SAX J1808.4−3658: high-resolution spectroscopy and decrease of pulsed fraction at low energies

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ABSTRACT

XMM–Newton observed the accreting millisecond pulsar SAX J1808.4−3658 during its 2008 outburst. We present timing and spectral analyses of this observation, in particular the first pulse profile study below 2 keV, and the high-resolution spectral analysis of this source during the outburst. Combined spectral and pulse profile analyses suggest the presence of a strong unpulsed source below 2 keV that strongly reduces the pulsed fraction and a hard pulsed component that generates markedly double peaked profiles at higher energies. We also studied the high-resolution grating spectrum of SAX J1808.4−3658, and found several absorption edges and oxygen absorption lines with whom we infer, in a model independent way, the interstellar column densities of several elements in the direction of SAX J1808.4−3658.

Key words: pulsars: general – pulsars: individual: SAX J1808.4−3658.

1 INTRODUCTION

The accreting millisecond X-ray pulsar (AMXP) SAX J1808.4−3658 (J1808 from now on) was the first X-ray binary found to pulsate in the millisecond range, with a spin period of 2.5 ms (Wijnands & van der Klis 1998). It has been observed in outburst six times, roughly every 2.5 yr since 1996. During the outburst, the magnetic field is thought to channel part of the disc material on to the neutron star magnetic poles. The radiation emitted from the impact region (hot spot) and/or a slab of shocked material above it is then modulated at the neutron star spin period. This radiation is observed as pulsed emission that adds to the unpulsed emission coming from the accretion disc. A Comptonizing medium surrounding the impact region can upscatter part of the radiation to higher energies (Poutanen & Gierliński 2003). The pulsations and the X-ray spectrum were observed during previous outbursts by RXTE and a first study of the 1998 outburst was performed using those data (Poutanen & Gierliński 2003; Ibragimov & Poutanen 2008). J1808 was never observed below 2 keV during an outburst (except in the 2000 and 2005 outbursts at very low luminosity levels, see Wijnands 2003; Campina, Stella & Kennea 2008). This energy range is important to understand the pulse formation mechanism because it is here that both the hot spot and the accretion disc thermal emissions are expected to peak. Also, many absorption lines from the interstellar medium (ISM) are expected in this energy range. These lines are important to definitively determine the interstellar column density towards the source. Broad band spectral analyses of this XMM observation were reported by Papitto et al. (2009) and Cackett et al. (2009), who both focused on the study of the iron line emission at 6−7 keV. Here, we present the first simultaneous spectral and timing analysis of the pulsations of J1808 as observed with XMM–Newton during the 2008 outburst, with a particular attention to the lower energy range (<2 keV).

2 X-RAY OBSERVATION

J1808 was observed in outburst with XMM–Newton on 2008 October 1 (MJD 54740), for 63 ks of on-source exposure time. At the time of this observation, J1808 was at the beginning of the exponential decay stage of the outburst, with a relatively high flux level [see Hartman et al. (2009) for a description of the overall outburst light curve]. The XMM–Newton Observatory (Jansen et al. 2001) includes three 1500 cm² X-ray telescopes with the European Photon Imaging Camera (EPIC), and a Reflecting Grating Spectrometer (RGS; den Herder et al. 2001). An Optical Monitor is also present (Mason et al. 2001). It is used to follow optical counterparts and will not be considered in this work. The EPIC camera is composed of two MOS CCDs (Turner et al. 2001) and a pn CCD (Strüder et al. 2001). Each EPIC camera has a fixed, mode dependent frame read-out frequency, producing event lists in the 0.1−12 keV energy range. The RGS is composed of a double array of gratings and produces high resolution spectra in the 0.33−2.5 keV energy range.

Data have been processed using SAS version 8.0.1, and we have employed the most recent calibration files (CCF) available at the time the reduction was performed (2009 February). Standard data screening criteria were applied in the extraction of scientific products. After removing solar flares and telemetry dropouts the net pn
exposure time is 41 ks. The central CCD of MOS1 was operated in full frame mode with thin filters, and is heavily piled-up. For this reason, we do not consider the MOS1 data any further. The MOS2 was operated in timing window mode, and is also excluded from our analysis since the 1.5 ms time resolution is insufficient to study the pulsations, and its spectral capabilities for very bright sources are not as much calibrated as the pn camera. The pn camera was operating in timing mode (with a thin filter), in order to reduce pile-up and allow the high precision timing analysis required for an AMXP. We extracted the source photons from the pn with RAWX coordinates 26–49. The background is obtained from a region of the same size, at RAWX 2–25. Only photons with PATTERN≤4 were used. The extracted spectrum was rebinned before fitting to obtain at least 100 counts per bin and the pn energy resolution was not oversampled by more than a factor of 3. We also extracted first and second order RGS1 and RGS2 spectra, using the standard procedure reported in the XMM–Newton analysis manual, and again we ensured to have at least 100 counts per spectral bin in any RGS spectrum.

3 TIMING ANALYSIS

We have first corrected the event times to the barycentre of the Solar system (using the SAS tool barycen, and the optical position given in Hartman et al. 2008) and then we applied the 2008 outburst timing solution published in Hartman et al. (2009) in order to predict the phases of each photon detected and reconstruct the pulse profiles (see Patruno et al. 2009 for a detailed explanation of the timing technique). For the timing analysis, we use events in the 0.3–12 keV energy range. The pulse profiles are built by folding data segments of length ~3500 s for the pulse phase analysis. This length is chosen to guarantee sufficiently high signal-to-noise profiles even if the pulsed fractions are small. The pulses are then decomposed by fitting two harmonics with frequency fixed at the pulse frequency (fundamental, ν) and twice the pulse frequency (second harmonic, 2ν) plus a constant representing the non-pulsed emission.

We did not attempt to calculate a new timing solution since the precision of the solution achievable with the short observation baseline of XMM is at least an order of magnitude lower than what was obtained with the RXTE data (Hartman et al. 2009). The short baseline of the observation is also insufficient to model the timing noise that affects the pulse phases and that was extensively discussed in Hartman et al. (2008, 2009) for J1808. If timing noise is present, a systematic error is introduced in the determination of the pulse phases and spin frequency (Patruno et al. 2009).

Therefore, we decided to subtract the solution reported in Hartman et al. (2009) and obtain the phase residuals with respect to that constant pulse frequency plus Keplerian circular orbit model. The pulse-phase residuals of the fundamental drift by ≈0.1 cycles during the observation. We also found a correlation between these pulse-phase residuals and the 0.3–12 keV X-ray flux. We fitted the data with a linear relation that gives a χ² of 11.4 for 10 degrees of freedom, and a slope of (9.9 ± 1.2) × 10⁻⁴ cycle ct⁻¹ s⁻¹ (we quote the 1σ error).

The second harmonic is significantly detected in only ≈1/3 of the profiles, where a detection is defined as a ratio between the pulse amplitude and its statistical error larger than 3. When not detected, the second harmonic fractional amplitude upper limit was between 0.4 and 0.6 per cent rms at the 98 per cent confidence level. No correlation between pulse phases and flux was found for the second harmonic.

To increase the signal to noise and calculate the harmonic content of the pulsations in the whole energy band, we folded the entire 41 ks data into one single pulse profile. The fractional rms amplitude of the fundamental and second harmonic in the 0.3–12 keV energy band is 0.98(2) per cent rms and 0.33(3) per cent rms, respectively (1σ uncertainties).

We then repeated the procedure by dividing the observations in nine energy bands between 0.3 and 12 keV. The fractional amplitude of the pulse profile increases from 0.3 to 3 keV, and then it remains constant within the errors up to 12 keV (Fig. 1). The fundamental tracks the behaviour of the total pulse profile. The second harmonic increases monotonically in the energy range considered. At energies above ≈6 keV the fractional amplitudes of the fundamental and second harmonic are comparable and the overall pulse profile is double peaked (Fig. 1, see also Hartman et al. 2009).

4 SPECTRAL ANALYSIS

We performed spectral analysis using the EPIC-pn spectrum (extracted as reported in Section 2) in the 0.6–12 keV energy range, and the RGS1 and RGS2 in the 0.4–1.8 keV energy range for the
first order, and 0.7–1.8 keV for the second order. {	extsc{xspec}} version 11.3 was used for the spectral analysis.

To account for relative flux calibration uncertainties between different instruments, we fitted a multiplicative constant with the model, allowing for up to 10 per cent relative calibration flux scaling between EPIC-pn and RGS.\(^1\) The relative offsets between the instruments are found to be less than 4 per cent in all our fits. Furthermore, we included a 1.5 per cent systematic to the errors of each spectral bin (using the relative {	extsc{xspec}} tool) to take into account the calibration inaccuracies of each single instrument used.\(^2\) We first used solar abundances from Anders & Grevesse (1989) and cross-sections from Balucinska-Church & McCammon (1992) for the photoelectric absorption. We tried an absorbed power-law plus a multitemperature disc and a single temperature blackbody model [\textcolor{red}{\textit{phabs ($\text{diskbb + bboby + powerlaw}$)}}] as suggested in Cackett et al. (2009) and Papitto et al. (2009). The \(\chi^2\) was unacceptable, mainly because of unmodelled features in the data points between 0.3–2 and 6–7 keV.

The 6–7 keV energy range is where fluorescence lines of Fe are expected (George & Fabian 1991). Following Cackett et al. (2009) and Papitto et al. (2009) who claimed the detection of a broad iron K\(_\alpha\) line in this energy range, we fitted this feature with a \textit{diskline} model (see Table 1). We refer to Cackett et al. (2009) and Papitto et al. (2009) for discussion of this broad iron line. To model the 0.3–2 keV features, we first tried several photoelectric cross-sections, and different element abundances. The residuals are not very sensitive to the photoelectric cross-section parameters, while they strongly depend on the assumed abundances. The best-fitting model, however not yet satisfactorily, was found using the Balucinska-Church & McCammon (1992) cross-sections, and the Wilms, Allen & McCray (2000) abundances. The stronger low energy features in the residuals were coming from absorption and emission features close to the oxygen K-edge (O\(_\text{K}\)-edge) at 0.543 keV. We decided to model only the continuum and the iron K\(_\alpha\) line as a first step, ignoring the data between 0.5 and 0.6 keV.

This energy range and the single features it contains were then investigated separately by using the RGS data (see Section 4.1, and Table 1 for the continuum and Fe line spectral results).

The two weak features at 1.8 and 2.2 keV are known to be due to the instrumental Si and Au K edges, not yet perfectly calibrated, especially when dealing with \textit{timing} mode observations (see the EPIC calibration report in the footnote). We do not find evidence of a 0.871 keV O \textit{VII} edge (reported in Papitto et al. 2009), and no other significant edges are detected in the 0.8–1 keV range.

After removing the O–Si–Au edges (0.5–0.6 and 1.6–2.3 keV), we obtain \(\chi^2_\nu = 1.41\) (4051 d.o.f.). Given the high quality X-ray spectrum, the relatively high value of \(\chi^2_\nu = 1.41\) is very likely due to inter-calibration problems between the pn and the RGS spectra, and to the calibration uncertainties of each camera which emerge when observing bright sources. In fact, when using only the pn spectrum, we obtain a statistically acceptable fit with \(\chi^2_\nu = 0.95\) for 235 d.o.f., with the same spectral parameters as reported in Table 1. The same model applied to the RGS alone gives a \(\chi^2_\nu = 1.1\). Therefore, we accept the \(\chi^2_\nu = 1.41\) and do not further complicate the spectral model.

\subsection*{4.1 High-resolution spectroscopy}

We inferred the ISM abundances in a model independent way, by separately fitting the absorption edges to the RGS data. We used only the RGS1 and RGS2 first order spectra, which are the best calibrated and have a higher number of counts. The continuum parameters were kept fixed at the value reported in Table 1. We used \textit{vphasr} that allows to set fixed abundance parameters with respect to the solar composition and to isolate the single absorption edges. The strongest features were observed around the O\(_\text{K}\) edge (O\(_\text{K}\); see Fig. 3). To model this edge, we fixed at zero the oxygen abundance of the \textit{vphasr} model, and fit only the data around the O\(_\text{K}\) with an \textit{edge} model (note that the continuum is relatively constant in the small energy range around the edge itself, hence the modelling is independent on the broad band continuum model). The best-fitting gives \(O\text{K} = 0.5421 \pm 0.0003\) keV and \(\tau = 0.66 \pm 0.01\), with \(\tau = N_\text{O}/\sigma\) and \(\sigma\) the photoelectric cross-section. With the same method, we fitted also the iron L (Fe\(_\text{L}\)), neon K (Ne\(_\text{K}\)), magnesium K (Mg\(_\text{K}\)) and silicon K (Si\(_\text{K}\)) edges that lie in the RGS band. The column density for each element is reported in Table 2. The absorption features close to O\(_\text{K}\) were fitted with \textit{absorption} edges (0.5–0.6 and 1.6–2.3 keV), and the Wilms, Allen & McCray (2000) abundances. The stronger low energy features in the residuals were coming from absorption and emission features close to the oxygen K-edge (O\(_\text{K}\)-edge) at 0.543 keV. We decided to model only the continuum and the iron K\(_\alpha\) line as a first step, ignoring the data between 0.5 and 0.6 keV. This energy range and the single features it contains were then investigated separately by using the RGS data (see Section 4.1, and Table 1 for the continuum and Fe line spectral results).

\begin{table}
\centering
\caption{Spectral parameters for J1808 in outburst, from combined pn and all RGS data. Errors are at 1\textsigma confidence level. \(N_\text{H}\) is calculated with abundances from Wilms et al. (2000). Unabsorbed fluxes are given in the 0.5–10 keV energy range. The blackbody radius is calculated assuming a distance of 3.5 kpc and a neutron star mass of 1.4 \(M_\odot\). (a) The lower limit is quoted at 95 per cent confidence level. (b) \(\beta\) is the power-law index of the emissivity.}
\begin{tabular}{ll}
\hline Parameters & DiskBB+BB+PL+Diskline \\
\hline \(N_\text{H}\) (10\(^22\) cm\(^{-2}\)) & 0.16 \pm 0.02 \\
Inner disc \(kT\) (keV) & 0.20 \pm 0.01 \\
Disc flux (erg s\(^{-1}\) cm\(^{-2}\)) & (1.89 \pm 0.21) \times 10\(^{-10}\) \\
\(kT\) (keV) & 0.33 \pm 0.01 \\
BB radius (km) & 10.6 \pm 3.2 \\
BB Flux (erg s\(^{-1}\) cm\(^{-2}\)) & (1.22 \pm 0.15) \times 10\(^{-10}\) \\
Photon Index \(\Gamma\) & 2.11 \pm 0.01 \\
PL flux (erg s\(^{-1}\) cm\(^{-2}\)) & (1.53 \pm 0.09) \times 10\(^{-9}\) \\
\(E\text{Fe}\) (keV) & 6.45 \pm 0.08 \\
EW (eV) & 97.7 \pm 31.4 \\
\(R\text{Fe}\) (km) & 20 \pm 2 \\
\(R\text{O}\) (km) & 193 \pm 15 \\
\text{Incl. (°)} & >44 \\
\(\beta\) & -2.1 \pm 0.1 \\
Fe-line flux (erg s\(^{-1}\) cm\(^{-2}\)) & (6.8 \pm 0.2) \times 10\(^{-12}\) \\
Flux (erg s\(^{-1}\) cm\(^{-2}\)) & (1.85 \pm 0.08) \times 10\(^{-9}\) \\
Absorbed flux (erg s\(^{-1}\) cm\(^{-2}\)) & (1.51 \pm 0.08) \times 10\(^{-9}\) \\
\(\chi^2_\nu\) (d.o.f.) & 1.41 (4051) \\
\hline
\end{tabular}
\end{table}

\(^{1}\) http://xmm2.esac.esa.int/docs/documents/CAL-TN-0052-5-0.ps.gz
\(^{2}\) http://xmm2.esac.esa.int/external/xmm_sw/calib
decrease below 2 keV. However, an empirical power-law model requires a disc contributing only \( \approx 20 \) per cent of the power-law flux below 2 keV (Fig. 2). Therefore, the disc is not the only responsible of the steep decrease of pulse fractional amplitudes below 2 keV. However, an empirical power-law model is unphysical, and a self-consistent physical scenario would require a sharp decrease of the power-law component below \( \approx 2–3 \) keV. In that case, the unpulsed disc emission might dominate below 2 keV and explain the sudden drop of the pulse amplitudes at those energies. A Comptonization model with a shocked plasma in a slab geometry is expected to cut-off below \( \approx 3 \) keV and was already proposed by Gierliński & Poutanen (2005) for the AMXP XTE J1751–305. The hot single temperature blackbody would then be produced by the pulsating emission of the hot spot, the multitemperature blackbody by the unpulsed radiation of the accretion disc and the hard component by the pulsed Comptonized radiation of the shock around the hot spot.

The origin of the second harmonic can be related to a different pulse profile of the hard emission compared to the lower-energy blackbody as was suggested by Gierliński, Done & Barret (2002) and Poutanen & Gierliński (2003) for RXTE observations of J1808, and by Gierliński & Poutanen (2005) for XMM and RXTE observations of XTE J1751–305. This might result from a different angular distribution of the Comptonized radiation, which is expected as it is produced in the optically thin accretion shock, but not at the stellar surface as the blackbody emission.

The reason why the phase of the fundamental is correlated with the X-ray flux while the second harmonic is not, can then be related with different formation processes for the fundamental and the second harmonic. If the hot spot contributes only to the fundamental frequency while the Comptonization region contributes to both the fundamental and the second harmonic, the fundamental pulse phase may track the hot spot position. The phase of the second harmonic instead will be affected by the Comptonization process and might come from an extended region around the hot spot, covering a large area of the neutron star surface. The hot spot can instead come from a well-defined region on the neutron star surface, and can move according to the X-ray flux fluctuations thus producing the pulse phase wandering correlated with X-ray flux (Romanova et al. 2004; Lamb et al. 2008).

We also measured the first model independent column densities of several elements in the line of sight of J1808 (Table 2). The most precise measurement comes from the oxygen column density, from which we could derive the equivalent hydrogen column density \( N_H = 1.4 \times 10^{21} \) cm\(^{-2}\), assuming abundances from Wilms et al. 2000. This determination is particularly important: (i) in the study of the X-ray emission of this object during quiescence and cooling, where the uncertainty in the assumed \( N_H \) value could alter the

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**Table 2.** ISM edges and lines in the direction of SAX J1808.4–3658.

| Edge  | Energy (keV) | \( \tau \) | \( \sigma \) | \( N_x \) |
|-------|-------------|----------|-----------|-----------|
| O\(_K\) | 0.5421 ± 0.0003 | 0.66 ± 0.01 | 5.642 | 11.7 ± 0.2 |
| Fe\(_L\) | 0.712 ± 0.005 | 0.08 ± 0.02 | 4.936 | 1.6 ± 0.4 |
| Ne\(_K\) | 0.865 ± 0.004 | 0.10 ± 0.02 | 3.523 | 2.8 ± 0.5 |
| Mg\(_K\) | 1.281 ± 0.007 | 0.06 ± 0.01 | 2.191 | 2.7 ± 0.4 |
| Si\(_K\) | 1.79 ± 0.007 | 0.14 ± 0.01 | 1.476 | 9.4 ± 0.6 |

\( 1.14 \times 10^{21} \) cm\(^{-2}\); Dickey & Lockman (1990) and Kalberla et al. (2005), respectively.

From the measurement of the EW of the O\(_I\), O\(_II\) and O\(_III\) 1s–2p transitions, using the method of the curve of growth, we have an independent measure of the relative oxygen abundances, using the formula \( EW_x = 8.85 \times 10^{-19} N_x \lambda^2 f_{ij} \), where \( \lambda \) is the wavelength of the line, and \( f_{ij} \) the oscillator strength for the transition (Spitzer 1978). We found an \( N_{\text{oxygen}} \) consistent with that inferred from the O\(_K\)-edge (see Table 2).

**Figure 2.** \( vF_v \) plot of the model used to fit the continuum. The power-law flux dominates over the other spectral components.

**Figure 3.** High-resolution RGS1 spectrum of J1808 around the O\(_K\) edge: O\(_I\), O\(_II\) and O\(_III\) absorption lines for the 1s–2p transition. The O\(_I\) line falls too close to the instrumental edge to be measured.
reliability of the source intrinsic luminosity (see e.g. Heinke et al. 2009 for cooling studies of SAX J1808.4−3658 and Yakovlev et al. 2005 for a discussion of the problem), and (ii) for optical studies who can now rely on a more precise determination of the extinction value towards this system.

It is interesting to compare the abundances we derived from the edge fitting with the expected value for the ISM (as reported by Wilms et al. 2000). We find that in the direction of J1808, the Ne/O abundance is ∼0.23, slightly larger than in the ISM (∼0.18), which maybe be pointing to an Ne-rich environment as observed in other low mass X-ray binaries (Juett, Psaltis & Chakrabarty 2001).

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REFERENCES

Anders E., Grevesse N., 1989, Geochim. Cosmochim. Acta, 53, 197
Balucinska-Church M., McCammon D., 1992, ApJ, 400, 699
Cackett E. M., Altamirano D., Patruno A., Miller J. M., Reynolds M., Linares M., Wijnands R., 2009, ApJ, 634, L21
Campana S., Stella L., Kennea J. A., 2008, ApJ, 684, L99
Costantini E., Freyberg M. J., Predehl P., 2005, A&A, 444, 187
den Herder J. W. et al., 2001, A&A, 365, L7
Diaz Trigo M., Parmar A. N., Boirin L., Motch C., Talavera A., Balman S., 2009, A&A, 493, 145
Dickey J. M., Lockman F. J., 1990, Ara&A, 28, 215
George I. M., Fabian A. C., 1991, MNRAS, 249, 352
Gierliński M., Poutanen J., 2005, MNRAS, 359, 1261
Gierliński M., Done C., Barret D., 2002, MNRAS, 331, 141
Gould R. J., Jung Y. D., 1991, ApJ, 373, 271
Hartman J. M. et al., 2008, ApJ, 675, 1468
Hartman J. M., Patruno A., Chakrabarty D., Markwardt C. B., Morgan E. H., van der Klis M., Wijnands R., 2009, ApJ, submitted (arXiv:0906.1470)
Heinke C. O., Jonker P. G., Wijnands R., Deloye C. J., Taam R. E., 2009, ApJ, 691, 1035
Kalberla P. M. W., Burton W. B., Hartmann D., Aarnio E. M., Bajaja E., Morras R., Pöppel W. G. L., 2005, A&A, 440, 775
Ibragimov A., Poutanen J., 2008, MNRAS, submitted (arXiv:0901.0073)
Jansen F. et al., 2001, A&A, 365, L1
Juett F., Psaltis D., Chakrabarty D., 2001, ApJ, 560, L59
Lamb F. K., Boutloukos S., Van Wassenhove S., Chamberlain R. T., Lo K. H., Clare A., Yu W., Miller M. C., 2008, ApJ, submitted (arXiv:0808.4159)
Mason K. O. et al., 2001, A&A, 365, L36
Patruno A., Di Salvo T., D’Azi A., Iaria R., Burderi L., Riggio A., Menna M. T., Robba N. R., 2009, A&A, 493, L39
Patruno A., Hartman J. M., Wijnands R., van der Klis M., Chakrabarty D., Morgan E. H., Markwardt C. B., 2008, Astron. Tel., 1760, 1
Patruno A., Hartman J. R., Wijnands R., Chakrabarty D., van der Klis M., 2009, ApJ, submitted (arXiv:0906.4323)
Poutanen J., Gierliński M., 2003, MNRAS, 343, 1301
Romanova M. M., Ustyugova G. V., Koldoba A. V., Lovelace R. V. E., 2004, ApJ, 610, 920
Spitzer L., 1978, Physical Processes in the Interstellar Medium. Wiley-Interscience, New York, p. 333
Strieder L. et al., 2001, A&A, 365, L18
Takei Y., Fujimoto R., Mitsuda K., Onaka T., 2002, ApJ, 581, 307
Turner M. J. L. et al., 2001, A&A, 365, L27
Verner D. A., Ferland G. J., Korista K. T., Yakovlev D. G., 1996, ApJ, 465, 487
Wijnands R., 2003, ApJ, 588, 425
Wijnands R., van der Klis M., 1998, Nat, 394, 344
Wilms J., Allen A., McCray R., 2000, ApJ, 542, 914
Yakovlev D. G., Gnedin O. Y., Gusakov M. E., Kaminker A. D., Levenson K. P., Potekhin A. Y., 2005, Nucl. Phys. A, 752, 590

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