IS THERMAL EXPANSION DRIVING THE INITIAL GAS EJECTION IN NGC 6251?

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ABSTRACT

The relativistic jets in active galactic nuclei (AGNs) are probably driven by the action of supermassive, spinning black holes. There is very little direct evidence for this, however, since the nuclei of active galaxies are difficult to study. This is now changing with new, high-resolution multiwavelength observations of nearby sources such as Sgr A* at the Galactic center and the nucleus of NGC 6251 (hereafter called NGC 6251*). In this paper, we explore the possibility that the radiative properties of the most compact region in NGC 6251* may be understood in the same sense as Sgr A*, though with some telling differences that may hint at the nature of jet formation. We show that observations of this object with ASCA, ROSAT, HST, and VLBI together may be suggesting a picture in which Bondi-Hoyle accretion from an ambient ionized medium feeds a standard disk accreting at \( \sim 4.0 \times 10^{22} \) g s\(^{-1}\). Somewhere near the event horizon, this plasma is heated to more than \( 10^{11} \) K, where it radiates via thermal synchrotron (producing a radio component) and self-Comptonization (accounting for a nonthermal X-ray flux). This temperature is much greater than its virial value and the hot cloud expands at roughly the sound speed \((\sim 0.1c)\), after which it begins to accelerate on a parsec scale to relativistic velocities. In earlier work, the emission from the extended jet has been modeled successfully using nonthermal synchrotron self-Compton processes, with a self-absorbed inner core. In the picture we are developing here, the initial ejection of matter is associated with a self-absorbed thermal radio component that dominates the core emission on the smallest scales. The nonthermal particle distributions responsible for the emission in the extended jet are then presumably energized, e.g., via shock acceleration, within the expanding, hot gas. The power associated with this plasma represents an accretion efficiency of about 0.54, requiring dissipation in a prograde disk around a rapidly spinning black hole (with spin parameter \( a \sim 1 \)).

Subject headings: accretion, accretion disks — black hole physics — galaxies: active — galaxies: individual (NGC 6251) — galaxies: jets — Galaxy: center

1. INTRODUCTION

The giant elliptical NGC 6251 is host to one of the most spectacular radio sources in the sky (Waggett, Warner, & Baldwin 1977), and at a distance of 106 Mpc (for \( H_0 = 70 \) km s\(^{-1}\) Mpc\(^{-1}\)), it is the farthest galaxy for which the presence of a massive black hole has been inferred on the basis of, e.g., the kinematic properties of its core. ASCA observations of its central engine (which we hereafter call NGC 6251*) have suggested the presence of an extremely broad 6.68 keV Fe emission line (Turner et al. 1997) due to Ñuorescence and back-scattering in the inner region of an optically thick accretion disk (Tanaka et al. 1995), though \( \sim 0.1c \) has yet to confirm this. More recent Hubble Space Telescope (HST) optical images of this galaxy’s core have facilitated a detailed study of its well-defined (and larger) dusty disk, whose Keplerian motion points to a central dark mass of \( M \sim 4\times 10^8 M_\odot \) (Ferrarese & Ford 1999). This disk, it seems, is about 730 pc in diameter and is inclined by 76° to the line of sight. A significant ionized gas component is confined to the central \( \sim 0.3 \) (\( \sim 150 \) pc) region, and the fact that the jet is not perpendicular to the dusty disk’s plane suggests that this 730 parsec scale structure is misaligned with respect to the hypothesized subparsec-scale inner accretion disk.

The nucleus of NGC 6251 may be a member of the (relatively small) class of low-luminosity active galactic nuclei (AGNs) for which reasonably secure black hole masses have been determined using dynamical measurements. The faintness of the core emission in these objects makes them difficult to observe, though several have been studied with sufficient precision for us to infer that their spectral energy distributions differ considerably from those of the luminous AGNs. This class of nuclei includes NGC 1316 and NGC 3998 (Fabbiano, Fassnach, & Trinchieri), Sgr A* (Melia 1994; Narayan, Yi, & Mahadevan 1995; Melia & Falcke 2001), NGC 3031 (M81; Ho, Filippenko, & Sargent 1996), NGC 4258 (Lasota et al. 1996), M87 (Reynolds et al. 1996), and NGC 4594 (Fabbiano & Juda 1997), among others (see, e.g., Ho 1999). Of these, Sgr A* at the Galactic center has been the most extensively discussed source, in part due to its proximity, which facilitates highly sensitive measurements with remarkable spatial resolution (now approaching \( \sim 1 \) A.U. or better; Falcke, Melia, & Agol 2000).

NGC 6251* appears to have many features in common with Sgr A*, yet they differ in several significant and important ways. For example, NGC 6251* is about 200 times more massive than Sgr A* and is correspondingly more luminous, but their core spectra are quite similar. On the other hand, NGC 6251* produces an obvious jet, whereas Sgr A* does not. Thus, a comparative study of these objects can be valuable in helping us to understand the underlying physical basis for their activity. A principal goal of this paper is to determine if NGC 6251* can be understood in

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the context of the accretion model for Sgr A*, thus helping us disentangle the physics of the nascent jet from the underlying processes driving the central engine.

It is, in fact, the jet in NGC 6251 that has dominated the study of this FR I radio galaxy (see, e.g., Bridle & Perley 1984). Morphologically, the jet and its core appear to be resolved into self-similar structures as one observes this source at progressively higher frequencies and therefore with higher spatial resolution (see, e.g., Fig. 12 in Jones et al. 1986). The radio spectrum of the jet itself is adequately described by a nonthermal synchrotron self-Compton model (see, e.g., Ghisellini et al. 1993; Guerra & Daly 1997; Mack, Kerp, & Klein 1997; see also Melia & Konigl 1989). The natural interpretation for this phenomenon is that the core is associated with optically thick emission at the base of the jet, probably due to a nonthermal distribution of particles sweeping outward beyond several parsecs. However, more recent observations of NGC 6251* on even smaller scales (within a fraction of a parsec) suggest that most of the particle acceleration occurs away from the hypothesized black hole in this system (see below). It is therefore possible that the particle distribution is evolving with distance inside the most compact region resolved thus far.

Our motivation for pursuing this idea stems from our study of Sgr A*, which shows that the basic accretion picture for nuclear black holes separates neatly into several categories, each of which is characterized by (1) the specific angular momentum accreted by the gas at the Bondi-Hoyle capture radius \( r_{\text{cap}} \equiv 2GM/v^2_{\text{esc}} \) in terms of the ambient gas velocity \( v_{\text{esc}} \), which determines the circularization radius of the accretion flow, and (2) the relative importance of cooling compared to compressional heating at \( r_{\text{cap}} \). For typical conditions in the interstellar medium (ISM), the initial temperature \( T(r_{\text{cap}}) \sim 10^{6} - 10^{7} \) sits on the unstable branch of the cooling function. Depending on the actual value of \( T(r_{\text{cap}}) \) and the accretion rate \( M \), the plasma settles either onto a hot branch (attaining a temperature as high as \( 10^{10} \) K or more at small radii) or a cold branch, in which \( T \) drops to \( \sim 10^{6} \) K. It would at first appear that NGC 6251* should be a member of the cold branch family, since the spectrum of its prominent UV emission can be fitted very well with a standard, geometrically thin disk whose existence is further motivated by the appearance of the broad Fe emission line in its spectrum. At higher energies, ROSAT observations suggest that the X-ray emission from NGC 6251* includes two contributions: a resolved thermal component with an extension of 2.5–1.3 kpc, a temperature of 0.5 keV, and an unresolved power-law component that correlates well with the core radio emission (Worrall & Birkinshaw 1994). Even so, the behavior of NGC 6251* cannot be easily explained in this fashion because the inferred accretion rate from the UV spectral fit is \( \sim 4.0 \times 10^{22} \) g s\(^{-1}\), which is not consistent with the power produced by the central engine if the plasma remains cold all the way to the event horizon. Instead, as we shall see, the strong radio emission from the most compact region of NGC 6251* may be due to synchrotron emission by a very hot plasma (in excess of \( 10^{11} \) K; Jones et al. 1986) within a few thousand Schwarzschild radii of the black hole, powering emission at about 0.5 of the rate with which rest mass energy is carried inward. Under such conditions, the hot plasma would then be unbounded.

Recent VLBA observations show that the extended radio jet accelerates on a subparsec scale, from \( \sim 0.13c \) at 0.30 pc to \( \sim 0.42c \) at 0.57 pc (Sudou et al. 2000). In this regard, it is noteworthy that the temperature (\( \sim 10^{11} \) K) required to produce the strong radio emission from the most compact region measured to date (assuming a compact thermal particle distribution) corresponds to a sound speed of \( \sim 0.1c \). The coincidence of these speeds strongly suggests to us that the nascent jet may be formed by the same hot expanding plasma that would then produce the VLBA core component via thermal synchrotron radiation. If this picture is correct, the nonthermal particles inferred from the jet emission on larger scales would then be accelerated—presumably via shock acceleration or an electrodynamic process—within the expanding hot gas. In this paper, we scrutinize the multiwavelength observations of NGC 6251* and invoke a hot expanding plasma to fit the radio spectrum of the nucleus and its self-Comptonized component, which in turn appears to account well for the unresolved power-law X-rays. We shall find that the implied mass-loss rate is a significant fraction of the accretion rate through the disk.

2. MULTIWAVELENGTH OBSERVATIONS OF THE NUCLEUS IN NGC 6251

The currently available observations of NGC 6251* are summarized in Table 1. VLBI maps of NGC 6251* have sufficient resolution to separate out the jet emission from the core down to a size of about 2500 Schwarzschild radii (e.g., Cohen & Readhead 1979; Jones et al. 1986); the corresponding flux varies significantly on a timescale of years. It should be emphasized that the cm–mm radio spectrum of the core on this scale differs considerably from that of the extended and the subparsec-scale jet components. Whether thermal or nonthermal, its rise toward mm wavelengths—reminiscent of the so-called mm to sub-mm bump in Sgr A* (Melia & Falcke 2001)—is a signature of self-absorbed synchrotron emission (e.g., Melia 1992, 1994). The possibility that the core component on this smallest scale is associated with the jet dynamics is underscored by the recent discovery of a subparsec-scale counterjet in this source (Sudou et al. 2000), which shows that the outflow is accelerated from \( \sim 0.13c \) at 0.30 pc to \( \sim 0.42c \) at 0.57 pc. The nascent jet therefore appears to accelerate to its terminal velocity well beyond the compact inner region studied here.

At X-ray energies, Birkinshaw & Worrall (1993) analyzed the ROSAT/PSPC data and concluded that nearly all (~90%) of the emission arises from a spatially unresolved power-law component with a diameter less than 200 pc (\( 3.5 \times 10^{0}r_{3} \)); this component correlates well with the core radio emission (Worrall & Birkinshaw 1994). Data now exist for the core of NGC 6251 across at least 9 orders of magnitude in frequency (see Fig. 1 below). The ROSAT observations are important also because they place a lower limit (of \( \sim 0.1 \) cm\(^{-3}\)) on the proton density of the ISM and the inferred intrinsic hydrogen column density is \( 5.0 \times 10^{20} \) cm. Ferrarese & Ford (1999) argue that the implied Bondi-Hoyle accretion rate is \( \sim 5 \times 10^{-4} M_{\odot} \) yr\(^{-1}\) \( \approx 3.2 \times 10^{22} \) g s\(^{-1}\).

Another important observation was made by ASCA. Its high spectral resolution makes it possible to resolve the emission line in the X-ray band. In NGC 6251*, the equivalent width of the Fe xxv 6.68 keV line is 392 ± 305 eV (Turner et al. 1997). This extreme width corresponds to a velocity of \( \sim 0.3c \), reminiscent of the accretion disk model for MCG − 6-30-15 (Tanaka et al. 1995).
3. STRUCTURE OF THE Emitting Gas AROUND NGC 6251*

Roughly speaking, the following inequality should be satisfied if the emitting gas near the central black hole is bounded:

\[
\alpha k_B T \leq \left( 1 - \frac{1}{\sqrt{1 - \frac{R}{r}}} \right) m_p c^2,
\]

where \( \alpha = 3 \) for a fully ionized but nonrelativistic plasma and \( \alpha = 9/2 \) when the electrons are relativistic. Also, \( k_B \) is the Boltzmann constant, \( m_p \) is the proton mass, and \( T \) is the temperature of the (assumed thermal) plasma. For NGC 6251*, the Schwarzschild radius is \( r_S = 1.77 \times 10^{14} \text{ cm} \) (assuming a mass of \( 6 \times 10^8 M_\odot \)). Thus, we should have

\[
T \leq 3.6 \times 10^{12} \left( 1 - \frac{1}{\sqrt{1 - \frac{r_S}{r}}} \right) \text{K},
\]

if the emitting gas is bounded.

However, this is not consistent with observations of NGC 6251* at 5 GHz, which show that the flux density of the core is 0.13 Jy per beam, with a beam size of 0.5 mas \( \times \) 0.5 mas. Because this flux should be less than that produced by an optically thick plasma, we have

\[
F_v \leq \left( \frac{R}{D} \right)^2 \frac{2 m k_B T v^2}{c^2},
\]

where \( F_v \) is the flux density, \( R \) is the characteristic radius of the emitting region, and \( D = 106 \text{ Mpc} \) is the distance to NGC 6251. That is, \( T (R/r_S)^2 \geq 1.8 \times 10^{17} \text{ K} \). Thus, if the radio emission is produced by a bound plasma, \( R/r_S \geq 2.3 \times 10^3 \), corresponding to an angular size of 25 mas, which is much larger than one-half the beam size within which the radio emission is supposed to be confined. Thus, if the gas producing the radio emission in NGC 6251* is thermal, it must have a temperature above its virial value. More specifically, the fact that the radio emission is confined to a region apparently no larger than 0.25 mas (\( \sim 2400 \text{ g} \)), the required temperature is \( T > 3.3 \times 10^{10} \text{ K} \). Here, we have ignored the effects of Doppler boosting, justified on the basis that the bulk velocity of the radio-emitting plasma is about 0.1c.

The UV spectrum and the tentative observation of a broad Fe emission line also suggest the presence of a standard optically thick disk, which must merge into the hot plasma described above. The size of this disk is determined by the specific angular momentum accreted with the gas following Bondi-Hoyle capture. Its temperature is a measure of the accretion rate. Since most of the UV radiation is produced near the inner region of this circularized flow, only the temperature (and hence the accretion rate) is an important adjustable parameter for fitting the observations.

On an even larger scale, the \( HST \) observations indicate that there exists a significant ionized gas component within 150 pc from the central black hole. For an accretor with mass \( \sim 6 \times 10^8 M_\odot \), the capture radius is approximately 20 pc (scaled to an ambient gas velocity of 500 km s\(^{-1}\)), so this ionized gas component must contribute a substantial fraction of the Bondi-Hoyle captured gas that flows inward to merge with the accretion disk as smaller radii (see below). The \( ROSAT \) observation shows that this gas component should also contribute to the extended thermal X-ray source, not unlike the situation now known to exist at the Galactic center following imaging observations with \( Chandra \) (e.g., Bagano† et al. 2001). The larger scale dusty disk imaged by \( HST \) has a radius of about 250 pc, and since this structure is relatively faint, we will not include it in our spectral modeling.

4. CALCULATION OF THE SPECTRUM

There are three dominant spectral components in our model (Liu & Melia 2000; Melia, Liu & Coker 2000): one is the thermal synchrotron (radio) emission from the expanding hot nuclear region—which we assume dominates the observed core radio flux associated with the inner 2500 Schwarzschild radii; the second is the self-Comptonized radiation from this region (contribution mostly to the nonthermal X-ray flux); and the third is the optically thick
emission from the standard accretion disk. The latter is a function of the accretion rate and the inclination angle. Based on their best fit to the line emission from the nucleus, Ferrarese and Ford (1999) inferred an inclination angle of 31°. Fitting the UV data with such a disk (see Fig. 1), we find that the required accretion rate is \( \dot{M} \approx 4.0 \times 10^{22} \, \text{g s}^{-1} \). This is significant in view of the fact that the Bondi-Hoyle capture rate within the ionized gas component is very close to this value (Ferrarese & Ford 1999; see also Coker & Melia 1997). It seems, therefore, that the disk is fed almost entirely from the ambient ionized medium, and that any energy flux advected through the disk must be a small fraction of the total power (cf. Narayan et al. 1995).

To model the thermal synchrotron-emitting plasma, it is necessary to make some simplifying assumptions, since we do not yet know precisely how this region is energized (but see Krolik 1999, Gammie 1999, Kowalenko & Melia 2000, and Agol & Krolik 2000 for some recent work on this topic). The structure (e.g., the radial stratification) of the inner hot plasma must therefore reflect the nature of this heating mechanism. As a first step, we will simply take this inner region to be a uniform sphere. Calculating the thermal synchrotron spectrum and its self-Comptonized component then produces the best-fit model shown in Figure 1—always under the assumption that any self-absorbed nonthermal synchrotron emission on this scale is small by comparison. The inset shows an enlarged view of the fit to the radio spectrum of the core in NGC 6251, together with data gathered at three different epochs (each set being connected by dashed lines). Our fit corresponds to the most recent observation, represented by the two lowest points in the diagram, since this occurred closest to the observations at other wavelengths. The calculated radio spectral index is somewhat larger than that observed, but given the oversimplified geometry adopted for this calculation and the strong temporal variability in the radio spectrum, the comparison is rather promising.

The best-fit model for the hot, expanding gas has a radius \( R = 450 r_s \), a temperature \( T = 10^{12} \, \text{K} \), an electron number density \( n_e = 300 \, \text{cm}^{-3} \), and a magnetic field \( B = 0.06 \, \text{G} \). All these parameters are guided by, and are consistent with, the limits set by Jones et al. (1986). As one can see from this figure, the radio spectrum produced in the optically thick region is that of a blackbody, consistent with a spectral
index of 2. In the optically thin region, the measured flux density is given by 
\[ F_v = \epsilon_v V / 4\pi D^2, \]
where \( V \) is the volume of the sphere. The emissivity \( \epsilon_v \) for thermal synchrotron emission is well-known and is given in Pacholczyk (1970). Also, although we here calculate the Comptonized component numerically, it is straightforward to estimate it as follows. At a temperature of \( 10^{12} \) K, the characteristic particle Lorentz factor is \( \gamma_c \approx 3k_B T / m_e c^2 = 506. \) Then Compton scattering will increase the photon frequency by a factor \( \sim \gamma^2 c = 2.6 \times 10^5. \) In reality, the electron Maxwell-Boltzmann distribution broadens the Comptonized component somewhat. The ratio of the scattered peak flux density to that in the radio is therefore \( \sim \sigma_T R_n c^3 / \epsilon_c, \) which is roughly \( 10^{-5} \) for the best-fit parameters. These values are in excellent agreement with the results of numerical calculations shown in Figure 1. In particular, it is evident from the figure that this compact nucleus can fit the radio and X-ray spectral components self-consistently. Indeed, because the X-ray emission is produced by self-Comptonization of the radio photons, these two components must be highly correlated, consistent with the assessment made by Worrall & Birkinshaw (1994).

The UV flux is produced predominantly within the inner \( \sim 20R_g \) of the optically thick accretion disk, whose inner radius in this simulation is set at \( 3R_g. \) Note that if the black hole is spinning, this inner radius is reduced even further (for a prograde orbit), making the required accretion rate somewhat smaller than the \( \sim 4.0 \times 10^{22} \) g s\(^{-1}\) inferred above. The spectral fit in this waveband appears to be quite satisfactory also.

Notice, however, that at EUV energies, both the disk and the self-Comptonized component from the expanding plasma contribute to the spectrum. The latter dominates progressively more and more toward higher frequency. The fact that the Comptonized component is produced in a relatively large region may explain the observed asymmetry of the EUV source. The \( \text{HST} \) observations found that only one side of the large-scale dusty disk is illuminated, suggesting a warped geometry (Crane & Vernet 1997). However, in the UV band, such a reflection component does not exist, indicating that the UV and EUV emissions from the inner region might have different origins. According to our model, the UV emission is produced in the inner region of the small accretion disk, whereas the UV radiation is due to self-Comptonization within the much larger expanding hot cloud. In this picture, it is therefore much easier to illuminate the large dusty disk at EUV rather than UV energies, which appears to be borne out by the observations.

5. CONCLUSIONS

From the parameters of the best-fit model, we can estimate the rate of mass loss associated with the expanding hot plasma in the nucleus

\[ \dot{M}_{\text{loss}} \sim \Delta \Omega \epsilon_c (f_c S) n \sim 9.6 \Delta \Omega (f_c S / 0.1c) \times 10^{21} \text{ g s}^{-1}, \]

where \( f_c S \) is observed to be about \( 0.13c \) at \( 0.30 \) pc, so \( f \) may be less than one closer to the black hole. Also, \( \Delta \Omega \) reflects the unknown geometry of the expanding gas—the more collimated the expansion is, the smaller the value of \( \Delta \Omega \) will be, though observationally it appears that \( \Delta \Omega \sim 0(1). \) The fact that \( \dot{M}_{\text{loss}} \) in this picture is similar to the inferred accretion rate through the disk suggests that much of the infalling matter is energized by the black hole and escapes via thermal expansion.

The need for a large efficiency in converting accreted rest-mass energy into the power of the central source can be inferred on the basis of several lines of evidence. First, in the X-ray band (0.2–2.4 keV), the luminosity is \( \sim 1.9 \times 10^{42} \) erg s\(^{-1}\) (assuming a spectral index of 1.0, as indicated by our best-fit model). The total X-ray luminosity is even larger than this. However, the dissipation of gravitational energy in the disk accounts for only \( 2.6 \times 10^{42} \) erg s\(^{-1}\), which is in fact equal to the UV luminosity. Second, the energy advection rate in the expanding cloud would have to be \( \sim 1.5 \times 10^{43} \) ergs s\(^{-1}\) if all of the accreting gas (i.e., about \( 4.0 \times 10^{22} \) g s\(^{-1}\)) is expelled from the nucleus. Thus, the total power produced near the black hole is \( \sim (15 + 4.5) \times 10^{42} \) ergs s\(^{-1}\), which then implies an efficiency \( \epsilon \approx 19.5/36 \approx 0.54. \) According to the classical estimates for the accretion efficiency (see, e.g., Bardeen 1970; Thorne 1974; Abramowicz, Jaroszynski, & Sikora 1978), this inferred value of \( \epsilon \) requires a rapidly spinning black hole with a spin parameter \( a \sim 1. \) A value of \( \epsilon > 0.42 \) may require additional physics associated with energy extraction via strong magnetic fields that couple the tightest orbits to those well beyond the inner edge of the disk (see, e.g., Krolik 1999; Gammie 1999).

An alternative model, in which no such conversion occurs but rather the disk is advection dominated and thereby releases its trapped energy at small radii, is unlikely to apply here. Given that a large fraction (perhaps all) of the accreted mass is lost in the expanding hot cloud, it is difficult to see why this unbound plasma would accrete down to small radii in the first place. In addition, a truncated standard disk (Quataert, Matteo, & Narayan 1999), as introduced in the ADAF model, cannot fit the UV spectrum. The reason is that to produce significant EUV emission, the temperature of the disk should be around 7000 K. For a truncated disk with such a temperature, the UV flux density is much larger. Also, the properties of the ionized gas surrounding NGC 6251\(^*\) inferred from the \( \text{ROSAT} \) observations constrain the accretion rate rather tightly. A model with a much larger accretion rate is not favored.

In summary, the multiwavelength observations of NGC 6251\(^*\) and the associated theoretical modeling of this source point to the following scenario as a viable description of the initial ejection of hot plasma near the black hole and its corresponding radio spectrum, which may dominate the core emission seen on the smallest spatial scales. Bondi-Hoyle accretion (starting at \( \sim 20 \) pc) from the surrounding ionized medium feeds a standard disk at a rate of \( \sim 4.0 \times 10^{22} \) g s\(^{-1}\). This disk produces the UV spectral component measured by \( \text{HST} \), but close to the event horizon (probably near the innermost stable orbit in a Kerr metric with \( a \sim 1. \)), the infalling gas is energized and radiates via thermal synchrotron processes to produce (much, or all, of) the core VLBI radio flux. The temperature of the gas is much greater than its virial value, and so the hot plasma expands at \( \sim 0.1c, \) close to its speed of sound. Very importantly (particularly for future modeling), most of the acceleration that produces the large-scale jet therefore does not occur within the core but rather acts some distance away. In this system, at least, the black hole energizes the infalling plasma and expels it to feed the nascent jet, but the
acceleration that drives the outflow to relativistic velocities occurs on a parsec scale, some $10^4 r_s$ beyond the event horizon.

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