Constraints on jet X-ray emission in low/hard state X-ray binaries

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ABSTRACT
We show that the combination of the similarities between the X-ray properties of low luminosity accreting black holes and accreting neutron stars, combined with the differences in their radio properties argues that the X-rays from these systems are unlikely to be formed in the relativistic jets. Specifically, the spectra of extreme island state neutron stars and low/hard state black holes are known to be indistinguishable, while the power spectra from these systems are known to show only minor differences beyond what would be expected from scaling the characteristic variability frequencies by the mass of the compact object. The spectral and temporal similarities thus imply a common emission mechanism that has only minor deviations from having all key parameters scaling linearly with the mass of the compact object, while we show that this is inconsistent with the observations that the radio powers of neutron stars are typically about 30 times lower than those of black holes at the same X-ray luminosity. We also show that an abrupt luminosity change would be expected when a system makes a spectral state transition from a radiatively inefficient jet dominated accretion flow to a thin disk dominated flow, but that such a change is not seen.

Key words: accretion, accretion disks – black hole physics – radiation mechanisms: non-thermal – X-rays: binaries – stars: neutron – radio continuum: stars

1 INTRODUCTION
Numerous similarities are have been found between low magnetic field accreting neutron stars and accreting stellar mass black holes. These similarities are most striking when the systems are accreting at relatively low fractions of the Eddington luminosity, \( L_{\text{EDD}} \), below the few percent of the Eddington limit where spectral state transitions from soft, quasi-thermal to hard power law dominated spectra are typically seen (Maccarone 2003), but above the \( \sim 10^{-5} L_{\text{EDD}} \) where the thermal emission from the surface of the neutron star becomes a substantial fraction of its total luminosity. In this range, the X-ray spectral energy distributions of black holes and neutron stars show no notable differences, and the X-ray power spectra show only minor differences apart from those which are attributable to the smaller mass and hence smaller characteristic timescale for the neutron stars. The similarity between the X-ray properties of these low magnetic field neutron stars and those of black holes strongly supports the suggestion that the fundamental physical processes in these systems producing X-ray emission in these systems must also be quite similar. On the other hand, the radio properties of accreting neutron stars and accreting black holes are quite different; at the same X-ray luminosity, the neutron stars are typically about 30 times fainter than the black holes (Fender & Hendry 2000; Migliari et al. 2003). In this paper, we will show that the similarity between the X-ray properties of neutron stars and black holes combined with the differences between their radio properties places strong constraints on the possibility that scale invariant jets can be responsible for the X-ray emission in both neutron stars and accreting black holes. Instead, these results provide support for the idea that the X-rays are, indeed, produced in a disk plus hot coronae system, and that the efficiency in extracting the disk’s energy into the jet is different for black holes and neutron stars. We also show that the smooth changes in luminosity across transition between the different spectral states are at odds with the predictions of jet models that the radiative efficiency of the accretion flow should change dramatically at the state transitions.

2 COMPETING PICTURES FOR X-RAY BINARY SPECTRAL MODELING

2.1 Black hole X-ray spectra
Black hole X-ray binaries are found in several spectral states, the two most common being the low/hard state, usually found at luminosities of less than about \( 2\% \) of the Eddington limit and the high/soft state, usually found at luminosities between about 2 and 30\% of the Eddington limit. Above \( 30\% \) of the Eddington limit, sources are usually in the very high state. We refer the reader to Nowak (1995) for a summary of the spectral state phenomenology. We also note that there is not one-to-one correspondence between luminosity and spectral state (see e.g. Miyamoto et al. 1995; Homan et al. 2001; Maccarone & Coppi 2003a - MCa).

We will focus on the two lower luminosity states, the low/hard state and the high/soft state. The high/soft state energy spectrum is typically very well fit by multi-temperature blackbody models, often with a weak power law tail. The high/soft state thus represents the case where the accretion flow is that of a standard
Shakura-Sunyaev (1973) geometrically thin, optically thick disk. The low/hard state spectra fit well phenomenologically to cutoff power laws, with a photon spectral index of about 1.7 and a cutoff at about 100 keV. These have historically been modeled as seed photons being Compton upscattered in a thermal plasma with a temperature of about 100 keV, and an optical depth of about unity (see e.g. Pottschmidt et al. 2003). More recently, it has been suggested that these low/hard state spectra can also be modeled as synchrotron X-ray jets (Markoff, Falcke & Fender 2001). In both spectral states, broad spectral bumps are seen at energies of about 30 keV, in addition to some lines edges from various elements. These features are generally attributed to reflection of the hard power law photons off the accretion disk (e.g. George & Fabian 1991).

It has been argued that some of the observed features are rather difficult to reproduce in a jet model – most notably the cutoff at about 100 keV and the evidence of reflection off the disk, which should not be seen if the X-ray emitting region is beamed strongly away from the disk (Poutanen & Zdziarski 2002). The former point boils down to the fact that the cutoff energies in X-ray binaries are almost always found to be very close to 100 keV, while in blazars, the synchrotron cutoff energy varies by large factors. However, measurements of the spectral cutoff in the γ-rays are made over a dramatically smaller range in luminosity than measurements of blazar cutoff energies, and the velocities of the X-ray emission regions of the jets are typically less than 0.3c. Heinz (2005) showed that pure synchrotron jets would have trouble simultaneously reproducing the observed X-ray spectra of X-ray binaries and AGN along with observed correlations between their masses and their fluxes in radio and X-rays (Merloni, Heinz & Di Matteo 2003; Falcke, Körödi & Markoff 2004), but could not rule out the case that inverse Compton emission from jets might be important. More stringent tests of the jet X-ray model are thus needed.

### 2.2 Neutron star X-ray spectra

The spectral state nomenclature for neutron stars is a bit different than that for black holes. Furthermore, the analogies between the states of neutron stars and the states of black holes have recently shown the need for refinement. The relatively low luminosity neutron stars (i.e. the atoll sources) were originally divided into island states, similar to the low hard states of black holes, and banana states, similar to the high/soft states (Hasinger & van der Klis 1989). More recently, the need for “extreme island states” (EIS) has been shown, in the sense that the island state properties correspond to something intermediate between the low/hard and high soft states of black holes, while the EIS corresponds much more closely to the low/hard state of black holes (see e.g. van der Klis 2005 and references within). When these EIS neutron stars’ spectra are examined, they are found to be quite similar to those of black holes in the low/hard state – compare for example the spectral fit parameters for Cygnus X-1 in Pottschmidt et al. (2003) with those of the neutron star Aql X-1 in its extreme island state in Maccarone & Coppi (2003b - MCB) – in both cases, the spectra are fit well by thermal Comptonization models with optical depth of about 1 and temperature of about 100 keV. An incorrect lore has developed that neutron stars never show spectra as hard as the low/hard state black holes. This is most likely because of the old belief that the low/hard state corresponded not to the EIS, but the classical island state. In the classical island state, typically optical depths of a few and electron temperatures of order 20 keV are found from Comptonization model fits (MCB), yielding softer spectra than low/hard state black holes.

### 3 SIMILARITIES OF VARIABILITY PROPERTIES IN LOW/HARD STATES

The timing signatures of both low/hard state and EIS systems are also very similar, being well described by a series of broad Lorentzians (see Nowak 2000 for a typical black hole; van Straaten et al. 2002 for a typical neutron star), with three key exceptions – the first being that the typical frequencies in the neutron star power spectra are a factor of about 5 lower than in black holes, the second being that the neutron star systems shows a slight excess of power at very high frequencies, and the third being that kilohertz QPOs are seen in the neutron stars, but not in the black holes in these states (Sunyaev & Revnivtsev 2000; Klein-Wolt 2004). It has also been shown that the lags between hard and soft photons are consistent with being the same in neutron stars and black holes in their low/hard states (Ford et al. 1999). It was noted in the abstract of Ford et al. (1999) that the time lags might present some problem for Comptonization models, but what was really meant by that statement is that the time lags might present some problem for models where the time lags are produced by light travel times through the Comptonizing medium (e.g. Payne 1980). It has since been shown that it is true that the time delays cannot be light travel times, but that fact does not prohibit the radiation mechanism from being Compton scattering (Maccarone, Coppi & Poutanen 2000).

These results imply that essentially the same processes are producing most of the radiation in black holes and neutron stars, and that the size scales for the emission regions should be linearly proportional to the mass of the compact object to within a factor of about 1.5. The other two differences between neutron stars and black holes – the extra high frequency power in neutron stars, and the kilohertz QPOs in neutron stars – may well be related to surface effects in the neutron star systems. The kilohertz QPOs show clear correlations with the spin frequency of the neutron star, since the separation between the QPOs is always approximately the spin frequency or half the spin frequency (van der Klis 2005 and references within), and theoretical models for these QPOs typically invoke the magnetic field of the neutron star or some non-uniform radiation pattern from its surface (e.g. Lamb et al. 1985; Miller, Lamb & Psaltis 1998). In any event, these kHz QPOs, while important probes of the physics of neutron stars, typically have amplitudes of no more than a few per cent and are hence energetically not very important. Sunyaev & Revnivtsev (2000) suggested that the excess of high frequency power in the neutron stars might be related to variability in the emission from the boundary layer on the surface of the neutron star, although we note that it might be related to the fact that black holes more efficiently extract energy from their accretion disks into their jets than do neutron stars.

### 4 PROPERTIES OF SCALE INVARIANT JETS

Throughout this paper, we will use the term “scale-invariant jet” to refer to jets whose relevant size scales are all linear with the mass of the compact object driving the jet. Given the similarities of the timing properties of the neutron star and black hole X-ray binaries in hard spectral states, except that the neutron stars’ variability is faster by a factor very similar to the mass ratio, it seems likely that the X-ray variability is produced in some scale-invariant manner, whether in a scale-invariant jet, or a corona which is scale invariant. In the next several subsections, we will show that scale invariant jets are not capable of reproducing the different ratios of X-ray to radio power seen in neutron stars and black holes.
4.1 Synchrotron jets

The properties of synchrotron emission from scale-invariant jets are the most straightforward of the different possible cases, as the relevant equations have been worked out in the past and tested observationally. It has been found that the mass dependence of the radio emission is such that \( L_R \propto L_X^{0.7} M_{CO}^{0.8} \), where \( L_R \) is the radio luminosity, \( L_X \) is the X-ray luminosity, and \( M_{CO} \) is the mass of the compact object (Merloni, Heinz & Di Matteo 2003; Falcke, K"ording & Markoff 2004). The mass difference between black holes and neutron stars would then account for a factor of about 5 difference in the radio-to-X-ray flux ratio, well below the observed factor of 30 difference. If we relax the assumption of scale invariance in these jets, and allow that the typical size scale can change independently of the mass, then we can solve for the size scale of the jets that would be required to match the observations. Both the particle energy density and the magnetic field energy density should scale as \( L/R^2 \), where \( L \) is the total luminosity and \( R \) is the characteristic size scale, for a system in equipartition (or with a constant ratio of magnetic field strength to equipartition strength). The frequency at which a jet becomes optically thin to synchrotron radiation is given by equation (14) of Heinz & Sunyaev (2003)\( -\nu_c \propto \left( R \left( L/R^2 \right)^{(p+3)/(p+4)} \right) \), which yields \( L \propto R^{-(p+3)/(p+4)} \), where \( p \) is the spectral index of the electron distribution. For \( p = 2.4 \), which is required to reproduce the typical X-ray binary flux spectral index of \( \alpha = 0.7 \), then the break comes at a frequency which scales as \( L R^{-1.68} \). The deviations from this relation are very small even for rather large changes in \( p \). The X-ray flux for a given radio flux then scales as the break frequency to the power of the spectral index, i.e., \( \left( L R^{-1.68} \right)^{\alpha} \), or \( L^{-0.7} R^{1.12} \). To reproduce the observed differences between black holes and neutron stars, then, the typical size scales in the neutron stars would have to be a factor of about 20 smaller than those in black holes at the same luminosity. This is inconsistent with the power spectral differences between black holes and neutron stars which show, at most, a factor of 10 difference between black holes and neutron stars’ variability timescales.

4.2 Compton scattered jets

Having established that the fraction of the synchrotron radiation emitted in the X-rays will not fall off fast enough with mass to allow that synchrotron X-ray jets provide for the differences between neutron stars and black holes, let us consider the possibility that X-ray jets may be dominated by Compton processes, rather than synchrotron X-rays. This allows another free parameter, the ratio between synchrotron and Compton fluxes.

Considering the case of Compton scattered emission, rather than synchrotron emission does not change the situation. Firstly, in scale free jets, the ratio of synchrotron to Compton luminosity, is independent of the compact object mass. Ghisellini & Celotti (2001) show that for synchrotron self Compton jets, the ratio of Compton to synchrotron luminosity goes as \( L_{sync} R^{-2} B^{-2} \), while \( B \propto L_{sync} R^{-3} \). Combining terms shows that the ratio of Compton to synchrotron luminosity goes as \( (L_{sync}/R)^{1/2} \), which makes this a scale independent quantity. Neither can this problem be solved by external seed photons for Comptonization. Firstly, the only natural source of such seed photons would be from the neutron star’s surface. The surface emission seems to be weaker than half the total luminosity in extreme island state neutron stars (e.g. Piraino et al. 1999; Jonker et al. 2004), which may be showing that some of the rotational energy that should be dissipated at the surface of the neutron star is going into the jet, or may be showing that these photons are being Compton scattered in the corona before reaching the observer (i.e. they are simply providing an extra source of seed photons to a corona with a much higher optical depth and covering fraction than the jet). It is clear that the photons are not being produced in a region which is not surrounded by the corona; that is, the photons cannot be produced from the surface of the neutron star, unless the jet’s opening angle is nearly 180 degrees. The jet may look like a lot a planar wind (see e.g. Junor, Biretta & Livio 1999) near the surface of the neutron star, so this argument alone is not robust.

Secondly, even if there were some other source of such photons, if the X-rays from X-ray binaries are Compton emission, then the spectrum should cut off at a much lower photon energy for neutron stars than for black holes, because the combination of the higher magnetic field strength and the extra source of seed photons will lead to a dramatically higher cooling rate. This cooling rate will lead to a lower cutoff energy for the electrons, and hence a lower cutoff energy for the Compton component (see e.g. the discussion of the effects on inverse Compton emission on the “blazar sequence” shown in Fossati et al. 1998). A related point is that Compton scattering produces upscattered photons with energy of \( \sim \gamma^2 E_0 \), where \( \gamma \) is the energy of the electron doing the upscattering, and \( E_0 \) is initial energy of the photon. While the acceleration of electrons may be governed by processes that lead to the roughly constant cutoff energy seen in hard state systems, it would require considerable fine tuning for the same Compton cutoff to be seen when the seed photons are thermal (\( \sim 1 \) keV) photons from the surface of the neutron star in one case, and synchrotron photons from the jet itself in the other case.

Finally, let us check the self-consistency of this picture. Taking the minimum energy requirements from Ghisellini & Celotti (2001), we find that the synchrotron luminosity from a jet which is in equipartition, and where the Compton scattered is dominated by external seed photons (since this is required to create a difference between neutron stars and black holes) will be \( L_{sync} = \left( \frac{L_{comp}}{L_{seed}} \right)^{2} \left( \frac{\pi R m_e c^2}{\gamma^2 E_0} \right) \).

This equation assumes the most favorable case for an external Compton dominated jet, which is a pair-dominated jet. A self-inconsistency will be found for the cases such as that of 4U 0614+091, where the spectrum shows the power law component which is at least 25 times brighter than the thermal component at a luminosity of about \( 4 \times 10^{36} \) ergs/sec (Piraino et al. 1999). In this case, the synchrotron luminosity would have to be at least \( 6 \times 10^{35} \) (and this is assuming an emission region of 10 km size scale, equal to the neutron star’s radius), while the blackbody luminosity would be \( 2 \times 10^{35} \) ergs/sec, about 3 times lower. Escaping this constraint requires violating equipartition by a substantial factor (the exact factor depending on how much bigger the emission region is than the neutron star). This may be possible, but would then require a large total kinetic energy in electrons, which would make the radiative efficiency even lower than it is normally assumed; since we show below that the low radiative efficiency of jets is already a problem for a jet X-ray scenario, this seems an unlikely possibility.

5 LACK OF ABRUPT LUMINOSITY CHANGES AT STATE TRANSITIONS

Synchrotron-emitting jets are radiatively inefficient by nature. Fender (2005) collected a variety of pieces of observational and
Theoretical evidence regarding the radiative efficiency of relativistic jets seen in X-ray binaries, all of which argue for a radiative efficiency of no greater than 15% (Blandford & Königl 1979; Fender & Preoley 2000; Markoff, Falcke & Fender 2001).

The outbursts of soft X-ray transients frequently show transitions between the different spectral states. It is generally believed that jet formation in the thin disks of the high/soft state is strongly suppressed, since jet production requires large scale height magnetic fields (Livio, Ogilvie & Pringle 1999). This claim is supported by the non-detections of radio jets from high/soft state X-ray binaries (e.g. Tananbaum et al. 1972; Fender et al. 1999). One exception has been found, but it is likely that the radio emission in this case was produced from a plasmon ejected before the transition to the soft state occurred, but which interaction with the interstellar medium during the soft state (Corbel et al. 2004). Let us assume that the accretion flow goes from being jet dominated in the X-rays in a hard state to being in a high/soft state where all the power is radiated from a geometrically thin disk. The radiative efficiency of the flow would then change abruptly from about 15% or less, in the X-ray jet, to nearly 100%, in the thin disk. We note that this change is in addition to the fact that jets are unlikely to extract 100% of energy from the accretion disks that feed them. Markoff et al. 2001 estimate that 0.1-10% of the disk’s energy is extracted into the jet. Given the most likely parameter values chosen in Markoff et al. (2001), a jet with 10% efficiency extracting 1% of the disk’s power, a factor of \(\sim 1000\) luminosity increase would be expected across the low/hard to high/soft state transition, assuming that the mass accretion rate is changing steadily at that time.

This requirement shows serious disagreement with the observations. The soft X-ray transients show smooth variations in luminosity, even across the state transitions, rather than factors of 10 jumps in the luminosity corresponding to changes in radiative efficiencies of the accretion flow (see e.g. Sobczak et al. 2000; Miller et al. 2001). At the state transitions, sharp changes are seen in the relative flux in the quasi-thermal and power law components, but no sharp changes are seen in the bolometric luminosity. That is, the spectrum re-configures itself without any dramatic change in luminosity, indicating that the radiative efficiency is making, at most, a small change. We note that this same argument applies to the arguments of Malzac, Merloni & Fabian (2004) that the jet should be heavily dominant over the disk+corona system in order to reproduce the complication correlations and anti-correlations between the optical and X-ray emission in XTE J1118+480. However, those authors results were also consistent with a less heavily jet dominated accretion flow, which would be consistent with no abrupt break in the X-ray luminosity at the state transition.

Some caveats do exist. A factor of two change in the radiative efficiency may be expected at the state transition, because the rotational energy of the inner edge of the accretion disk should be advected in the high/soft state. Some of this rotational energy is probably supplied to the jet in the low/hard state. Additionally, at least half the accretion power is dissipated by the thermal accretion disk in the highest luminosity low/hard states. The smallest possible luminosity change across the state transition for a jet dominated power law would then be a factor of 2, which is still unlikely given the observational data, but which cannot be ruled out without well-sampled soft X-ray through \(\gamma\)-ray monitoring.

Also, the high/soft state could have a jet at very high Lorentz factor (see e.g. Meier 1999 who argues that jets powered by thin disks should be faster than those powered by thick disks; see also Fender, Belloni & Gallo 2004 for tentative observational evidence that the softer the state of the accretion disk from which a jet is ejected, the faster the jet), which could transport away a large amount of power from the system. These jets might be essentially unobservable, because of the very low probability that the observer would lie within the beaming cone of the jet. In any cases, even if such jets do exist, it is likely that they are substantially weaker than jets powered by geometrically thick accretion flows. Searching for the jet-ISM interaction site in the high/soft state source LMC X-1 could help test whether it has a strong but invisible jet.

6 DISCUSSION

As we have now established that it is quite difficult to explain the relevant similarities and differences between neutron stars and black holes in context of jet models, it is important that we show that a standard Comptonization model does not present similar qualitative difficulties in explaining the data. First, we note that neutron stars are likely to extract less of their accretion power into jets than are black holes. Their potential wells are not as deep, leading to more slowly rotating orbits around the compact object, and they spin much more slowly, so they have less spin energy to extract. As a result, the two most prominent sources for extracting energy into jets, the rotational energy of the compact object (Blandford & Znajek 1977), and that of the accretion disk (Blandford & Payne 1982) are suppressed in neutron stars relative to rotating black holes.

Meier (2001), for example, calculated the jet power provided from an advection dominated accretion flow (see e.g. Narayan & Yi 1995) through the Blandford-Znajek (1977) mechanism and the Blandford-Payne (1982) mechanism. He found that the jet power should be proportional to \(0.55 f^2 + 1.5 fj + j^2\) for black holes, where \(j\) is the dimensionless angular momentum parameter for black holes, and \(f\) is a dimensionless parameter less than 1, which is the ratio between the rotational velocity of particles in the ADAF calculations of Narayan & Yi (1995) and the actual value. Models of high frequency quasi-periodic oscillations from black holes typically require \(j\) in these systems to be in the range 0.7-0.95 (e.g. Strohmayer 2001; Abramowicz & Kluzniak 2001; Rezzolla et al. 2003), while the accreting neutron stars rotational velocities are generally in the range 300-600 Hz, which gives \(v/c\) of about 0.05-0.1. The treatment of a neutron star as a black hole of the same mass and angular momentum is not strictly valid, but we are interested here only is showing that reasonable parameter values can reproduce the observed differences between neutron stars and black holes. Evaluating over the bound from 0 to 1 for \(f\), this gives a possible range of 3-400 for the ratio between the jet powers of neutron stars and black holes, assuming that spin is the only effect, and that the accretion flow feeding the jet is in the form of an ADAF. It has also been suggested that magnetic reconnection powered coronae (see e.g. Haardt & Maraschi 1993) would have sufficiently strong poloidal magnetic fields that they could power strong jets (Merloni & Fabian 2002). The dependence of the jet power on the compact object’s spin should be rather similar to that for the ADAF model calculated by Meier (2001). It should be noted that other effects of the difference between black holes and neutron stars, most notably the neutron stars’ magnetic fields and boundary layers, might also be important.

Next, we speculate that one of the key differences between the Fourier spectra of black holes and neutron stars might be explained by the differences in their abilities to extract power from the jet. Jets in low/hard state black holes are likely to extract a large fraction of the total accretion power as kinetic power (e.g. Meier 2001;
Fender, Gallo & Jonker 2003; Malzac et al. 2004). The fraction must increase with decreasing accretion rate, so that the faintest sources are totally jet dominated, but the sources at luminosities just below the state transition are not losing more than half their power to the jet. This extraction is most likely to be important from the innermost part of the accretion flow, where the poloidal magnetic fields are strongest and the rotational velocities are highest.

This thus means that at some point, the radiative efficiency in the black holes should drop due to the jet’s extraction of power, and that this effect should be more important in black holes than in neutron stars. Thus the smallest spatial scales where the fastest variability is seen should produce a smaller fraction of the power in the black hole systems relative to the neutron star systems, while there should be no effect on the relative variability amplitudes in the black holes and neutron stars at lower frequencies, where the power spectra are observable to differ only through the mass dependence.

All this is not to say that jets never produce detectable X-rays. It is known, for example, that blazars produce synchrotron photons out to very high energies in some cases (e.g. Pian et al. 1998). Blazars also often show the jet luminosity to be dominated by X-ray from the Compton component of the jet. In these cases, there is likely to be a significant contribution of seed photons for Comptonization from the accretion disk, which is obviously not possible in a system where the total luminosity is dominated by the jet (Fossati et al. 1998). In some AGN, X-ray jets are resolved (Wilson & Yang 2002; Sambruna et al. 2004), but in these cases, the size scales on which the resolve jets are seen are equivalent to the interactions sometimes seen between jets and the ISM in X-ray binaries; the AGN do not provide a useful direct test for whether X-ray binaries’ X-ray emission comes from jets. What seems plausible is that a small fraction of the X-ray emission, especially in the soft X-rays, does come from the synchrotron jet in X-ray binaries, but that the jet spectrum is softer than assumed by past work suggesting that the bulk of the X-ray power is synchrotron emission.

Standard Comptonization models, rather than synchrotron jet models are most likely responsible for the bulk of X-ray emission from X-ray binaries. Compton corona models are more capable of matching the different jet properties of black holes and neutron stars. They also predict continuous variations in luminosity across the state transitions, as observed, rather than sharp jumps in the luminosity. Models where the X-ray emission is Compton scattering from a jet are restricted to a rather small range in parameter space.

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