The Complex Radio Morphology of Markarian 6 and Implications for Seyfert life-cycles

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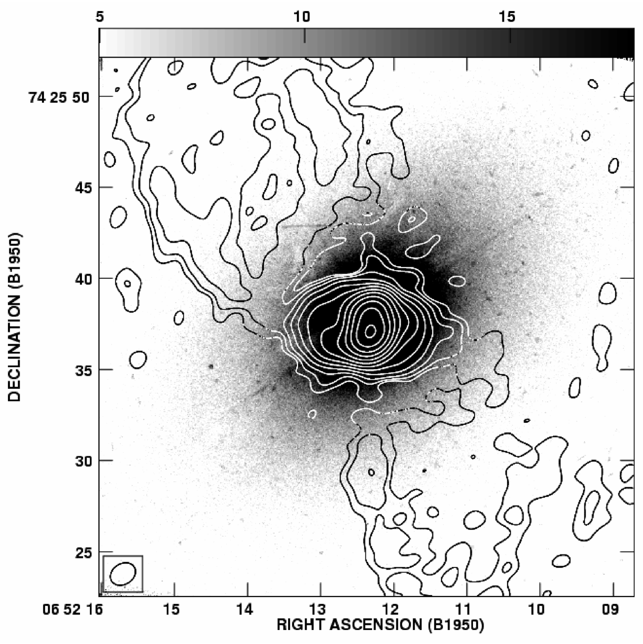

Fig.1 The 20cm radio contours superimposed on the greyscale image of HST (WFPC2/F606W) optical continuum from the central regions of the S0a host galaxy. The outer bubble-like structures are projected roughly orthogonal to the major axis of the host galaxy. The radio structures lie within the extent of the galaxy (> 11 kpc by 15 kpc (NED)).

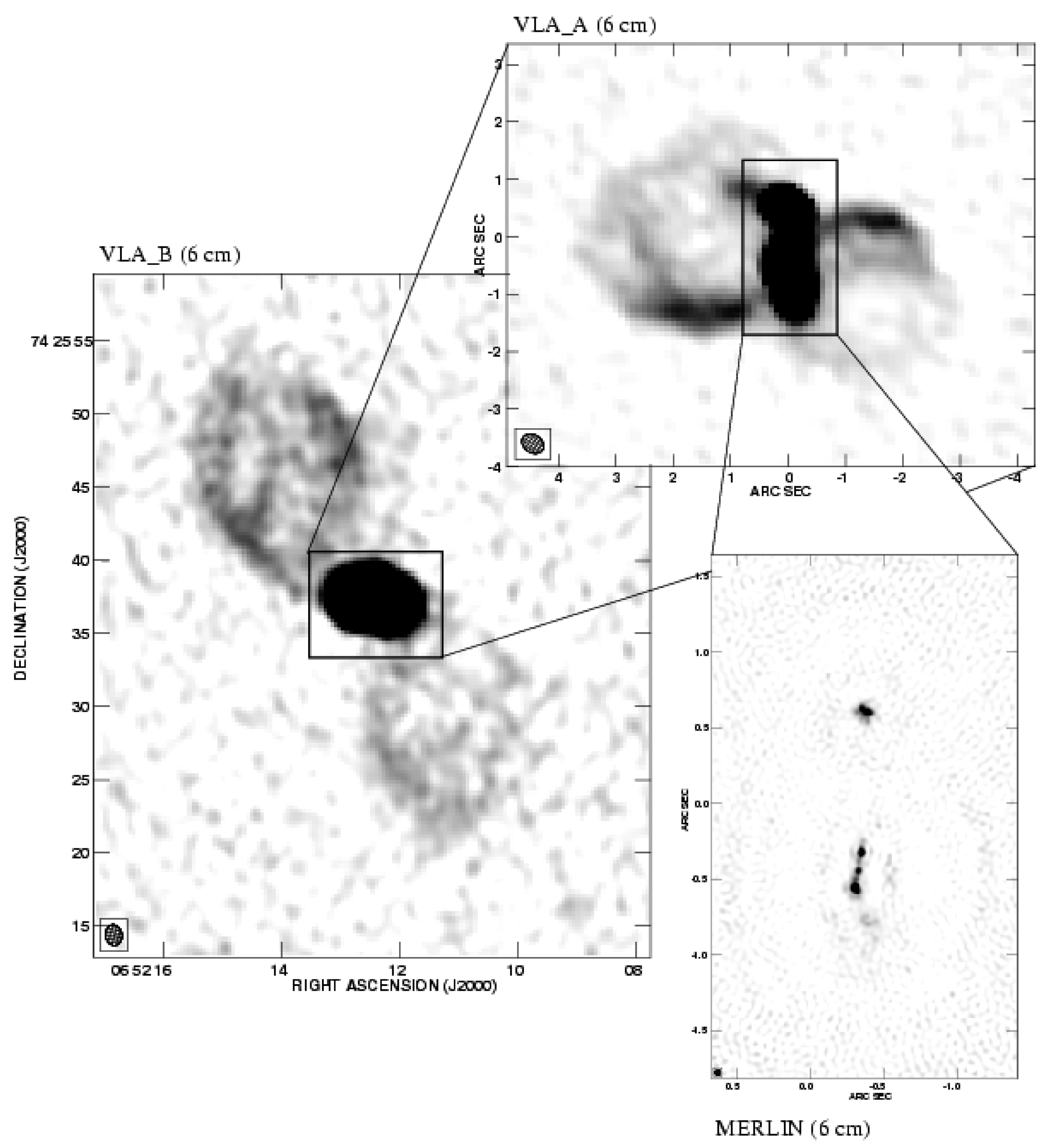

Fig.2 Grey scale image of the 6cm radio structures observed in Mrk 6 with the VLA. The MERLIN map of the inner jet is from Kukula et al., 1996. The centre of the optical host galaxy lies close to the (0,0) position (with a 3σ uncertainity of 0.27") in the MERLIN image. There is no radio "core" coincident with that position.

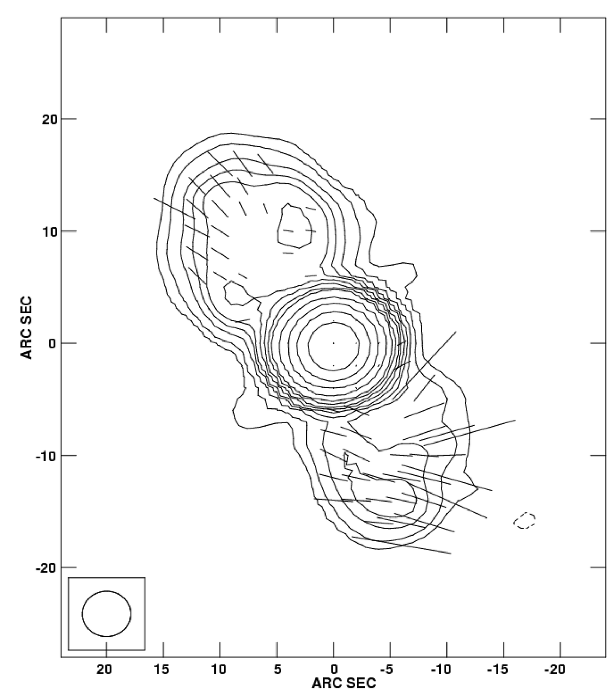

Fig.4 The VLA C-array 6cm radio map of Mrk6 with polarization electric vectors superimposed.
Contour levels:7.45x 10^{-5}x (-1,1,2,4,6,8,12,16,24,32,64,128,256,512) Jy/beam, Beam:4.2"x4.0".
1" in length of polarization vector = 10 % polarization.
The fractional polarization along edges of "bubbles" range from 20% - 40%, typical of AGN jets.
Typical values for measured polarization of supernova remnants, on the other hand, are <10% on all scales.

Markarian 6

Mrk6 is a Seyfert 1.5 galaxy at a redshift of z=0.018. It is hosted by an S0a spiral galaxy (Fig.1). Mrk6 is located in a sparse environment (Dahari et al, 1985), and shows no visible signatures of merger-activity. It emits copious amounts of radio emission on kpc scales.

Observations

We observed Mrk6 with the Very Large Array (VLA)[1] at 6cm (4860 MHz) and 20cm (1430 MHz) during 1995-1996, using almost all VLA configurations. 3C286 was the flux density and polarization calibrator and 0614+607 was the phase calibrator for the experiment. Data were processed with the AIPS software using standard imaging and self-calibration procedures.

We discovered that radio emission occurs on three spatial scales in Mrk6: There is a ~7.5 kpc** Outer "bubble", a ~1.5 kpc Inner "bubble", and a ~1 kpc jet. All three structures lie roughly orthogonal to each other (Fig.2).

We examined various models to understand the complex radio morphology; two main scenarios are described below.

1. Nuclear-Starburst-driven Bubble Scenario

Assuming that the "bubbles" are formed through starburst winds energized by supernovae explosions, we estimated the energy budget:
Energy required for the bubbles to expand to the present sizes adiabatically within the ISM of pressure 10^{-10} dynes /cm^2 is = 1.7x10^{57} ergs.
ie., 1.7x10^6 supernova explosions with individual explosive energy of 10^{51} ergs.
For wind speeds of 1000 km/s, time required for bubbles to expand to present size is = 7x10^6 yrs. Thus, required supernova explosion rate = 0.24 /yr
Assuming a Salpeter IMF over mass range 0.1 < M/$M_\odot$ < 100, we obtain a star-formation rate (SFR) of ~33 $M_\odot$ /yr (using eqns. in Condon92,Condon02).
An upper limit to SFR in Mrk6 comes from Spitzer IRAC observations (Buchanan06):
Using relation, SFR = 2.0x10^{-43} ν L_ν (8μm) ergs /sec (Calzetti et al. 2006, in prep)
and 8μm flux density of 0.1 Jy, from the central 7" region (2.7 kpc), we obtain an SFR (M>0.1 $M_\odot$) = 5.5 $M_\odot$ /yr.
Therefore, a starburst alone cannot meet the energy requirements for the creation of the bubble-like structures in Mrk6.

2. Episodically-powered Precessing Jet Scenario

In this model, an episodic precessing jet is the prime mover that has produced all of the radio structure observed in Mrk6. Assuming a jet velocity of ~10^4 km /s (Bicknell, 1998) and the bubbles-edges to be a precessing jet, the outer bubbles would have resulted in >7x10^5 years and the inner bubbles would need 1x10^5 years to form. The jet flips its axis by ~140 degrees between the two epochs (see Fig.3, and Table below).

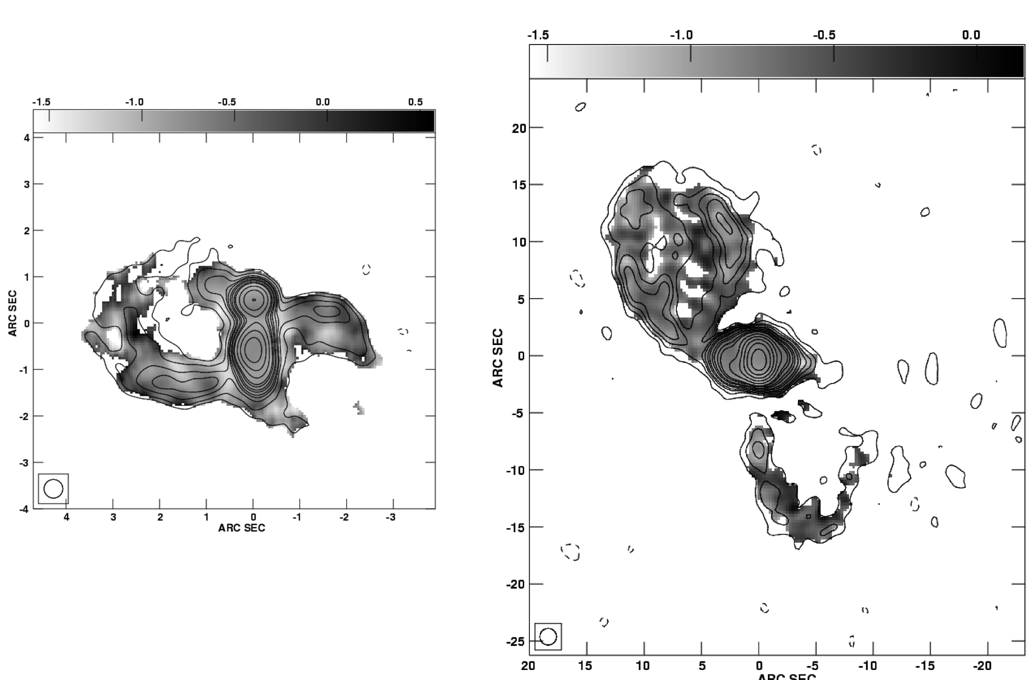

Fig.5 Spectral index (between 1.4 & 5 GHz) map in greyscale overlaid on the (right) 6cm and (left) 20cm A-array contour maps. Contour levels and Beam-sizes:
(right) 7.0x10^{-5}x(-1,1,2,4,6,8,12,16,24,32,64,128,256,512) Jy/beam and 0.5"x 0.5";
(left) 8.8x10^{-5}x (-1,1,2,4,6,8,12,16,24,32,64,128,256,512) Jy/beam and 4.5"x 4.5".
From Fig.3, we expect the sides marked "New" to show a flatter spectral index than the sides marked "Old", assuming adiabatic losses and minimal radiative losses. This is indeed observed. We derived a spectral age using the difference in spectral indices and obtained a value of 4x10^5 years. This estimate is a good match to the timescale the Inner jet was "on" in the precessing jet model (See Table on Right).

Precessing Jet parameters

(using precessing jet eqns. from Hjellming & Johnston, 1981)

Structure	*i* (deg)	*ψ* (deg)	*χ* (deg)	*β*	*P* (yr)	*t* (yr)
1	2	3	4	5	6	7
Outer jet	153	24	-30	0.03	3x10^6	1.7x10^6
Inner jet	9	9	-30	0.03	4x10^5	4x10^5

In the precessing jet model, the Outer and Inner jet correspond to Outer and Inner "bubbles". The Outer jet precesses clockwise while the Inner jet precesses counterclockwise.
Col.2: Inclination angle of the jet axis
Col.3: Half-opening angle of the precession cone
Col.4: Angle needed to rotate the geometrical model so that axes coincide with true north & east
Col.5: Jet speed with respect to speed of light
Col.6: Precession period in years
Col.7: Total time the jet was "on" in years.

What could cause Jet-precession

- Binary blackholes (Caproni & Abraham, 2004) and blackhole mergers that might result in short timescale redirection of the jet axis (Merritt, 2005).
- An accretion disk which is irradiated by a central AGN can become unstable to becoming warped, resulting in the wobbling of the jet (Pringle,1997) and severe misalignment of the jet axis and the axis of the outer accretion disk.
- Near-Eddington accretion events may alter the spin of the supermassive black hole, in turn affecting the orientation of the radio jet (Natarajani & Pringle, 1998).

Implications of an Episodic Precessing Jet

An episodically-powered precessing jet model in Seyfert galaxies implies that radio activity is a short-lived phenomenon in the lifetime of a Seyfert galaxy. Further, multiple episodes of ejection are possible, each being a result of an accretion event.

Possibly due to the smaller blackhole masses in Seyfert galaxies compared to typical radio galaxies (McLure & Dunlop 2001), the spinning blackhole axis and consequently the radio jet axis is perturbed easily when accretion events take place, resulting in precessing jets and switches in jet-orientation.

Conclusions

- A starburst alone cannot meet the energy requirements for the creation of the bubbles in Mrk6.
- An episodically-powered precessing jet can naturally explain the complex radio morphology.
- It is also consistent with the energetics, the spectral index (Fig.4), and the polarization structure (Fig.5).
- Radio emission in this scenario is short-lived phenomenon in the lifetime of a Seyfert galaxy which results due to an accretion event.

Further, possibly due to the smaller blackhole masses in Seyferts compared to typical radio galaxies, the spinning blackhole axis and consequently the radio jet axis is perturbed easily when accretion events take place, resulting in precessing jets.
- Multi-wavelength comprehensive radio studies of Seyfert galaxies would therefore reveal many more sources with similar complex radio structures as Mrk6.

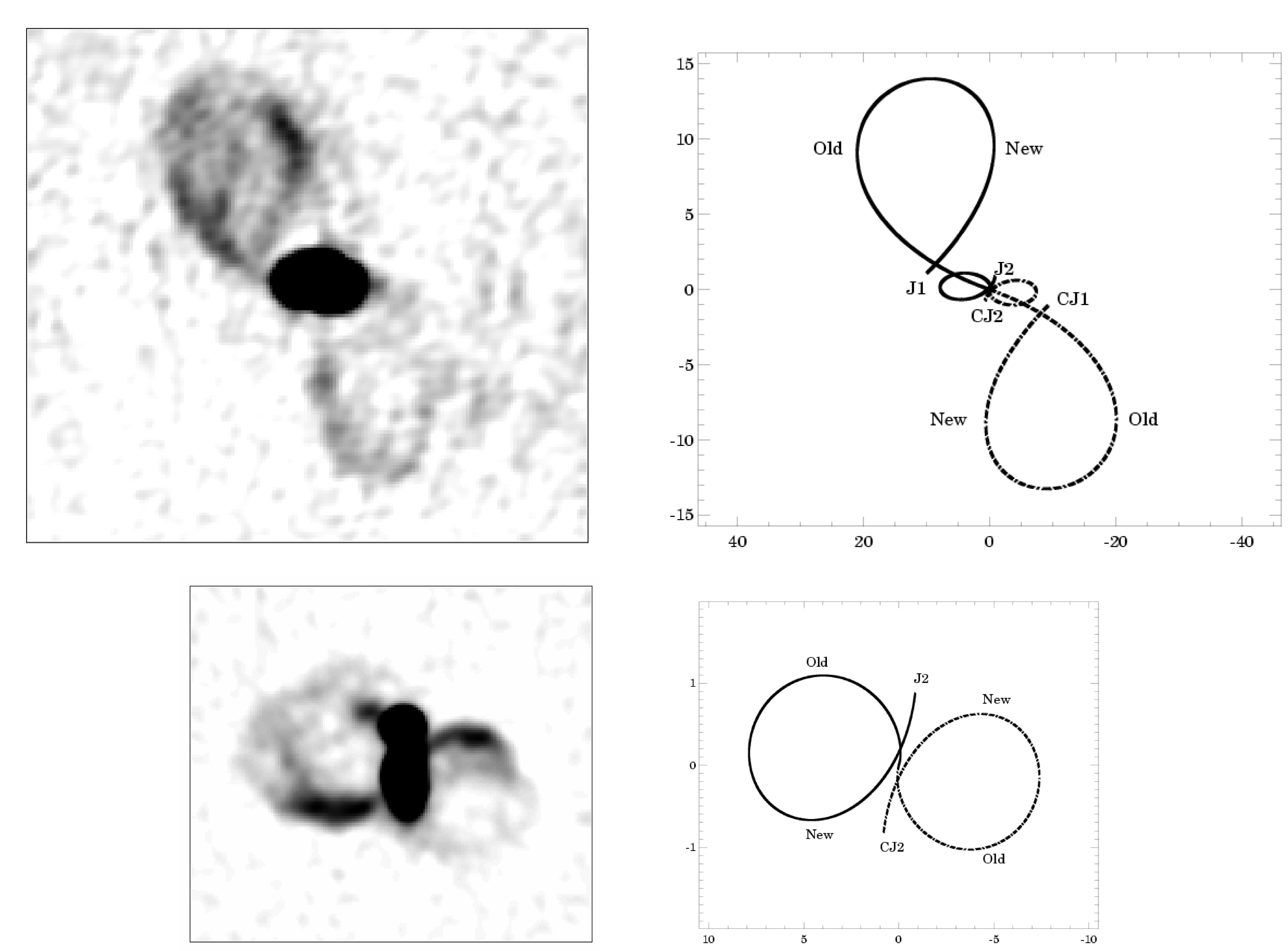

Fig.3 A comparison of the morphology of an episodically-powered precessing jet (right) and the 20cm radio image (left). The axes coordinates are in arcseconds. (Right) Plots of the proper motions of the precessing jet projected on the sky (Hjellming & Johnston, 1981). Solid line = approaching jet; Dashed line = receding jet.
The Outer and Inner "bubbles" are jets from two different phases of activity of the AGN. J1, CJ1, J2 and CJ2 indicate the jet and counterjet from the two phases and their approximate end-positions. In the precession model, the right edge of the Northern Outer bubble and the left edge of the Southern Outer bubble (marked "New") would be brighter and have a flatter spectral index, as it corresponds to the most recent position of the jet. The same applies to the bottom edge of the Eastern Inner bubble and the top edge of the Western Outer bubble. This agrees with the image on the left. Finally, the S-shaped MERLIN jet is easily reproduced in this model.

References

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** Cosmology: H_0=71 km/s/Mpc, Ω_m=0.27, Ω_{vac}=0.73
For Mrk6, 1" = 377 parsec

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