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Discovery of radio emission from the symbiotic X-ray binary system GX 1+4

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ABSTRACT

We report the discovery of radio emission from the accreting X-ray pulsar and symbiotic X-ray binary GX 1+4 with the Karl G. Jansky Very Large Array. This is the first radio detection of such a system, wherein a strongly magnetized neutron star accretes from the stellar wind of an M-type giant companion. We measure a 9 GHz radio flux density of 105.3 ± 7.3 μJy, but cannot place meaningful constraints on the spectral index due to a limited frequency range. We consider several emission mechanisms that could be responsible for the observed radio source. We conclude that the observed properties are consistent with shocks in the interaction of the accretion flow with the magnetosphere, a synchrotron-emitting jet, or a propeller-driven outflow. The stellar wind from the companion is unlikely to be the origin of the radio emission. If the detected radio emission originates from a jet, it would show that strong magnetic fields ($\geq 10^{12}$ G) do not necessarily suppress jet formation.

Key words: accretion, accretion discs – stars: neutron – pulsars: individual: GX 1+4 – X-rays: binaries.

1 INTRODUCTION

GX 1+4 is an accreting X-ray pulsar with a long, ∼120 s rotation period, which was discovered in 1970 with balloon X-ray experiments (Lewin, Ricker & McClintock 1971). Glass & Feast (1973) identified its optical counterpart as the M6III-type red giant V2116 Oph. The companion star orbits the pulsar most probably in a wide, 1161 d orbit (Hinkle et al. 2006; Iłkiewicz, Mikołajewska & Monard 2017), although a shorter orbital period of ∼304 d has also been claimed (Cutler, Dennis & Dolan 1986). The magnetic field strength of GX 1+4 is debated: standard disc accretion theory predicts a magnetic field $B \sim 10^{13}$–10^{14} G (Dotani et al. 1989; Cui & Smith 2004), while both Rea et al. (2005) and Ferrigno et al. (2007) marginally detected a possible cyclotron line implying a field of $B \sim 10^{12}$ G. While the former estimate would be among the largest inferred field strengths in accretion-powered slow pulsars, the latter is more typical for this class of sources.

Jets, strongly collimated outflows, are ubiquitous in accreting systems. Accreting black holes (BHs) show a correlation between their X-ray emission (tracing the accretion flow), their radio emission (tracing the jets), and BH mass, spanning over eight orders of magnitude in mass (Merloni, Heinz & di Matteo 2003; Falcke, Körding & Markoff 2004; Plotkin, Gallo & Jonker 2013). The subset of neutron star (NS) low-mass X-ray binaries (LMXBs) that accrete through Roche lobe overflow of the companion has been suggested to follow similar correlations, although no universal relation has emerged (Migliari & Fender 2006; Gusinskaia et al. 2017; Tudor et al. 2017). Despite the ubiquity of jets, their formation and collimation are still poorly understood. Hence, comparing jet properties between classes of accreting systems can reveal relevant parameters and necessary conditions for jet formation. For instance, no jets have to date been observed in accreting NS systems where the magnetic field strength exceeds $\sim 10^9$ G (Fender et al. 1997; Fender & Hendry 2000; Migliari & Fender 2006; Migliari et al. 2011b, 2012). Indeed, theoretical arguments exist in support of the suppression of jet formation by stronger magnetic fields (Meier, Koide & Uchida 2001; Massi & Kaufman Bernadó 2008).

A class of systems where (radio) jets have not yet been detected are the symbiotic X-ray binaries (SyXRBs), which are NS LMXBs accreting from the stellar wind of an M-type giant donor. With V2116 Oph as its optical counterpart, GX 1+4 was the first discovered SyXRB, although the larger object class of SyXRBs has

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only emerged in the past decade (e.g. Masetti et al. 2006, 2007a,b; Nespoli, Fabregat & Mennickent 2008; Bahramian et al. 2014; Kuranov & Postnov 2015). Currently, eight accreting NSs have been confirmed as SyXBRs, and six more have been proposed (e.g. Bahramian et al. 2014; Kuranov & Postnov 2015). More commonly observed than SyXRBs are their white-dwarf equivalents, called symbiotics or symbiotic stars (SySts), of which around 200 sources are known (e.g. Rodríguez-Flores et al. 2014). Jets have been observed in several SySts, both through resolved radio imaging, and X-ray or optical spectroscopy (see Brocksopp et al. 2004, for a list).

In this letter, we report on the discovery of radio emission from the SyXRB GX 1+4 using the Karl G. Jansky Very Large Array (hereafter VLA). This detection constitutes both the first radio detection of an SyXRB and the first hints of a jet from an accreting X-ray pulsar with a strong magnetic field. After describing the observations and the results, we will consider the nature of the radio emission, compare the detection with other classes of accreting systems and discuss the implications for jet formation mechanisms.

2 OBSERVATIONS

2.1 Radio

We observed GX 1+4 with the VLA (project code: VLA/13A-352, PI: Degenaar) on 2013 June 16 from 06:24:49 to 07:08:41 UT for an on-source time of ∼27 min, as part of a larger programme studying persistent X-ray bright NS LMXBs. We observed at X-band in the frequency range from 8 to 10 GHz. The primary calibrator used was J1331+305, while the nearby phase calibrator was J1751-2524 (angular separation: $4\overset{\circ}{.}5$). During the observation, the VLA was in C-configuration, corresponding to a resolution of a 4.05 arcsec × 1.80 arcsec synthesized beam (with a position angle of $1\overset{\circ}{.}59$).

We used the Common Astronomy Software Applications package (CASA) v.4.7.2 (McMullin et al. 2007) to calibrate and image the data. There was no significant RFI during the observation. We imaged Stokes I and V using the multifrequency, multiscale CLEAN task, with Briggs weighting and a robustness of zero. We note that we did not explicitly apply a polarization calibration, which means that our estimates of the circular polarization might be affected by beam squint at the level of a few per cent. In the absence of bright radio emission in the field, we did not apply any self-calibration. We reached an RMS noise of ∼7.3 μJy beam^{-1}, corresponding to a 3σ threshold of ∼22 μJy beam^{-1} for a detection. As we expect LMXBs to be point sources at the available resolution, we determined flux densities by fitting in the image plane using the IMFIT task, forcing an elliptical Gaussian with the same FWHM as the synthesized beam. Additionally, we searched for time and frequency variability; we imaged each of the three target scans separately to search for time-variability and imaged the 8–9 and 9–10 GHz bands separately to place constraints on the radio spectrum of GX 1+4.

2.2 X-ray

We searched the archives for X-ray observations of GX 1+4 contemporaneous with the VLA radio observations. Only the *MAXI* monitoring telescope onboard the International Space Station (Matsuoka et al. 2009) performed X-ray observations of GX 1+4 around the time of our radio epoch. We downloaded the 2–20 keV Gas Slit Camera (GSC) spectrum for entire day of 2013 June 16 from the *MAXI* website (http://maxi.riken.jp). Despite the relatively low spatial resolution of *MAXI*, no known bright X-ray sources were located in the automatically selected source extraction region, so our obtained source spectrum should be free of contamination by any source. The background region does overlap with the ultracompact X-ray binary SLX 1735-269, which was undetected by *MAXI* during the VLA epoch, and the NS LMXB GX 3+1. The background spectrum might thus be slightly contaminated.

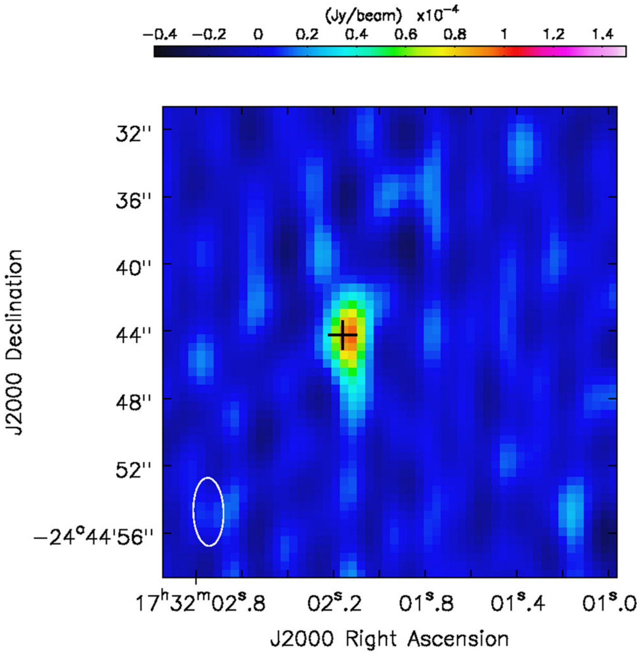

Figure 1. VLA 9 GHz image of GX 1+4. The black cross shows the most accurate position of GX 1+4, from 2MASS (near-infrared), which is accurate to 0.1 arcsec. The half-power contour of the synthesized beam is shown in the bottom left corner.

3 RESULTS

3.1 Radio

Fig. 1 shows the zoomed, full-bandwidth VLA target image of the entire observation. GX 1+4 is detected at an ∼14.4σ significance with a radio flux density S_ν = 105.3 ± 7.3 μJy at 9 GHz. Assuming a distance of $D = 4.3$ kpc (Hinkle et al. 2006) and using $L_R = 4\pi\nu S_\nu D^2$, this corresponds to a luminosity of $L_R = (2.10 \pm 0.15) \times 10^{28}$ erg s^{-1}. GX 1+4 is not detected in Stokes V, implying a 3σ upper limit of 21 per cent on the circular polarization. This rules out a coherent emission mechanism, as then an ∼100 per cent circular polarization is expected. The target is also significantly detected in each of the separate 8–9 GHz and 9–10 GHz bands, at 109 ± 11 and 93 ± 10 μJy, respectively. Due to the small frequency range and relatively large uncertainties, the spectral index α (where $S_\nu \propto \nu^\alpha$) remains poorly constrained at $\alpha = -0.7 \pm 3.3$. We do not detect any significant intra-observational time variability, as the flux densities for each individual source scan (96 ± 13, 82 ± 13 and 106 ± 13 μJy) are consistent within their uncertainties.

The full observation provides a source position of RA = $17^{\rm h}32^{\rm m}02\overset{\rm s}{.}13 \pm 0\overset{\rm s}{.}008$ and Dec. = $-24^\circ44'44\overset{''}{.}37 \pm 0\overset{''}{.}28$. The uncertainties on this position are calculated by dividing the synthesized beam size by the S/N ratio of the detection. Our position is consistent with the best known source position from the near-infrared 2MASS survey (Skrutskie et al. 2006, object name J17320215-2444442), which has a positional accuracy of 0.1 arcsec. We overlay this near-infrared position with the radio image in Fig 1.

3.2 X-ray

We estimate the X-ray flux and luminosity by fitting the *MAXI* GSC spectrum. The GSC spectrum contains ∼850 counts, sufficient for a basic model fit in XSPEC. We model interstellar absorption using TBABS, assuming abundances from Wilms, Allen & McCray (2000). An absorbed POWERLAW-model does not provide a decent fit, with a χ^2 of 34.7 for 12 degrees of freedom. An absorbed BBODYRAD-model instead returns a better fit with an unabsorbed 0.5–10 keV flux of $(4.6 \pm 0.6) \times 10^{-10}$ erg s^{-1} cm^{-2} and a χ^2 of 5.4 for the same number of parameters. For a distance of 4.3 kpc (Hinkle et al. 2006), this flux corresponds to an X-ray luminosity of $L_{\rm X} = (2.0 \pm 0.2) \times 10^{36}$ erg s^{-1}, of the order of ∼1 per cent of the Eddington luminosity. While a blackbody model most accurately describes the spectrum, it is difficult to assign an X-ray state to the source as it is unclear whether there is an accretion disc, the spectrum is of low quality and GX 1+4 does not show canonical NS LMXB states.

4 DISCUSSION

We report a 105.3 ± 7.3 μJy (>14σ significance) radio detection of the SyXRB GX 1+4 with the VLA at 9 GHz. Previously, Seaquist, Krogulec & Taylor (1993) and Fender et al. (1997) reported non-detections with upper limits of 90 μJy at 8.3 GHz and 240 μJy at 2.3 GHz, respectively. Martí et al. (1997) presented a marginal 3σ detection of the source (60 ± 20 μJy at 5 GHz) with the VLA from the best-known optical position of GX 1+4 at the time, but did not claim a significant detection. As their radio position is consistent with ours, it is likely that they indeed observed GX 1+4. Our analysis presents the first significant detection of radio emission from GX 1+4.

Manchanda (1993) reported the detection of two radio sources approximately equidistant to (∼4 arcmin) and aligned with the optical position of GX 1+4, proposing that these two emission regions could be radio lobes from a jet. Similar to Martí et al. (1997) and Fender et al. (1997), we detect these two emission regions. However, we measure their positions to be consistent with the Manchanda (1993) detections, implying they do not move away from the binary system. Furthermore, as already noted by Fender et al. (1997), one of the two sources is resolved into two individual sources, and no radio emission is detected connecting them to GX 1+4. Hence, they are likely unrelated to GX 1+4 and their alignment is probably coincidental.

The origin of the detected radio emission is not immediately obvious. Coherent emission, which would be ∼100 per cent circularly polarized, is ruled out by the non-detection in Stokes *V* implying a 21 per cent upper limit on the circular polarization. Here, we will discuss several alternative possibilities: the stellar wind, shocks in the magnetosphere, a jet and a propeller-driven outflow. Since the evidence for the cyclotron line in GX 1+4 is weak at best (Rea et al. 2005; Ferrigno et al. 2007), we will consider these mechanisms for both the magnetic field implied by the cyclotron line (∼10^{12} G, typical for a slow X-ray pulsar), and the maximum field inferred from standard disc theory (∼10^{14} G).

As Fender & Hendry (2000) suggested for the marginal radio detection by Martí et al. (1997), the radio emission could arise from the stellar wind in GX 1+4. A similar scenario has been postulated for the radio detection of the high-mass X-ray binary GX 301-2, which accretes from the wind of a B-hypergiant with a very high mass-loss rate of ∼10^{-5} M$_\odot$ yr^{-1} (Pestalozzi et al. 2009). For GX 1+4, we can estimate the radio flux density from free–free emission from a stellar wind using (Wright & Barlow 1975):

$$S_\nu = 7.26 \left(\frac{\nu}{10\,{\rm GHz}}\right)^{0.6} \left(\frac{T_{\rm e}}{10^4\,{\rm K}}\right)^{0.1} \left(\frac{\dot{M}}{10^{-6}\,{\rm M_\odot yr^{-1}}}\right)^{4/3} \times \left(\frac{\mu_{\rm e} v_\infty}{100\,{\rm km\,s^{-1}}}\right)^{-4/3} \left(\frac{d}{\rm kpc}\right)^{-2} {\rm mJy}, \quad (1)$$

where ν is the observing frequency, $T_{\rm e}$ the electron temperature, $\dot{M}$ the mass-loss rate, $\mu_{\rm e}$ the mean atomic weight per electron and v_∞ the terminal wind velocity. We assume that $\mu_{\rm e} = 1$ (i.e. a pure hydrogen wind) and set $v_\infty = 100$ km s^{-1}, consistent with measurements in cool, evolved stars (Espey & Crowley 2008), the escape velocity of the donor and the wind velocity estimates in GX 1+4 by Chakrabarty & Roche (1997) and Hinkle et al. (2006). For our basic estimate, we ignore the $T_{\rm e}$ term due to its low power and hence negligible effect on the radio flux.

To estimate the mass-loss rate, we use the semi-empirical relation for cool, evolved (for instance M-type) stars given by Reimers (1987, but see also Espey & Crowley 2008):

$$\dot{M} = 4 \times 10^{-13} \eta (L/{\rm L_\odot})(g/g_\odot)^{-1}(R/{\rm R_\odot})^{-1} {\rm M_\odot yr^{-1}}, \quad (2)$$

where $1/3 < \eta < 3$ is a dimensionless scaling to account for the uncertainty in $\dot{M}$ measurements, L is the bolometric luminosity, $g \propto M/R^2$ is the surface gravity, and R and M are the stellar mass and radius. For the range of stellar parameters of GX 1+4 as found by Chakrabarty & Roche (1997), we estimate 3×10^{-9} M$_\odot$ yr^{-1} $\lesssim \dot{M} \lesssim 7 \times 10^{-8}$ M$_\odot$ yr^{-1}. This yields a wind radio flux of 0.14 μJy $\lesssim S_\nu \lesssim$ 11 μJy. Since we detect radio emission at a level of ∼100 μJy, the stellar wind is unlikely to account for the detected flux. However, caution should be exercised when estimating the mass-loss rate in late type M stars; while the mass-loss rate is lower than in the B-type hypergiant in GX 301-2, and can be estimated through the equation above, the mass-loss rates for the M-type giant donors in SyXRBs and SySts are poorly known and estimates span orders of magnitude from ∼10^{-10} to ∼10^{-5} M$_\odot$ yr^{-1} (Espey & Crowley 2008; Enoto et al. 2014).

Alternatively, we might observe radio emission from shocks as the accretion flow interacts with the magnetosphere. The Compton limit on the brightness temperature of 10^{12} K sets a minimum size of the emission region of ∼7.5×10^4 km. The size of the magnetosphere, set by the radius where magnetic and gas pressure are equal, depends on the magnetic field strength and the mass accretion rate, estimated from the X-ray flux (e.g. Cackett et al. 2009, equation 1). For our observed flux and standard NS parameters, GX 1+4's highest estimated magnetic field strength of 10^{14} G yields a magnetosphere size of ∼2.4×10^5 km. Hence, such shocks are compatible with the properties of GX 1+4 if the magnetic field is indeed as high as ∼10^{14} G. However, if the magnetic field is only 10^{12} G, the magnetosphere is smaller than the minimum emission region size.

The radio emission could also be synchrotron emission from a collimated jet: the observed combination of $L_{\rm X}$ and L_R is in agreement with the radio and X-ray luminosities in a large sample of low-magnetic field accreting NSs (e.g. $\lesssim 10^9$ G; Migliari & Fender 2006; Migliari, Miller-Jones & Russell 2011a; Migliari et al. 2012; Tetarenko et al. 2016; Gusinskaia et al. 2017; Tudor et al. 2017), where the radio originates from such a jet. However, a jet identification will require independent confirmation through new observations, as we discuss below. Interestingly, while slow disc winds have been inferred in a handful of NSs with magnetic field strengths above $\sim 10^9$ G (e.g. Degenaar et al. 2014, and references therein), no radio jets have been observed in such sources (Fender et al. 1997; Fender & Hendry 2000; Migliari & Fender 2006; Tudose et al. 2010; Migliari et al. 2011b, 2012).

Massi & Kaufman Bernadó (2008) argue that a jet can only form when the magnetic pressure is lower than the gas pressure at the truncation radius of the disc, as otherwise the field lines will not be twisted by the disc rotation. In this scenario, slow X-ray pulsars would indeed not launch a jet due to their strong magnetic field. If a jet is actually present in GX 1+4, or alternatively in Her X-1, a strong-magnetic field intermediate-mass X-ray binary where we also recently discovered radio emission (Van den Eijnden et al. 2017), either this argument is incomplete or an alternate jet launching mechanism occurs for strong magnetic fields.

If we observe a jet, the alternative launching mechanism might be a magnetic propeller. Such an outflow has been inferred from X-ray observations in two high-magnetic field X-ray pulsars (Tsygankov et al. 2016), and has been proposed earlier for GX 1+4 based on its correlated X-ray flux and pulsation behaviour (Cui & Smith 2004). A magnetic propeller can arise when, at the radius where the magnetic pressure equals the gas pressure, the rotational velocity of the field (the pulsar spin P) exceeds the Keplerian velocity of the disc, creating a centrifugal barrier. As the gas pressure depends on the mass accretion rate and thus the X-ray luminosity, we can estimate the maximum X-ray luminosity for a propeller to occur as a function of magnetic field strength and pulsar spin (e.g. Campana et al. 2002):

$$L_{\mathrm{X,max}} \approx 4 \times 10^{37} k^{7/2} B_{12}^{2} P^{-7/3} M_{1.4}^{-2/3} R_{10}^{5}\,\mathrm{erg\,s^{-1}}, \qquad (3)$$

where k is a geometry factor, typically assumed to be 0.5 for disc accretion, B_{12} is the magnetic field strength in units of 10^{12} G, $M_{1.4}$ is the pulsar mass in 1.4 $\mathrm{M}_\odot$ and finally R_{10} is the pulsar radius in 10 km.

For the highest magnetic field estimate of GX 1+4 (i.e. $\sim 10^{14}$ G) and standard NS parameters, $L_{\mathrm{X,max}} \approx 5 \times 10^{35}\,\mathrm{erg\,s^{-1}}$, which differs by only a factor of a few from our observed X-ray luminosity. Indeed, our observed X-ray flux is similar to the X-ray flux where Cui & Smith (2004) infer the onset of the propeller regime (i.e. $3 \times 10^{-10}\,\mathrm{erg\,s^{-1}\,cm^{-2}}$). However, this propeller scenario might be difficult to reconcile with the marginal radio detection by Martí et al. (1997), where L_{X} was an order of magnitude higher (Galloway 2000) and a propeller was thus not expected. Furthermore, if the magnetic field is instead $\sim 10^{12}$ G, $L_{\mathrm{X,max}}$ drops by four orders of magnitude and a propeller scenario can be excluded.

The above calculation assumes disc accretion, although in GX 1+4 it is unclear whether the NS accretes directly from stellar wind or there is a wind-fed disc (e.g. Lü et al. 2012). In SySts, such a disc is only inferred in 4 out of 10 sources known to launch a jet (Sokoloski, Bildsten & Ho 2001). Using $k = 1$, as appropriate for spherical accretion, the maximum inferred magnetic field yields $L_{\mathrm{X,max}} \approx 6 \times 10^{36}\,\mathrm{erg\,s^{-1}}$, implying that GX 1+4 was in the propeller regime. However, we again note that the cyclotron-line estimate of the magnetic field rules out a magnetic propeller, even with $k = 1$.

While GX 1+4 is the first SyXRB where radio emission is detected, radio emission and jets are more common in SySts, i.e. white dwarf equivalents of SyXRBs. Six SySts show a resolved radio jet, while four more systems have a jet as inferred from X-ray or optical spectroscopy (e.g. Brocksopp et al. 2004, and references therein). Contrary to GX 1+4, the magnetic field of the WD accretor in SySts is typically orders of magnitude weaker than that required to suppress jet formation in the argument of Massi & Kaufman Bernadó (2008): Z And has the strongest inferred magnetic field in jet-forming SySts at $\gtrsim 10^5$ G.

The point source nature and the luminosity of the radio emission in GX 1+4 are consistent with the radio properties of the detected SySts: while all are resolved by MERLIN, VLA or ATCA (angular extents of 0.1–3 arcsec, corresponding to hundreds of au), five out of six sources are significantly closer than GX 1+4 and their angular extent would not be resolved with the VLA in C-configuration at 4.3 kpc (Padin, Davis & Bode 1985; Dougherty et al. 1995; Ogley et al. 2002; Brocksopp et al. 2004; Karovska et al. 2010). The sixth source, HD 149427, is located at a larger distance and was resolved by ATCA (Brocksopp, Bode & Eyres 2003), but only because its angular extent is exceptionally large in comparison with the other sources. The SySts show a large range of radio luminosities, spanning up to three orders of magnitude ($\sim 10^{27}$–$10^{30}\,\mathrm{erg\,s^{-1}}$). GX 1+4 falls well within this range, with a radio luminosity similar to the SySts Z And, AG Dra and CH Cyg.

While the stellar wind is unlikely to be the origin of the radio emission in GX 1+4, shocks, a jet, and a magnetic propeller all cannot be excluded. More observations are required to better understand the radio emission; for instance, a jet nature can be tested by measuring the spectral index from multiple radio bands, searching for linear polarization or an extended structure, or potentially detecting a jet break in the broad-band spectrum. By observing the source simultaneously at radio and X-ray wavelength around the X-ray luminosity where the propeller is expected to switch on and off, the magnetic propeller explanation can also be tested: above the X-ray luminosity threshold, the radio is expected to be quenched in this scenario. Furthermore, this first radio detection of an SyXRB warrants follow-up radio observations of this class of sources, to establish whether these sources generally are radio emitters or GX 1+4 is an outlier. Finally, also motivated by our recent radio detection of the strongly magnetized X-ray pulsar Her X-1 (Van den Eijnden et al., submitted), the hypothesis that strong magnetic fields suppress jet formation should be revisited with deep radio observations of a large sample of such X-ray pulsars.

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