Scale Interactions and Galaxy Evolution

Daniel Pfenniger
University of Geneva, Geneva Observatory

September 30, 2002

Abstract. To understand galaxies and their evolution, it is necessary to describe how the different scales interact: how the microscopic physics, such as star formation, or the large scale physics, such as galaxy interactions may modify the galaxy global shapes. The purpose of this review is to point out some general or recent topics related to such scale interactions, both observational and theoretical, which are relevant in the present understanding of galaxies.

Keywords: galaxies — N-body simulations — statistical mechanics — ISM — galactic dynamics

1. Introduction

The purpose of this talk is to review the general mechanisms acting between the scales in gravitating systems such as galaxies, and that lead to evolution. The Universe is certainly hierarchically organized, and at different scales different phenomena interact with the adjacent scales. For the sake of simplicity it has been customary for a long time to consider one scale at a time and to neglect scale interactions. Scientists have been inclined to discard scale interactions already because distinct disciplines are specialized according to the astrophysical object sizes. As a consequence some attempts to introduce scale interactions such as galaxy mergers met much resistance.

But nowadays it becomes clearer that as stars are built upon nuclear and atomic physics, galaxies are also built upon the ISM physics and star formation processes. Conversely galaxy clusters and large scale structures do matter for understanding galaxy evolution, which in turn cannot be ignored when trying to explain star formation, while stellar evolution do certainly plays a role in the chemical composition of matter. Despite a disparity of phenomena, we see common phenomena through the scales because some of the involved physics is scale-free, namely gravitational dynamics.

Statistical physics provides an example how adjacent scales may be sometimes absorbed by a proper theoretical frame. The small scale physics is absorbed by statistical concepts, such as the "molecular chaos", while the large scale physics is absorbed by proper boundary conditions, such as the extensivity of the system. Thus one can obtain a useful description of gases without including the detailed knowledge of molecules, which are actually quite complex objects. Without any particle computer simulations statistical physics can describe the fate of a gas enclosed in a box, the shape of which is unimportant.

However, if the box size increases too much we know well that a sufficiently large volume of gas becomes self-gravitating, and then the usual tools of statistical mechanics do not work well with gravitating systems. We briefly review on the reasons in Sect. 2. In Sect. 3 we discuss the small scale interactions in galaxies, i.e., the ISM and star formation physics for which very interesting developments have occurred in the recent years. In Sect. 4 some rarely discussed issues about the large scale interactions of galaxies are presented. Finally, we conclude in Sect. 5.

2. Statistical mechanics of gravitating systems

The fundamental problem of adapting statistical mechanics to gravitating systems and other non-extensive systems remains to be worked out. In fact, statistical mechanics is deeply designed for *extensive* systems because, first, these systems are very common in terrestrial conditions, and, second, the extensivity (that certain macroscopic quantities such as energy and entropy *scale linearly with the volume*) allows drastic simplifications of the system description. It is therefore paradoxical that concepts like “temperature” or “pressure” are constantly used in astronomy, but these concepts have been designed during the XIX$^{\rm th}$ century especially for extensive systems in which self-gravitation is negligible.

This issue is important because self-gravity is ubiquitous in astrophysical systems. With proper statistical mechanics tools we should be able to understand on a deeper theoretical basis the stellar and galactic systems, and also the behaviour of N-body simulations. After all classical statistical mechanics allows to describe particle systems such as gases without requiring N-body simulations. The mere necessity of N-body simulations in astrophysics illustrates the practical non-applicability of classical statistical mechanics to systems with long range forces.

A basic unsettled issue is the meaning and definition of entropy. As long as entropy remains a fuzzy concept (a measure alternatively of the available phase space, of disorder, or of information) little change to the situation has to be expected. However, the awareness is growing that the extensivity requirement must be abandoned in order to handle gravitating systems, as well as small N systems (Gross 2002). For both types of systems the particle interactions play a global role, therefore the system is not extensive.

The gravitational perfect gas sphere is perhaps the simplest system where gravitation is combined with statistical concepts, since it already contains the particular difficulties brought by the long range gravitational force. It has been worked out by a number of authors (e.g. Ebert 1955; Lynden-Bell & Wood 1968; Chavanis 2002). The most notable feature is that below a critical temperature, the *specific capacity* (or *specific heat*) of the gas sphere becomes negative. Such states, forbidden by classical statistical mechanics, are thermally and dynamically unstable, and are closely related to Jeans' unstable states. In other non-gravitational systems, such negative specific capacity states are called phase transitions (Lynden-Bell 1999), and are known to develop spontaneously long range correlations, "giant fluctuations", fractal states, etc. For such states the fluctuations develop until the small scale and large scale physics react. At intermediate scales, new scaling relations may occur. The system, at least in a transient phase, may develop scaling relations different from the classically assumed extensivity.

In other words, in negative specific capacity states scale interactions play a decisive role, as well as the boundary conditions. The small scale physics is often the fastest, so is the most important to include faithfully. For negative specific capacity states it is necessary to include a description of the effective microscopic physics, contrary to the positive heat capacity states where the small scale molecular physics is irrelevant.

Such effects have been recently studied by Huber & Pfenniger (2002) via N-body simulations. In this study, the gas sphere is simulated by gravitating particles slowly dissipating energy. As long as the system specific capacity is positive, the particle system follows well the analytical theory of Plummer softened particles developed by Follana & Laliena (2000), but as soon as the specific capacity becomes negative, i.e., the system is gravitationally unstable, strong differences occur (Fig. 1). In such latter states the growth of long range correlations in phase space, fractal states, occurs in the particle system which are not descriptible with the analytical theory, but resemble the correlations of Larson (1981) observed in the cold ISM. The specific behaviour and evolution followed by the N-body system is then strongly dependent on the adopted small scale physics, i.e., the particular softening properties.

All these theoretical issues have important consequences for the way we understand galaxies and other gravitating systems:

1. In N-body simulations, during the fragmenting phases developing down to the particle level one cannot trust the numerical model

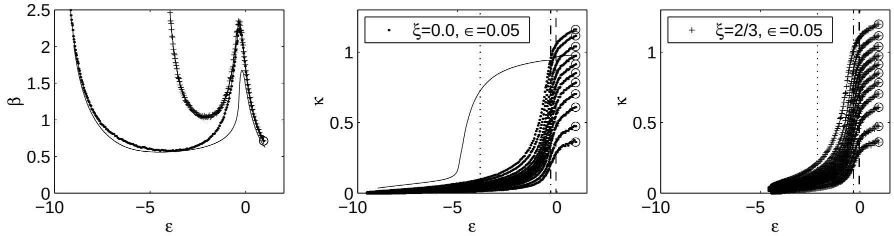

Figure 1. **Left:** Energy ε as a function of the inverse temperature β of a particle system softened with a Plummer potential with softening $\epsilon = 0.05$, and confined by a spherical box of unit radius. The thin solid curve corresponds to the analytical model of Follana & Laliena (2000), and the thick dots to a similarly softened N-body simulation (Huber & Pfenniger 2002), while the crosses follow another model with a small scale repulsive softening. Negative specific capacity phases occur when the slope of these curves is positive, so are narrower when the particles have a repulsive core.
Middle: The Lagrangian radii κ of the Plummer softenend particle system do not follow the analytical prediction during the negative specific capacity phase, marked by vertical dashed lines, during which long range correlations in phase space develop.
Right: The Lagrangian radii of the repulsive softening core system.

as simulating faithfully the real natural systems as long as the microscopic physics included in the model does not match the relevant microscopic physics in the natural system. In particular, negative specific capacity at the particle level is up to now never included in N-body simulations. In the future this aspect should be taken into considerations since in galaxies and cosmology such gravitationally unstable states, i.e., with negative specific capacity, occur frequently.

As found in Huber & Pfenniger (2002) the bias in today's particle simulations is that softening acts systematically as keeping the specific capacity at the particle level at positive values. The same bias occurs in gas simulations where the small scale physics is generally represented by a perfect gas.

2. The important consequence for real galaxies is that the fragmenting and clustering phases must depend strongly on the small scale physics. As for stars, the general properties of galaxies should be searched also and perhaps principally in their internal properties, and less in their initial conditions, as has been for a long time exclusively considered. The problem is hard because it involves extremely non-linear and chaotic phenomena, such as the star formation process, which must be understood first if we want to model their impact at the galaxy level.

3. Internal scale interactions in galaxies

3.1. The new stellar and galactic dynamics

The "microscopic" physics of galaxies, i.e., the ISM physics, the physics of star formation, the physics associated with stellar evolution is crucial in order to understand galaxies. It is obvious that a mass condensation that is called galaxy must contain a minimum amount of stars, so the star formation process belongs by definition to the galaxy formation process. For a long time this early epoch of galaxy formation was thought to be confined to a restricted time period, so it was convenient to simplify the description of galaxies as collisionless ensemble of stars. With this model N-body simulations could account for a large number of galaxy properties, and the tendency was to neglect the ISM and stellar physics. Later numerous simulation works did include some representation of gas dynamics, as well as recipes of star formation.

But a fundamental aspect, perhaps much more important for galactic and stellar dynamics that 2-body relaxation or Liouville's theorem, the overall mass loss from stars, has been considered only very recently (e.g., Kroupa, 2002; Bournaud & Combes 2002). Indeed, besides energy, stellar populations do return a substantial fraction ($> 20\%$) of their mass to the ISM over $5 - 10\,$Gyr, especially after the red giant phase. As consequence momentum, angular momentum and mechanical energy mixing must also occur between stellar populations and the diffuse, energy dissipative hot gas component. This is especially true for elliptical galaxies, which were considered for a long time as perfect gasless and collisionless pure stellar dynamical systems! Since the mixing of several percents of mass due to stellar mass loss means a substantial dissipation for a mechanical system, it turns out that over time-scales longer than a couple of Gyr galaxies must be viewed as essentially dissipative structures. In comparison to the effect of stellar mass loss, the much longer 2-body relaxation time is completely irrelevant concerning the effective global relaxation. Over time-scales shorter than a few Gyr, still an order of magnitude larger than the galaxy dynamical time, the collisionless description remains however valid.

As example of consequence that stellar mass loss may lead to, Bournaud & Combes (2002) show that several phases of bar destruction and reformation are possible in N-body simulations including mass loss and external gas accretion.

3.2. The new ISM physics

From observational constraints molecular clouds appear increasingly as transient structures with a lifetime reduced by an order of magnitude with respect to earlier estimates, stars form essentially over a free-fall time according to Elmegreen (2000).

The more diffuse HI also is subject to an deep rediscussion about its lifetime and origins. For a long time HI in the outer galactic disks was seen as almost primordial, or at least a long lived phase, but recent observational works suggest something very different. The study of M101 by Smith et al. (2000) suggests that the HI is a by-product of the FUV radiation, HI is observed in proportion of the exciting UV radiation, which means that a cold molecular susbtrat must exist even in the outer HI disks. Deep photometric observations by Cuillandre et al. (2001) of the extreme outer disk of M31 reveal the unambiguous existence of stars, while extinction of stars and background galaxies reveal that dust exists in the HI. Blue clustered stars indicate that stars do form inconspicuously even in the extreme outer regions of M31's disk. But as far as we know stars require cold and dense molecular clouds for forming, thus there is little freedom left from the conclusion that molecular hydrogen does exist even in extreme outer galactic disks (Allen 2001). Similar conclusions were reached from distinct motivations for explaining the baryonic dark matter in spirals (Pfenniger & Combes 1994).

3.3. Internal energetics and global galaxy parameters

Traditionally the global galaxy parameters have been explained as relics of particular *initial conditions.* The general correlations among galaxies, such as the Hubble sequence, and the Tully-Fisher relation, have been sought as relics of correlations existing in the initial conditions.

However the virial theorem in the form $E_{\rm tot} = -E_{\rm kinetic}$ shows immediately that to condense matter with little specific energy from infinity into a bound system, one must dissipate the present specific kinetic energy. The dissipative nature of galaxy formation is essential. So a galaxy rotating at $V_{\rm rot} = 200\,{\rm km\,s^{-1}}$ must have dissipated away its specific kinetic energy $V_{\rm rot}^2$, at least about $208\,{\rm eV/nucleon}$, a value intermediate between typical chemical binding energy (of order of eV) and nuclear binding energy (of order of MeV). In addition the galaxy mass is made of a fraction of stars, each nucleon in a Sun-like star requires additionally to have dissipated away its present thermal energy ($\approx 400\,{\rm eV/nucleon}$). In comparison, a black-hole requires about $2\cdot 10^6$ times more specific dissipation ($0.5\,c^2 \approx 1\,{\rm GeV/nucleon}$), which means that the fractional mass of black-holes becomes dominant in the global energetics when it exceeds $\approx 0.5\cdot 10^{-6}$. Already the modest Milky Way black-hole with $2-3\cdot 10^6\,M_\odot$ exceeds this threshold.

Internal processes are powerful enough to control or modify the process of galaxy formation or transformation, provided that the emitted energy can interact with the galaxy scale. At any time what matters is the exchanged *power* between the scales. The maximum dynamical power $L_{\rm dyn}$ that a gravitating system can exchange is given by the ratio of its energy and dynamical time, which takes a particularly simple form in term of virial velocity V (cf. Pfenniger 1991):

$$L_{\rm dyn} = \frac{|E|}{t_{\rm dyn}} = \frac{V^5}{G} \qquad (1)$$

This order of magnitude scaling is resembling the IR Tully-Fisher scaling ($L_{\rm IR} \propto V_{\rm rot}^{4.9}$) not only in the exponent, but also in the zero point. For example if $V = 200\,{\rm km\,s^{-1}}$ then $L_{\rm dyn} = 1.2 \cdot 10^{10}\,L_{\odot}$. The physical interpretation of this is that independently of the origin of the Tully-Fisher relation, galaxies deliver in the form of light, i.e., nuclear energy, a power comparable to the power required to mechanically transform secularly its global structure.

Thus the secular impact of radiation over the global galaxy mechanical energy appears important, especially because galaxies are nowadays known to be only semi-transparent. The similarity of values and velocity scaling between luminosities and dynamical power is unlikely a coincidence. Via global dynamical reaction (bars and spirals in marginally stable disks), spiral galaxies can adjust their size to the internal energy production related to stellar activity (SN explosions, WR winds, outflows, radiation, HI holes, etc.). The galaxy global parameters are then not only determined by the initial conditions of formation, but much more by the internal micro-physics (ISM and star formation).

4. External scale interactions in galaxies

4.1. The energy–angular momentum budget of interactions

Galaxies frequently interact with the higher scale, with gas infall, accretion, tidal interactions, galaxy collisions or mergers. But often the infall, accretion or merger processes are viewed as simple mass addition processes. Consequently, the history of galaxy build-up is summarized by a "merger tree", which leads to the approximate view that galaxy formation is a hierarchical *addition* of masses as a function of time. In fact, N-body simulations show that mergers may be fairly complex, and until a quasi steady state of the merger remnant is found, much occur, not only regarding the morphological evolution of the primary galaxy, but also because each important event ejects a non negligible fraction of mass, sometimes over 10%, escapes to sufficiently large distances to be considered as infinity (i.e., the ejected mass return time-scale is much longer than the merger remnant dynamical time).

Mass escaping the system means that angular momentum and energy is also transported with values not necessarily equal to the merger remnant ones. When considering galaxies, to first order they are well explained by the scale-free Newtonian gravitational physics, so the total mass is irrelevant; one can thus normalize with the mass. A succession of merger events correspond then to a complicated walk in the *specific* angular momentum–energy parameter space.

It is easy to see with a simple dimensional model how angular momentum constraints the galaxy global parameters. The system specific energy e and the specific angular momentum l read:

$$e = \frac{1}{2}\left(V_{\rm rot}^2 + \sigma^2\right) - \frac{GM}{\alpha R}\,, \quad \beta l = \alpha R\, V_{\rm rot}\,, \tag{2}$$

where the kinetic energy part is decomposed into the ordered bulk rotational part with the average rotational velocity $V_{\rm rot}$, and the disordered kinetic energy velocity dispersion σ. M is the total mass and R the virial radius. α and β are constants of order of 1. By the virial theorem, the system specific energy is also minus the kinetic energy:

$$e = -\frac{1}{2}\left(V_{\rm rot}^2 + \sigma^2\right) < 0\,. \tag{3}$$

Now it is useful to express the previous equations for the latter fragile but observable quantities R, $V_{\rm rot}$, and σ as functions of the robust but hardly observable quantities M, l, and $e < 0$:

$$\alpha R = \frac{GM}{2|e|}, \quad V_{\rm rot} = 2|e|\frac{\beta l}{GM}, \quad \sigma^2 = 2|e|\left[1 - 2|e|\left(\frac{\beta l}{GM}\right)^2\right]. \tag{4}$$

This simple model captures the essential effects due to interactions or other perturbations to the systems integral quantities. The system radius decreases if M decreases or $|e|$ increases (i.e., when energy is lost), but is insensitive to variations of l. The rotational velocity $V_{\rm rot}$ increases either if energy is lost, or if l increases, or if M decreases. Finally, the velocity dispersion σ has a richer behaviour, summarized by Fig. 2, with a large forbidden region: σ decreases, i.e., the system cools, when l is sufficiently increased. Low l, large $|e|$, and large σ correspond to hot, slowly rotating systems, while large l, small $|e|$, and small σ correspond to disk systems.

With this gained insight it is now easy to predict conditions favorable for interactions or other factors leading not necessarily toward hotter, slower rotating systems, as usually expected, but toward the opposite,

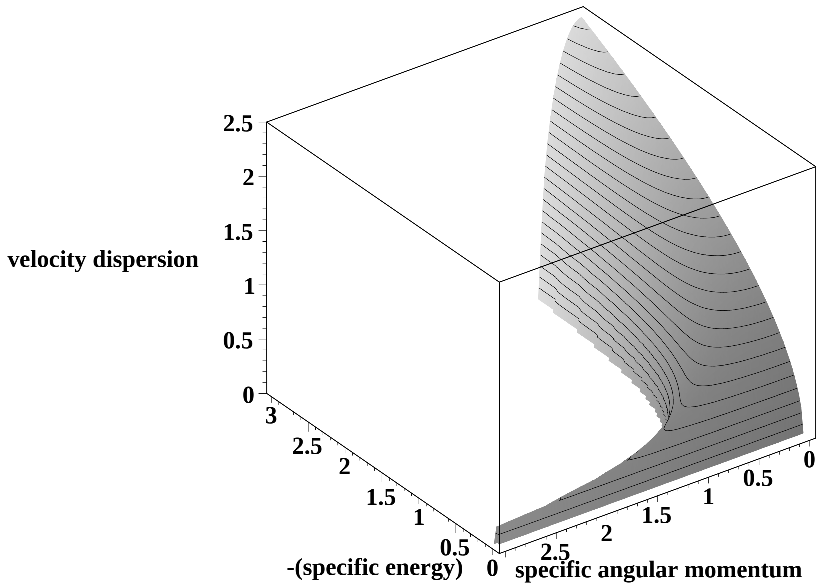

Figure 2. Velocity dispersion as function of specific angular momentum and energy.

disky systems: one factor is to raise the system specific angular momentum, and the other is to inject also energy, to decrease $|e|$. So prograde mergers, and internal energy injection by stellar activity both favors a galaxy toward a disky state.

4.2. HVC accretion and dark matter halo shape

The angular momentum constraint can be used in the scenario that High Velocity Cloud (HVC) infall secularly increases the Galaxy mass by a few $M_{\odot}\,\mathrm{yr}^{-1}$ (e.g., Blitz et al. 1999). First, the Magellanic Stream as a source of HI has the wrong angular momentum vector since it is on almost polar orbit. Second, since the HVC's appear to contain individually an order of magnitude more dark matter, as the HI outer disk does, one must conclude that the accreted dark matter is substantial, and contains a similar specific angular momentum as the baryons. Consequently the dark mass should be expected to adopt a shape of a fast rotator (outwards flaring thick disk), which are known to depart substantially from the spheroidal shape almost exclusively contemplated in the literature for pressure supported systems. Notice that a substantial rotational support for the dark matter may resolve several current conflicts about cuspy CDM cores, since "hollow" dark mass distributions surrounding maximum optical disks are then possible (Pfenniger & Combes 1994).

5. Conclusions

Scale interactions are important in astrophysics because the negative specific capacity states are ubiquitous. These states are unstable and develop phase-space correlations which trigger the interactions of scales. This poses several deep problems for the current way to perform N-body simulations, but this also indicates that galaxies should not be seen as isolated system insensitive to their scale boundary conditions. At small scale stellar mass loss is secularly important, over several Gyr galaxies must be seen as dissipative structures. Also the stellar energy input is important enough to compete with dynamics and is sufficient to determine the global spiral parameters. At large scales, galaxy interactions lead to a a walk through the mass, energy, and angular momentum space, since at each interaction a substantial amount of matter may be recycled through the IGM. Also the angular momentum constraint linked to dark matter rich gas infall indicates that flaring disk-like rotationally supported dark matter distributions should be considered too, not exclusively pressure supported spheroids.

Acknowledgements

The conference organizers and Kiel University staff are gratefully acknowledged for the inordinate amount of efforts dedicated for insuring a smooth and enjoyable conference. This work has been supported by the Swiss National Science Foundation.

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