

## LECTURE 4

## The Role of Interactions and Mergers

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## 1. INTRODUCTION

A long way has been run from the first views developed to explain the formation of galaxies. In 1962, Eggen, Lynden-Bell & Sandage designed the collapse scenario, where all galaxies are created with their morphological type, according to their angular momentum. Their potentials remained axisymmetric, so that no angular momentum could be redistributed through gravity torques; the total mass and gas content was already there at first collapse. For elliptical galaxies, the violent/single collapse picture still remains in some modified form, although the most developed and adopted scenario is through agglomeration of a large number of clumps (e.g. van Albada 1982, Aguilar & Merritt 1990), that produces de Vaucouleurs profiles in  $r^{1/4}$ . The merger picture (Toomre 1977, Schweizer 1990), where ellipticals are formed by progressive interaction and coalescence of many parent galaxies, is favored in hierarchical cosmogonies.

For spiral galaxies, the scenario involves now much more internal dynamical evolution. Due to gas dissipation and cooling, gravitational instabilities are continuously maintained in spiral disks, and they drive evolution in much less than a Hubble time. Spiral galaxies are open systems, that accrete mass regularly, and their morphological type evolves along the Hubble sequence. Non-axisymmetric perturbations, such as bars or spirals, produce gravity torques that drive efficient radial mass flows; vertical resonances thicken disks and form bulges, and the mass central concentration can destroy bars. Accretion of small companions can also disperse bars and enlarge the bulge. A major merger can destroy disks entirely and form an elliptical.

The first role of galaxy interactions is to trigger internal evolution, that we

will consider now, in the next section. Specific aspects of galaxy interactions and mergers will then be detailed in section 3.

## 2. INTERNAL PROCESSES

### 2.1. Gravitational Viscosity

During their life, galaxies accrete and concentrate mass; this requires that angular momentum is redistributed, and essentially is transferred in the outer parts. For interstellar gas, viscous torques could be thought of to get rid of the angular momentum. However, normal viscosity is not efficient, due to the very low density of the gas. Even with macroturbulent viscosity, the time-scales are longer than the Hubble time at large radii, and could be effective only inside the central 1kpc (Lynden-Bell & Pringle 1974).

The other efficient way to transfer angular momentum is through gravity torques, due to non-axisymmetric perturbations, or density waves. In the stellar component, trailing spirals transport momentum outwards (Lynden-Bell & Kalnajs 1972), and if the spiral is open (i.e. the pitch angle large enough), there exists a phase-shift between the stellar density and the potential of the spiral, such that a torque is exerted on the particles, and momentum is redistributed (Zhang 1996). This process is even more important in the gas component, since it is more responsible to gravitational instabilities, due to efficient cooling. The coupled star-gas components are more unstable than each separately (e.g. Jog 1992, Romeo 1992). The gravity torques due to instabilities have been called "gravitational viscosity" (Lin & Pringle 1987a).

Gravitational instabilities are suppressed at small scales through the local velocity dispersion  $c$ , and at large scale by rotation. The corresponding limiting scales are the Jeans scale for a 2D disk  $\lambda_J \sim c^2/(G\mu)$ , and  $\lambda_c \sim G\mu/\kappa^2$ , where  $\mu$  is the disk surface density, and  $\kappa$  the epicyclic frequency. Scales between  $\lambda_J$  and  $\lambda_c$  are unstable, unless  $c$  is larger than  $\pi G\mu/\kappa$ , or the Toomre  $Q = \frac{c\kappa}{\pi G\mu}$  is larger than 1. If the disk is cold at the beginning (general case for the gas), instabilities set in, which heat the disk until  $Q \sim 1$ , and those instabilities provide the necessary angular momentum transfer (or viscosity) to concentrate the mass. Since the size of the region over which angular momentum is transferred is  $\sim \lambda_c$ , and the time-scale is a rotation period,  $2\pi/\Omega$ , the effective kinematic viscosity is  $\nu \sim \lambda_c^2\Omega$ , and the typical viscous time  $\tau_\nu \sim R^2\Omega^3/(G^2\mu^2)$ .

### 2.2. Exponential Disks

A galactic disk, submitted to gravitational instabilities can then be compared to an accretion disk. In the theory of viscous accretion disks, the main effect of viscosity is to move angular-momentum outward and mass inward. In the particular hypothesis of equal time-scales between viscosity and star formation, i.e.  $\tau_\nu \sim \tau_*$ , it can be shown that the final surface density of the stellar disk is

exponential (Lin & Pringle 1987b). An exponential distribution of metallicity can also be derived in these circumstances Tsujimoto et al. (1995).

The viscous and star-formation time-scales are of the same order of magnitude, since the two processes depend exactly on the same physical mechanism, i.e. gravitational instabilities. As shown empirically by Kennicutt (1989), the Toomre parameter  $Q$  appears to control star-formation in spiral disks. Therefore, if the regulating instabilities have time to develop, one can expect that  $\tau_\nu \sim \tau_*$ , as required for exponential light and metallicity distribution.

### 2.3. Bars and Nuclear Bars

A bar is the most efficient non-axisymmetric perturbation able to drive radial gas flows. But a single dynamical structure can act only over a limited range of radii, between the two most characteristic Lindblad resonances; to have a continuous action over a large radial range, and drive the gas to the nucleus, multiple-scale perturbations are required, such as bars within bars (e.g. Shlosman et al 1989). Bars are frequently triggered by galaxy interactions, and once the matter has been driven towards the center, the inner disk becomes in turn unstable to bar formation. Nested bars are often observed in spiral disks (e.g. Jarvis et al 1988, Wozniak et al 1995), and even more easily in the near-IR band (Shaw et al 1993, Friedli et al 1996, Jungwiert et al 1997). One of their main characteristics is that the nuclear bars are inscribed inside the nuclear ring of the primary bar (corresponding to its inner Lindblad resonance), and that they can have any orientation with respect to the primary bar.

Numerical simulations have described the numerical process leading to their formation (Friedli & Martinet 1993, Combes 1994). In concentrating the mass towards the center, the first bar modifies the inner rotation curve, and the precessing rate  $(\Omega - \kappa/2)$  of the  $m = 2$  elliptical orbits in the center is elevated to large values. This strong differential precessing rate prevents the self-gravity from matching all precessing rates in the center, and decoupling occurs: two bars rotating at two different pattern speeds grow. In the simulations, the two bars have a resonance in common, most often the inner Lindblad resonance of the primary bar is the corotation of the secondary one. It is probable that the two bars exchange energy at this common resonance, and that is the reason of their growth (Tagger et al 1987).

## 3. GALAXY INTERACTIONS

Tidal interactions are the main external trigger of dynamical processes that induce galaxy evolution. They produce non-axisymmetrical perturbations, that concentrate mass and trigger star-formation. Starbursts are observed when a huge gas mass is concentrated in the center of the interacting/merging system. CO emission suggest that the molecular gas represents a significant part of the dynamical mass there (Scoville et al 1991). Non nuclear starbursts are very

rare (cf Stanford et al 1990, Yun et al 1994). To trigger such starbursts, gas must be brought towards the center in a time-scale short enough with respect to the feedback time-scale of star-formation (a few  $10^7$  yr), that will blow the gas back outwards (e.g. Larson 1987). It is through numerical simulations that insight has been gained in those systems, although many uncertainties remain about the physics of gas and star formation (see the review by Barnes & Hernquist 1992).

### 3.1. Numerical Codes and Star Formation

It is necessary to take into account all components self-consistently, stars, gas and dark matter. The latter participates actively in dynamical friction and receives the extra angular momentum, allowing the visible galaxies to merge.

Gas dissipation is a key factor in the formation of density waves and non-axisymmetric structures, although viscous torques are negligible versus the gravity torques (Combes et al. 1990). We don't know precisely the actual viscosity of the ISM, but given its very complex multi-phase and small-scale structure, it is not relevant to model it in any accurate manner. Any large-scale hydrodynamical simulation can reproduce the main characteristics of gas flow in galaxies, provided that viscous torques are negligible. Two families of gas modelisations are currently used, one based on a continuous diffuse fluid, essentially governed by pressure forces. Such modelisations include artificial viscosity to spread shock waves over a few resolution cells. The physics of the gas is assumed to be isothermal at  $10^4$ K (case of SPH or finite difference codes). The other modelisation used in galaxy hydrodynamics is the sticky particles approach, where an ensemble of gas clouds move in ballistic orbits and collide, without extra pressure and viscosity terms. This modelisation represents more closely the fragmented structure of the molecular component.

As for star-formation, the numerical codes are very schematical, since the detailed processes (SFR, IMF) are still unknown. Since stars are observed to be formed inside giant molecular clouds in our Galaxy, the latter being the result of agglomerations of smaller entities, one process could be to relate star formation to cloud-cloud collisions, in the sticky particles modelisation (Noguchi & Ishibashi 1986). Another more widely used is to adopt a Schmidt law for the SFR, i.e. the rate is proportional to a power  $n$  of the gas volumic density,  $n$  being between 1 and 2 (Mihos et al 1992). In both cases, it was shown that interacting galaxies were the site of strong starbursts, that could be explained both by the orbit crowding in density waves triggered by the tidal interactions, and by the gas inflow and central concentrations, accumulating the gas in small and very dense regions. This depends of course on the non-linearity of the Schmidt law, and SF-efficiency strongly depends on the power  $n$  (see e.g. Mihos et al 1992). Mihos & Hernquist (1994) use a hybrid-particles techniques, within SPH, to describe the effects of gas depletion and formation of a young star population. The SPH/young star particles are converted from gaseous to collisionless form, as soon as their gas mass fraction drops below

5%. Although this method has many computational advantages (number of particles fixed), it does not decouple the behaviour of young stars and gas, especially in the shocks. This also inhibits contagious star formation, or any feedback mechanisms (Struck-Marcell & Scalo 1987, Parravano 1996).

### 3.2. Major and Minor Mergers

During the interaction of galaxies of comparable mass, strong non-axisymmetric forces are exerted on the interstellar gas. But contrary to what could be expected, the main torques responsible for the gas inflow are not directly due to the companion, but to internal processes triggered by it. The tidal perturbations destabilise the primary disk, and the non-axisymmetric structures generated in the primary disk (bars, spirals) are responsible for the torques. The self-gravity of the primary disk, and its consequent gravitational instabilities, play the fundamental role. The gas fuel is provided by the primary disk itself, and not by the companion. This is why the first parameter determining the characteristics of the merger event is the initial mass distribution in the two interacting galaxies (Mihos & Hernquist 1996). The mass ratio between the bulge and the disk is a more fundamental parameter than the geometry of the encounter.

The central bulge stabilises the disk with respect to external perturbations. If the bulge is sufficiently massive, the apparition of a strong bar is delayed until the final merging stages, and so is the gas inflow, and the consequent star-formation activity. But the starburst can then be stronger. When the primary disk is of very late type, without any bulge, the gravitational instability settles in as soon as the beginning of the interaction, there is then a continuous activity during the interaction, but at the end the starburst is then less violent, since most of the gas has been progressively consumed before.

In the simulations, about 75% of the gas is consumed during the merger, whatever the internal structure of galaxies, or the geometry of the encounter (Mihos & Hernquist 1996). This is the most uncertain parameter, however, since the physics of the gas is only schematically reproduced, with too much viscosity. What is the fate of the rest of the gas? In general long tidal tails are entrained in the outer parts, especially in neutral hydrogen, since this is the most abundant component in external parts of galaxies. But most of the material of the tails is still bound to the system, and will rain down progressively onto the merger remnant (Hibbard 1995).

During less equal galaxy interactions, where the mass ratio between the two colliding galaxies is at least 3, the same features can be noticed: the first relevant parameter is the mass concentration in the galaxies before the interaction (Hernquist & Mihos 1995). The torques responsible for the gas mass inflow are exerted by the non-axisymmetric (essentially  $m = 2$ ) potential developed in the disk.

### 3.3. Tidal Tails and Dark Matter

The extent of tidal tails can help to constrain the amount of dark matter around galaxies. Simulations have shown that, as the dark-to-luminous mass ratio increases, the length of the tails and the mass involved in them is considerably reduced (Dubinski et al 1996). Larger masses imply higher speed encounters, that will detune resonances between the angular frequency of the orbital and internal motions, required to form tails. The deeper potential wells to climb induce shorter tails. Simulations are compatible with observations for dark-to-luminous mass ratios between 0 and 8, but not higher. This corresponds to the dark matter detected from HI rotation curves, but rules out more massive determinations, such as from timing argument for the Milky Way ( $10^{12} M_{\odot}$  from the orbit of our companion M31).

### 3.4. Interactions and Disks

Galaxy interactions can easily thicken or even destroy a stellar disk (e.g. Gunn 1987). The fragility of stellar disks with respect to thickening has been used by Toth & Ostriker (1992) to constrain the frequency of merging and the value of the cosmological parameter  $\Omega$ . They claim for instance that the Milky Way disk have accreted less than 4% of its mass within the last  $5 \cdot 10^9$  yrs. Numerical simulations have tried to quantify the thickening effect (Quinn et al 1993, Walker et al 1996). They show that the stellar disk thickening can be large and sudden, but it is strongly moderated by gas hydrodynamics and star-formation processes, since the thin disk can be reformed continuously through gas infall. Galaxies presently interacting have their ratio  $h/z_0$  of the radial disk scale-length  $h$  to the scaleheight  $z_0$  1.5 to 2 times lower than normal (Bottema 1993; Reshetnikov & Combes 1997). However, since galaxies have experienced many interactions in the past, including the presently isolated galaxies, all these perturbations, thickening of the planes and radial stripping, must be transient, and disappear after an interaction time-scale, i.e. one Gyr. Present galaxies are thought to be the result of merging of smaller units, according to theories of bottom-up galaxy formation; a typical galaxy has accreted most of its mass, and the existence of shells and ripples attests of the frequency of interactions (Schweizer & Seitzer 1992). This implies that the global thickness of galaxy planes can recover their small values after galaxy interactions. Or in other words, the disk of present day spirals has been essentially assembled at low redshift (Mo et al 1998).

### 3.5. Ring Galaxies

Ring galaxies, like the Cartwheel, are believed to be formed during a head-on encounter between a disk galaxy and a companion crossing its plane (e.g. Lynds & Toomre 1976, Theys & Spiegel 1976). They constitute an ideal laboratory to understand the dynamics and physics of the gas in galaxy collisions, since a

single impulse is given by the companion, and the geometry of the phenomenon is very simple, (see e.g. Appleton & Struck-Marcell 1996).

Ring galaxies are not among the most violent starburst ( $> 100 M_{\odot}/\text{yr}$ ), but they reveal about 10 times the star formation activity of normal galaxies. They are among the rare objects where the starburst is non-nuclear. In the Cartwheel, the  $H\alpha$  comes exclusively from the outer ring (Higdon 1995), and 80% of it comes from just one quadrant, quite asymmetrically. The recent star formation rate ( $H\alpha$ ) is about 10 times that over the last 15 Gyrs (B-band), and the consumption time-scale of the HI gas (although abundant  $1.3 \cdot 10^{10} M_{\odot}$ ) is only 430 Myrs, of the same order of the ring expansion time-scale.

There are many unsolved problems in ring galaxies, and in the Cartwheel in particular: the region of the maximum HI density in the ring does not coincide with the region of maximum star formation (Higdon 1996); but of course we still do not know the  $H_2$  distribution (cf Horellou et al 1995). Also, there is no gas in the spokes, nor in the center (Higdon 1996), while N-body simulations of the encounter predict there a gas concentration (e.g. Hernquist & Weil 1993).

### 3.6. Groups and Clusters

Although the galaxy volumic density is larger in clusters, the relative velocity also, and tidal interactions might be less effective than in the field. Distorted galaxies with asymmetries, tails and plumes are often observed in the stellar component (which cannot be due to ram-pressure), but starbursts are less frequent, since they require a large abundance of gas in the outer parts of galaxies, available for gas inflow, and this gas is removed by tidal stripping. It is heated and forms then the coronal gas observed in X-ray in compact groups and clusters. In the case of strong gas deficiency, the interaction frequency can even be anti-correlated with star-formation rate.

This is true even in compact groups, where the relative velocity is not too high. There is some (controversed) evidence of excess far-infrared emission (Zepf 1993, Sulentic et al 1993) indicating more star-formation than isolated galaxies (especially the  $60/100\mu$  colors). There is also excess radio emission (Menon 1995) and HI deficiency (Williams et al 1991), which confirm their peculiarity with respect to field galaxies. A recent ROSAT survey of 22 HCGs (Ponman et al 1996) detected the hot coronal gas through X-ray radiation in 75% of them. But there is no evidence of higher molecular gas content in most HCG galaxies (Boselli et al 1996, Leon et al 1998). Therefore, although there exist some obvious signs of interaction, galaxy collisions have limited efficiency (there is no merging), and limited star-formation triggering.

The effect of gas stripping is even more important in rich clusters (e.g. Cayatte et al 1990). In Virgo, there is evidence that the global star formation rates have been reduced (Kennicutt 1983). The accumulation of frequent high-speed close encounters, dubbed "harassment" by Moore et al (1996), has peculiar consequences, quite different from the normal galaxy-galaxy binary interactions and merging. Simulations have shown that these close encounters,

although they are not resonant with the internal motions, can produce the tidal damage observed in most perturbed galaxies in clusters (e.g. Combes et al 1988). One issue is to distinguish between the influence of the global tidal action of the cluster, and the two-body encounters between individual galaxies. The former global effect is expected to be significant only in the central part, while the best cases of tidal deformations are observed on the periphery.

Harassment is so efficient that it is possible to account for the rapid galaxy evolution in rich clusters (Moore et al 1996): within 4-5 Gyr, the morphology of galaxies in clusters can be transformed from late-type spirals to early-type, lenticulars and ellipticals. Only 4-5 high-speed collisions are necessary for this evolution.

## 4. EVOLUTION WITH REDSHIFT

### 4.1. Observations of High- $z$ Galaxies

The advent of the Hubble Space Telescope has allowed, through high resolution imaging, to study galaxy morphology at intermediate redshift ( $0.1 \leq z \leq 1.0$ ). A striking feature is that high- $z$  galaxies are often seen with tidal features, distorted morphologies indicative of interactions and mergers. This might be surprising since tidal arms and distortions are generally weak features, of relatively short life-time, and their detectability is reduced at high redshift (Mihos 1995). The debris and signatures of mergers become invisible after 1 Gyr for  $z = 0.4$  and after 0.2 Gyr only at  $z = 1$ . The fact that tidal distortions are so omnipresent in high- $z$  galaxies, in spite of this bias, is a clue to the huge increase of interactions and mergers with  $z$ .

In clusters, the relative importance of "nature or nurture" in accounting for the large percentage of elliptical galaxies, is still a debated question: are elliptical galaxies formed at once from rapid collapse in rich environment that are to become clusters, or are they the result of late merging of disk galaxies, when the cluster virializes? High-resolution images of clusters at high  $z$  can bring some light to this problem. Dressler et al (1994) have imaged a cluster at  $z = 0.4$ , and suggest that the excess blue galaxies seen in distant clusters are predominantly normal late-type spirals, undergoing tidal interactions or mergers. The Butcher-Oemler effect, associated with enhanced star-forming activity appears now convincingly to be due to enhanced interactions, arising from hierarchical merging. Clusters at  $z = 0.4$ , i.e. 3-4 Gyr ago, appear to possess a much larger fraction of disk-dominated galaxies than present day clusters (Couch et al 1994).

In the frame of hierarchical cosmological scenarios, it is expected that the number of galaxies in a comoving volume increases with redshift, while their mass decreases. Some trends in that sense have been revealed by HST at very high redshift ( $z \approx 2-3$ ). A population of faint, small, compact objects has been identified to the sub-galactic clumps, or building blocks of present day galaxies



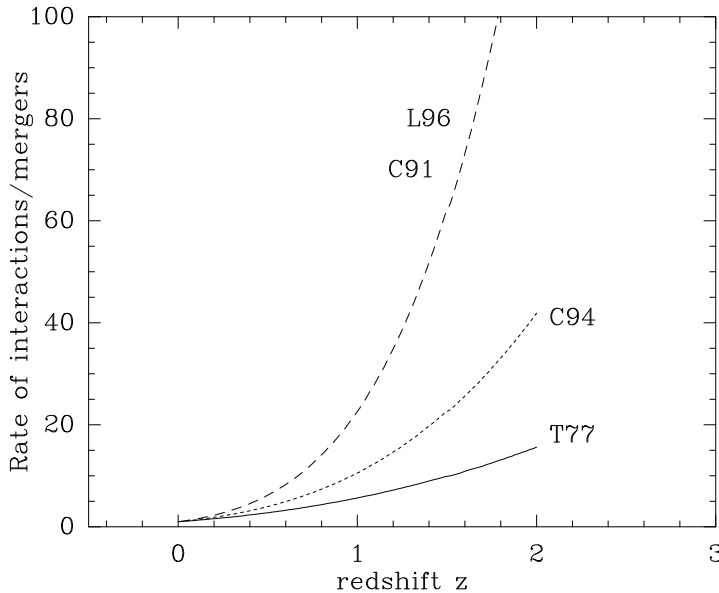


Fig. 1. — Evolution of the rate of interaction and mergers as a function of redshift, from various estimations. Solid line: estimation from the present number or merger remnants in the NGC catalog, and frequency of apparition of binary periods  $P$  in  $P^{-5/3}$  from Toomre (1977, T97); no evolution is postulated here. Dashed line: from the frequency of collisional ring galaxies in deep HST fields (Lavery et al 1996, L96) and various other objects (pairs, Butcher-Oemler effet, IRAS faint sources, QSOs, Carlberg 1991, C91). Dotted line: from the number of interacting pairs (Carlberg et al 1994, C94). The observed power laws (for  $z < 1$ ) have been extrapolated to  $z = 2$ .

through multiple merging processes (Pascarelle et al 1996, Steidel et al 1996). However, caution must be used to interpret high redshift data, since fading of low surface brightness features (as  $(1+z)^{-4}$ ), and k-correction effects transform galaxies in later types and more irregular objects, even without evolution (Giavalisco et al 1996). For instance, van den Bergh et al (1996) have claimed that barred and grand design galaxies appear under-represented in distant deep field samples, with respect to early-types galaxies. But this could be only the bias against detecting disks at high  $z$ . At very high redshifts, only the high surface density objects, such as bulges and ellipticals, can be detected.

Galaxy interactions were undoubtedly more frequent in the past, and many groups have tried to quantify the effect. Already Toomre in 1977 has estimated the number of mergers from their observed frequency at  $z = 0$  just taking into account the probability of excentricities of binary orbits. Statistics of close galaxy pairs from faint-galaxy redshift surveys have shown that the merging

rate increases as a power law with redshift, as  $(1+z)^m$  with  $m = 4 \pm 1.5$  (e.g. Yee & Ellingson 1995). Lavery et al (1996) claim that ring galaxies are also rapidly evolving, with  $m = 4-5$ , although statistics are still insufficient. Many other surveys, including IRAS faint sources, or quasars, have also revealed a high power-law (see fig 1).

#### 4.2. Different Evolution Time-scales

We already see at  $z = 0$  a wide range of galaxy properties, that appear to correspond to various stages of evolution. The main parameter determining the Hubble sequence is the bulge-to-disk luminosity ratio, which increases from late to early type spiral galaxies. In other words, the mass concentration, and therefore the evolution stage, increases from Sc to S0. From recent near-IR surveys, de Jong (1996) and Courteau et al (1996) claim that the bulge mass is even a better criterion than the bulge-to-disk ratio to define the sequence. The total mass increases from Sc to S0, and might be the essential parameter (e.g. Gavazzi et al 1996). Late-type galaxies and irregulars possess a much larger gas fraction than early-types, which is also a clue of their low evolution. Galaxy evolution is indeed driven both by dynamical processes, that concentrate the mass (see section 2), and star formation that consumes the available cold gas.

Also in the recent years, we have realized the importance of Low Surface Brightness galaxies (LSB), which appear unevolved systems, with large gas fraction, and low mass concentration (Bothun et al 1997). Compared to High Surface Brightness galaxies (HSB), they are more dominated by dark matter, even within the optical disks, as are dwarf irregulars (de Blok & McGaugh 1997). The clue to their long evolution time-scales might be their poor environment, and low interaction frequency (Bothun et al 1997).

N-body simulations have shown that bars and density waves through their gravity torques can concentrate galaxy masses on a time-scale much shorter than the Hubble time. Since most spiral galaxies are observed with these features, this implies rapid evolution along the Hubble sequence. But along the sequence, galaxies gain visible mass, and their dark-to-luminous mass ratio decreases: this suggests that some of their dark matter has been transformed in visible stars (Pfenniger et al 1994, Pfenniger & Combes 1994).

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