Computational Star Formation
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Galactic scale star formation: Interplay between stellar spirals and the ISM

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Abstract. Spiral structures in the disk galaxies have been extensively studied by many theoretical papers, but conventional steady-state models are not consistent with what we observe in time-dependent, multi-dimensional numerical simulations and also in real galaxies. Here we review recent progress in numerical modeling of stellar and gas spirals in disk galaxies. The spiral arms excited in a stellar disk can last for 10 Gyrs without the ISM, but each spiral arm is short-lived and is recurrently formed. The stellar spirals are not waves propagating with a single pattern speed. The ISM is concentrated in local potential minima, which roughly follow the galactic rotation together with the stellar arms, therefore galactic dust lanes are not the classic 'galactic shocks'.

Keywords. N-body simulation, SPH, hydrodynamics

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1. Introduction

What we probably learned from conventional textbooks and papers on galactic spirals would be, for example:

- The 'winding dilemma' is tricky.
- Galactic stellar spiral arms are stationary waves propagating with a single pattern speed, and they reflect at resonances or Q-barrier.
- The ISM (or some kind of dissipation) is necessary to keep the long-lived stellar spirals.
- Gas spirals (or dust lanes) are caused by 'galactic shocks', which are offset against the stellar arms.
- GMCs are formed through gravitational instability in the shocked layers, and thereby star formation is triggered.

The concept of galactic shock was originally proposed by Fujimoto (1968) and extensively studied by many followers, e.g. Roberts (1969) and Shu (1973). Fujimoto found a stationary solution that represents a standing shock in a tightly wrapped spiral potential. When a supersonic flow of the gas passes through a spiral potential which is caused by a stellar density wave, the flow is decelerated, and often makes a shock. The subsonic flow behind the shock is then accelerated again toward the other spiral potential (Fig. 1). Due to the radiative cooling, the ISM is strongly compressed at shocked layer, then molecular clouds are formed through gravitational and thermal instabilities followed by star formation (e.g. Hartmann *et al.* 2001; Vazquez-Semadeni 2006; Heitsch *et al.* 2009). As a result, spiral arms in galaxies are illuminated by massive stars and HII regions. This is a conventional, and widely accepted picture, but it is not clear whether the stationary shocks predicted by theories are consistent with the star formation process, which is a basically unstable phenomena. In fact, recent time-dependent simulations suggest that

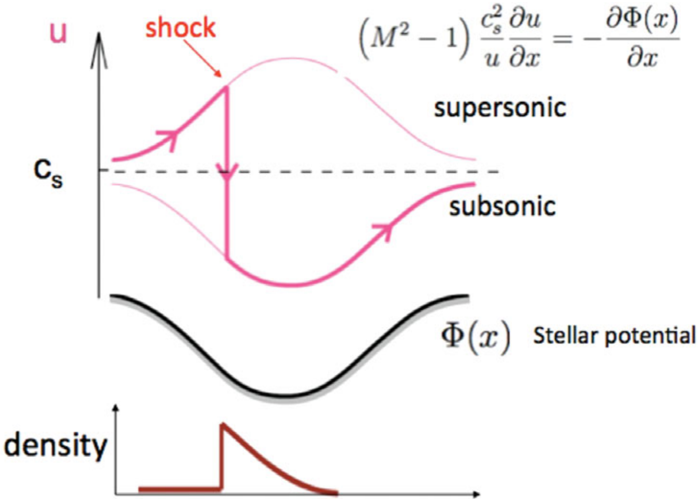

Figure 1. An one-dimensional image of 'galactic shock'.

spiral shocked layers are not always stable (e.g. Shetty & Ostriker 2006; Dobbs *et al.* 2008). Wada & Koda (2004) showed that spiral shocks are unstable ('wiggle instability'), if the Mach number and pitch angles are large enough. The substructures in the inter-arm regions (i.e. 'spurs') are naturally formed as a result of formation of clumps in the layers†. A similar phenomenon can be seen even in 'cloud-fluid' simulations by e.g. Tomisaka (1986). The wiggle instability seen in the hydrodynamic simulations is essentially the Kelvin-Helmholtz instability, but this is not the only process to generate complex structures in the ISM. Various physics, such as magnetic field, self-gravity of the gas, radiative cooling, heating by stars could affect stability, structures and dynamics of the gas in a spiral potential (see e.g. Kim *et al.* 2010 and references therein).

Using three-dimensional hydrodynamic simulations, taking into account the self-gravity of the gas and radiative cooling/heating and supernova feedback, Wada (2008) found that the classic galactic shocks are unstable and transient, and they shift to a globally quasi-steady, inhomogeneous arms due to the nonlinear development of gravitational, thermal, and hydrodynamical instabilities (Fig. 2). As a result, the arms with many GMC-like condensations are formed, but those substructures are not steady. The clumps eventually move into the inter-arm regions, and they are tidally stretched, eventually turn into spurs. In the quasi-steady state, the density enhancement tends to be associated with the spiral potential. This chaotic state is no longer a 'shock', but more resembles the spiral arms in real galaxies, in a sense that high density regions like GMCs coexist in the quasi-steady arms.

However, Wada (2008) as well as most other previous hydrodynamic and magneto- hydrodynamic simulations in spiral potentials still did not deal with an important aspect in spiral galaxies. The spiral potentials in these previous simulations are time-independent, therefore gravitational interaction between stars and gas is not properly considered. This is an essential point on dynamics of spirals, especially if spiral potentials are not steady, which is actually the case as will be discussed in the next section.

† Note that spurs are not 'waves'. Clumps formed by any kind of instabilities near the potential trough, such as gravitational instability, can be sheared off, and as a result elongated structures in the inter-arm regions are formed.

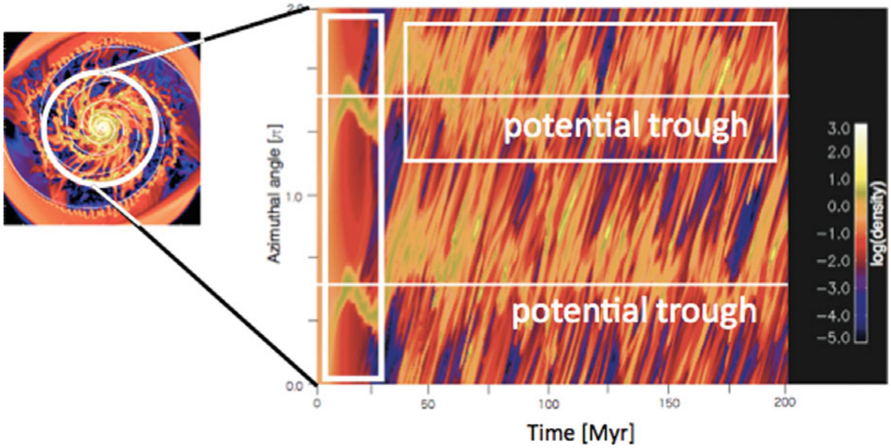

Figure 2. Time evolution of the azimuthal density profile. The horizontal lines show the positions of the minimum of the spiral potential. The initially appeared shocks turn to be stochastic arms consisting of many substructures after $t \sim 50$ Myrs (Wada 2008).

2. Evolution of Pure Stellar Disks

Using 3-D N-body (tree-GRAPE) simulations, Fujii *et al.* (2010) showed that stellar disks can maintain spiral features for several tens of rotations without the help of cooling mechanisms, such as dissipational effects of the ISM. In the simulations, multi-arm spirals developed in an isolated disk can survive for more than 10 Gyrs, if the number of particles is sufficiently large, e.g., $N > 3 \times 10^6$ (Fig. 3). They claimed that there is a self-regulating mechanism that maintains the amplitudes of the spiral arms. Interestingly, they found that spiral arms developed in the disk are not steady, but rather recurrently formed. Locally developed arms often merge into other high density regions, and form grand-design spiral arms. However, the grand-design arms are short-lived structures, and break into local arms. The process is repeated, and as a result the dominant Fourier mode is also time-dependent, and it radially changes (see the bottom panels of Fig. 3).

In fact, the non-steady spiral is a common feature seen in previous N-body simulations. In other words, it is hard to produce 'steady' spirals that can be understood by Lin and Shu's density wave theory, in time-dependent simulations of collisionless disks. For example, Sellwood & Carlberg (1984), using 2D, particle-mesh simulations, pointed out that spirals become faint in about ten rotations ($\sim$ a few Gyrs) †. In order to keep spirals for many rotations, they claimed that some mechanisms to reduce the velocity dispersion of stars are necessary. They added 'dynamically cold' stars, that is, stars with small velocity dispersion, and showed that spirals can last for more rotational periods. Since dynamically cold stars could be formed from the cold ISM, one might think that the ISM is essential to keep spirals long-lived. However, as mentioned above, the recent results by Fujii *et al.* (2010) suggest that this is not actually true.

3. Interplay between gas and stellar spirals

Even if the N-body models suggest that spiral arms can survive without help of the ISM, the ISM is actually present in galactic disks, and it is still not clear how the ISM reacts with the time-dependent, transient stellar spirals. Stellar spirals could be also affected by the ISM. In order to see the interplay between stellar spirals and the ISM,

† See also the recent review by Sellwood (2010) on the life time of spirals.

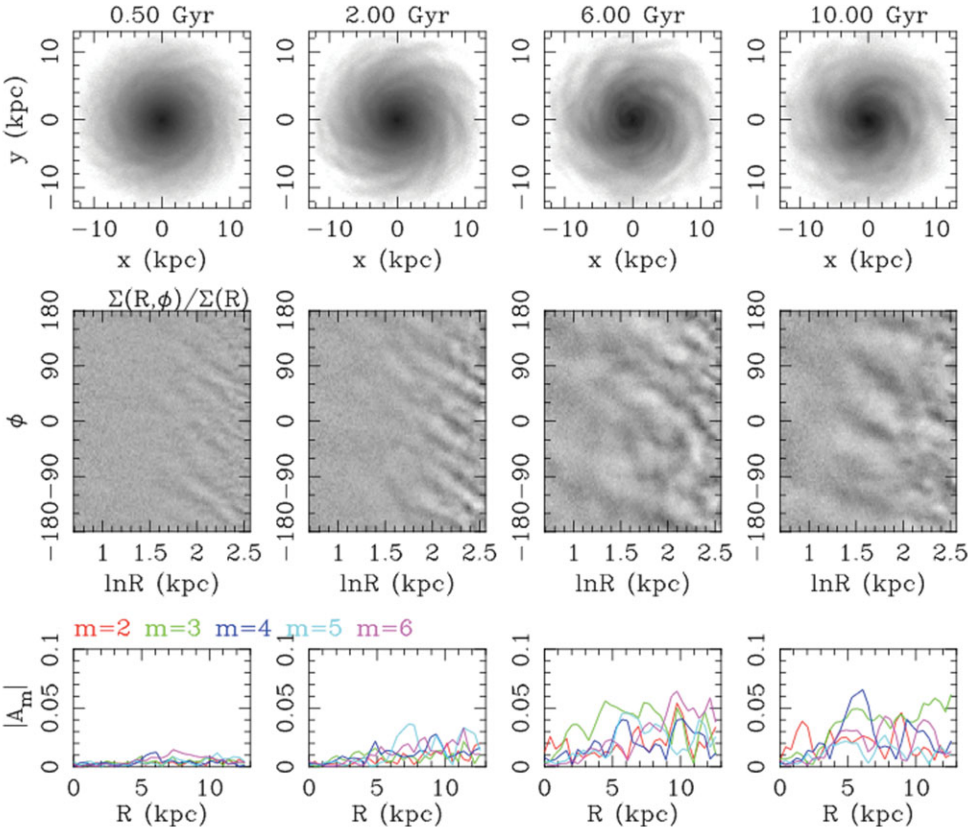

Figure 3. Evolution of spiral arms in a pure N-body disk with $N = 9 \times 10^6$. Top panels show the surface density, middle panels shows the surface density normalized at each radius, and bottom panels show the Fourier amplitudes. (Fujii *et al.* 2010).

and to see how spiral structures and star forming regions are formed, we performed N-body/SPH simulations of a disk in a fixed spherical potential. The initial profile of the disk is exponential, and 1×10^6 SPH particles and 3×10^6 N-body particles are used. The numerical code used here is ASURA (Saitoh *et al.* 2008, 2009; see also Baba *et al.* 2009). We adopted a fixed, spherical dark matter (DM) halo as a host of a stellar disk. The density profile of the DM halo follows the Navarro-Frenk-White (NFW) profile. The treatment of star formation and the heating due to the SN feedback are the same as those in Saitoh *et al.* (2008).

Figure 4 shows a snapshot of stars and gas in a typical model. Depending on the initial mass profile, either mullti-arm spirals with large pitch angle as seen in Fig. 4 or a central bar associated with spiral arms as shown in Baba *et al.* (2009) is formed. Cold gas forms filamentary and clumpy structures, in contrast to the relatively smooth distribution of stellar spirals. Young stars formed from gas in a cold, dense phase are roughly distributed along stellar spirals.

One should note that these stellar and gas spiral arms do not propagate in the stellar disk with a single pattern speed. In other words, they do NOT show a rigid rotation. Figure 5 shows motions of spiral arms at three different radii. It is clear that the stellar arms roughly follow the radial change of the galactic rotation, represented by the solid lines, at each radius. This means that spiral arms are in fact 'wound up', therefore each spiral arm should not be long-lived. This kinematical feature seems to be consistent with

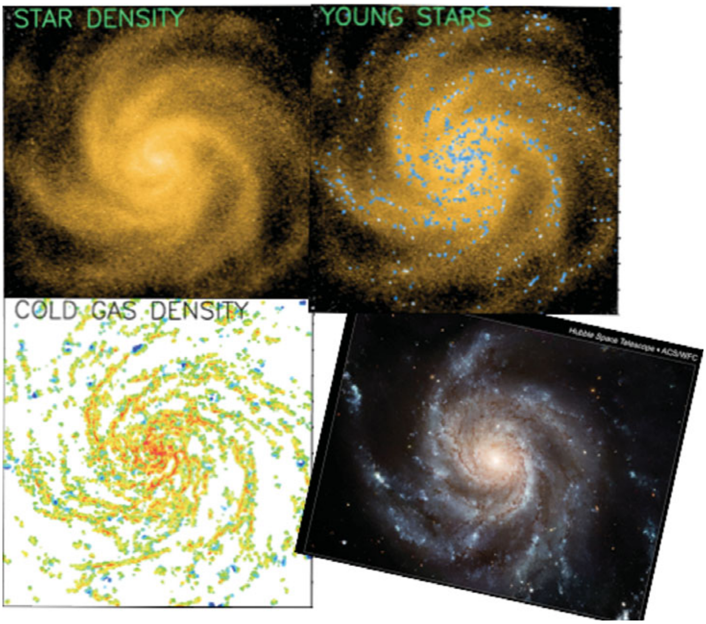

Figure 4. Multi-arm spiral 'galaxy' reproduced by N-body/SPH code: ASURA (Saitoh *et al.* 2008). Stars formed form cold and dense gas are represented by dots (upper right panel). Cold gas roughly follow the stellar spirals, but it has complicated structures. The morphology at this snapshot incidentally looks similar to M101 (bottom right: HST image. ©NASA/ESA).

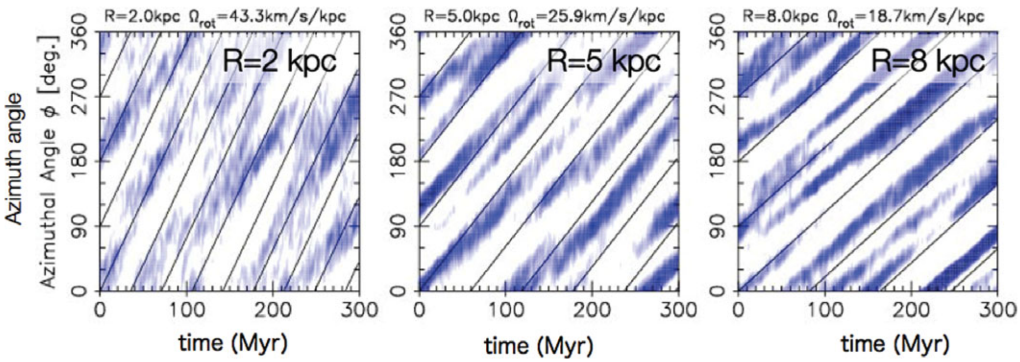

Figure 5. Kinematics of stellar arms at three radii. Stripes represent how the position of high density regions of stars move. Solid orthogonal lines represent galactic rotation at the radius.

some observations in M51 and NGC 1068, in which a radially declining 'pattern' speed is reported using the Tremmaine-Weinberg method (Merrifield *et al.* 2006; Meidt *et al.* 2008).

Figure 6 is cross-sections at five different galactic radii, showing amplitudes of stellar spirals and gas density. Relatively smooth curves represent stellar density; for example there are four arms at $R = 5$ kpc . Gas density, on the other hand, is more spiky, and there are many peaks. However, high density regions on average are roughly associated with stellar arms. Moreover, the complicated structure of the gas is not steady at all, and cannot be simply explained by the standing galactic shock solution. It is also clear that there is no apparent offset between stellar arms and high density regions of the gas.

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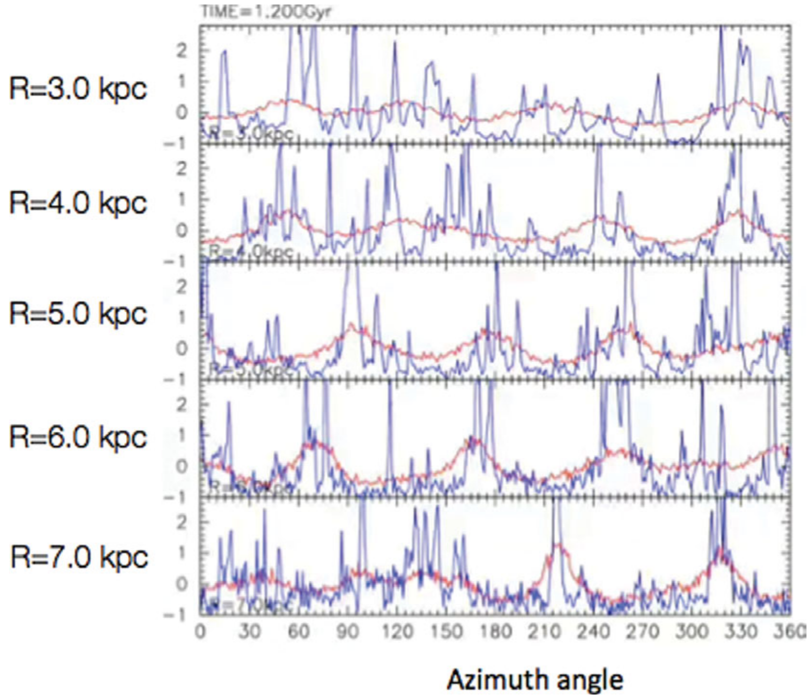

Figure 6. Gas and stellar density at different radii.

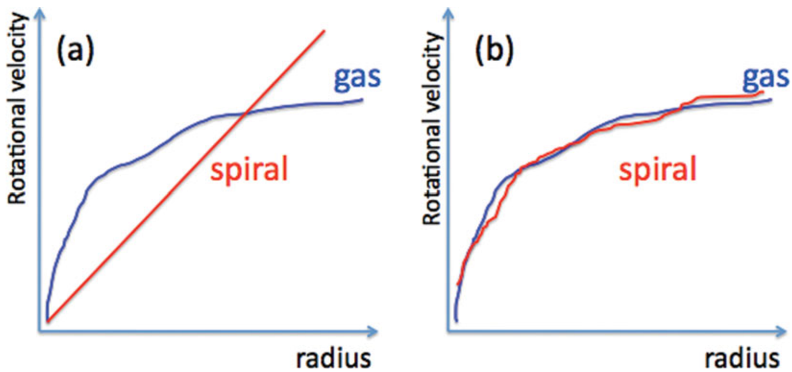

Figure 7. Rotation curve of the gas and stellar spiral. (a) A grand-design spiral with a constant pattern speed. (b) More realistic case.

A similar conclusion was also proposed by Dobbs & Bonnell (2008). They take a time-dependent gravitational potential from N-body simulations of Sellwood & Carlberg (1984), and run 3-D, two-phase (i.e. cold and warm) SPH simulations. They pointed out that "*c gas generally falls into a developing potential minimum and is released only when the local minimum dissolves. In this case, the densest gas is coincident with the spiral potential, rather than offset as in the grand-design spirals*". This is indeed what we see in more self-consistent (i.e. in terms of interaction between stars and ISM, thermal properties of the ISM, and star formation) N-body/SPH simulations.

Figure 7 shows schematically the difference between the rotation curves of spiral and gas (a) in the classical picture and (b) in the N-body/SPH simulations. If the multi-arm spiral structures are naturally developed in the galactic disk, the rotational velocity of the

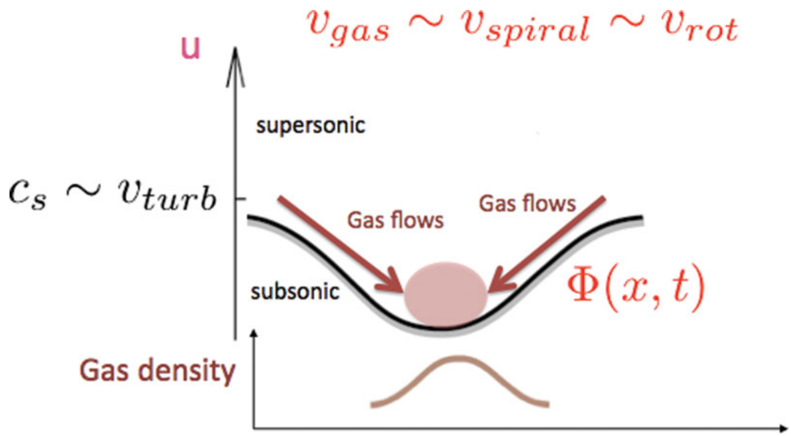

Figure 8. A modern picture of galactic spirals.

gas and stars should not be very different as shown in Fig. 7(b). Therefore, in contrast to the classical 'galactic shock' (Fig. 1), the ISM is always 'subsonic'† relative to the spiral potential, since the ISM basically moves together with the stellar spirals at any radii. In this case, as schematically shown in Fig. 8, the ISM falls into the spiral potential from both sides, and forms condensations at the bottom of the potential. Depending on the gas density, the condensation fragments and forms sub-structures. As a result, it is natural that there is no clear offset between stellar arms and gas arms, as seen in Fig. 6.

We also found that the ISM is not dynamically essential to keep stellar spirals, but it temporarily enhances the amplitude of local stellar arms. This is simply because the ISM tends to concentrate near the bottom of the potential as mentioned above. One should note that the local stellar potential is not steady, but time-dependent. Each stellar arm becomes faint or merges into other arms on a time scale of the galactic rotation, or even shorter. This local change of the potential can make the gas concentrations, like Giant Molecular Associations (GMA), gravitationally unbound. Therefore the time-evolution of the perturbation in the stellar potential should be considered when we discuss life-time of GMAs. The interaction between non-steady spirals and the ISM also causes large non-circular motions of the ISM. This is in fact observed in our Galaxy as the peculiar motions of the star forming regions (Baba *et al.* 2009).

4. Summary

The 'standard' picture of galactic spirals should now be replaced with a modern picture, which has been revealed by hydrodynamic and N-body simulations. Although some of them were already recognized by theorists since 1960s, recent progress in numerical techniques more clearly showed the dynamical nature of the galactic spirals in a more self-consistent manner. Some important features in the modern picture can be summarized as follows:

- There is NO winding dilemma!
- Spiral dust-lanes are not shocks.
- Galactic stellar spiral arms follow the galactic rotation . They are wound up locally,

† Here we assume the effective sound velocity of the ISM is comparable to its random motion, i.e. $\sim$ 10 km s^{-1}.

and recurrently connect to form global spirals, therefore they are highly time-dependent phenomena.

• The ISM is 'subsonic' to the stellar spiral potential, and no global shocks are formed†.
• Gas arms and young stars are associated with stellar arms, without clear offset.
• Gas is NOT necessary to keep the long-lived stellar spirals. It could temporarily enhance them.

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† Even in this picture, 'local' shocks associated with collision between clouds, where thermal temperature is smaller than 100 K, can be formed.

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