Mixing and Transfer of Elements by Interactions and Mergers

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Abstract. Galaxy interactions produce strong torques that generate radial gas flows. There are two opposite tendencies of these flows, regarding abundance gradients: homogeneization and gradient flattening, and enhanced star formation in the center, and gradient steepening. Mechanisms to create abundance gradients are discussed, and comparison with observations is detailed, concerning spirals (such as collisional rings, starbursts..) or ellipticals (formed or not in mergers). A review of N-body simulations predictions, taken into account star formation, is also presented.

1. Introduction

In the mixing and transfer of elements, gas and stars have completely different roles. The stellar component is not dissipative, and its density in phase space cannot increase, so that dynamical events like interactions or mergers tend to homogeneize the system towards a well-mixed state. On the contrary, gas dissipates energy through radiation, can concentrate with large proportions towards the nuclei, and trigger starbursts; since the star formation rate is not linear with gas density, this tends to re-build abundance gradients. Therefore, we have to consider these two opposite behaviours in the dynamics of interactions of galaxies and mergers.

2. Mechanisms to create abundance gradients

Exponential abundance gradients are generally observed in spiral galaxy disks. The explanation is strongly linked to the building of an exponential radial distribution of the density. If the latter is obtained through dynamical processes, then the abundance gradient will follow from the fact that the star formation is a non-linear function of gas density (e.g. the Schmidt law, where the SF rate is $\propto \rho_g^n$, with $n > 1$).

2.1. Theory of viscous disks

It is now well known in the theory of viscous accretion disks that the main effects of viscosity is to move angular-momentum outward and mass inward. In the particular hypothesis of equal time-scales between viscosity and star formation, i.e. $\tau_\nu \sim \tau_*$, it can be shown that the final surface density of the stellar disk
Gravitational instabilities regulate the transfer of angular momentum, through a feedback process, so that we can talk of "gravitational viscosity": in the first step, the disk is cold \( Q < 1 \), and therefore unstable to spiral waves; second, the disk has developed waves, that create non-axisymmetry and gravity torques, that transfer the angular momentum outwards (trailing waves). The waves heat the disk, until \( Q \approx 1 \). Then a disk with only a stellar component will remain stable, while a gaseous disk can cool back to step 1.

2.2. Gravity torques

What is the nature of the viscosity, effective in galactic disks? Normal viscosity is not efficient, due to the very low density of the gas. One could think of macroturbulent viscosity, but the time-scales are longer than the Hubble time at large radii, and could be effective only inside the central 1kpc. Instead, if the galaxy disks develop non-axisymmetric density waves such as spirals or bars, gravity torques are then very effective at transferring the angular momentum outward. This led Lin & Pringle (19987b) to propose a prescription for an effective kinematic viscosity for self-gravitating disk undergoing gravitational instabilities.

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

Why should there be approximate agreement between the two time-scales, viscosity and star-formation? This comes from the fact that the two processes depend exactly on the same physical mechanism, i.e. gravitational instabilities. As shown empirically by Kennicutt (1989), the Toomre parameter $Q$ appears to control star-formation in spiral disks. Therefore, if the regulating instabilities have time to develop, one can expect that $\tau_v \sim \tau_*$, as required for exponential light and metallicity distribution.

This balance could however be broken in two cases:

- either the gas flows are too rapid with respect to star-formation; this can occur in the case of a strong bar instability just settling. We have then $\tau_v << \tau_*$, and the abundance gradients are smoothed out (Friedli & Benz 1995, Friedli et al 1994, Martin & Roy 1994, 1995).

- or a starburst is triggered, which makes $\tau_*$ small again, and the gradients are enhanced; the competition between enhanced star formation and gas flows has been studied by Edmunds & Greenhow (1995).

### 3. Observations

#### 3.1. Interacting galaxies

There is a category of interacting galaxies where the dynamics and star formation processes should be very simple, and therefore easy to interpret and quantify, they are the collisional ring galaxies, which prototype is the Cartwheel (e.g. Appleton & Struck-Marcell 1996). It is expected that a burst of star formation occurs at the passage of the ring wave across the disk, and strong color gradients are indeed observed across the ring. In the Cartwheel, the H$\alpha$ comes exclusively from the outer ring (Higdon 1995), and 80% of it comes from just one quadrant, quite asymmetrically. However, the quarter of the maximum HI density in the ring does not coincide with the quarter of maximum star formation (Higdon 1996). A solution to this problem is to invoke large amounts of invisible H$_2$ gas, although 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. Simulations have been carried out (e.g. Hernquist & Weil 1993), but they predict concentrations of gas in the spokes and in the center, that are not observed. The collisional ring galaxies are in fact much more complex systems than they first appear.

Another interesting case is that of polar ring galaxies, where a large amount of gas has been accreted during an interaction. The event is old enough that old stars are observed now in the accreted gas disk. In fact, the accreted system displays normal abundances for spiral disks (Eskridge & Pogge 1997), and appears to be very stable and long-lived, possibly because of the triaxial structure (Peletier et al 1993). Dynamical models of polar rings reveal that the rings are very massive, and even could be the more massive system (Combes & Arnaboldi 1996, Arnaboldi et al 1997). This made Schweizer (1997) to suggest that the
accreted system is the central lenticular (it would be a “failed” bulge). This is unlikely however, since in a merging the stellar component is heated and dispersed all around, while only the gas can cool down and settle in a perpendicular disk. There could not have been two gaseous disks in the interaction, since they would then have settled in a single disk.

3.2. Mergers

The merging event can provide one of the most extreme mixing of matter and elements, while triggering a violent relaxation. Starbursts are often associated with mergers, and will contribute to enhance gradients, since a huge amount of gas is piling up in the center. But in the same time long gaseous tidal tails are dragged away. The extent to which gas can be splashed over is spectacular in many systems: M81/M82 (Yun et al 1993), NGC7252 (Hibbard et al 1994), Arp295, NGC520, the Mice (Hibbard 1995). Figure 2 is showing how the fraction of HI gas in the tails increases along a merging sequence. In fact, most of this gas remains bound to the merged system, and already some of the bases of the tails are turning back towards the center. This is done through a phase-wrapping process, and shells and ripples are formed. Since the HI gas is more and more present in the tails at more advanced stages, it appears to have little influence on mixing and abundance gradients. The time-scale to return is a significant fraction of the Hubble time. On the contrary, huge molecular concentrations are observed through the CO lines in mergers, sometimes up to 50% of the dynamical mass in the center (Scoville et al 1994). In general, there is much more CO emission in interacting galaxies, and it is more concentrated (e.g. Braine & Combes 1993). The main result is certainly to rebuild abundance gradients in the merging system, which will become an early-type or elliptical.

Abundances can be determined in the molecular medium through trace molecules such as CO, CS, CN, HCN, HNC, HCO$^+$ and their isotopes (e.g. Henkel & Mauersberger 1993). Nuclei of starburst galaxies reveal anomalous isotopic ratios, in particular $^{12}$C and $^{18}$O are enhanced. Since high mass stars transform $^{14}$N in $^{18}$O, this has been interpreted through an IMF favoring high mass stars in starbursts (e.g. Doyon et al 1994). As a frequent feature of mergers, the $^{13}$CO/$^{12}$CO ratio is observed to be 4-5 times the usual one in disks (Aalto et al 1991). This can be explained by infall of fresh gas, which is not enriched in the secondary element $^{13}$C (Casoli Dupraz & Combes 1992).

3.3. Ellipticals: results of mergers?

Abundance gradients are generally observed also in elliptical galaxies (cf Worthey, O’Connell, this meeting). The interpretation of the observations in terms of stellar populations and ages encounter many difficulties and ambiguities: age-metallicity degeneracy, dust reddening. Line indices Mg2, Fe, H$\beta$ can provide more information through theoretical diagrams (Worthey et al 1994). These indicate that ellipticals are old in general (13-15 Gyrs), but with very different histories of star formation. The duration of the star formation period appears inversely proportional to the velocity dispersion (Bressan et al 1996). There might be a dichotomy between spheroids and ellipticals (Gorgas et al 1997).

Vazdekis et al (1997), studying 20 absorption lines, find good fits for both models: either a single-age single-metallicity model or a full chemical evolution-
Figure 2. Fraction of light and atomic gas contained within the inner regions of systems along a merging sequence. Systems at left are beginning their interaction, while at right they are merged (NGC 7252). The fraction of the HI gas remaining in the center drops drastically in the merging process, while the gas is dragged out in tidal tails (from Hibbard 1995).

Contrary to what could be expected a priori for merged systems with a lot of mixing, it is quite easy to form abundance gradients in elliptical galaxies, even with dissipationless collapse (Stiavelli & Matteucci 1991). The de Vaucouleurs light profile in $r^{1/4}$ is obtained if ellipticals are formed rapidly through collapse of clumps (van Albada 1982, Aguilar & Merritt 1990). Abundance gradients build in when considering star formation in the clumpy gas to be extended in time, though fast (but not instantaneous, as oversimplified). The presence of dark matter (at least half of the total mass), helps the collapse of the gas to produce abundance gradients. The effect of dark matter (DM) is that galactic winds occur much later to prevent star formation. In the absence of DM, a greater amount of dissipation is required to obtain the same gradients (Stiavelli & Matteucci 1991). However, in dissipative models, it is concluded that DM reduce the agreement with observations (e.g. Carlberg 1984). The gas must be self-gravitating, to obtain velocity anisotropy (no DM necessary, or less than half the mass). Models reproduce the observed relation between metal abundance and mass (or $\sigma$). The gas physics has an effect only for low mass galaxies that
are not dominated by gravity. Under the effects of gas pressure, the system tends to be more isotropic.

Elliptical systems have in general low rotation, and radial orbits tend to wash out the gradients. However, isochromes are smoothed out later than isophotes. More than 20 crossing times are necessary to mix stars born at different epochs. Even if the gas is efficiently smoothed (i.e. all stars born at the same time have the same metallicity), the abundance gradients can come from spatial segregation of the various stellar generations (Stiavelli & Matteucci 1991). Young and high-Z stars form in more collapsed and compact gas in the center, such that isochromes are more flattened than isophotes.

4. N-body simulations

Simulations help to understand the mixing effects of galaxy interactions. In fact, they show that the violent relaxation is never complete, so that the pre-existing abundance gradients in the merging spirals remain (Mihos & Hernquist 1994b). Moreover, abundance gradients are enhanced through violent starbursts.

4.1. Modelisation of the star formation

The star formation rate and IMF are not well known, especially in perturbed circumstances, therefore this modelisation is at best exploratory. Taking into account the star formation is however essential for the dynamics: there is energy released in the gas, some gas mass locked up into the dissipationless component, which slows down the inward mass flow. In the literature, the star formation rate has been derived from cloud-cloud collisions (Noguchi & Ishibashi 1986), or more generally from the empirical Schmidt law (Mihos et al 1992), with an exponent $n \sim 1.5-2$, i.e. a non-linear law with density. In every cases, tidal interaction and mergers increase the SFR transiently by an order of magnitude, because of the concentration of the gas mass in small regions. The efficiency strongly depends on the exponent $n$ of the Schmidt law. Simulations have not enough dynamical range to deal properly with star formation (a single particle is of the order of $10^6 \, M_\odot$), and simple recipes have been adopted to transform gas in stars and reciprocally (Mihos & Hernquist 1994a): the same particles are X% stars and (1-X)% gas for instance. This couples young stars and gas kinematics artificially, and also inhibits contagious star formation, or feedback mechanisms (Struck-Marcell & Scalo 1987).

4.2. Gas flow and starburst triggering

In major merger simulations, strong non-axisymmetric forces are exerted on the gas. The main torques responsible for the gas flow are not directly due to the companion, but to the tidally-triggered perturbations on the primary disk: bars, spirals. Self-gravity plays the essential role: internal perturbations are generated on the primary gas disk (the gas accreted from the companion is not predominant). The essential parameter is the bulge-to-disk ratio in the primary, regulating the instabilities (Mihos & Hernquist 1996). With large-bulge galaxies, instabilities are delayed, and the interaction ends with a strong starburst. In small-bulge galaxies, there is continuous activity, weaker at the end when the gas
has been consumed up. The geometry of the encounter has only minor effects (external manifestations such as tails, debris). Globally about 75% of the gas is consumed during the merger. The tidal tails gas will rain down, in 1 Gyr scale, but in the outer parts essentially.

5. Conclusion

Paradoxically, the mixing is not predominant in interactions and mergers. On the contrary abundance gradients are enhanced in such events, because of gas concentration and starburst, except for very rare cases of mergers of pure stellar systems.

We have shown that the angular momentum is transferred essentially through gravity torques, and therefore the abundances are strongly coupled to the dynamics. Star formation triggering and efficiency are not yet well known in interacting galaxies. It turns out quite easy to build abundance gradients in ellipticals, either through rapid initial formation, merger, or less violent evolution, so the observed gradients are not a stringent test of the formation processes.

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