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SPIN EQUILIBRIUM WITH OR WITHOUT GRAVITATIONAL WAVE EMISSION: THE CASE OF XTE J1814-338 AND SAX J1808.4-3658

B. HASKELL AND A. PATRUNO
Astronomical Institute "Anton Pannekoek," University of Amsterdam, Postbus 94249, 1090 GE Amsterdam, The Netherlands
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ABSTRACT

In this Letter we present a new analysis of the torques acting on the accreting millisecond X-ray pulsars SAX J1808.4-3658 and XTE J1814-338, and show how our results can be used to constrain theoretical models of the spin evolution. In particular, we find upper limits on any spin-up/down phase of XTE J1814-338 of $|\dot{\nu}| \lesssim 1.5 \times 10^{-14}$ Hz s^{-1} at 95% confidence level. We examine the possibility that a gravitational wave torque may be acting in these systems and suggest that a more likely scenario is that both systems are close to spin equilibrium, as set by the disk/magnetosphere interaction.

Key words: gravitational waves – pulsars: individual (XTE J1814-338, SAX J1808.4-3658)

Online-only material: color figures

1. INTRODUCTION

Accreting millisecond X-ray pulsars (AMXPs) are one of the best laboratories to test our understanding of strong gravity and of matter at extreme densities. In these systems a neutron star (NS) in a binary accretes gas from a less evolved low mass donor. During the accretion process angular momentum is transferred to the NS, which can be spun up to millisecond periods.

This picture is not, however, without its complications. As more AMXPs and millisecond radio pulsars are discovered there appears to be strong evidence for a cutoff in the distribution of the spin rates at approximately 730 Hz, which is well below the Keplerian breakup frequency for these objects (Chakrabarty et al. 2003; Patruno 2010). It thus appears that the torques acting on these systems are stopping them from spinning up to the breakup limit. A detailed analysis of the torques acting on an AMXP in a low-mass X-ray binary (LMXB) is a challenging problem, both from a theoretical and an observational point of view. Observationally the problem is complicated by the presence of strong timing noise that appears to be correlated with the X-ray flux in at least six AMXPs (Patruno et al. 2009). Theoretically, on the other hand, it is believed that the NS could also be spun down during accretion if the angular momentum transferred from the gas is not high enough, in what is known as the "propeller" phase (Illarionov & Sunyaev 1975). In fact, recent simulations have shown that spin-down torques are present for a wide range of accretion rates (Rappaport et al. 2004; D'Angelo & Spruit 2011). Furthermore, the rapidly rotating NS may be emitting gravitational waves (GWs) that remove angular momentum from the system at a rate that is sufficient to halt the spin-up at a frequency of ≈700 Hz (Bildsten 1998). Finally, accretion torques that spin up the NS act only during short outbursts, whereas the NS is spun down by magneto-dipole torques during long quiescence periods. Therefore, the AMXP spin frequency might reach a long-term equilibrium even if accretion torques are present during outbursts (Patruno 2010).

We present a new analysis of the torques acting on the AMXP XTE J1814-338 (referred to as XTE J1814) and use the results, together with those already obtained by Hartman et al. (2008, 2009) for SAX J1808.4-365 (SAX J1808), to constrain theoretical models of the spin evolution.

2. OBSERVATIONS AND DATA ANALYSIS

2.1. SAX J1808.4-3658

SAX J1808.4-3658 is a 401 Hz AMXP in a 2.01 hr binary orbit (Wijnands & van der Klis 1998; Chakrabarty & Morgan 1998) that has undergone six outbursts since 1996. Five outbursts have been monitored with the *Rossi X-ray Timing Explorer* (*RXTE*). No significant spin-up/down episodes are detected during these outbursts, with upper limits of the order of $|\dot{\nu}| \lesssim 2.5 \times 10^{-14}$ Hz s^{-1} (Hartman et al. 2008, 2009). A long-term spin-down is detected when comparing the constant spin frequencies measured in different outbursts. The measured long-term spin-down is $\dot{\nu}_{\rm sd} \simeq -5.5 \times 10^{-16}$ Hz s^{-1}, which has been interpreted as due to magneto-dipole torques induced by a NS magnetic field of $\sim 1.5 \times 10^8$ G. For this source we will use the results reported by Hartman et al. (2008, 2009) and not perform any new data analysis.

2.2. XTE J1814-338

XTE J1814 was discovered in 2003 (Markwardt & Swank 2003), during an outburst that lasted nearly two months. Only one outburst has been detected so far with an extensive coverage of *RXTE* whereas a tentative recurrence time of 19 yr has been proposed based on previous *EXOSAT* observations (Wijnands & Reynolds 2003). Therefore the quiescence timescale is currently unknown. The pulsar has a spin frequency of 314.4 Hz and orbits in 4.3 hr around a $\sim 0.1\,M_\odot$ companion (Markwardt & Swank 2003). We used all available X-ray data taken with the *RXTE* Proportional Counter Array in Event mode (time resolution 2^{-13} s) and Good Xenon mode (time resolution 2^{-20} s) in the 2.5–15 keV energy range. We closely follow the data reduction procedure outlined in Watts et al. (2008) to which we refer for details. A total of 28 thermonuclear X-ray bursts are detected and removed in about 425 ks of data. Accretion-powered pulsations have a strong overtone at twice the spin frequency (Watts et al. 2005). The times of arrival (TOAs) of the pulsations were calculated by cross-correlating a ∼500 s long folded profile with a single sinusoid whose frequency represents the NS spin frequency. The entire procedure is then repeated for the overtone. The effect of the Keplerian orbital motion is removed and a constant spin frequency is fitted to the TOAs.

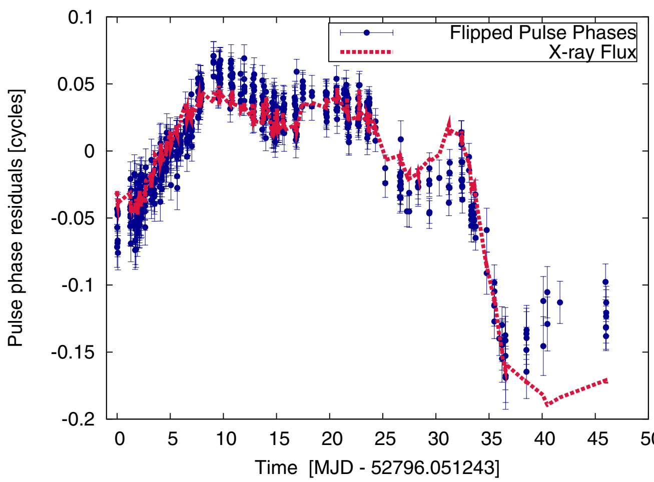

Figure 1. Phase residuals (sign reversed) of the fundamental frequency (blue dots) and 2.5–15 keV light curves overplotted (red line) in arbitrary units. Phase–flux correlations can be seen on all timescales, with small deviations at the very end of the outburst. Similar results are obtained for the first overtone.

(A color version of this figure is available in the online journal.)

The X-ray flux is calculated as the total counts in each pulse profile, normalized to Crab units using the Crab spectral shape (van Straaten et al. 2003).

2.2.1. The Phase–Flux Correlation

XTE J1814 is the AMXP that shows the strongest linear correlation between pulse phase and X-ray flux (Patruno et al. 2009). This correlation has been interpreted as possibly being generated by a moving hot spot on the surface of the NS (Patruno et al. 2009, 2010). Such an interpretation is supported by recent results obtained by means of three-dimensional MHD simulations of AMXPs (Romanova et al. 2003; Bachetti et al. 2010). Special care must be taken as flux induced pulse phase variations may resemble spin frequency variations. In Figure 1, the effect of the phase–flux correlation is made evident by overplotting flipped pulse phase residuals (with respect to a constant spin frequency model) of the fundamental and the X-ray light curve.

It is obvious how variations of the pulse phase closely follow variations in the X-ray flux. In standard coherent pulsar timing the spin frequency derivatives are measured by fitting a quadratic function to the pulse phases; by doing so for XTE J1814 the measured quadratic component will simply be a measure of the effect that the X-ray flux has on the pulse phases.

2.2.2. Upper Limits on the Spin Frequency Derivative

To measure the spin frequency derivative we have first removed the effect of flux variations by using the linear phase–flux correlation (for both harmonics). After "cleaning" the pulse phases, the residual rms variability is of the order of 0.02 cycles. We then fit a quadratic function to the cleaned pulse phases and calculate the errors on the fitted spin parameters by means of $\sim 10^4$ Monte Carlo simulations to account for the residual unmodeled variability, as described in Hartman et al. (2008).

The results indicate upper limits on the spin frequency derivative of the order of $|\dot{\nu}| \lesssim 1.5 \times 10^{-14}\,\mathrm{Hz\,s^{-1}}$ at the 95% confidence level. The upper limits are of the same order of magnitude as those reported by Hartman et al. (2008) for SAX J1808. These results strongly contrast with the measurements obtained without cleaning the pulse phases (see, e.g., Papitto et al. (2007) who report $\dot{\nu} \approx -7 \times 10^{-14}\,\mathrm{Hz\,s^{-1}}$).

3. TORQUE ANALYSIS

Standard accretion theory predicts a spin-up of the form (Bildsten et al. 1997)

$$\dot{\nu} \approx 2.3 \times 10^{-14} \xi^{1/2} \dot{M}_{-10}^{6/7} B_8^{2/7} M_{1.4}^{-5/21} R_{10}^{6/7}\,\mathrm{Hz\,s^{-1}}, \quad (1)$$

where $\dot{M}_{-10}$ is the accretion rate in units of $10^{-10}\,M_\odot\,\mathrm{yr}^{-1}$, B_8 is the magnetic field in units of 10^8 G, $M_{1.4}$ is the mass of the NS in units of $1.4\,M_\odot$, R_{10} its radius in units of 10 km, and ξ parameterizes the uncertainties in evaluating the torque at the edge of the accretion disk and is thought to be in the range $\xi \approx 0.3$–1 (Psaltis & Chakrabarty 1999). The average accretion rate for the outburst is $\simeq 5 \times 10^{-10}\,M_\odot\,\mathrm{yr}^{-1}$ and $2 \times 10^{-10}\,M_\odot\,\mathrm{yr}^{-1}$ for SAX J1808 and XTE J1814, respectively, when considering the bolometric flux (using the data reported by Heinke et al. 2009; Wijnands & Reynolds 2003). The expression in Equation (1) would thus give $\dot{\nu} \simeq 9 \times 10^{-14}\,\mathrm{Hz\,s^{-1}}$ for SAX J1808 and $\dot{\nu} \simeq 4 \times 10^{-14}\,\mathrm{Hz\,s^{-1}}$ for XTE J1814, both larger than the observational upper limits.

Our results suggest that during the outburst SAX J1808 and XTE J1814 spin up/down less than the observational uncertainty and that the accretion torque is thus much weaker than the estimate in Equation (1), or that there is an additional spin-down torque acting on the star, due, for example, to GW emission.

3.1. Gravitational Wave Torques

Gravitational wave emission was first suggested as the cause for the cutoff in the LMXB spin distribution more than 30 years ago (Papaloizou & Pringle 1978). The main emission mechanisms that could be at work are crustal "mountains" (Bildsten 1998; Ushomirsky et al. 2000), magnetic deformations (Cutler 2002; Melatos & Payne 2005), or unstable modes (Andersson 1998). All these processes can produce a substantial quadrupole Q_{22} and thus a spin-down torque due to GW emission.

3.1.1. Crustal Mountains

The crust of a NS is a thin layer (≈ 1 km thick) of matter in a crystalline phase, that can support shearing and the presence of a small asymmetry, or "mountain." The crust consists of several layers of different nuclear composition and as accreted matter gets pushed further into the star it undergoes a series of nuclear reactions, including electron captures, neutron emission, and pycnonuclear reactions (Sato 1979; Haensel & Zdunik 1990). The heat deposited in the whole crust due to these reactions is $Q_H \approx 1.5$ MeV per accreted baryon, but most of the heat is released by reactions occurring close to neutron drip (Haensel & Zdunik 1990). These reactions will heat the region by an amount (Ushomirsky & Rutledge 2001)

$$\delta T \approx 10^3 C_k^{-1} p_d^{-1} Q_n \Delta M_{22}\ \mathrm{K}, \quad (2)$$

where C_k is the heat capacity in units of k_B (the Boltzmann constant) per baryon, p_d is the pressure at which the reactions occur (in units of $10^{30}\,\mathrm{erg\,cm^{-3}}$), and Q_n is the deposited heat per accreted baryon in MeV. ΔM is the accreted mass in units of 10^{22} g, which for the systems we consider is approximately the amount of matter accreted after a few days of outburst. If the energy deposition is (partly) asymmetric this would perturb the equilibrium stellar structure and give rise to a quadrupole (Ushomirsky et al. 2000):

$$Q_{22} \approx 1.3 \times 10^{35} R_6^4 \left(\frac{\delta T_q}{10^5\,\mathrm{K}}\right)\left(\frac{Q}{30\,\mathrm{MeV}}\right)^3 \mathrm{g\ cm}^2, \tag{3}$$

where δT_q is the asymmetric (quadrupolar) part of the temperature increase and Q is the threshold energy for the reaction. The quadrupole required for spin equilibrium during an outburst is $Q \approx 10^{37}$ g cm^2 for both systems (Ushomirsky et al. 2000). It is clear from Equations (2) and (3) that even under the most optimistic assumptions it is unlikely to build a "mountain" large enough to balance spin-up during accretion.

3.1.2. Magnetic Mountains

It is well known that a magnetic star will not be spherical and, if the rotation and magnetic axes are not aligned, one could have a "magnetic mountain" leading to GW emission (Cutler 2002). However, such deformations are unlikely to be large enough to balance the accretion torques in weakly magnetized systems such as the LMXBs (Haskell et al. 2008) and would persist in quiescence, leading to a rapid spin-down, of the order of the spin-up in Equation (1), which is not observed in SAX J1808 (Hartman et al. 2009).

Another possibility is that the magnetic field lines are stretched by the accreted material as it spreads on the star, giving rise to a magnetically confined mountain. The results of Melatos & Payne (2005) suggest that the quadrupole built this way could balance the accretion torque only if the surface field is significantly stronger than the external dipole component. Furthermore, such a mountain would persist on an ohmic dissipation timescale $\tau_{\mathrm{Ohm}} \approx 10^2$ yr (Melatos & Payne 2005) and thus should also give rise to a strong spin-down in quiescence.

3.1.3. Unstable Modes

A more promising scenario is that of an oscillation mode of the NS being driven unstable by GW emission, the main candidate for this mechanism being the $l = m = 2$ r-mode (Andersson 1998). An r-mode is a toroidal mode of oscillation for which the restoring force is the Coriolis force. It can be driven unstable by GW emission, as long as viscosity does not damp it on a faster timescale. This will only happen in a narrow window in frequency and temperature which depends on the microphysical details of the damping mechanisms (for a review, see Andersson & Kokkotas 2001).

Of particular interest in this context is the situation in which the frequency at which the mode is driven unstable (the "critical" frequency) increases with temperature in the range we consider ($T \approx 10^7$–10^8 K). This could lead to the system being in equilibrium at the critical frequency and emitting GWs at a level that will balance the accretion torque (Andersson et al. 2002). This would be the scenario if the core contains hyperons (Nayyar & Owen 2006; Haskell & Andersson 2010) or deconfined quarks (Andersson et al. 2002). If this is the case the dimensionless amplitude of the mode α (as defined by Owen et al. 1998) will be approximately constant in time, i.e., $\dot{\alpha} \approx 0$, and if we assume that GW emission is balancing the accretion torque one has

$$\alpha \approx 1.9 \times 10^{-6} \dot{M}_{-10}^{3/7} \nu_{400}^{-7/2} \xi^{1/4} B_8^{1/7}, \tag{4}$$

where $\nu_{400} = \nu/400$ Hz and we have assumed a 1.4 $M_\odot$ mass and 10 km radius, which we now take as standard values.

After the outburst, when accretion ceases, the system will cool and spin-down following the critical frequency curve. The mode amplitude would thus be approximately constant resulting in a spin-down rate $\dot{\nu} \approx -7 \times 10^{-14}$ Hz s^{-1} for both systems. This is considerably higher than the observed quiescent spin-down rate for SAX J1808 of $\dot{\nu} \approx -5.5 \times 10^{-16}$ Hz s^{-1}.

Furthermore, the shear from the mode will heat the star at a rate (Andersson & Kokkotas 2001)

$$\dot{E} \approx 1.8 \times 10^{44} \alpha^2 T_8^{-5/3} \nu_{400}^2\,\mathrm{erg\ s}^{-1}, \tag{5}$$

where $T_8 = (T/10^8\,\mathrm{K})$. Let us first of all assume that the core cools due to modified URCA neutrino emission processes, which leads to an energy loss $\dot{E} \approx 8.4 \times 10^{31} T_8^8$ erg s^{-1} (Page et al. 2006). Balancing this energy loss with the viscous r-mode heating in Equation (5) leads to an equilibrium temperature of $T \approx 1.4 \times 10^8$ K for SAX J1808 and $T \approx 1.5 \times 10^8$ K for XTE J1814. Let us now estimate the temperature in the presence of the strongest possible neutrino emission processes. We therefore assume that nucleon direct URCA processes are possible, which may be the case in SAX J1808 (Yakovlev et al. 2003), and that the core is not superfluid, with $\dot{E}_\nu \approx 4 \times 10^{39} T_8^6$ erg s^{-1} (Page et al. 2006; similar processes would be at work if hyperons or deconfined quarks are present). Note that in the presence of superfluidity these processes would be strongly quenched (for a recent analysis of r-mode heating see Ho et al. 2011). The temperatures we obtain for the stars are $T \approx 1.5 \times 10^7$ K for SAX J1808 and $T \approx 1.6 \times 10^7$ K for XTE J1814.

How do these temperatures compare with observational constraints? Both systems have upper limits on their temperature from quiescent observations (Heinke et al. 2009). One can map the surface temperature to the temperature at the top of the crust via the relation given by Potekhin et al. (1997) for an accreted crust:

$$\left(\frac{T_{\mathrm{eff}}}{10^6\,\mathrm{K}}\right)^4 = \left(\frac{g}{10^{14}\,\mathrm{cm\ s}^{-2}}\right)\left(18.1\frac{T}{10^9\,\mathrm{K}}\right)^{2.42}, \tag{6}$$

where g is the gravitational acceleration at the surface. By assuming that the star is isothermal, which is roughly correct if the thermal conductivity is high, as observations of cooling X-ray transients suggest (Brown & Cumming 2009), one can obtain a core temperature of $T < 1 \times 10^7$ K for SAX J1808 and $T < 4.1 \times 10^7$ for XTE J1814.

It would thus appear that the presence of an unstable r-mode is not consistent with the observed quiescent spin-down of SAX J1808, while it could be marginally consistent with the temperature of both sources only in the presence of direct URCA processes. We have not considered the role of the magnetic field, but this is likely to stabilize the mode (Rezzolla et al. 2000), consistently with observations.

3.2. Accretion Torques

The interaction between the accretion disk and the magnetosphere is the natural candidate to explain not only the behavior of our two systems, but also the cutoff in the spin distribution of the millisecond pulsars. This mechanism was considered in detail by White & Zhang (1997), whose study seemed to indicate an unexpected link between the accretion rate and the magnetic field strength. This led to the suggestion that GW torques may be active, as in this case the dependence of the field strength on the accretion rate is weaker.

Recent work has, however, shown that more detailed modeling of magnetic torques in the disk can alleviate this problem

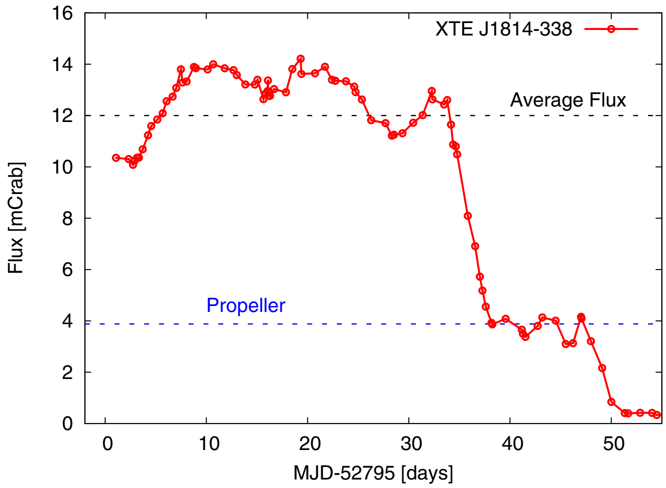

Figure 2. X-ray light curve (2.5–15 keV) of XTE J1814. The dashed blue line indicates the possible onset of the propeller ($r_m = r_c$) while the dashed black line is the average flux, which is close to the equilibrium condition $r_m \approx 0.8\, r_c$. (A color version of this figure is available in the online journal.)

(Andersson et al. 2005). Furthermore, the tendency of accreting systems to settle in a state where the inner edge of the disk tracks corotation has been documented by D'Angelo & Spruit (2011). It could, therefore, be the case that both SAX J1808 and XTE J1814 are close to the equilibrium spin rate set by such a process and that the torques are much weaker than the estimate in Equation (1). We will use the simple model of Andersson et al. (2005) to show that this is a more promising explanation than GW emission.

We assume that a propeller phase starts at the reflaring stage for SAX J1808 (see a discussion of this possibility in Patruno et al. 2009). In XTE J1814 we assume that the onset of the propeller is at the point where the pulse phases deviate from a linear correlation (see Figures 1 and 2).

We calculate the average X-ray flux during an outburst and the flux at the onset of the propeller for XTE J1814 (see Figure 2) and SAX J1808 and assume that the X-ray flux is a good tracer of the mass accretion rate. We assume that at the onset of the propeller the magnetospheric radius (Bildsten et al. 1997)

$$r_m = 35\xi \dot{M}_{-10}^{-2/7} M_{1.4}^{-1/7} R_{10}^{12/7} B_8^{4/7}\ \mathrm{km} \tag{7}$$

is approximately equal to the corotation radius

$$r_c = 31 M_{1.4}^{1/3} \nu_{400}^{-2/3}\ \mathrm{km}. \tag{8}$$

The results of Andersson et al. (2005) indicate that the torque will vanish when the ratio between propeller flux ($f_{\rm prop}$) and average flux ($f_{\rm avg}$) is such that $(f_{\rm prop}/f_{\rm avg})^{2/7} \approx 0.8$. We find that $((f_{\rm prop}/f_{\rm avg})^{2/7} \approx 0.75$ for XTE J1814 and 0.75–0.84 for SAX J1808 in the 2002, 2005, and 2008 outbursts.[1] These values are very close to the theoretical value 0.8, which is encouraging given the large uncertainties in both the theoretical calculations and the observations.

This does not mean that the accretion torques vanish during an outburst, but only that the spin variations can be smaller than those predicted by standard accretion theory.

[1] Only these outbursts had good enough observational coverage to allow the calculation.

4. CONCLUSIONS

We have presented a new analysis of the torques acting on XTE J1814 during the 2003 outburst and have interpreted the observed long-term spin-down of SAX J1808 over a 10 yr baseline. We have found that there are no significant spin frequency derivatives that can be measured during the 2003 outburst of XTE J1814, with upper limits of $|\dot{\nu}| \lesssim 1.5 \times 10^{-14}\ \mathrm{Hz\,s^{-1}}$, of the same order of magnitude as the values determined for SAX J1808: $|\dot{\nu}| \lesssim 2.5 \times 10^{-14}\ \mathrm{Hz\,s^{-1}}$ (Hartman et al. 2008, 2009). This implies that accretion torques during an outburst are smaller than expected from standard accretion theory for both AMXPs.

We have analyzed the two main mechanisms that could explain such a feature, namely the presence of GW torques and the possibility that the system may be close to spin equilibrium, as set by the disk/magnetosphere interaction. For SAX J1808 it is reasonably safe to say that GW torques can be excluded. For XTE J1814 a definite conclusion is harder to draw, as only one outburst has been observed and thus there is no measurement of the spin-down in quiescence. GW emission may still be marginally consistent with observations.

A more promising possibility is that both systems are close to spin equilibrium, as set by the disk/magnetosphere interaction. We have shown that the simple model of Andersson et al. (2005) predicts spin equilibrium close to the average accretion rate for the outbursts, thus leading to a reduced torque. Further work is necessary to analyze the problem with the use of refined disk models (e.g., D'Angelo & Spruit 2011), a task which is beyond the scope of this Letter.

Note that the case of bright sources such as Sco X-1 could be quite different, as high accretion rates would prevent the system from reaching spin equilibrium and GWs may play a significant role.

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