Three Dimensional Analysis of Jet Formation in Cassiopeia A

URCA
Undergraduate Research in Computational Astrophysics

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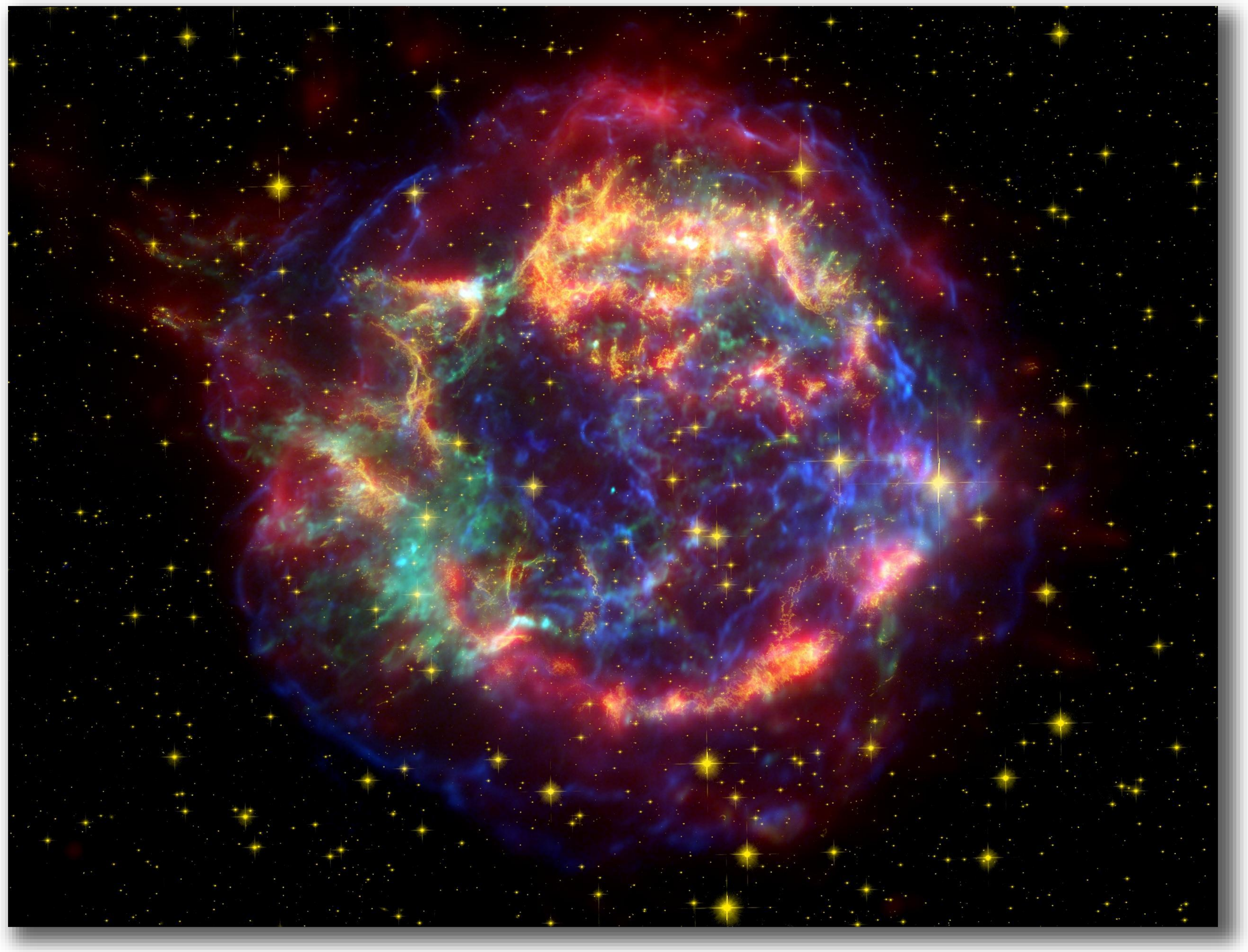

Cassiopeia A; Spitzer crop[2]

Introduction

- Cassiopeia A (Cas A) is a supernova remnant (SNR) in the Milky Way approximately 320 years old, which exhibits notable and controversial "jets."
- Some hypotheses attribute the structures to a jet-driven supernova explosion from deep within the progenitor, but these hypotheses do not fully explain several observations of the SNR, such as elemental distribution and neutron-star kick[1].
- It is possible that the jets in Cas A (a type IIb SN) could have been produced by expansion into asymmetric circumstellar medium (CSM).
- This asymmetry would be expected in a progenitor like Cas A, which experienced intensive mass loss before exploding and which was thought to have a companion star, which would have affected the pre-SN wind.
- We ran a large 3D simulation in the VH1 hydrodynamics code to determine whether asymmetric CSM alone could have produced the jets seen in Cas A.

Model

The Power Law Model for Ejecta-Driven Explosions

- To set up the hydrodynamic simulation we let **3.2 $M_\odot$** of ejected stellar material expand with a kinetic energy of **2.5×10^{51} ergs s^{-1}** , based on observational data[3].
- For the ejecta density profile we implemented a series of power laws: a constant density "core" (normalized), an **ejecta power law region** $\propto$ **$r^{-10.12}$** , and a **circumstellar medium density** $\propto$ **r^{-2}** (based on theoretical models for type II Sne). Ejecta velocities were initialized on a normalized linear scale from the center to the edge of the ejecta envelope[4].

Creating the Asymmetry

In two and three dimensions we introduce a density variation in the CSM in line with what would be expected from a system like Cas A. Such systems typically have large pole to equator density variations. We used a normalized gradient multiplying function in theta to achieve this effect:

$$\rho(\theta) = C\rho_{ave}\left[1 + A\frac{exp(-2\beta sin^2(\theta)-1}{exp(-2\beta)-1}\right] \qquad (5)$$

Where α = 1 / 1-A is the density ratio between pole and equator and β is the steepness parameter. C is simply a normalizing constant.

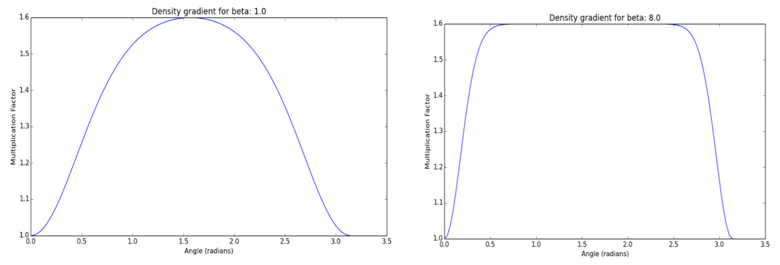

Fig. 1. Plots for different beta parameters with a fixed alpha. Shallow betas (left) produce a bell-like curve with a peak density factor. Aggressive or steep betas produce a large slab of higher density though most angles excluding the poles. We chose a beta of 1.0 to ensure jets could form under the least aggressive conditions.

Results

High Resolution Three Dimensional Simulation

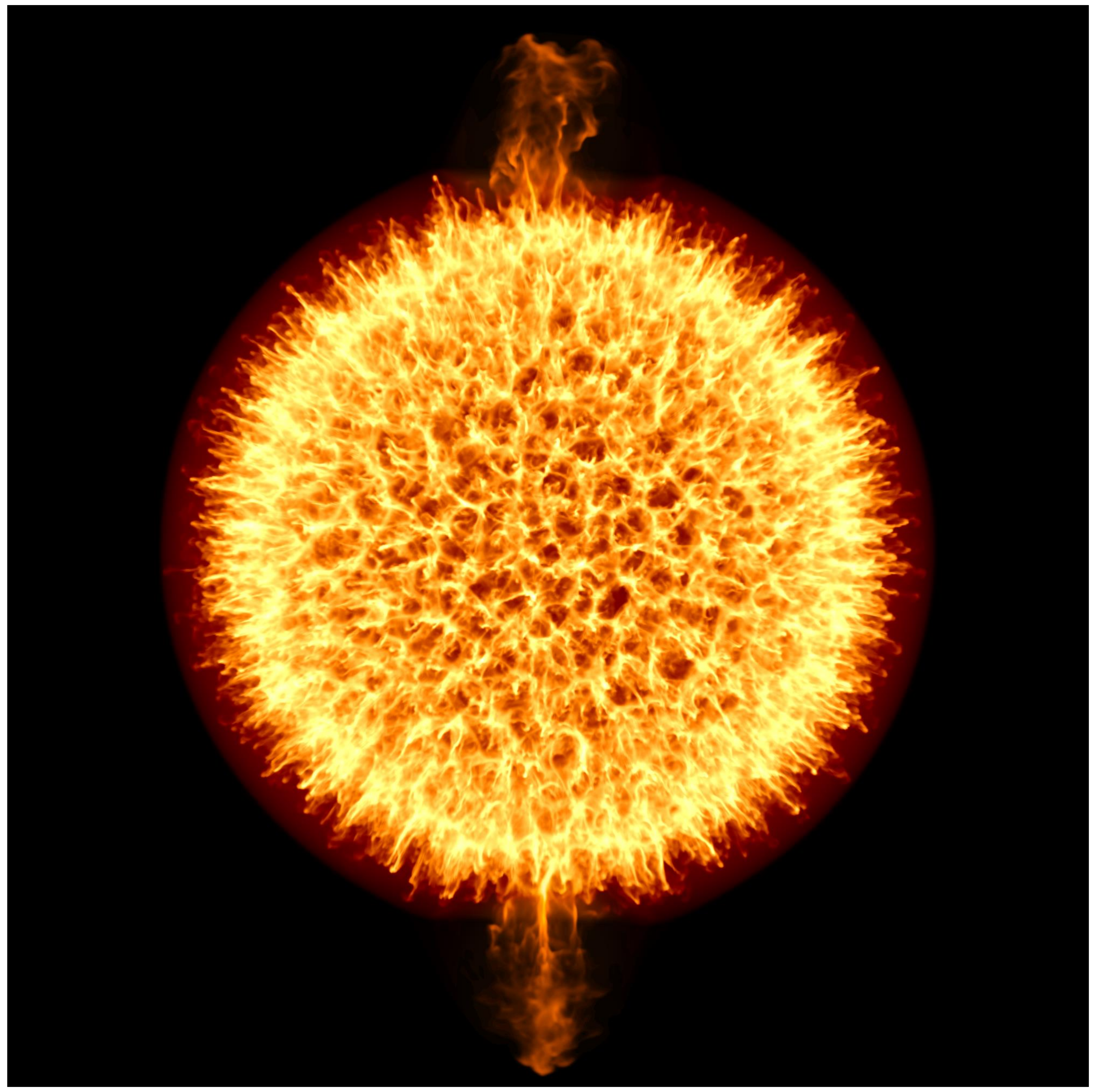

Fig. 3. [line of sight image]. We used a line-of-sight integration code to produce sky-plane images of our 3D data-set from various viewing angles. Here we take the jets to lie in the plane of the sky, as they do (primarily) in Cas A. These images demonstrate the ability for a simple, shallow CSM density gradient to produce strong jet-like structures during the evolution of the SNR. In addition to the jets, the Rayleigh-Taylor fingers can be visualized. Note that our model was only seeking to replicate the jet structures, not the overall structure of the SNR, to do so would require the addition of a more asymmetric set of initial conditions to the explosion.

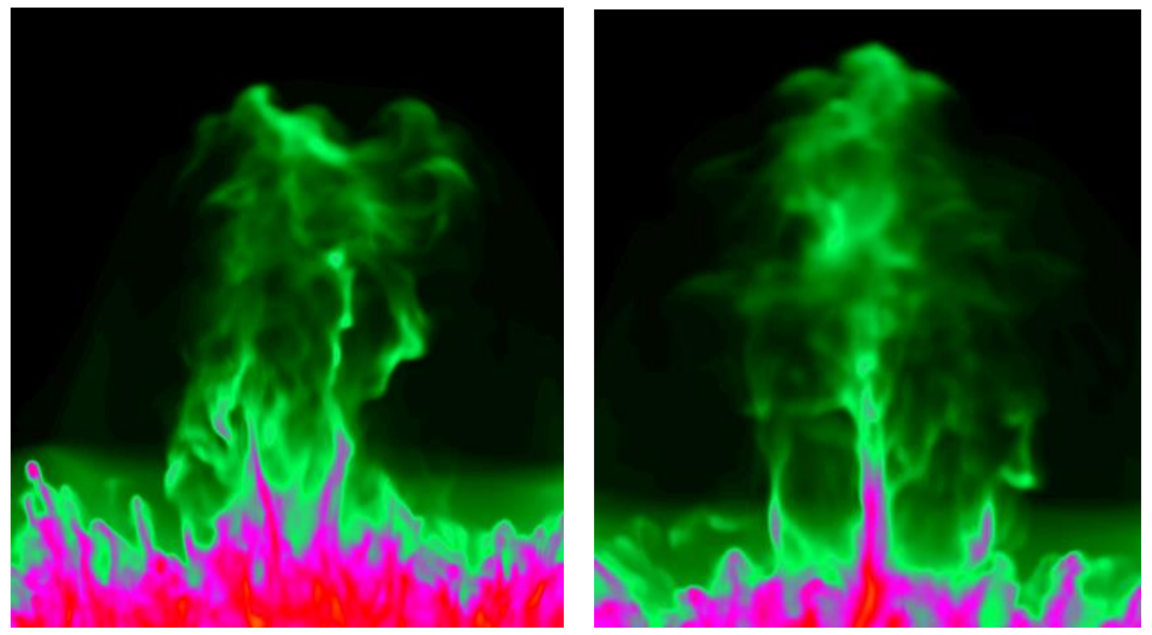

Fig. 3. [Detailed visualization of the jet regions, high contrast]. When closely examining the jet regions, the differences in structure between the "north pole" jet (left) and the "south pole" jet (right) become apparent. Asymmetry between the jets is to be expected and is indeed a major feature of the jets in Cas A. The high contrast highlights the concentrated, higher density ejecta, which has an opening angle of approximately 13 degrees.

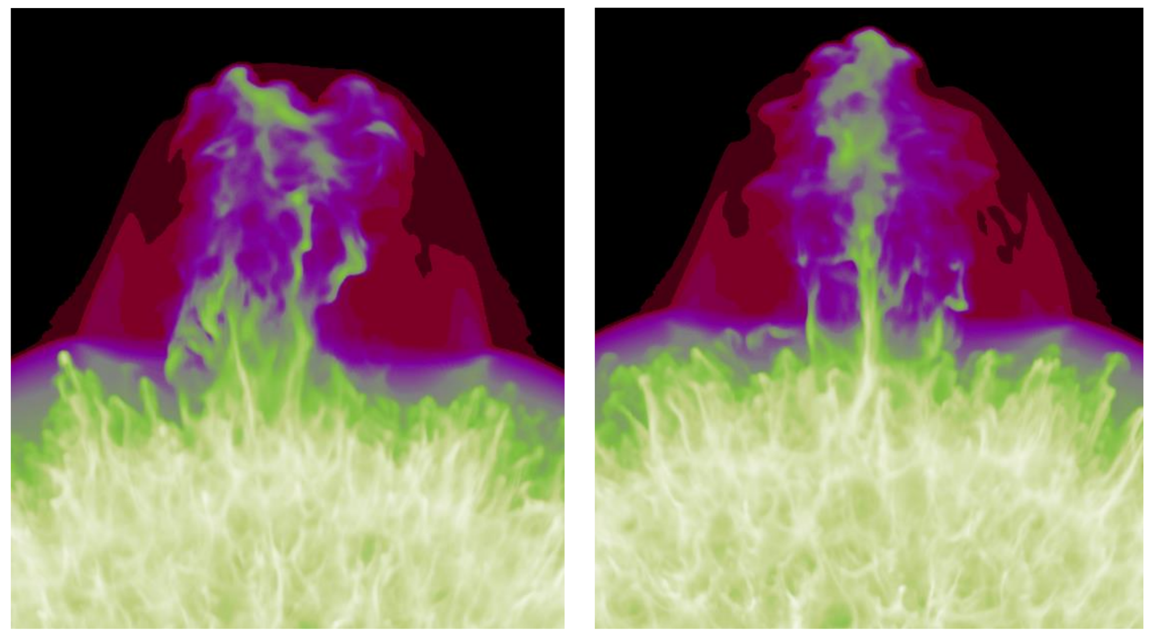

Fig. 4. [Detailed visualization of the jet regions, low contrast]. Lowering the contrast allows for the visualization of the bulk of the ejecta in the jets, which forms a wider, fan-like structure. We measured opening angles for the wide jets to be approximately 38 degrees, remarkably close to the 40 degrees measured in Cas A. Questions remain, however, as it appears the edges of the ejecta in Cas A do not all point to the explosion center.

Conclusions

- Two and three dimensional models of spherically symmetric SNe expanding into asymmetric CSM show every indication that jet-like structures can be produced by a marginally density-variant CSM alone.
- While it is clear that Cassiopeia A was a turbulent and likely inherently asymmetric explosion, it does not appear that a "jet-driven explosion"[6] mechanism is required to explain the jet regions that astronomers have observed in the system.

References

1. Hwang, U., et al. 2004, ApJ, 615:L117-L120
2. Kraus et al., courtesy of Nasa/JPL-Caltech
3. Chevalier, R.A., & Oishi, J., 2003, ApJ, 593:L23-L26
4. Schure, K. M., Vink, J., Segura, G. G., & Achterberg, A., 2008, ApJ, 686:399-407
5. Blondin, J. M., Lundqvist, P., & Chevalier, R. A. 1996, ApJ, 472:257-266
6. Khokhlov, A. M., Hoeflich, P. A., Oran, E. S., Wheeler, J.C., & Wang, L., 1999, ApJ, 524:L107-L110

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