k$, so that a GRS 1915+105 QPO appears at the RE J1034+396 PSD frequency $2.53 \times 10^{-4}$ Hz. Correspondingly, the powers of a GRS 1915+105 PSD are multiplied by the same factor. Fig. 9 shows that there is a marked similarity between the RE J1034+396 PSD curve and the GRS 1915+105 PSD curve with the high-frequency QPO, primarily in terms of the QPO width and the higher power at the longer time-scales. This is, however, not true for the GRS 1915+105 PSD curves for C-type QPOs. We, therefore, identify the RE J1034+396 QPO as a high-frequency QPO. The corresponding $k$-value is $67.5 \pm 2.5 \times 10^{-4} = 266 \ 798$, implying a mass of $(3.4 \pm 0.6) \times 10^6 M_\odot$ for the black hole in RE J1034+396. This is consistent with the mass ranges for this object reported by Gierliński et al. (2008) for the first time as well as by Czerny et al. (2016) more recently.
In conclusion, in this work we have presented the light curves and spectra of RE J1034+396 obtained from the SXT and LAXPC instruments of AstroSat. We have found an indication of an increase in the variability as a function of energy and also at longer timescales. We have combined these results with other archival data and found a reasonable indication of a wide-band PSD bearing a close resemblance to that seen in the galactic black hole source, GRS 1915+105. We conclude that the QPO seen in RE J1034+396 is more likely to be a high-frequency QPO, and use this to infer a mass for the black hole in RE J1034+396.

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