Evolution from the Asymptotic Giant Branch to Planetary Nebulae

Sun Kwok,[†]

Institute of Astronomy and Astrophysics, Academia Sinica, Taipei, Taiwan
Dept. of Physics & Astronomy, University of Calgary, Calgary, Canada

Abstract. The post-asymptotic-giant-branch (post-AGB) or pre-planetary nebulae (PPN) phase of stellar evolution plays an important role in the dynamical shaping of PNe. While the interacting stellar winds model has achieved tremendous success in the explaining of the 1-D structures (shells, crowns, haloes) of PNe, the origins of arcs, rings, and multipolar structures remain a mystery. The synthesis of gas-phase molecules and solid-state compounds that begin in the stellar winds from AGB stars also undergo significant evolution during the post-AGB phase. Organic compounds of both aliphatic and aromatic structures are produced, which carries significant implications on the chemical enrichment of the interstellar medium.

Keywords: planetary nebulae, AGB and post-AGB stars, stellar winds
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INTRODUCTION

There period between the asymptotic giant branch (AGB) and planetary nebulae (PNe) phase is the most fascinating period of stellar evolution. Nowhere else in the life of a star that so much happens over so little time. Over a period of $\sim 10^6$ yr of thermal-pulsing AGB, He, C, N, and other heavy elements are synthesized in the core and dredged up to the surface. Hydrogen, together with molecules and dust condensing in the upper stellar atmospheres are ejected in the form of a stellar wind. The rate of mass loss is so high that the entire hydrogen envelope is depleted in $\sim 10^5$ years. Hydrogen shell burning further exposes the electron-degenerate core, causing the effective temperature of the star to increase by a factor of 10 in only a few thousand years. This period, known as the proto-planetary nebula (PPN) phase, is ended by the onset of photoionization and the emergence of emission lines. At $\sim 30\,000$ K, the amount of Lyman continuum photons set off an ionization front through the circumstellar material, bringing on $\sim 10^4$ years of glorious display of radiation from radio to X-ray in the PNe phase (Fig. 1).

At the end of the AGB and the beginning of the PPN phase, we also witness the onset of a different kind of stellar wind–a faster, and collimated wind that craves out the remnant of the AGB circumstellar envelope, allowing stellar light to escape through the emptied out cones, creating reflection nebulae of bipolar shapes (Fig. 2). As the star evolves to higher temperatures, the wind speed increases to thousands of km per second, sweeping up the remnant of the AGB envelope. The interactions between the fast wind and the swept-up shell and the shell with the AGB wind generate two shocks, with the shocked fast wind reaching temperatures of 10^6 K. The thermal pressure from this hot bubble drives the expansion of the shell until the fast wind dies down as the nuclear fuel is exhausted and the star falls in luminosity and evolves to the white dwarfs stage [1]

CHANGING MORPHOLOGY AND NEBULAR DYNAMICS

In the past 25 years, we have witnessed a tremendous degree of progress in our understanding of the dynamical evolution. The apparent complicated structure of PNe consisting of shells, bubbles, crowns, and haloes can be very successfully modeled by 1-D time-dependent interacting winds model coupled with stellar evolution [2, 3, 4, 5, 6, 7, 8]. These models are able to explain the density, temperature, velocity structures, as well as the 1-D morphological evolution of PNe.

However, many PNe have bipolar shapes and are not spherically symmetric. Bipolar PNe are not limited to PNe with apparent butterfly morphology (e.g. NGC 2346), but also ring-like objects which are bipolar nebulae inclined on the plane of the sky (e.g., NGC 6720, [9]; NGC 3132, [10]). Since molecular imaging of AGB envelopes shows that AGB winds are largely spherically symmetric, this morphological transformation must be rooted in an anisotropic dynamical phenomenon. The discovery of bipolar PPNe suggests that the shaping of PNe occurs early, probably shortly after the end of the AGB [11, 12].

Furthermore, new observations, in particular those obtained with the *Hubble Space Telescope (HST)* have revealed microstructures that are not predicted by the inter-

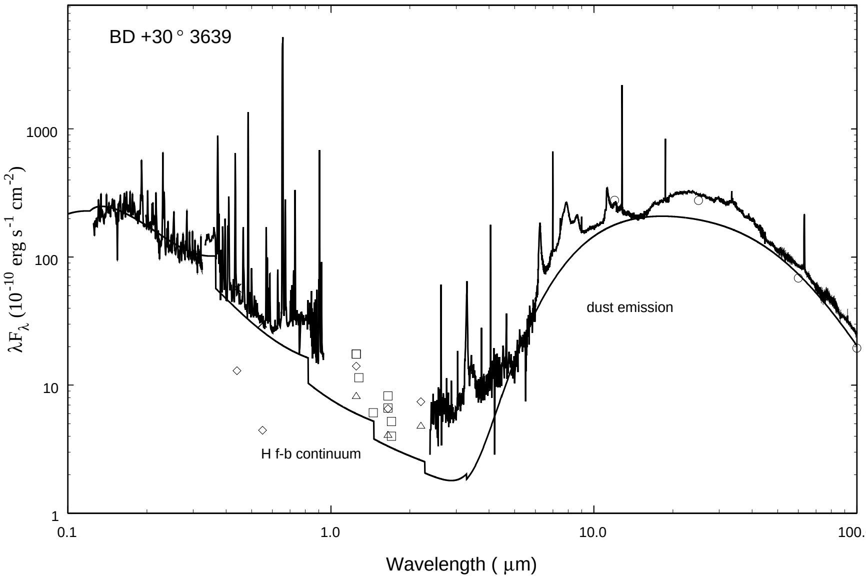

FIGURE 1. The spectral energy distribution of the PN BD+30 3639 showing the spectral richness of the PN phenomenon. Recombination lines of H and He and collisionally excited lines of metals dominate the UV, visible, and IR parts of the spectrum. In the far-IR and submm, rotational transitions of molecules are present (not shown). For the continuum, 2-γ radiation dominates in the UV, b-f emission in the visible and near IR, thermal emission from hot gas in the X-ray (not shown), dust emission in the IR, and f-f emission in the radio (not shown). Some of the broad emission features in the IR are due the stretching and bending modes of aromatic compounds.

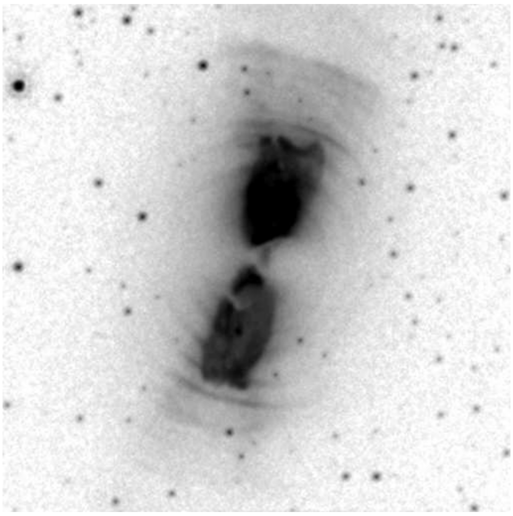

FIGURE 2. The visual brightness of the bipolar PPN IRAS 17150−3224 is completely due to scattered starlight by dust in the lobes. Multiple concentric arcs can be seen in the lobes [12].

acting winds model. These include FLIERS, concentric arcs, 2-D rings, point-symmetric structures, and bipolar, rotating, episodic jets (BRET). FLIERS are pairs of small, bright knots of low excitation gas found along the major axes of PNe [13]. Hydrodynamic models have shown that FLIERs and BRETs could be naturally produced by the ISW process if the mass loss rate and velocity of the fast wind are functions of both time and direction [14]. The change in outflow direction could be the result of rotation and magnetic fields [15].

Linear structures (jets) can be seen in two of the corners of the [N II] image of NGC 6543. The existence of these features suggests that the fast outflow could be collimated rather than spherical. point-symmetric pairs of knots in an S-shape structure (BRETs), have been seen in a number of PNe (e.g. KjPn8, [16]; NGC 6884, [17]). Some PNe have been found to have more than one polar axis (Fig. 3), suggesting that the outflow direction has changed with time (e.g. NGC 2440, [18]; M1-37 and He2-47, [19]). Some PNe (*e.g.,* M2-9, [20]) and PPNe (*e.g.,* Hen 3-401, [21]) have extreme bipolar (cylindrical) shapes, suggesting that their morphology is shaped by a collimated outflow.

The direct imaging of bipolar lobes emerging from a circumstellar disk in the PPN IRAS 17106−3046 [22] suggests that disks could play a role in the collimation of the bipolar flows. The dark lane found in the optical im-

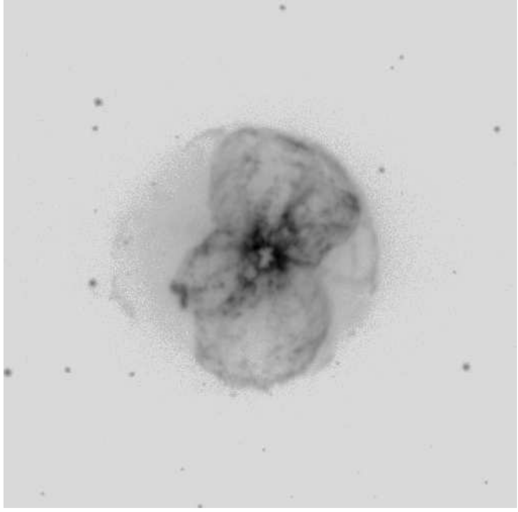

FIGURE 3. Two pairs of bipolar lobes can be seen in the [N II] image of NGC 2440 taken at the CFHT.

ages of PNe and PPNe can be imaged in the mid-infrared. Figure 4 shows the mid-infrared images of the PPN IRAS 17441−2411. Unexpectedly, the orientation of the disk as seen in emission the infrared is not perpendicular to the optical bipolar lobes.

Concentric circular arcs have been observed in both PNe (*e.g.*, Hb 5, NGC 6543, NGC 7027) and PPNe (*e.g.*, AFGL 2688, IRAS 17150−3224, Fig. 2). These arcs are of almost perfectly circular in shape, and have relatively uniform separations of $\sim 10^2$ yr [23]. Similar arcs have been detected in the carbon star IRC+10216, suggesting that these features originate in the AGB phase. The coexistence of these perfectly circular features with bipolar lobes suggests that the arcs are projections of undisturbed spherical shells on the sky. Possible mechanisms for the creation of such arcs include dynamical instability in the gas-dust coupling in the AGB outflow [24], perturbation by a binary companion [25], and magnetic cycle [26, 27].

Two-dimensional rings perpendicular to the bipolar axis have been found in several PNe, including MyCn18 [28] and NGC 6881 (Fig. 5, [29]). The origin of these rings is not understood.

There are ∼3 500 knots, each of mass $\sim 3 \times 10^{-5}$ $M_\odot$, in NGC 7293 [30], making the total mass contained in these knots about the same as in the ioinized gas component. If these planet-mass knots survive the PN phase and enter the ISM, they would represent a new, unseen component of the ISM [31].

ROLE OF BINARY CENTRAL STARS IN PN EVOLUTION

The discovery of the binary nature of some central stars of PNe has led to the speculation on what role they may play in the formation and evolution of PNe [32]. Many stars are born in binary systems, some of which will undergo mass transfer, common envelope, or even merger in the red giant or AGB phases of evolution. The possibility that common envelope ejection is responsible for the creation of PN was considered 30 years ago. However, common envelope ejection, like all other sudden ejection scenarios, is unsatisfactory because no sudden ejection can be so precise in leaving $< 10^{-3}$ M⊙ envelope mass above the core. Any larger amount will leave the central star in the AGB stage and the ejected envelope will never be photoionized. The possibility that α_{CE}, the efficiency of converting orbital energy into ejection energy, can be so precise is highly improbable.

Observationally, about 5 000 AGB stars have been detected in the Galaxy to have stellar winds. This suggests that stellar winds are common in the AGB phase and significant amount of H-envelope mass of AGB stars is ejected in the form of a wind. They are responsible for the termination of the AGB and the materials in the AGB circumstellar envelope are the source of mass of PNe. As discussed in the previous section, the observed morphology of PNe (shells, crowns, haloes) requires an extended period ($\sim 10^5$ yr) of mass loss prior to photoionization. So even if there is a common-envelope event, it has no consequence in the formation of PNe. The presence of a binary companion, however, may have an effect on the properties of the later-developed fast wind, e.g., in introducing a directional dependence of the wind [33].

It is well known that mass transfer between a red giant or AGB star with a white dwarf companion can re-ignite H-shell burning, either violently (a nova) or quiescently (a symbiotic star). These phenomena are distinct from PNe because after ignition, the star is either not evolving (in a symbiotic star) or evolving backwards toward the AGB (as in the case of novae) until the accreted mass is depleted by a combination of nuclear burning or mass loss [34]. The fact the PNe and D-type symbiotics are so similar observationally is a constant source of confusion between these two classes of objects [35].

CHEMICAL EVOLUTION

Since carbon, nitrogen, and most of the s-process elements are synthesized in AGB stars and ejected into the ISM through the AGB stellar wind, AGB stars are drivers of chemical enrichment and evolution of the Galaxy. Theories of nucleosynthesis can be tested by observing

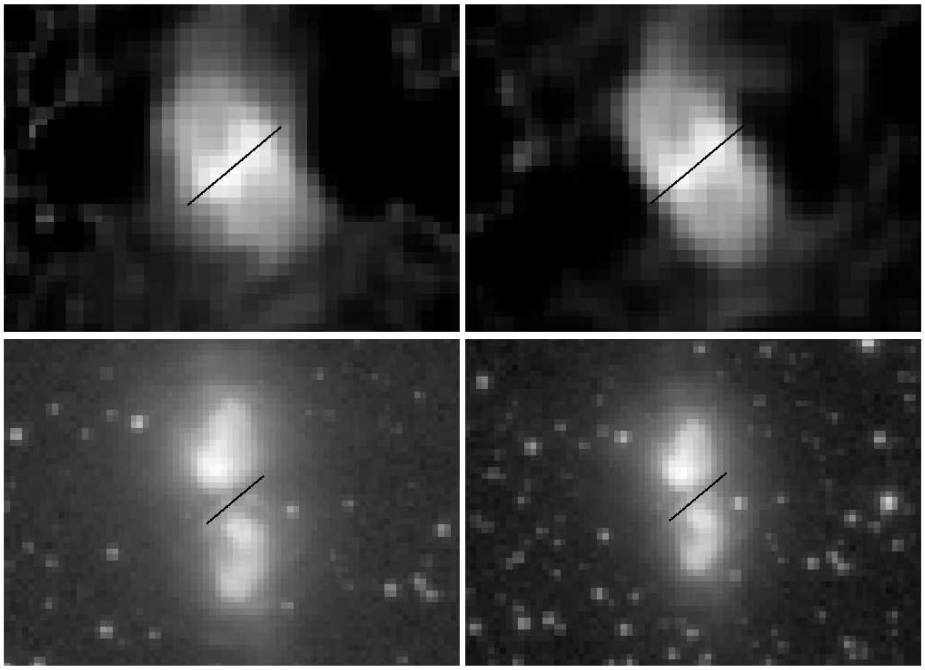

FIGURE 4. Gemini T-ReCs 8.8 and 11.7 μm images of PPN IRAS 17441$-$2411 (top row). The orientation of the infrared disk is overlaid on the optical R band *HST* image in the bottom row (image courtesy of Kevin Volk).

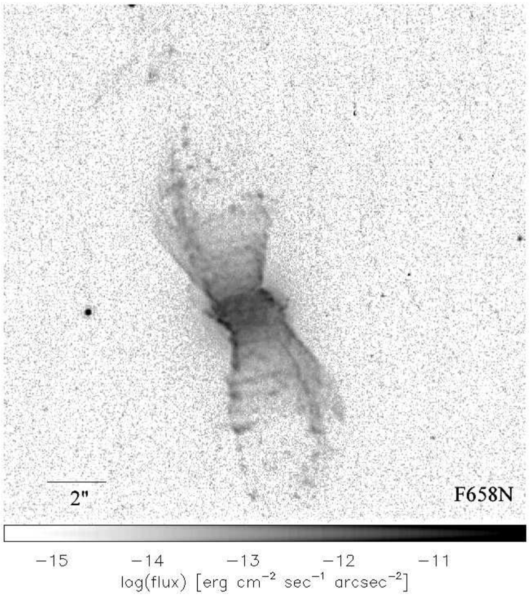

FIGURE 5. A number of 2-D rings can be seen in the lobes of the qudrupolar PN NGC 6881.

the abundance of s-process elements in the photospheric spectra of post-AGB stars [40]. Elemental abundance can also determined from emission lines in the spectra of PNe. The recent availability of ultraviolet and infrared spectroscopic observations through the *FUSE* and *ISO* missions has resulted in an increasing degree of sophistication and accuracy in the determination of the abundance of elemental abundance and isotopic ratios. The development of integral field spectroscopy has finally allowed the possibility of resolving the decades-old discrepancy of abundance determination from collisionally excited lines and optical recombination.

The development of millimeter-wave spectroscopy has led to the detection of rotational transitions of over 50 molecules (including carbon chains as large as HC_9N and cyclic molecules such as C_3H_2) in the circumstellar envelopes of AGB stars and PNe, suggesting that these objects are also major sources of molecular enrichment of the ISM. The detection of HCO^+ in PNe demonstrates the importance of photo-chemistry and shows that gas-phase chemistry is still actively ongoing in the molecular envelopes of PNe [36, 37]. Infrared spectroscopy from *ISO* has made possible the observation of stretching and bending modes of molecules, leading to the detection a variety of new species including diacetylene, triacetylene and benzene in PPNe [38, 39]. These results clearly show that the synthesis of organic molecules are occuring through the AGB-PN transition.

Solid-state compounds in the form of amorphous silicates and silicon carbides are commonly found in AGB stars, and these grains are expected to survive through the PNe stage. However, recent infrared observations have

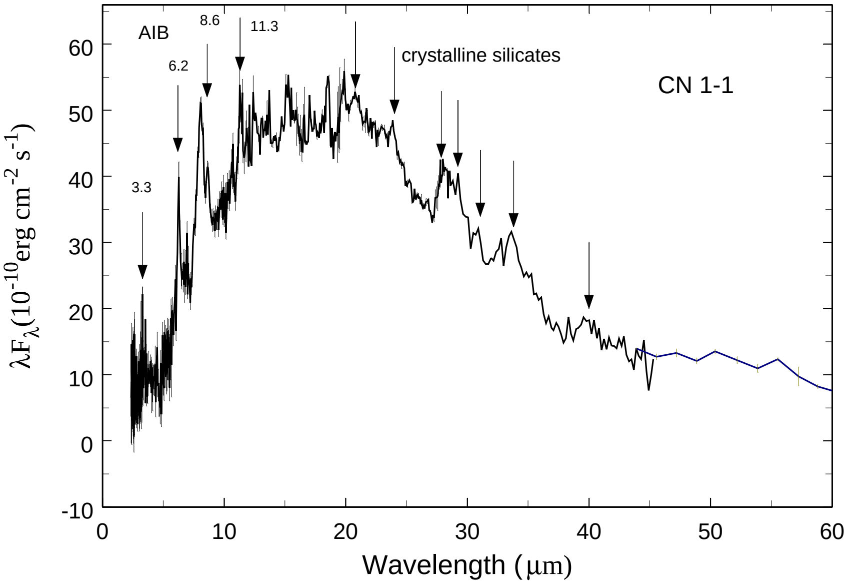

FIGURE 6. *ISO SWS* spectrum of the PN CN1-1 showing the presence of both AIB and crystalline silicate features (data courtesy of Kevin Volk).

revealed that, in addition to these species, the dust envelopes of PPNe and PNe contain other inorganic and organic compounds. The infrared spectra of PNe show strong aromatic infrared bands (AIB) at 3.3, 6.2, 7.7, and 11.3 μm. Aliphatic features at 3.4 and 6.9 μm are seen in the spectra of PPNe, but weak in PNe. Broad emission plateaus at 8 and 12 μm in the spectra of PPNe have been identified as due to a variety of aliphatic sidegroups attached to aromatic rings [41]. The difference in spectral behavior between PPNe and PNe could be the result of photochemistry. These discoveries, together with the detection of crystalline silicates in PNe (Fig. 6), suggests that the solid-state component is also under change in the PNe environment [42].

There is now strong evidence that meteorites contain grains of presolar origin. The detection of silicon carbide in meteorites [43] clearly suggests that solid state materials made in AGB stars can pass through the ISM and survive the formation of the solar system. This was followed by the detection of presolar grains of corundum and spinels [44], which probably originate from oxygen-rich AGB stars. The similarity between the 3.4 μm features seen in meteorites and galactic dust also suggests a common origin due to CH_2 and CH_3 side groups [45]. The fact that many organic compounds including alipahatic and aromatic hydrocarbons, alcohols, amines, amides, and carbonyl compounds are found in meteorites raises the question what fraction of these organic compounds originate from PPNe and PNe.

The 21 μm feature is prominently present in 12 PPNe (Fig. 7), and the 30 μm feature is very strong in PPNe and PNe. The origin of these emission features is still uncertain. Another unsolved mystery of the solid-state component in PNe and PPNe is the extended red emission (ERE) phenomenon. ERE is the consequence of photoluminescence powered by far ultraviolet photons. Although initially discovered in the spectrum of the Red Rectangle, ERE is now seen in H II regions, diffuse ISM, and haloes of galaxies. In the diffuse ISM, $\sim$4% of the energy absorbed by dust at $\lambda < 0.55\,\mu$m is emitted in the form of ERE. This limits the chemical composition of the ERE carrier to a few abundant elements. Since metals do not undergo photoluminescence, the most likely candidates are C and Si. The likelihood that the carrier is C-based is supported by the strong correlation that ERE is only observed in C-rich PN [46].

The circumstellar environment of AGB stars, PPNe and PNe is a rich laboratory for chemical synthesis of molecules and grains. In spite of the low-density environment, chemical reactions proceed rapidly, resulting in inorganic and organic compounds with unexpected complexity.

QUESTIONS

While we have made great progress in the theoretical understanding of the evolution between AGB and PN phases, recent observational discoveries have pose new challenges on the morphological and chemical evolution during this transition. Here are some outstanding ques-

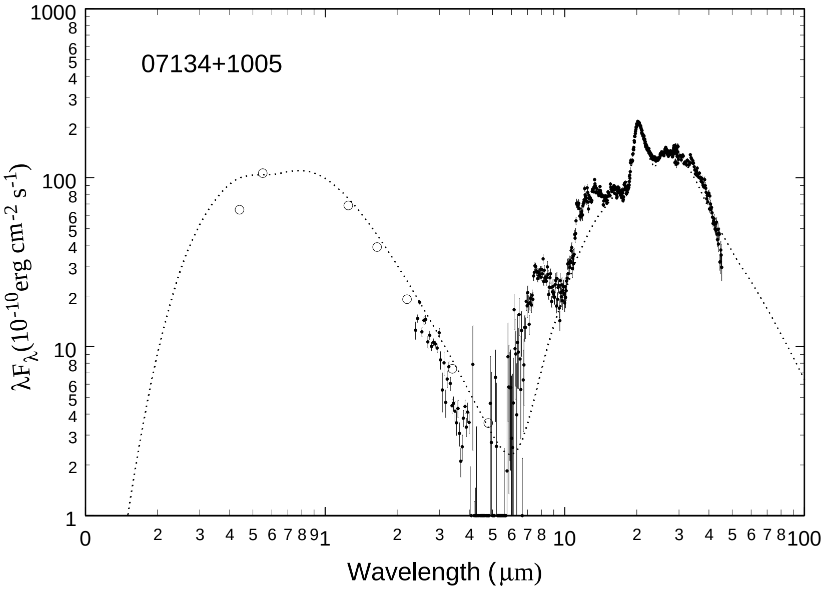

FIGURE 7. The spectral energy distribution of the PPN IRAS 07134+1005. Above the dust (presumably amorphous carbon) continuum are the 8 and 12 μm emission plateaus and the 21 μm emission feature.

tions that we can discuss today.

- What are the mechanisms responsible for changing chemistry and morphology: when and how?
- What initiates the fast collimated outflow? It is evident that in some cases disks are involved, but the origin of the disk is not clear. Do the presence of a binary companion or magnetic fields play any role?
- What causes multipolar structures? Appearance suggests precession, but the lobes seem to be of similar sizes, ruling out a continuous process.
- What are the dynamical processes that lead to arcs and rings?
- What is the distribution of dust in PN? Are the distributions of the continuum (presumably amorphous carbon) different from those of the AIB emissions?
- What are the carriers of ERE, the 21 μm, and the 30 μm features?
- What is the origin of the knots and do they represent a major mass component returned to the ISM by PNe?

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