LECTURE 3

Starburst Triggering and Environmental Effects

Françoise Combes

Observatoire de Paris, DEMIRM, 61 Av. de l'Observatoire, F-75 014, Paris, FRANCE

1. INTRODUCTION

Observations of star-forming galaxies reveal an obvious relation between the star-formation rate and dynamical features. Spiral arms are mostly a tracer of young stars, giant HII regions often accumulate at the extremities of bars, or in conspicuous hot spots delineating nuclear rings; the most spectacular starburst occur in tidally interacting galaxies and mergers. The problem is to understand in details the large-scale mechanisms that trigger star-formation coherently over such scales (larger than one kpc), and their relation with the small-scale physics: cloud gravitational collapse, and feedback processes provided by the newly formed stars such as stellar winds, jets, supernovae, etc...

The triggering of cloud collapse followed by star-formation is to be searched in gravitational instabilities, but the problem of the stability of two-fluid media, where a non-dissipative component (stars) is coupled to a dissipative one (the gas) is complex (cf Jog & Solomon 1984; Jog 1992). The stability of the stellar component alone and its possible structures have been widely studied: even when a stellar disk is stable against axisymmetric perturbations (i.e. the velocity dispersion is enough for the equivalent pressure to prevent Jeans instability at small scales, while the large scales are stabilised by rotation, Toomre 1964), it can develop spiral and bar waves, or z-intabilities. But these gravitational instabilities saturate rapidly, since they heat considerably the stellar disk, that can then no longer sustain spiral structure, or thicken so that z-instabilities are suppressed. Any instability can be totally suppressed by increasing the velocity

dispersion, or by the addition of a hot spherical component (bulge) which both reduce the self-gravity of the stellar disk. The relevant scale of the self-gravity is $\lambda_c = 4\ \pi^2\ \mathrm{G}\ \Sigma(\mathrm{r})/\kappa^2(\mathrm{r})$, where $\Sigma(\mathrm{r})$ is the disk surface density and $\kappa(\mathrm{r})$ the epicyclic frequency (λ_c is typically varying from 1 to 15 kpc over galaxy disks).

The behaviour of the gas component is completely different. Alone, submitted only to its self-gravity, it will never be stable on a galactic scale. Its dissipation, and propension to radiate quickly its kinetic energy away, keeps its velocity dispersion always lower than the critical one. It will be Jeans unstable at any scale, which will results in a patchy and clumpy structure, leading in some cases to star formation. Only when coupled to a non-dissipative component such the stellar or dark component, can it self-gravity be reduced, and the critical velocity brought down below its velocity dispersion. In that case, it can stay as stable as a diffuse component. However, the coupling between the various components cannot be neglected, and separate stability analysis are misleading.

2. STABILITY OF A TWO-FLUID MEDIUM

For a single component, the standard stability criterion against local axisymmetric perturbations, developped first by Safronov (1960) is

$$Q = \frac{\kappa c}{\pi G \Sigma} > 1$$

where c is the one-dimensional random velocity or sound speed. The numerical coefficient π corresponds to a fluid approach, while the kinetic theory would give 3.36 (Toomre 1964). This criterion can be applied separately to the stellar and gas component, where the corresponding values of Σ and c are used, leading to Q_s and Q_g. Jog & Solomon (1984) showed however that, since $c_g << c_s$, only a small percentage of mass in gas can destabilize the whole disk, even when $Q_s > 1$ and $Q_g > 1$. They give a condition of neutral stability in the form of the dispersion relation:

$$\frac{2\pi G k \Sigma_s}{\kappa^2 + k^2 c_s^2} + \frac{2\pi G k \Sigma_g}{\kappa^2 + k^2 c_g^2} = 1$$

where k is the wave number. This formula has the advantage to give directly an idea of the relative weight of gas and stars in the instabilities. However, there is no simple criterion of local stability, and the study can only be done numerically (Jog 1996). Indeed the equation above is only the condition ω^2=0, where ω is the angular frequency of the radial perturbation of wave number k. But the neutral equilibrium requires the simultaneous solution of $d\omega^2(k)/dk = 0$; the system have several solutions, and the analysis is cumbersome. Fig. 1 gives a global idea of the numerical solutions, in terms of a two-fluid Q_{s-g} value, which is always lower than the Q_s or Q_g values. The stability problem depends strongly on the gas mass fraction ϵ (between 5 and 25%). The fastest growing

Fig. 1. — A contour plot of Q_{s-g} the local stability parameter for a two-fluid star-gas disc, as a function of Q_s and Q_g. The gas mass fraction is ϵ (from Jog 1996).

two-fluid modes are characterized by a dimensionless wavelength $l_{s-g}\lambda/\lambda_c = \kappa^2/2\pi G k(\Sigma_s + \Sigma_g)$, which is displayed in fig 2. What is striking is how sharp is the transition from high to low values of l_{s-g}, as the mass fraction increases from $\epsilon = 0.1$ to 0.15 for instance. Also, l_{s-g} can be very low, and equal to the gas l_g when Q_s is high and Q_g is low. These results imply several interesting effects: a gas-rich galaxy (with $\epsilon > 0.25$) is only stable at very low surface densities (this explains the Malin 1-type galaxies, Impey & Bothun 1989); the center of early-type galaxies, where Q_s is high, and Q_g might be low (low gas velocity dispersion), could be dominated by the gas wavelength, even at very low gas mass fraction: this can explain spiral arms in galaxies such as NGC 2841 (Block et al 1996). Also interaction of galaxies, by bringing in a high amount of gas, may change abruptly the fastest growing wavelength from l_s to l_g, and trigger star-formation.

It is important to note that, even beyond the neutral stability criterium, when $Q_{s-g} > 1$, a galaxy disk can be unstable with respect to non-axisymmetric perturbations, such as bars or spirals; in this case also, the two-fluid coupling increases the instability, i.e. the disk will form a bar, even if the stars or the gas alones are stable with respect to such perturbations (Jog 1992).

Also important are the stabilising effects of the vertical thickness of the galactic planes (e.g. Romeo 1994). These can be represented by reduction factors for stars and gas $f_s = (1+kh_s)^{-1}$ and $f_g = (1+kh_g)^{-1}$ of scale-heights h_s and h_g respectively. Note that the stabilising effects depend on wavelengths $2\pi/k$. The vertical and planar heating mechanisms, and related self-regulation processes, are almost decoupled, as well as stability properties (Romeo 1992).

Fig. 2. — A contour plot of l_{s-g} the dimensionless wavelength corresponding to the fastest growing mode of the two-fluid star-gas disc, as a function of Q_s and Q_g, for ϵ the gas fraction equal to 0.15 and 0.20 (from Jog 1996).

3. MECHANISMS TO TRIGGER STARBURSTS

Several mechanisms to explain enhanced star formation in colliding galaxies have been proposed in the literature. Since Giant Molecular Clouds (GMCs) are in our Galaxy the sites of massive-star formation, and that they are just in virial equilibrium, with a rather low star formation efficiency, it was proposed that the direct collision between them at high velocities could trigger their instability. Harwit et al (1987) have proposed such a model based on direct collisions between GMC of the two galaxies, at a relative velocity of about 300km/s. But since the filling factor of molecular clouds is so low, they required that the collision between the two galaxies be edge-on. Jog & Solomon (1992) have taken along this idea, but only the HI gas with a large filling factor was able to collide directly, form a hot ionized, high pressure medium. This overpressure caused a radiative shock compression of the outer layers of the GMCs and triggered the burst of star formation. This occured in the region of overlap of the two galaxies ($\approx$ 1kpc in size), and not in the galaxy nuclei.

But the energy deposited by a direct collision, given the very restricted overlap zone, and the small mass involved (the diffuse HI gas) is negligible in respect of the energy available in a galaxy interaction. Tidally interacting galaxies reveal active star-forming zones without any contact, and the most frequent starbursts occur at the nuclei. The fundamental reason for starbursting activity in interacting galaxies is more the dissipative character of the collision: the energy to dissipate is the total relative orbital energy of the two colliders. This is at least 5 orders of magnitude larger than the energy dissipated in the direct collision of diffuse clouds at the overlaping zone. Through tidal interaction

and dynamical friction, all the energy ends up in deformation and heating of the galactic disks (velocity dispersions, waves, etc..), which triggers the star formation. In particular, the large gas inflows driven by the waves produce huge gas surface densities in spiral arms and particularly in the nuclei, where gravitational instabilities at all scales are quickly growing. Other possibilities have been suggested, as the enhanced rate of cloud-cloud collisions (Noguchi & Ishibashi 1986, Sanders et al 1988). In any case, the rate of star formation ends up as a non-linear function of the gas density, as is observed empirically as the Schmidt law (e.g. Larson 1987).

4. DYNAMICAL MECHANISMS: NON-AXISYMMETRY AND TORQUES

4.1. Angular momentum transfer for the stellar component

In a pioneering paper, Lynden-Bell & Kalnajs (1972) have shown how spiral waves can carry angular momentum (A.M.), and that only trailing spirals can carry it outwards, which explains the predominance of trailing waves in observations. For a steady wave, stars can exchange angular momentum at resonances only: they emit A.M. at inner Lindblad resonance, while they absorb at corotation and outer resonance. They also show that, while stars do not gain or lose angular momentum on average away from resonances, they are able however to transport angular momentum as lorries in their orbiting around the galactic center. When they are at large radii, they gain A.M., while they lose some at small radii: even if the net balance is zero, they carry A.M. radially, and the sense of this lorry transport is opposite to that of the spiral wave. This phenomenon can then damp the wave, if the amplitude is strong enough. Lynden-Bell & Kalnajs (1972) noticed that this damping phenomenon became negligible for small wavelengths, i.e. when kr $>>1$.

This A.M. transport has been investigated recently by Zhang (1996), who puts forward another point of view: due to the phase-shift between the stellar density and the potential of the spiral wave, gravity torques are exerted by the wave on the basic state stars, and stars gain or lose angular momentum, even away from resonances. This is the consequence of a kind of dissipational process, corresponding to small-angle scatterings of neighboring stars in the spiral arm. This process transforms ordered motions into disordered ones (resulting in increased velocity dispersion, or large epicycle amplitudes), and when collective effects are taken into account, secular modifications of the stellar orbits can result: they can lose energy and angular momentum inside corotation.

4.1.1. Expressions for the torque and phase-shift

It is obvious that the torque exerted by the wave on particles is a second order term, since the tangential force $\frac{\partial V_1}{\partial \theta}$ is first order, and has a net effect only on the non-axisymmetric term of the surface density $\Sigma_1(r,\theta)$. The torque $T(r)$

applied by the wave on the disk matter in an annular ring of width dr, can be expressed by (Zhang, 1996):

$$T(r) = rdr \int -\Sigma_1(r,\theta)\frac{\partial V_1}{\partial \theta} d\theta$$

On that formula, it is easy to see that the torque vanishes if the density and potential spiral perturbations are in phase. But there must be a phase-shift in the general case, according to the Poisson equation. The potential is non-local, and is influenced by the distant spiral arms. So the sign and amplitude of the phase-shift depends on the radial density law of the perturbation. It has been shown by Kalnajs (1971) that the peculiar radial law of $r^{-3/2}$ for an infinite spiral perturbation provides exactly no phase shift. The phase-shift is such that the spiral density leads the potential if the radial falloff is slower than $r^{-3/2}$, and the reverse if it is steeper.

Now in a self-consistent disk, the phase-shift given by the Poisson equation must agree with that given by the equations of motion. Through the computation of linear periodic orbits in the rotating frame, Zhang (1996) has found that the forcing consists of two terms in quadrature, and that the phase shift δ of the orbit orientation with respect to forcing potential has the expression:

$$tan(m\delta) \approx \frac{-2\Omega}{(\Omega - \Omega_p)kr}$$

This shows that in the WKBJ approximation, the phase shift is negligible (kr>>1), and that it changes sign at corotation. The fact that the torque is a non-linear effect, and vanishing in the WKBJ approximation, may explain why it was neglected before, but it has a quite important effect in real spiral galaxies. Inside corotation, we expect that the density leads the potential, and the contrary outside corotation. These predictions have been confirmed through N-body simulations by Zhang (1996), as for the sign of the phase-shift on each side of the corotation. The amplitude of the phase-shift appears quite high, up to 20°. The existence of the phase-shift is no surprise of course, but the amplitude of δ was not suspected to be so high.

I have reproduced a comparable N-body simulation (2D polar grid PM with 10^5 particles), and reported the Fourier analysis results in Figure 3. In this simulation, initial parameters were chosen such as to stabilise the stellar disk with respect to bar formation, through the presence of an analytical bulge component of mass equal to the mass of the self-gravitating stellar disk. A bar developped still, but was delayed until 2 10^9 yrs, i.e. $\approx$ 20 dynamical times. In the mean time, a spiral wave developped, and remained for several dynamical times. Its power spectrum revealed a well-defined pattern speed, at least up to corotation ($\approx$ 7 kpc). We can see in fig. 3 that the phase-shift between stellar density and potential is indeed quite high, up to 28° inside corotation, where it is the most meaningful.

Fig. 3. — Results of the Fourier analysis of the stellar density (crosses) and potential (full lines) in a purely stellar N-body simulation, while a spiral structure rotates in the disk. Plotted here are the phases of the pattern at each radius. The density leads the potential almost everywhere inside corotation. The perturbation was weaker outside corotation.

Fig. 4. — Same as fig. 3 for an N-body simulation taking into account gas and stars, and where a bar develops. The phases of the gas pattern are indicated by asterisks, while crosses indicate the stars, and the full lines the potential. Now the potential is in phase with the stellar density in the bar, and leads the density in the spiral outside corotation.

4.1.2. *Exchange of A.M. between particles and wave*

Previous studies had neglected the exchange of energy and angular momentum between the stars and the wave outside resonances (Lynden-Bell & Kalnajs 1972; Goldreich & Tremaine 1979). This interaction is mediated by the graininess of the particles, which under the local gravitational instabilities in the spiral arms, can scatter particles and produce dissipation (Zhang 1996).

During all its growth, and unstable spiral mode is able to deposit negative angular momentum in every annulus inside corotation, and positive angular momentum outside corotation. As the wave reaches nonlinear regime, an increasing fraction of the deposited angular momentum by the spiral wave is being channeled to the basic state, since by the very definition of the quasi-steady state the wave should not grow any further. We can note that this stellar collective dissipation process and angular momentum transport, induced by the phase-shift between density and potential, is inexistent for a bar. The latter can therefore be robust and long-lived in a collisionless ensemble of particles (galaxy disk without gas).

4.2. Angular momentum transfer for the gas component

The mechanism of the A.M. transfer for the gas is the same that was previously described: the gas settles in a spiral structure which is not in phase with the potential. Gravity torques are exerted by the wave on the gas. The dissipation here is of course different, since the gas radiates away its energy. The gas component is then maintained cool and responsive to new gravitational instabilities. This is the source of more drastic secular evolution, with the possibility of the whole gas component inflowing towards the center.

The gas response in a barred potential has been tackled through many simulations by several authors (e.g. Sanders & Huntley 1976, Schwarz 1981) and can be understood in terms of periodic orbits families in a bar potential (e.g. Combes 1988). The sign of gravity torques also change at corotation. They can change also at ILR, according to the shape of the $\Omega - \kappa/2$ precession-rate curve.

Figure 4 shows the relative phases of the gas and stellar component with respect to the total potential, in an N-body simulation, while a bar was developping, with its external spiral structure at the same pattern speed. There is now a negligible phase-shift of the stellar density with respect to the potential in the bar, while there is a slight gas phase-shift. In the arms, outside corotation, the potential leads both components, but the phase-shift is always larger for the gas.

What is the actual role of dissipation? In an axi-symmetric galaxy, viscous torques would also transfer the A.M. of the gas towards the outer parts, but the time-scale would be longer than a Hubble time at large radii (Lin & Pringle 1987a). Gravity torques are then directly responsible for the gas inflow, and dissipation prevents the gas heating, and maintains the non-axisymmetric

features required for gravity torques (Combes et al 1990a). That is why the global gas behaviour should not depend much on the gas hydrodynamics, and the point of view adopted: gas as a fluid or as ballistic colliding clouds. In details it is not quite true, the two approaches lead to different results: the characteristic shocks along the dust lanes in a barred galaxy are reproduced only with the fluid approach, and all the variety of resonant rings are better obtained with the sticky particles approach. The reality must be in between, when the multi-phase property of the gas is taken into account.

4.3. Feedback and self-regulation

Given the importance of gravitational instabilities in cloud and star formation, it is interesting to summarize here observational data about Q values. The stellar dispersion has been studied in our own galaxy and in a few external galaxies by Lewis & Freeman (1989) and Bottema (1993). The velocity dispersion decreases exponentially with radius, in parallel to the stellar surface density, and Q_s appears to be constant in function of radius, at least for large galaxies, and vary between 2 and 3 from galaxy to galaxy.

If the stellar disk can be considered as a self-gravitating infinite slab, locally isothermal (σ_z independent of z), its density obeys:

$$\rho = \rho_0 sech^2(z/z_0) = \frac{\rho_0}{ch^2(z/z_0)}$$

where z_0 is the characteristic scale-height of the stellar disk, given by

$$z_0 = \frac{\sigma_z^2}{2\pi G \Sigma_s(r)}$$

where σ_z is the vertical velocity dispersion, and $\Sigma_s(r) = z_0\rho_0$ is the surface density. The latter has a general exponential behaviour (e.g. Freeman 1970), with a radial scale-length h. The scale-height z_0 has been observed to be independent of radius (van der Kruit & Searle 1981, 82), and there are only small departures from isothermality in z (van der Kruit 1988). Then, if the mass to light ratio is constant with radius for the whole stellar disk, and there is no or little dark matter within the optical disk, we expect to find a velocity dispersion varying as $e^{-r/2h}$. This is exactly what is found, within the large uncertainties (Bottema 1993). Since some galaxies of the sample are edge-on and others face-on, the comparison requires to know the relation between z and r projection of the dispersion. In the solar neighbourhood, $\sigma_z = 0.6\sigma_r$, and this ratio is assumed to be valid in external galaxies too.

As for the gaseous component, the vertical velocity dispersion is constant with radius in the outer parts of galaxies, where the rotation curve is flat (Dickey et al 1990): $c_g \approx 6km/s$. The behaviour of $\kappa \propto 1/r$ (for a flat rotation curve) is exactly parallel to the gas surface density $\Sigma_g \propto 1/r$ (e.g. Bosma 1981), and therefore $Q_g \propto c_g\kappa/\Sigma_g$ is constant with radius in the outer parts.

This strongly suggests a regulation mechanism, that could maintain the values of Q about constant for both stars and gas.

The mechanism could be simply gravitational instabilities coupled with gas dissipation. When the medium is cool enough, so that the Q value is too low, gravitational instabilities quickly provide heating. The stellar component cannot cool down and keeps hot, although this is somewhat moderated by the gravitational action of the gas, and the young stars born in the cool component. The gas is even more sensitive to the heating, but it can dissipate its disordered motions. The key point is that cooling encourages dynamical instabilities, and therefore produces heating, which is how the regulation works (cf Bertin & Romeo 1988).

Kennicutt (1989) remarks that the extreme radius of HII regions in galaxies coincides with the radius where Q_g is about 1, in a one-fluid analysis of a thin plane; he then suggests that there is a gas surface density threshold for star formation in galaxy disks, and that this threshold corresponds to the onset of gravitational instabilities. In fact, the existence of a star-formation threshold is unavoidable, but could be slightly different than the cloud-formation threshold constrained by gravitational stability criteria. In the outer parts of galaxies, the HI gas that extends much further than the last radius of star-formation, appears patchy, clumpy, and following some kind of spiral structure. The outer gas is unstable at any scale. This suggests that instabilities are present, at the origin of cloud formation, and are the regulator of the constant c_g and Q_g. Sellwood & Carlberg (1984) have shown by simulations that such a feedback occured, and Lin & Pringle (1987b) proposed that the self-gravitational instabilities act as a local effective viscosity, giving rise to a local heating time-scale $\propto Q^2/\Omega$ for $Q < 1$.

It is interesting to note that there are several ways to maintain Q constant, and that the stars and gas have chosen two different ways: the stellar component keeps its scale-height constant, while its velocity dispersion is exponentially decreasing with radius; the gas keeps its velocity dispersion constant, while its scale-height increases steadily with radius (linearly, when the rotation curve is flat). This might be related to the different radial distribution. The gas does not display an exponential radial profile, may be due to continued infall or accretion.

5. FUELING ACTIVITY BY BARS

Activity can be used here to represent either starburst in the central region, or nuclear activity. They are often related, since they are both triggered by central massive gas inflow in a spiral galaxy. The issue has been addressed by many authors, observationnally as well as theoretically. I refer to the proceedings of "Mass-transfer induced activity in galaxies", ed. by Shlosman (1994). The main problem to solve in this matter is that of the angular momentum. We have already seen above the efficiency of non-axisymmetric perturbations and

Fig. 5. — a) Periodic orbits in a $\cos 2\theta$ potential. Their orientation rotates by $\pi/2$ at each resonance. b) The gas tends to follow these orbits, but is forced to precess more rapidly while losing energy and angular momentum.

gravity torques. Since they are efficient on a time-scale of the order of the rotation time-scale, their efficiency is increasing towards the center, where the dynamical time is short. This is specially true in mass-concentrated galaxies, where the rotation curve has a steep central gradient (typically $V_{rot} \approx 200$km/s in nuclear rings of 100pc radius, corresponding to rotation periods of 3 Myr). Even at those scales, the viscous torques are less efficient. Only dynamical friction exerted on the GMCs could be considered: the Chandrasekhar time-scale is about 3 10^7 yr at r=200pc for a cloud of mass 10^7 $M_\odot$ in our Galaxy, and it varies as the square of the distance from the center.

5.1. The inner Lindblad resonance

Radial gas flows are driven the most efficiently by a bar, or a companion producing an $m = 2$ non-axisymmetric potential. Simkin et al (1980) show that bars are also the main agent to bring gas towards active nuclei and to fuel their strong energetic activity. However, as emphasized by Combes and Gerin (1985), the gas is in general efficiently driven to the inner Lindblad resonance, where it accumulates, but not to the very center. We can try to understand schematically, in terms of orbits, the sense of winding of gaseous spiral arms in the center, and consequently the sense of gravity torques.

In a $\cos 2\theta$ bar potential, the main families of periodic orbits are aligned or anti-aligned to the bar, according to the position with respect to Lindblad resonances (see Figure 5). Due to dissipation or cloud collisions, the gas component cannot follow these periodic orbits; instead, upon losing energy, the gas streams in elliptical trajectories at lower and lower radii, with their major axes leading more and more the periodic orbit, since the precession rate (estimated by $\Omega - \kappa/2$ in the axisymmetric limit, for orbits near ILR, and by $\Omega + \kappa/2$ near

Fig. 6. — a) Without a central mass concentration, the gas winds up in a leading spiral inside the ILR ring; b) with a central mass concentration, the gas follows a trailing spiral structure.

OLR) increases with decreasing radii in most of the disk. This regular shift forces the gas into a trailing spiral structure, from which the sense of the gravity torques can be easily derived. Inside corotation, the torques are negative, and the gas is driven inwards towards the inner Lindblad resonance (ILR).

Inside the inner ILR, and from the center, the precessing rate is increasing with radius, so that the gas pattern due to collisions will be a leading spiral, instead of a trailing one (see Figure 6). The gravity torques are positive, which also contributes to the accumulation of gas at the ILR ring. This situation is only inverted in the case of a central mass concentration, like a black hole, for which the precession rate $\Omega - \kappa/2$ is monotonically increasing towards infinity with decreasing radii. Only then, the gravity torques will pull the gas towards the very center, and "fuel" the nucleus.

Note that inside the two ILRs, it is not easy to predict whether the gas spiral will be leading or trailing. This depends on the gas density radial distribution, which will determine the dominant contribution. Gas simulations do tell us that the gas accumulates then at the inner ILR (e.g. Combes & Gerin 1985). The torque is therefore negative inside the two ILRs, and the dominant spiral must be leading.

If there is no central mass concentration, the torque is positive inside the inner ILR (leading spiral) and the gas is not driven towards the very nucleus. To fuel the nucleus, we are therefore back to the formation of the active nucleus or mass concentration in the first place. This might be a formation in several steps, since bars can be weakened or destroyed by a sudden mass concentration, and reformed afterwards. The first gas accumulation, followed by star formation, can steepen the rotation curve; this will generate a large gradient in dynamical time-scales, and produce a decoupling of a second bar inside the primary bar. This nuclear bar, and possibly other ones nested inside like russian dolls, can

take over the action of gravity torques to drive the gas to the nucleus, as first proposed by Shlosman et al. (1989).

5.2. Nuclear disks and nuclear bars

This is a phenomenon progressively revealed by increasingly high spatial resolution: either optically through HST imaging (Barth et al 1995), and high-resolution spectroscopy, or by observation of the molecular gas with millimetric interferometers (Ishizuki et al 1990). Recently, Rubin et al (1996) have studied a sample of 80 Virgo cluster galaxies, and have identified 14 ($\approx$ 20%) with a decoupled nuclear disk or ring, of at most 500pc in radius, and revealing large velocity gradients. When face-on these decoupled central disks show frequently a nuclear ring of star formation (e.g. NGC 1068, 1097, 7469, Genzel et al 1995). When edge-on, these systems are peculiar from their large velocity gradients, often showing "forbidden" velocities, like in the Milky Way (Dame et al 1987).

In these decoupled nuclear disks, the gas surface density is often very high, explaining the star formation bursts traced by the Hα hot spots. This high density makes the gas more self-gravitating and unstable against bar formation in the center. A secondary bar can form inside the first one, with a common resonance with the primary one. The more general case is that the ILR of the primary is the corotation of the second one (Friedli & Martinet 1993).

Depending on the physical parameters, and essentially the physics of the gas (dissipation, star formation), there can form a secondary component perpendicular to the primary, but with the same pattern speed, or a secondary bar with a higher speed (Combes 1994). In these two cases, the torques exerted on the gas are quite different. The phase-shift between the gas bar and the potential is very large in the second case, and the amount of fuel arriving on the nucleus is much larger. The high-speed nuclear bar can live several rotations, until the non-axisymmetry of the potential is destroyed.

Asymmetries and lopsidedness is often observed in these nuclear disks. Any $m = 1$ wave is not expected to amplify in the stellar component, but in the presence of a sufficiently high gaseous mass, there exist amplification mechanisms (Shu et al 1990). However, the developpment of such a wave does not favorise gas inflow (Junqueira & Combes 1996).

The phenomenon of nuclear disk decoupling can occur on very small scales, as is observed in our neighbour M31, thanks to it proximity. The nucleus of M31 appears like a compact stellar disk completely decoupled morphologically and kinematically from the surrounding bulge and large-scale disk. Its radius is less than 10pc. The rapid rotation is known from the early work of Lallemand et al (1960), who showed that the rotation curve is very compact in the nucleus, returning to zero at about 2" from the center. With higher resolution, the rotation peak has increased to 200km/s, which implies the presence of a mass concentration of the order of a few 10^7 $M_\odot$ (Kormendy & Richstone 1995). The dynamics is complicated by the appearance of a double nucleus (Lauer et al 1993), and an $m = 1$ asymmetry.

5.3. Bar destruction through mass concentration

When gas is not present, a bar instability can be very robust in the stellar component, as demonstrated by N-body simulations. The spiral structure that develops at the beginning of the instability, and which transfers the angular momentum outwards to allow the bar growth, quickly disappears through heating. The bar then stays until the end of the simulations, i.e. of the order of a Hubble time. But as soon as a small fraction of gas is present, this is not true anymore. The bar can trigger its own destruction, through the gravity torques exerted on the gas. When enough mass is driven into the center (at least 5% of the mass), the bar begins to dissolve. Hasan & Norman (1990) have shown that the central mass concentration prevents the regular $x1$ orbits building the bar. In deflecting the central particles, the central mass transforms the inner orbits in chaotic ones. In other words, the central mass deepens the potential, and modifies the characteristic frequencies Ω and $\Omega - \kappa/2$: the resonance structure is lost, and the orbital distribution as well (Pfenniger & Norman 1990, Hasan et al 1993).

Although the central mass considered in models is often a black hole, in real galaxies it is more likely a massive enough decoupled nuclear disk or compact bulge. In that case, the growth of the central mass concentration is slow, and the bar destruction is likely to be a self-regulated process, based on gas accretion. Several bar episodes can successively occur in the same galaxy.

Let us follow such a process: a first strong bar instability develops in the disk; the torques due to this strong initial bar drive the gas inwards in a short timescale. This increases the central mass concentration, up to the point where the bar weakens; the bar begins to dissolve as soon as there exists two well defined ILRs in the center (due to the perpendicular $x2$ orbits between the ILRs, not supporting the bar). The bar torques weaken and the gas infall is slowed down or halted; the gas coming from the outer parts of galaxies has now time to form stars in the disk, which re-establishes the mass balance between the nucleus and the disk. The central mass concentration loses its dynamical efficiency, and a new bar can form through gravitational instability, which closes the cycle. To have several such cycles in a Hubble time requires however a substantial mass accretion, i.e. important gas reservoirs in the outer parts of galaxies (cf Pfenniger, Combes & Martinet 1994). Another possible loop of the cycle is provided by the decoupling of a second bar, as developped in the previous section.

One consequence of this feedback cycle is that in evolved bars, there are always just about 2 ILRs. The destruction of the bar first takes place in its intermediate radii. In the center, orbits remain regular, due to the axisymmetry of the dominant mass concentration (figure 7). Then comes a region of chaotic orbits, where the central mass is in competition with the bar influence: this region of the bar is destroyed. Near the end of the bar is a region still dominated by the x_1 elongated orbits. This development of chaotic orbits during the central mass growth could produce the characteristic lenses, often observed

Fig. 7. — Steps in bar destruction, according to the amount of central mass concentration. The destruction of the bar begins in its middle regions, due to the existence of chaotic orbits.

associated with barred galaxies. These orbits are bounded only by their limiting energy curve, in the rotating frame, where the potential is $\Phi(r) - 1/2\Omega^2 r^2$, so that outside corotation, there is no bound. Moreover, most orbits between CR and -4/1 resonance are stochastic (Contopoulos & Grosbol 1989). For the ensemble of chaotic orbits inside CR, the corotation region acts as a boundary. This could explain the sharp cut-off at the border of observed lenses.

5.4. Gas-dominated central disk

When the gas mass is a large fraction of the dynamical mass in the center, the violent Jeans instability prevents any bar or coherent wave formation (Shlosman & Noguchi 1993). The gas gathers into big clumps; these clumps are first trapped in almost radial orbits, lose energy through collisions and shocks and form finally a binary system, that evolves into a single object at the nucleus. Inhomogeneities in the gas heat up the stellar component, which cannot sustain any bar either. Heller & Shlosman (1994) have simulated the gas flows with or without the presence of a central black hole. The infall is accelerated by dynamical friction against the stellar component, very efficient for such big gas clumps. A mass of 10^9 $M_\odot$ can be gathered inside 100pc within 6 10^8 yr. However, the rate of infall is uncertain, since including star-formation acts as a very efficient feed-back in depositing energy, and also stops the infall in locking part of the gas in a non-dissipative component. When a black hole already sits in the center, it helps the disruption of the big gas clumps through its tidal forces.

6. ENVIRONMENTAL EFFECTS

Mergers are without doubt the most efficient starburst triggers. Observationally, the cause of the starburst appears to be the concentration of a huge gas mass in the center of the merged system. CO emission suggest that the molecular gas represents a significant part of the dynamical mass in the center (Scoville et al 1991). Non nuclear starbursts are very rare (cf the Antennae, Stanford et al 1990, Whitmore & Schweizer 1995; Arp299, Sargent & Scoville 1991; VV114 Yun et al 1994). They occur in less advanced mergers, where some star formation is enhanced both in giant complexes in the disks, and in the center.

Numerical simulations have brought much of our understanding in those systems, although many uncertainties remain about the physics of gas and star formation (see the review by Barnes & Hernquist 1992a). 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). This requires extremely strong gravity torques. We have seen that viscous torques are not able to drive the gas on such short time-scales.

6.1. Numerical codes and gas modelisation

Thanks to the increased power of modern computers, completely self-consistent simulations are now current, including the stellar and gas components. The dark matter haloes are also included self-consistently, and this is very important since the haloes participate actively in the angular momentum transfer. Barnes (1993) has shown that the dark matter component received all the angular momentum from the central parts, allowing a rapid merger of the luminous component. The deformation of the haloes also accelerates dynamical friction and the sinking of the satellites. There are however fundamental uncertainties in any simulation, since the physics and spatial distribution of most of the mass (the dark component) is unknown, and the physics of the dissipative component, the gas, is not well known either.

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. 1990a). Dissipation essentially cools down the gas clouds, and cloud collisions deviate their trajectory to form the spiral structure. But only a few collisions per rotation are necessary, and that alone will be insufficient to drive the gas inwards in a Hubble time. Once the non-axisymmetric structure is built in, gravity torques produce the gas flows. We dont 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 modeli-

sations include artificial viscosity to spread shock waves over a few resolution cells. The physics of the gas is assumed to be isothermal at 10^4K (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.

6.2. Star formation processes

A large-scale star-formation rate and an IMF are not known in every dynamical circumstance, and present simulations taking into account star formation, and the gas released by young stars, can be at best exploratory. Note that the star formation is itself fundamental for the dynamics, since it can lock the gas into the non-dissipative medium and halt for a while the mass transfer towards the center. 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 (1994a) 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).

6.3. Formation of large complexes

It has long been suggested that instabilities in the long tidal tails could form condensations of gas of masses and sizes characteristic of dwarf galaxies. Star formation has been observed in such condensations in the antennae and super-antennae (e.g. Mirabel et al 1992). Hernquist & Barnes (1994), and Elmegreen et al (1993) have shown that such condensations easily occur in N-body simulations. More generally, the ISM of interacting galaxies is likely to condense in large gaseous complexes, of say 10^8 $M_\odot$.

One of the most striking feature in interacting galaxies, is the enhanced

velocity dispersions in the gaseous component. This comes from the gravitational perturbations, that produce streaming motions, asymmetries, spiral arms, strong bars, etc.. In particular, in the molecular gas of M51, the 500pc-scale average of the dispersion is 25km/s, while it is more around 6km/s in a quiet population (Garcia-Burillo et al 1993). This has the consequence to increase the critical Jeans scale for gravitational instabilities, and to create giant complexes (e.g. Rand 1993). The global Jeans length is $\lambda \propto \sigma^2/\Sigma_g$, where σ is the velocity dispersion and Σ_g is the gas surface density of the galactic disk. The corresponding growth time is $\tau_{ff} \propto \sigma/\Sigma_g$, and the instabilities will occur as soon as $Q \propto \sigma\kappa/\Sigma_g$ becomes lower than 1. For the same ratio σ/Σ_g, a perturbed system with elevated σ and Σ_g will see the condensations of larger complexes of mass $M \propto \sigma^4/\Sigma_g$, in the same time-scale τ. These complexes with larger internal dispersions, and larger gravitational support will be less easy to disrupt through star-formation, which enhances the star-formation efficiency (Elmegreen et al 1993). The thermal Jeans length is also larger, due to the hotter gas temperature induced by the larger number of stars in the clouds, and high mass stars are favored.

This can explain the formation of giant and dense star clusters, and the presence of young globular clusters in mergers (e.g. Schweizer 1993). This interesting issue is a clue to the formation of ellipticals through mergers, since present-day ellipticals are clearly richer in globular clusters than their presumed spiral progenitors. Ashman & Zepf (1992) and Zepf & Ashman (1993) have developped a semi-analytical model where globular clusters (GC) form in the merger of two spirals, and predict the existence of several populations of GC, more centrally concentrated and metal-enriched for the more recently formed ones. This receives support from the observations of metal-enriched GC in the cD galaxies M87 and NGC1399 (Mould et al 1990, Geisler & Forte 1990), and recent discovery of young GC with HST in NGC 7252 (Schweizer & Seitzer 1993, see also Meurer, 1996), and NGC1275 (Holtzman et al 1992): the latter detected 50 bright and blue clusters in the cD of the Perseus cluster, and estimated from population synthesis models their age to 3 10^8 yrs and their mass to 10^7 $M_\odot$. These would evolve into the well-known halo globular clusters in about 15 Gyr. The uniformity of colors and derived ages supports their formation in one violent merging event. Note that the 'turbulent' conditions giving rise in a merger to new GC must be very similar to the pregalactic collapse conditions, where the first GC are supposed to be formed.

6.4. Lessons from mergers

In major mergers, where the two interacting galaxies are of comparable mass, strong non-axisymmetric forces are exerted on the gas. But contrary to what could be expected, the main torques responsible for the gas inflow are not directly due to the companion. 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 internal structure therefore takes over from the tidal perturbations on the outer parts. The gas is provided by the primary disk itself. Again it is not the gas accreted from the companion which is the main trigger for activity, until the final merger of course. 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 (see fig 8).

The effects of the geometry are more visible on the direct manifestations of the tidal interaction, i.e. on the tails and debris. For the galaxy experiencing a retrograde collision, no extended tidal tail is formed. There is no resonance effects in the target galaxy disk, and less violent material perturbations; a transient leading tidal arm is instead developped. There is however a tidally-induced two-arm density wave, and the subsequent torques produce gas inflow towards the center, as for the prograde encounter. During the interaction, it happens that the retrograde disk has more star formation than the prograde one, due to the larger gas content. For coplanar merger, the retrograde disk accretes a significant fraction of the gas from the prograde disk (Mihos & Hernquist 1996).

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. 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 minor mergers, 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 developped in the disk. The torques are much stronger towards the center; the inflow time is of the order of the rotation time-scale at each radius.

Fig. 8. — a) Evolution of the gas and young stellar components in a merger between two spiral galaxies with bulges. b) evolution of the global star formation rate as a function of time for the mergers of spirals with and without bulges; c) evolution of the total gas mass, for the same runs, from Mihos & Hernquist (1996).

6.5. Gas morphology in mergers

The HI gas is present in the outer parts of galaxies, well beyond the optical disk. There the matter is less bound to the galaxy, and is very sensitive to tidal forces, which grow as r^2. Spectacular HI tidal tails and bridges are observed in mergers. Several systems have recently been observed with high sensitivity and resolution with the VLA: M81/82 (Yun et al 1993), Arp 295, NGC 520 and the Mice (Hibbard et al 1993), NGC 7252 (Hibbard et al 1994).

It appears that the percentage of the total HI mass that is contained in the tidal tails is increasing during evolution towards the final merger stage. Only 20% of the HI is in the tidal tails in the M81 system, it amounts to 30% in Arp295, 60 to 65% in the Mice and NGC 520, and 75 % for NGC 7252 and NGC 3921, both advanced mergers. The total HI content, however, remains normal, between 10^9 and 10^{10} $M_\odot$.

Detailed simulations of the gas behaviour in mergers help to interprete these observations (Barnes & Hernquist 1992b, Hibbard & Mihos 1995). Only a fraction of the disk gas can be ejected into the tails; due to the symmetric nature of the tidal force, this fraction is at most 50%. Once launched, the tidal tails are not in free expansion, but more than 99% of the visible matter remains bound to the remnant. The bases of the tail, that are more tightly bound than the ends, turn around quickly in their orbits, and fall back towards the remnant (see fig. 9). The phenomenon is a phase wrapping of the material in the central potential that becomes more and more time independent, and approaches an elliptical. Progressively the rest of the tail will rain down, but slower and slower; for may be 20% of the tail material, this will take more than a Hubble time. This phase wrapping creates loops, shells and ripples, such as those frequently observed in merger remnants. As the HI rains down into the merger remnant, it must be tranformed into other phases, since no atomic gas is observed within the inner regions of merger (e.g. Hibbard et al 1994). These forms can be molecular gas, stars, and/or hot ionised medium (Dupraz et al 1990, Wang et al 1992). The observation of merger remnants in X-rays have not however disclosed large amounts of hot gas, the L_X/L_B ratio is much lower than in elliptical galaxies (Fabbiano & Schweizer 1995, Read et al 1995).

It appears therefore more likely that the HI gas is transformed into the molecular phase. This corresponds to the large column densities of H_2 observed towards the nuclei of merging galaxies, with millimetric interferometers. Masses up to 10^{11} $M_\odot$, i.e. 10 to 50 times the normal molecular content of a spiral galaxy, are detected in the ultra-luminous infrared galaxies (Sanders et al 1991). These high concentrations of molecular matter in the nuclei explain easily the violent nuclear starbursts: the gas density is well above the critical one for global gravitational instabilities. In the center, the molecular component can represent up to 45% of the dynamical mass (Scoville et al 1994). It is very rare to find CO extensions in maps of merging galaxies, since more than 50% of the molecular component is concentrated to the central spot (about 1.7" in Arp 220, i.e. 300pc).

Fig. 9. — The orbital structure of the tidal tails in the NGC 7252 merger remnant, from the simulations of Hibbard & Mihos (1995). a) Radial velocity as a function of radius (dash lines indicate turn-around). b) Energy as a function of radius.

Such high gas concentrations in nuclei, and the violent starburst that results, solve a long-debated problem about the elliptical formation through mergers: it was objected that the central phase-space density in the cores of ellipticals is much larger than in the spiral precursors, and that in a non-dissipative merging, the phase-space density could only decrease (e.g. Carlberg 1986). In fact, we know now that the gas density becomes a large fraction of the total density in merger nuclei, and the process is far from non-dissipative. Mihos & Hernquist (1994b) find even too strong central concentrations in simulations of disk galaxies mergers. The driving of the gas towards the center is so efficient, that subsequent star formation produces dense stellar cores in the merger remnant that are not consistent with the $r^{1/4}$ radial profile of elliptical galaxies. This is however strongly model dependent, i.e. the viscosity of the gas could be artificially enhanced in the simulations, or the star-formation law too much non-linearly dependent on local density, etc...

6.6. 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).

6.7. Ring galaxies

6.7.1. Dynamics

Ring galaxies, which have the Cartwheel as prototype, 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). Although they are rare objects, ring galaxies are an ideal laboratory to study the dynamical triggering of starburst. An impulse is given by the crossing of the plane by the companion, which gives the start of the dynamical perturbation in the gas and stellar disk, that will eventually trigger the starburst. This school-case triggering event is not perturbed by multiple tidal perturbations. The disk of the target remains in general intact, the star formation is enhanced outside the nuclear regions, in the disk. The geometry of the phenomenon is very simple, relative to messy mergers, and it is relatively easy to follow the chronology of the star formation, in the expanding ring, involving more and more gas (see e.g. Appleton & Struck-Marcell 1996).

The dynamical perturbation is a density wave that propagates outward in the target disk. In a first approximation, justified if the collision occurs at high velocity, the positions of the particles are assumed the same just before and after the collision, only each particle has acquired an inward velocity, this is the impulse approximation. The orbits of the stars can then be followed as if they performed radial epicyclic oscillation; most of the effect can be obtained through the kinematic approximation, neglecting self-gravity. Since the period of oscillation is an increasing function of radius (increasing linearly for a flat rotation curve for instance), the central particles have time to reach the center and begin to move outwards, while particles from a larger radius are still moving inwards. This will therefore build a ring of higher density where the orbits crowd, and this ring will expand as a density wave. When the central particles oscillate inward again, the same phenomenon can form a second ring, however expanding much more slowly and phase mixing soon washes out any structure (see fig. 10). The radii of the rings, their width and their spacing, and their expansion rates depend only on the mass distribution of the primary, i.e. on the rotation curve. The amplitude of the perturbation determines the amplitude of the epicyclic motions, and therefore the radial extents of the rings (or caustics) zone.

In that context, we can expect that gas will experience shocks, or in any case enhanced collisions in the crowded region of the ring-like density wave, enhancing star formation. The behaviour of gas depends strongly on its clumpy or diffuse nature; if highly fragmented with a low volume filling factor, its behaviour should approach that of the stars, and the gas will rebound outside

Fig. 10. — Kinematic model of ring wave formation, during the head-on collision of two galaxies. The lines are radial trajectories of particles as a function of time.

of the ring. On the contrary, the diffuse gas is braked, and by dissipation falls inwards.

6.7.2. "Wheels of fire"

Ring galaxies are the site of enhanced star formation. Even if they are not among the most violent starburst (> 100 $M_\odot$/yr), they reval about 10 times the star formation activity of normal galaxies. The dynamical triggering is then effective. They are among the rare objects where the starburst is non-nuclear, but occuring in the disk. In the Cartwheel, the Hα comes exclusively from the outer ring (Higdon 1995), and 80% of it comes from just one quadrant, quite asymmetrically. The recent star formation rate (Hα) 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 10^{10} $M_\odot$) is only 430 Myrs, of the same order of the ring expansion time-scale.

This prototypical behaviour is reproduced in every ring observed in the Hα survey of Marston & Appleton (1995) (except in a Seyfert galaxy): star-formation is exclusively found in the outer ring, and not in the central ring or nucleus. Within the ring, the star formation is distributed unevenly, with some privileged quarters, and in strong discrete knots. The whole ring is also traced by diffuse, broadly distributed, Hα emission. These asymmetries, and strongly preferential regions for star formation, suggest the existence of a threshold dependence on ring gas density to trigger the burst. However, this simple view does not seem to be supported by observations. The Cartwheel is in this respect exemplary: the quarter of the maximum HI density in the ring does not coincide with the quarter of maximum star formation (Higdon 1996). ([1])

([1]) A solution to this problem is to invoke large amounts of invisible H_2 gas, al-

The history of star formation has been studied within different hypotheses about the gas structure by Appleton & Struck-Marcell (1987): interesting phenomena are predicted if the ring expansion time-scale commensurates with the collision time τ_c between clouds in the galaxy disk. Star formation is strongly enhanced in the leading edge of the density wave. If a third time-scale is introduced, corresponding to the cloud collapse time, or the time-scale of the feedback cycle (τ_d) then a series of quasi periodic secondary peaks are expected, as a secondary inner ring. However, this is not observed, and predictions of the gas infall towards the nucleus are not supported by observations as well.

Completely self-gravitating models, with stars and gas have been widely developped in the 1990s, and are quite instructive about the details of gas dynamics and star formation triggering. Gravitational instabilities, mainly in the more sensitive gas component, arise in the disks in the spacing between two rings, and are wound by differential rotation: these might be the explanations of the spokes, although no gas is observed in the spokes of the Cartwheel, nor recently formed stars. Dissipation appears necessary for spoke formation in the models. The number of spokes is predicted to be $R/a = 6$ the ratio of teh radius to thickness of the ring.

The VLA HI map by Higdon (1996) does not reveal any correlation of the HI emission with the spokes. The central region including the inner ring appears devoid of gas, since there is no CO detection in this galaxy either (Horellou et al 1995). This appears in contradiction with the models, that predicts a large gas concentration in the center through dissipation (e.g. Hernquist & Weil 1993). One explanation is that there was no gas in the center at the time of the impulsion. This is not likely, however, since the lack of gas in the center is an universal feature of ring galaxies. Self-consistent models show however that the gas and stars are decoupled in their ring-like response. There exist some epochs of the simulation, where the center is completely deprived of gas, confined into an outer ring (somewhat doubled, see fig. 11), while the stars have already fallen back to the center. This could correspond to the time where rings are more conspicuous on the sky, and explain the observations. At that stage, the spokes are not well developped, but this could be an artifact of the limitations of the model (not enough particles, excess heating of the stellar component cutting off gravitational instabilities, etc...). This stage corresponds to the higher compression in the gaseous rings, and must imply the most spectacular starburst. Self-gravity in the compressed rings trigger fragmentation, and the formation of star-forming complexes (knots).

The third dimension of the simulation reveal the characteristic z-perturbations suffered by the disk (Hernquist & Weil 1993, Horellou & Combes 1994). The stellar disk is heated and thickens, while the dissipation in the gas maintains a very small thickness. After new stars have formed in the disk, this could

though no CO emission has been detected in this galaxy (cf Horellou et al 1995). The CO-to-H_2 conversion ratio could be much higher than standard in this low-metallicity object

Fig. 11. — Time evolution of the gas component of the primary galaxy in a head-on collision, from Hernquist & Weil (1993).

explain why the galactic disks remain relatively unperturbed, in spite of the frequent interactions since their formation.

6.8. Groups and clusters

6.8.1. Limited star-forming efficiency

If there is a large amount of data in favor of enhanced star-formation in interacting galaxies (see Roberto Terlevich, this summer school), the evidence in groups and clusters of triggered activity is much less abundant. Tidal interaction is however effective: distorted galaxies with asymmetries, tails and plumes are often observed in the stellar component (which cannot be due to ram-pressure), but stellar activity requires a large abundance of gas in the outer parts of galaxies, available for gas inflow, and this gas is likely to be 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.

6.8.2. Compact groups

Compact groups are small systems composed of 4 to 6 galaxies tightly packed on the sky, isolated from other galaxy clusters. Since their internal velocity dispersion is of the same order as the rotational velocity inside an individual galaxy ($\approx$ 200km/s), tidal interactions are expected to be quite efficient. Their small size ($\approx$ 40kpc) and their density ensure frequent galaxy encounters, and they appear as ideal laboratories to study the effect of environment on galaxy evolution. The sample of Hickson compact groups (HCG) has been widely studied at all wavelengths. Their reality as physical groups was questioned (e.g. Mamon 1986), since their merging time shoud be much shorter than a Hubble time. But the observations of tidal tails and deformations of the galaxies in the group has been advanced as an evidence for the existence, instead of a chance alignment (Mendes de Oliveira & Hickson 1994). 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 & Rood 1987, 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. Pildis et al (1995) show that there is a correlation between extended X-ray emission and low spiral fraction in compact groups. Contrary to binary galaxies, where CO emission is enhanced (Combes et al 1994), there is no evidence of higher molecular gas content in most HCG galaxies (Leon et al 1996, Boselli et al 1996). Therefore, although there exist some obvious signs of interaction, those indicate limited efficiency (there is no merging), and limited star-formation triggering. One interpretation could be that frequent and repeated close tidal interactions, on time-scale short with respect to the

usual dynamical friction time ($\sim$ 1 Gyr) has for main consequence to strip galaxies from their gas, which is heated to the virial temperature of the group system. The gas, extended and diffuse, and hot enough to emit in X-rays, does not participate to the dissipation and braking of galaxies, nor to the star-formation in individual galaxies.

Another possibility is that compact groups are compact only in projection, that they are filaments structures seen edge-on. Pildis et al (1996) propose a scenario of formation of compact groups, within the CDM model ($\Omega = 1$, $\Omega_b = 0.1$). Groups form along filaments of matter, and become compact only in the final 20% of the simulation. They contain X-ray emitting gas well before becoming compact. However, their end-state at $z = 0$ are more gas-rich, and have an X-ray temperature 3 times too low compared with observations.

6.9. Rich clusters

6.9.1. HI-deficiency

It has been claimed about two decades ago (Davies & Lewis 1973), and further established (Chamaraux et al 1986) that spiral galaxies in Virgo are actually HI deficient with respect to field galaxies. Cayatte et al (1990) show that the deficiency is a function of distance from the center (M87). CO emission does not seem to follow this trend, and is not depleted in Virgo spirals (Kenney & Young 1989). This can be understood since CO emission comes only from the central parts of galaxies (the optical disk), probably due to radial metallicity gradients. Tidal stripping occurs only in the outer parts, outside the optical disk. The tidal forces increase as r^2 with the distance to the galaxy center, and the gas in the outer parts is much less gravitationnally bound to the disk.

As far as star-formation is concerned, rich clusters are not very peculiar, the star-forming activity of their remaining spirals follows the CO content (Boselli et al 1995). In Virgo, there is even evidence that the global star formation rates have been reduced (Kennicutt 1983). There exists however some distorted galaxies with evidence of enhanced star formation (Cayatte et al 1990): the triggering is likely to be due to normal tidal interaction, since these galaxies are binaries. Here the effects of stripping are much more important, and the remaining spirals could only be due to galaxies that have entered the cluster recently.

Since the HI deficiency in clusters is related to the amount and density of hot X-ray gas detected, it has been proposed that the main cause of stripping is ram-pressure or thermal evaporation. The geometry of the HI deficiency, where all gas-rich galaxies are confined in the border of the cluster, supports this idea. However, the competing effects of tidal stripping and ram-pressure cannot be disentangled, since they both occur preferentially in the cluster center. Moreover, the existence of the hot gas itself could come from the tidal stripping of neutral gas from galaxies: the two processes are intimately related. Some clues to the non-predominance of ram-pressure is the stripping of the clumpy molecu-

lar gas (Combes et al 1988), the existence of many gas rich dwarf galaxies, only moderately HI-deficient, in Virgo (Hoffman et al 1988). Gavazzi & Jaffe (1987) find that the Coma Supercluster spirals tend to have stronger radio-continuum emission, and they identified three cases of distorted galaxies, good candidates for an ICM-ISM interaction. However, the red and NIR images of these galaxies are also distorted. It is difficult to know whether this comes from the old stellar disk (in that case the galaxies are tidally distorted), or whether recent star formation in the ICM-distorted gas could account for the data (Boselli et al 1994). It has been proposed that the first encounter of the intra-cluster gas by a galaxy entering the cluster could enhance star-formation in its disk, by the shock-waves produced. The supposed over-pressure exerted on the HI gas could compress them to form molecular clouds, site of star formation. However the ICM pressure, even in the center of the Coma cluster, is only comparable to the internal pressure of a normal ISM (see e.g. Kenney 1990).

6.9.2. Harassment and evolution

The accumulation of frequent high-speed close encounters, dubbed "harassment" by Moore et al (1996a), 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. But this is not a strong argument, given the morphological segregation: only early-type galaxies (ellipticals, or lenticulars with large bulges) survive in the center, and they are not sensitive to tidal perturbations.

It is instructive to compute the order of magnitude of the two effects: tidal interactions between two galaxies are important, as soon as their relative distance is of the order of their diameters. For galaxies located at the periphery, the ratios of tidal forces from the nearby companions and from the cluster is proportional to the ratio of masses ($\sim$ 100), divided by the cube of the distances ($\sim$ 1000). Two-galaxies interactions will dominate at the periphery, but not in the center. This is only an indication, since the number of penetrating collisions, more frequent in the center, has not been estimated. The collision time is of the order of $t = (n\sigma v)^{-1} \sim 1Gyr$, with a density of galaxies of n= 100 Mpc^{-3}, and a velocity dispersion of v=1000km/s.

Stripping due to the global tides of the cluster can be estimated through the tidal radius r_T (cf Merritt 1984): near the core radius of the cluster r_c, $r_T/r_c \approx 0.5 v_g/v_c$ where v_g and v_c are respectively the velocity dispersions of a galaxy and the cluster. This gives an order of magnitude of 15kpc for r_T in a typical rich cluster of v_c = 1000km/s.

Harassment is so efficient that it is possible to account for the rapid galaxy

evolution in rich clusters (Moore et al 1996a): 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. However, the whole picture is made uncertain by our missing knowledge of the gas dynamics, and the repartition of the dark matter: either bound to each galaxy, or diffuse and bound to the cluster globally. The "overmerging" problem faced in dissipationless N-body simulations could be cured by the consideration of the gas component (Moore et al 1996b).

7. GALAXY EVOLUTION

7.1. Evolution along the Hubble sequence

The Hubble sequence is morphological and determined by some main physical parameters:

1- the bulge-to-disk luminosity ratio increases from late to early type spiral galaxies. Given the similar mass-to-light ratios for both components, this means that the mass concentration increases from Sc to S0. If there is an evolution along the sequence, it can only be from late to early, since the mass concentration is irreversible.

2- the total visible mass increases also from late to early types. This confirms the sense of evolution.

3- the percentage of gas mass decreases from Irr and Sc to S0 and E. This had been already noticed by Hubble (1926) and Sandage (1961), due to the patchy aspect of late-types, with a lot of dust. HI observations demonstrate clearly the progression of gas mass fraction along the sequence, while the situation is not so clear for the molecular gas component. The CO emission is not varying as much as the HI emission along the sequence (Young & Scoville 1991), but this could be a metallicity effect, the CO emission being depleted in late-type galaxies.

4- the percentage of dark matter decreases from Sc to Sa. This is known from recent results of HI rotation curves in early-type galaxies. These galaxies possess much less gas, and more sensitive studies are necessary to actually sample the rotation curves in the outer parts. Casertano & van Gorkom (1991) and Broeils (1992) have established that the rotation curves of early-type galaxies tend to fall at large distance from the center, while rotation curves are still rising for very late galaxies (see also the compilation by Persic et al 1996). There is a clear evidence of decreasing dark-to-visible mass ratio along the Hubble sequence.

5- A secondary morphological parameter noted by Hubble is the pitch angle of the spiral: early-types tend to be more wound, and late-types more open. This is only a consequence of mass concentration, and bulge-to-disk mass ratio. Early-types have a much larger epicyclic frequency for a given disk, and their Q parameter is higher. They are less violently unstable with respect to spirals,

and their pitch angle is smaller. The critical wavelength is $\lambda_c \propto \Sigma/\kappa^2$ (cf section 1), which also points towards smaller wavelengths for early types.

We know that bars and spiral waves can transfer angular momentum, and cause mass concentration 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, from late to early types. 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).

Recent large galaxy surveys in the near-infrared band has slightly modified and clarified the criteria of Hubble sequence. These surveys are less affected by dust extinction, which blurs the classification. de Jong (1996) and Courteau et al (1996) claim that the bulge mass is a better criterion than the bulge-to-disk ratio to define the sequence. The total mass is also a fundamental parameter (e.g. Gavazzi et al 1996). Courteau et al (1996) see moreover a constant ratio between the characteristic scales of bulge and disks ($r_b/r_d \approx 0.1$); according to these authors, this supports theories of bulge formation through a secular evolution from the disks (e.g. Pfenniger & Norman 1990). Andredakis et al (1995) emphasize that the bulge morphology evolves continuously from late to early types, from an exponential radial distribution to a de Vaucouleurs $r^{1/4}$ profile. The smooth sequence observed for bulges along the Hubble sequence suggests a single mechanism for bulge formation.

Alternatively, there could be two main processes contributing to bulge formation. First, strong bar instabilities in late-type systems can be the cause of box- or peanut-shapesd bulges, due to vertical Lindblad resonances (Combes et al 1990b). This secular evolution can form small bulges, of exponential profiles essentially. Second, minor mergers, or the accretion of a small companion may form bigger bulges, of de Vaucouleurs profiles (Pfenniger 1991). These processes are cumulative along the evolution.

7.2. Fragility of disks

The main argument against frequent interactions in a galaxy life, or formation of the bulge through minor mergers, is that galaxy interactions can easily thicken or even destroy a stellar disk (e.g. Gunn 1987). Vestiges of interactions, such as ripples, plumes, shells (e.g. Schweizer 1990) do witness some interactions, but those must have been occured in the past, before the formation of the disks. 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 Ω. They claim for instance that the Milky Way disk have accreted less than 4% of its mass within the last 5 10^9 yrs. Numerical simulations have tried to quantify the thickening effect (Quinn et al 1993, Walker et al 1995). 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.

Since the efficiency of disk thickening is not yet settled, it is interesting to check observationally the influence of tidal interactions on the disk thickness of galaxies. In a sample of 31 edge-on galaxies, out of which 24 were interacting, B, V and I photometry has been analysed, to tackle particularly this problem (Reshetnikov & Combes 1996). It was found that the ratio h/z_0 of the radial disk scalelength h to the scaleheight z_0 is indeed 1.5 to 2 times lower for interacting galaxies than for a normal sample. While the h/z_0 ratio is 11 for late-type galaxies, and 5.2 at minimum for large galaxies in a control sample (Bottema 1993), it is 2.9 in average in tidally interacting galaxies. This comes both from an increase of z_0 and a slight decrease of h through stripping. This is in good agreement with simulations.

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 several tens of percents 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. Since the stellar component alone cannot cool down, this can only be the result of gas accretion. Such an accretion is possible from the huge HI reservoirs that late-type galaxies possess in their outer parts. This gas is driven inwards by gravity torques during a tidal interaction (Braine & Combes 1993). The accretion also produce a deeper potential well in the plane, and the stellar component will react with a slightly reduced thickness; the main effect will be the formation of young stars, in a much thinner disk. The signature of past interacting events can thus be found in the existence of thick disks (cf Burstein 1979). In the Milky Way, the thick disk has been widely studied (e.g. Robin et al 1996). We can note that the low value of h/z_0 in our Galaxy is a sign that it is still presently interacting.

7.3. Evolution at high redshift

High resolution imaging with HST have recently allowed to study galaxy morphology at intermediate redshift ($0.1 \leq z \leq 1.0$), and often revealed tidal features, distorted morphologies indicative of interactions and mergers. To interprete these data, we must be aware that the detectability of tidal features is reduced at high redshift (Mihos 1995). Tidal tails and bridges rapidly disperse, and fall below the surface density limit for detection. The debris and signatures of mergers become invisible after 1 Gyr for z=0.4 and after 0.2 Gyr only at z=1. This leads to underestimating the influence of tidal interactions in objects displaying spectroscopic signatures of starbursts. For instance, E+A galaxies could be in fact merger remnants.

From high-resolution images of a cluster at z=0.4, Dressler et al (1994) suggest that the excess blue galaxies seen in distant clusters are predomi-

nantly normal late-type spirals, undergoing tidal interactions or mergers. The Butcher-Oemler effet, associated with enhanced star-forming activity appears now convincingly to be due to enhanced interactions, arising from the hierarchical merging of clusters. 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), and galaxy interactions were undoubtedly more frequent at high z.

At very high redshift (z $\approx$ 2-3), HST images have revealed a population of faint, small, compact objects, that were identified to the sub-galactic clumps, or building blocks of present day galaxies through multiple merging processes (Pascarelle et al 1996, Steidel et al 1996). However, caution must be used to interprete 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, the fact that barred and grand design galaxies appear under-represented in distant deep field samples, while early-types are not (van den Bergh et al 1996) could be only an artifact of the non-detectability of disks. At very high redshifts, only the high surface density objects, such as bulges and ellipticals, can be detected.

In spite of all these biases underestimating the influence of interactions, many studies have put forward evidence for an increasing merger rate with redshift, as $(1+z)^m$ with $m = 2-3$ (e.g. Yee & Ellingson 1995). Lavery et al (1996) claim that ring galaxies are even more rapidly evolving, with $m = 4-5$, although statistics are still insufficient. Evolution at high redshift is a rapidly growing field, but results are not yet settled on very firm grounds.

8. GAS AND DARK MATTER

The possibility that there exists large amounts of gas in the Universe, up to reach the closure density, has been considered mainly in the 1960's (see the review by Peebles, 1971). The hypothesis was rejected, since the gas was assumed homogeneous, and self-gravity was ignored. For an homogeneous gas, the Gunn-Peterson test applies, i.e. absorption lines accumulate along the line of sight in front of a remote continuum source such as a quasar, and we should detect a trough of absorption for redshifts lower than the quasar redshift. The results of the tests at many wavelengths constrain the density of any intergalactic gas several orders of magnitude below the closure density. However, the test is not valid for a clumpy medium, where the filling factor is very small. Most of the time, the line of sight will be empty, except some lines of sight where the absorption will be highly optically thick.

The hypothesis that cold gas could be in fact the dark matter has been reconsidered only recently, when it was realised that the fundamental state of the cold self-gravitating gas is not homogeneous, but a hierarchical structure of dense clouds, permanently gravitationally unstable, very similar to the fractal

structure of the detected interstellar medium (Pfenniger et al 1994). Several models were developped, considering the cold gas either in the halo, associated with clusters of Machos (de Paolis et al 1995, Gerhard & Silk 1996), or confined to a self-gravitating disk (Pfenniger & Combes 1994). In the latter model, dark matter around galaxies is made of basic "clumpuscules" of molecular hydrogen, of a Jupiter mass (10^{-3} $M_\odot$), but with a much smaller density than brown dwarfs, with $10^{9-10}\,cm^{-3}$ and radius of ≈ 20 AU. All along the hierarchy, structures are unstable gravitationally, permanently coalescing and fragmenting in the isothermal regime. The clumpuscules are self-gravitating, statistically in equilibrium with pressure forces, at the limit of the adiabatic regime, since then the radiation transfer time equals the dynamical time. They compose the smallest scale of a hierarchical structure, that ranges over six orders of magnitude, up to giant molecular clouds of 100 pc; above this scale, bigger gaseous complexes are torn apart by galactic shear. The ensemble of clumpuscules is in quasi isothermal equilibrium with the bath of photons of the cosmic background radiation at $T = 2.73\,K(1+z)$. Due to the fractal structure (of dimension $D < 2$), the clumpuscules collide together frequently, with, for such fractal dimension, a rate of the order of the cooling-heating and dynamical times. The condensed structure resembles closely the well-studied ISM gas, already known as a $D < 2$ fractal-like structure over several orders of magnitude in scale (Larson 1981; Scalo 1985; Falgarone et al. 1992). The main difference is that star-formation in the visible disk has metal-enriched the medium that can then cool down much faster, and the heating sources have partly destroyed the condensed fractal and formed a diffuse intercloud medium.

In galaxy outskirts, the condensed H_2 phase is almost only in contact with the intergalactic radiation field, which photodissociates a small fraction of it into HI gas, because at the envisaged column densities ($\sim 10^{25}\,cm^{-2}$) H_2 can self-shield easily. From this point of view, the atomic gas in the outer parts serves as a tracer of dark matter. This easily explains why, observationally, the gas and dark matter appears to be intimately related. From the flat rotation curves, the surface density of dark matter Σ_{DM} varies asymptotically as r^{-1}, and as well the HI surface density Σ_{HI}. Bosma (1981) was the first to notice a constant ratio of Σ_{DM}/Σ_{HI} as a function of radius in spirals, which has been confirmed by many authors (Sancisi & van Albada 1987; Puche et al. 1990), and varies between 10 and 20 according to the morphological type (Broeils 1992, Carignan 1996).

The hypothesis of cold gas as dark matter helps also to explain the evolution of the Hubble sequence (and in particular the decreasing dark-to-luminous mass ratio along the evolution, cf above), the overabundance of gas in interacting galaxies (Braine & Combes 1993), and also the presence of huge amounts of hot gas in clusters.

8.1. Hot gas in rich clusters

The larger sensitivity of the ROSAT satellite, that allowed to detect the hot gas in the outer parts of clusters, and its spatial resolution, from which the temperature as a function of radius $T(r)$ was obtained, have considerably changed our physical view of clusters. David, Jones and Forman (1995) summarize the results, and emphasize that some of the previously dubbed dark matter is now seen as hot gas. The mass of the hot gas is increasing with scale, and reaches 30% of the total mass, including the remaining dark matter. This leads to the so-called baryon catastrophy, since the baryon fraction in rich clusters is representative of the baryon fraction in the Universe; in other words, the dark matter cannot be segregated outside of clusters (White et al 1993). This high baryon fraction (30%) is incompatible with $\Omega = 1$ given the constraints of primordial nucleosynthesis ($\Omega_b < 0.1$).

David et al (1995) show that the mass-to-light ratio is not increasing with scale, as was previously believed, but remains of the order of 100-150 on scale 10^{12} $M_\odot$ to 10^{15} $M_\odot$. They compare the mass of hot gas around a giant elliptical, in loose groups, clusters, and rich clusters. The gas mass fraction increases from 2 to 30%. The radial distribution of hot gas reveals a flatter distribution than for the other visible mass, and even the dark matter. The hot gas could be only a tracer of a multiphase medium, with even more mass in a cold gas phase (Ferland et al 1994, Pfenniger & Combes 1994).

These new results reveal a striking phenomenon: the dark matter is more important relatively at galaxy scale than at cluster scale (see figure 12). In other words, some of the dark matter becomes visible as hot gas when galaxies belong to rich clusters, or when large-scale structures virialize and relax gravitationally. It has been proposed that feedback from galaxy formation can reheat the intergalactic medium, and especially galactic winds can produce the flatter gas distribution relative to the gravitating mass observed. Alternatively, galaxy interactions and tidal stripping could produce the hot gas from the cold gas reservoirs present around spiral galaxies in large amounts (Pfenniger et al 1994).

8.2. Self-gravity and fractal structure of the ISM

The hypothesis of cold gas as dark matter is based on the existence of a fractal structure for the molecular clouds, in isothermal equilibrium with the cosmic background radiation. If we consider the outer parts of galaxies, devoid of any heating and star formation, we can consider the gas only submitted to its own gravity. The theory of such a medium has not yet been established. We are presently trying to built such a theory, which will explain why the medium has to form a fractal structure, and to predict what is the Haussdorf dimension d_H of the fractal (de Vega, Sanchez & Combes, 1996). The underlying idea is that the fractal is build through recursive Jeans instability and fragmentation. In an isothermal context, the gas has the tendency to collapse and follow an

Fig. 12. — Ratio of total gravitating mass-to-luminous mass (gas plus stars) as a function of the total gravitating mass, for various systems and scales, from a single galaxy to rich clusters (David et al 1995).

isothermal sphere, but as soon as the density contrast reaches a critical value, fragmentation occurs: the large-scale structure fragments in clouds, for which the same collapse instability applies. This recursive fragmentation proceeds until the density is high enough to reach the adiabatic regime. Therefore, self-gravity alone could be the origin of the fractal, with generated turbulent motions in virial equilibrium at each scale.

We have developped the grand partition function of an ensemble of particles, interacting only through their own gravity, and in equilibrium at a given temperature T. The number of particles N is allowed to vary, keeping the gravito-chemical potential μ constant. In transforming the partition function through a functional integral, it can be shown that the system is exactly equivalent to a scalar field theory. The theory does not diverge, since the system is considered only between two scale limits: the short-scale cut-off (the size of the smallest fragments, or clumpuscules), and the large-scale limit (the largest self-gravitating entities, or GMCs). We demonstrate through a perturbative approach that the system has a critical behaviour, for any parameter (effective temperature and density). That is, we can consider the self-gravitating gaseous medium as correlated at any scale, as for the critical points phenomena in phase

transitions.

Since scaling behaviours are the best studied through renormalisation group theory, we use these methods to derive by analogy the critical exponents of the system. It is shown that the critical exponent ν of the correlation length can be identified with the inverse Haussdorf dimension $d_H = 1/\nu$. The long distance critical behaviour must then be governed either by the Ising fixed point, for which $\nu = 0.63$, or the mean field point ($\nu = 0.5$). Both fixed points give a fractal dimension compatible with observations. It is well known that there exists only two independant critical exponents: the second one concerns the potential, and this theory makes some specific predictions, that could be checked through gravitational lenses observations in front of remote sources.

This study shows that self-gravity can account alone for the fractal structure of a self-gravitating isothermal medium. It is well known that fixed points are quite robust with respect to perturbations, and we can hope that this generalises to the interstellar medium, provided that it is not too much perturbed by star formation. The latter heats the medium and destroys progressively the fractal and condensed structure to the benefit of the diffuse phase.

9. CONCLUSION

The high level of star formation found in starbursts (10-100 times the normal rate), is almost always due to a dynamical triggering. Galaxy interactions are the main agent to de-stabilise gravitationally a galaxy, and trigger the development of spiral and bar waves. These non-axisymmetric perturbations produce gravity torques, that transfer the gas inwards, and agitate the medium with the consequence to elevate the velocity dispersion. When the interacting galaxies are bound, they merge rapidly through dynamical friction: galaxy collisions are highly inelastic, and the relative orbital energy is dissipated in galaxy deformations and heating. Star formation is then more efficient, since these perturbations produce gas accumulations and piling up towards the center, and the star formation rate is non-linear with density (global Schmidt law, due to cloud-cloud collisions, gravitational instabilities, etc..). A starburst is obtained when the gas inflow is provided on time-scales shorter than the feedback processes of star formation (supernovae, stellar winds, bipolar flows..). This occurs for strong enough perturbations, tidal interactions and subsequent bars.

Processes triggering star-formation are not yet known in details: criteria for gravitational instabilities just control the cloud formation, but interstellar clouds can be quiescent even when unstable to fragmentation and small-scale structure formation. Certainly the final criterion is dynamic (and not static) and must take into account the energy liberated in the first stars formed.

Galaxy evolution therefore depends strongly on the environment. Dynamical interactions and subsequent evolution make galaxies more concentrated, with higher surface densities. Low surface density galaxies (such as Malin I types) are always found in poor environments; they have not suffered many galaxy

interactions, which has slowed down their evolution. They might represent a state close to primeval galaxies.

It is well known that non-axisymmetries like spirals and bars transfer angular momentum, and produce central mass concentrations. Since these non-axisymmetries are observed in most disk galaxies today, the evolution along the Hubble sequence, from late to early types, must be very rapid, on time-scales shorter than the Hubble time. A bar can be destroyed through mass concentration, but another one might be reformed later, provided that the galaxy has accreted enough fresh gas. The evolution could then be punctuated by several interacting events, triggering the formation of bars. To understand why galaxies have still some gas today, and their disks are not all very thick due to interactions, the accretion of large amounts of gas must be invoked during evolution. A possibility is that dark baryons exist under the form of cold gas in the outer parts of galaxies. This gas will be heated through galaxy collisions in clusters, and account for the huge amounts of hot gas observed there through X-rays.

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