Abstract. Today we have numerous evidences that spirals evolve dynamically through various secular or episodic processes, such as bar formation and destruction, bulge growth and mergers, sometimes over much shorter periods than the standard galaxy age of $10^{-15}$ Gyr. This, coupled to the known properties of the Hubble sequence, leads to a unique sense of evolution: from Sm to Sa. Linking this to the known mass components provides new indications on the nature of dark matter in galaxies. The existence of large amounts of yet undetected dark gas appears as the most natural option. Bounds on the amount of dark stars can be given since their formation is mostly irreversible and requires obviously a same amount of gas.

1. Introduction

Until the recent years the concepts prevailing in understanding galaxy evolution have been largely dominated by the ELS scenario (Eggen, Lynden-Bell & Sandage 1962). The views issued from it favour a synchronous and rapid ($\approx 100$ Myr) formation of the galaxies at a particular early time in the universal expansion. In this context, the properties of present galaxies, such as their typical scale and mass, must depend directly on the initial conditions fixed by the physical state of the Universe at the “galaxy formation epoch”. The only subsequent significant evolution in galaxies to be discussed was the slow changes in their stellar populations. Dynamical processes could be assumed to be settled, and therefore ignored.
Since then major observational and theoretical progresses of direct relevance occurred, which resulted in a gradual shift in the meaning of galaxy evolution. It suffices to remind that basically all the advances in non-linear dynamics, including the recognition of the fundamental rôle of chaos, and in computer simulations of galaxies have been made in between.

Today, in all its steps the ELS scenario is no longer tenable, as explained in the following. This is still not perceived as a necessity in fields loosely connected with the recent advances in gravitational dynamics.

An instance of inadequation between the ELS scenario and more recent works appears in cosmological simulations at several 100 Mpc scale (see e.g., White 1994). In such simulations nothing like homogeneous collapses do occur, instead hierarchical clustering proceeds at all the computable scales with different speeds. This implies that galaxies and galaxy clusters, exactly as stars, form in different regions of the sky asynchronously. The formation process covers several dex of time-scales, so not only the free-fall time, but merging and later infall participate to it. For many galaxies the formation/evolution should be considered as not terminated even now. The galaxy age looses its original meaning because the aging, traced by various observables, may occur at widely different speeds.

A central aspect not considered in the ELS picture is the likely coupling of dynamics with stellar activity. In the recent years the large FIR emission of spirals, which even largely dominates the light in starburst galaxies, was found substantial particularly over the “late” part of the spiral sequence. The FIR emission, coming mostly from UV and visible light absorbed and recycled in the FIR by dust, is consistent with the also recent recognition of the partial opacity of the optical region of spirals (e.g. Davis et al. 1993). It turns out that the total bolometric luminosity is comparable to the power that dynamics can exchange (Pfenniger 1991b). This coincidence is best explained by a coupling of star formation and dynamics via a feed-back mechanism (Quirk 1972; Kennicutt 1989). The interesting aspect of this coupling is that the systematic global properties of galaxies are then no longer necessarily determined by the initial conditions of collapse. As for stars, the galaxy properties would then be encoded in their internal small scale physics, i.e. star formation and ISM physics. This may solve the old problem of the absence of galactic scale at the radiation-matter decoupling epoch, particularly if galaxy formation covers a sizable fraction of the Hubble time. The galactic scale would result mainly from the balancing of stellar activity effects, particularly during starburst phases, and dynamics.

The Hubble sequence is most probably an incomplete sample. For example many low surface brightness galaxies may well be missed (e.g. Bothun et al. 1990). However, whenever fast morphological changes do occur in normal galaxies (bars, mergers), they must correspond to shifts within the
sequence, because the already existing stars certainly survive the changes.

The general properties of the Hubble sequence have been progressively determined (e.g. de Vaucouleurs 1959; Broeils 1992; Roberts & Haynes 1994; Zaritsky et al. 1994). In order to extract useful information of this "zoo", we must consider only the most general properties, keeping in mind that galaxies form a variety of objects with different ages and aging speeds. For example mergers (Schweizer 1993) certainly accelerate morphological changes at speeds which depend on the fortuitous interaction strengths.

The following list summarises the main trends and properties along the spiral sequence from Sm to Sa, that are useful for the discussion.

| Property                  | Equation                     | From | To |
|---------------------------|------------------------------|------|----|
| Total mass                | $M_{\text{tot}} \approx 1 \rightarrow 100 \cdot 10^{10} \, M_\odot$ | 1    | 10 |
| Kinetic energy            | $\frac{1}{2} V_{\text{max}}^2 \approx 25 \rightarrow 500 \, \text{eV/ nucleon}$ | 1    | 50 |
| Bulge-disk ratio          | $L_{\text{sph}} / L_{\text{tot}} \approx 0 \rightarrow 0.6$ | 0    | 0.6 |
| Symmetry                  | $12 + \log(O/H) \approx 8.3 \rightarrow 9$ | 8.3  | 9  |
| Metallicity               | $M_{\text{HI}+\text{H}_2} / M_{\text{tot}} \approx 0.10 \rightarrow 0.07, \, M_{\text{HI}+\text{H}_2} / M_{\text{stars}} \approx 1.4 \rightarrow 0.1$ | 0.1  | 0.1 |
| Detected gas              | $M_{\text{dark}} / M_{\text{lum}} \approx 10 \rightarrow 1$ | 10   | 1  |

2. Sense of Evolution from Irreversible Processes

In fact, already a systematic sense of evolution is clear by making a list of the major irreversible processes known in spirals. Each of them gives a possible criterion and a sense of aging.

1) The energy dissipation in gravitating systems is measured by the present amount of kinetic energy, which equals the minimum energy the system had to release in order to reach the present bound state. In spirals the rotation speed is an excellent indicator of the specific energy dissipated since the rotation curves vary slowly with radius. Because disks are systems having lost the maximum of energy while conserving angular momentum well, further energy dissipation necessarily implies dissipation of angular momentum, which is best achieved by some mass transport and breaking of axisymmetry. Bars and spiral arms are just manifestations of this necessity. The energy factor already indicates clearly that the Sa side of the spiral sequence is energetically more evolved than the Sm side.

2) Building a central bulge or spheroid by heating a disk, by whatever process (see next Sect.), is also a stellar dynamical irreversible process, because there is no way to "cool" stars following fat orbits back toward circular orbits. From the stellar dynamical point of view Sa galaxies with big bulges are thus more evolved than bulgeless Sm galaxies.
3) Overall, if galaxian shapes tend toward some attractors, the degree of organisation and symmetry toward these shapes is a sign of evolution. Clearly the spiral sequence looks increasingly organised in the sense Sm to Sa, which is also consistent with the decreasing spiral pitch angle.

4) The transformation of gas into stars in cold clouds is mainly an irreversible process, star formation locking most of the mass for time-scales longer than galaxy ages. So the ratio of stellar to gas mass is a tracer of evolution, and Sa’s are more evolved in this respect than Sm’s. In this context, the dark matter fraction decreasing systematically along the spiral sequence to low “non-problematic” values on the Sa side is remarkable.

5) Obviously related to the previous criterion, the nucleosynthesis within stars is also irreversible, the more metal rich and dusty galaxies have a longer history through the internal activity of their stars. Sa’s are more enriched than Sm’s, which again indicates a sense of evolution.

Finally, the total mass along the sequence increases strongly from Sm to Sa in average, though with a considerable spread at constant type. This is not astonishing because the classification criteria are mass independent. We interpret the mass trend as indicative that massive proto-galaxies evolve in average faster than light ones. The proto-galaxies of today (Im’s, Sm’s) are probably lighter than the corresponding ones in the past.

In summary, the only consistent sense of aging along the spiral sequence is from Sm to S0. The important consequence is that proto-galaxies would then be mostly bulgeless gas rich disks like Sm-Sd’s, or even pure gas disks, instead of initial spheroid dominated galaxies of the ELS scenario.

3. Evolution from Dynamics and Observations

Contemporary to the ELS scenario, Safronov (1960) and Toomre (1964) realised the unexpected fact that gaseous and stellar disks with too much circular motion are gravitationally unstable. So energy dissipation with angular momentum conservation brings first collapsing gravitating systems toward disk shapes with an increasing fraction of kinetic energy in rotational motion. But subsequent dissipation brings disks ineluctably toward a global instability. A first ground was found that disk galaxies may be dynamically unstable, so may evolve with dynamical time-scales.

Shortly hereafter computer simulations of stellar disks (e.g. Miller & Prendergast 1968; Hohl & Hockney 1969) allowed to simulate the non-linear phase of disk instability. They showed a systematic tendency to produce a robust bar. These results illustrated an example of major and fast morphology change (within a couple of rotational periods) of galaxy type from non-barred to barred.
The other significant proposition in the 70’s came from Toomre & Toomre (1972) in which ellipticals may result from the merging of spirals or other ellipticals. Another case of major and fast change of galaxian morphology was put forward. Despite many resistances this scenario appears today as the most natural way of forming ellipticals, although it is not necessarily the only one. In fact, the more violently a galaxy is shaken, for whatever reason, the more it ends up like an elliptical.

In the 80’s the bar phenomenon was investigated in more depth. From observational material, Kormendy (1982) pushed forward the idea of secular evolution in barred galaxies. The reason why bars do exist in the first place was understood by studies of their periodic orbits in the plane (Contopoulos 1980, Athanassoula et al. 1983) and in 3D (Pfenniger 1984, 1985). It was discovered that bars may evolve into boxy bulges via vertical resonances boosting bending instabilities transverse to the plane (Combes & Sanders 1981; Combes et al. 1990; Raha et al. 1990). It became also clear that chaotic orbits are playing an important role in bars. Later it was understood how the accretion of only a few percents of mass within the Inner Lindblad Resonance (ILR), either by dissipation of gas (Hasan & Norman 1990; Pfenniger & Norman 1990) or by dynamical friction on galaxy satellites (Pfenniger 1991a), may rapidly destroy a bar into a spheroidal component of similar size. This led to an increased confidence that many of the non-linear events and morphologies observed in galaxies and in N-body simulations, can be interpreted, and even predicted, via the knowledge of the underlying periodic orbits (Pfenniger & Friedli 1991). These studies of bars showed that isolated galaxies must also be seen as structures with possible fast dynamical evolution phases.

In the recent years more works have completed the above picture. Secondary bars (Friedli & Martinet 1993), gaseous and star formation effects (e.g. Friedli & Benz 1993, 1995), interactions with external galaxies and mergers (e.g. Barnes 1992) continue to be investigated. In any cases, these additional complications make even harder to freeze galaxy morphologies beyond a few Gyr. The obvious requirement is then to understand the general time-sequence of galaxy morphologies.

Independently of dynamics, several observational results strongly indicate significant secular evolution within much less than 10 Gyr:

1) From halo stellar cluster abundances Searle & Zinn (1978) arrived to an alternative scenario to ELS. From the observations they concluded that the Milky Way stars did form inside-out over several Gyr.

2) In galaxy clusters the Butcher-Oemler (1978) effect (see also Rakos & Shombert 1995) indicates that galaxies are increasingly bluer at higher redshifts. Furthermore, the morphology-radius relationship (Dressler 1980; Whitmore 1993) shows that the majority of galaxies at cluster periphery
Figure 1. Composition diagram along the spiral sequence. The thick line separates the detected matter from the dark matter. The dark stellar-like objects (DS) are assumed here to be proportional to the stars. The arrows indicate that the DS mass is an upper limit and the dark gas a lower limit.

are spirals, as in the field, but these are replaced by lenticular and then ellipticals at smaller radii. To a dynamicist this relationship tells that spirals do not survive to a single center crossing or so, because the galaxies within a cluster are expected to move on rather elongated orbits. If correct the spiral morphological evolution accelerated by environmental disturbances is then directly revealed. Either spirals end in part as ellipticals, and/or they are largely dissolved and contribute to the cluster hot gas and metallicity.

4. Constraints from an Evolutive Spiral Sequence

If we take the published data about the ratios of the different known matter forms along the spiral sequence (e.g. Broeils 1992 for the stars and HI; Young & Knezek 1989 for H$_2$ derived from CO emission), we can solve for the mass fraction of each component: stars, HI, H$_2$ from CO, and the rest, dark matter (for more detail, see Pfenniger 1996). We obtain the composition diagram of the spiral sequence shown in Fig. 1.

Now if spirals do evolve along the sequence from Sm to S0, then several constraints follow (Pfenniger, Combes & Martinet 1994; Martinet 1995). We must consider that stars or jupiters are made from the gas and lock most of it for $\gg 5 - 10$ Gyr, and that for dynamical reasons little accretion (less than a few % in mass) can occur transversally to a stellar disk without heating it to too high values (Tóth & Ostriker 1992).

Most of the usual dark matter candidates such as CDM particles, neutrinos, jupiters, brown dwarfs, and black-holes, are inconsistent with the
spiral sequence properties including dynamical evolution, mainly because evolutive phases (e.g. a merger) can be sporadic. Since the star fraction increases from Sm to Sa in a proportion exceeding the detected gas content, everything happens as if dark matter is transformed into stars, i.e. a substantial fraction of dark matter should be dark gas. We have explained elsewhere (Pfenniger & Combes 1994, and elsewhere in this volume) the many reasons why today we can consider this conservative candidate, for long totally neglected, as worth to be more investigated.

Others did arrive also to the conclusion that much more gas should exist in spirals. Toomre (1981) argued that the cold dynamics and chaotic structure of Sc’s require much more gas than observed to maintain their patchy structure. Also just to sustain the present star formation rates over several Gyr Sc’s require much more gas (Larson et al. 1980).

Not all the dark matter in spiral is necessarily dark gas, because the uncertainties on the stellar mass contributed by brown dwarfs and dark remnants, or by stars obscured by dust, are still substantial (∼50%). We call these dark or obscured stars DS for short. However, the fact that S0’s and ellipticals are dynamically evolved systems at the end of the gas-to-star transformation process, but with still ∼40% of dark matter, hints toward the presence of non-gaseous components such as DS. If we assume that a population of DS pre-exists to a galaxy (the same rôle would be played by CDM particles), its maximal fraction is determined by the final S0 stage, ∼40%. In previous stages the difference must be gas to make future stars. Less speculatively, as shown in Fig. 1, if instead we assume that DS’s form proportional to the stars as galaxies evolve (for example just from the increasing fraction of dust), the amount of dark gas required is correspondingly increased. For the Milky Way (an SBbc) the fraction of DS’s would be <40% in the first case, and <20% in the second case.

5. Conclusions

Galactic dynamics forces us to see spirals as structures with possible “bursts” of dynamical evolution involving short time-scales. Taking into account today’s observational and theoretical constraints, the only possible sense of evolution is from Sm to S0. During evolution everything happens as if dark matter in galaxies is transformed into stars, that is dark gas is required.

A possible solution to the dark matter problem in galaxies is that gas in outer HI disks clumps along a fractal structure down to solar system sizes, as explained elsewhere in this volume. The smallest clumps are then very dense and cold which makes them presently hard to detect. A sizable amount of dark (or dust obscured) stars can also be argued just from the fact that evolved galaxies (Sa-S0’s) still contain about 40% of dark matter.
References

Athanassoula E., Bienaymé O., Martinet L., Pfenniger D. 1983, *A&A* 127, 349
Barnes J.E. 1992, *ApJ* 393, 484
Bothun G.D., Shombert J.M., Impey C.D., Schneider S.E. 1990, *ApJ* 360, 427
Broeils A. 1992, *Dark and visible matter in spiral galaxies*, PhD Thesis, U. Groningen
Butcher H., Oemler A. 1978, *ApJ* 219, 18
Combes F., Debbasch F., Friedli D., Pfenniger D. 1990, *A&A* 233, 82
Combes F., Sanders R.H. 1981, *A&A* 96, 164
Contopoulos G. 1980, *A&A* 81, 198
Davies J.I., Phillips S., Boyce P.J., Disney M.J. 1993, *MNRAS* 260, 491
de Vaucouleurs G. 1959, in *Handbuch der Physik LIII, Astrophysik IV: Sternsysteme*, S. Flügge (ed.), Springer-Verlag, Berlin, 275
Dressler A. 1980, *ApJ* 236, 351
Eggen O.J., Lynden-Bell D., Sandage A.R. 1962, *ApJ* 136, 748 (ELS)
Friedli D., Benz W. 1993, *A&A* 268, 65, and 1995, *A&A* 301, 649
Friedli D., Martinet L. 1993, *A&A* 277, 27
Hasan H., Norman C. 1990, *ApJ* 361, 69.
Hohl F., Hockney R.W. 1969, *J. Comput. Phys.* 4, 306
Kennicutt R.C. 1989, *ApJ* 344, 685
Kormendy J. 1982, in *Morphology and Dynamics of Galaxies*, 12th Advanced Course Swiss Soc. Astr. Astrophys., Martinet L., Mayor M. (eds.), Geneva Observ., 115
Larson R.B. 1981, *MNRAS* 194, 809
Larson R.B., Tinsley B.M., Caldwell C.N. 1980, *ApJ* 237, 692
Martinet L. 1995, *Fundamental of Cosmic Physics* 15, 341
Miller R.H., Prendergast K.H. 1968, *ApJ* 151, 699
Pfenniger D. 1984, *A&A* 134, 373
Pfenniger D. 1985, *A&A* 150, 112
Pfenniger D. 1991a, in *Dynamics of Disc Galaxies*, B. Sundelius (ed.), Göteborg U., 191
Pfenniger D. 1991b, in *Dynamics of Disc Galaxies*, B. Sundelius (ed.), Göteborg U., 389
Pfenniger D. 1996, in *Third Paris Cosmology Colloquium*, H.J. de Vega, N. Sánchez (eds.), World Scientific, Singapore, in press
Pfenniger D., Combes F. 1994, *A&A* 285, 94
Pfenniger D., Combes F., Martinet L. 1994, *A&A* 285, 79
Pfenniger D., Friedli D. 1991, *A&A* 252, 75
Pfenniger D., Norman C.A. 1990, *ApJ* 363, 391
Quirk W.J. 1972, *ApJ* 176, L9
Raha N., Sellwood J.A., James R.A., Kahn F.D. 1991, *Nat.* 352, 411
Rakos K.D., Schombert J.M. 1995, *ApJ* 439, 47
Roberts M.S., Haynes M.P. 1994, *ARA&A* 32, 115
Safronov V.S. 1960, *Annales d’Astrophysique* 23, 979
Schweizer F. 1993, in *Physics of Nearby Galaxies, Nature or Nurture?*, T.X. Thuan, C. Balkowski, J.T.T. Van (eds.), Editions Frontières, Gif-sur-Yvette, 283
Searle L., Zinn R. 1978 *ApJ* 225, 357
Toomre A. 1964, *ApJ* 139, 1217
Toomre A. 1981, in *The Structure and Evolution of Normal Galaxies*, S.M. Fall, D. Lynden-Bell (eds.), Cambridge Univ. Press, 111
Toomre A., Toomre J. 1972, *ApJ* 178, 623
Tóth G., Ostriker J.P. 1992, *ApJ* 389, 5
White S.D.M. 1994, *Formation and Evolution of Galaxies*: Les Houches Lectures, preprint astro-ph/9410043
Whitmore B.C. 1993, in *Physics of Nearby Galaxies, Nature or Nurture?*, T.X. Thuan, C. Balkowski, J.T.T. Van (eds.), Editions Frontières, Gif-sur-Yvette, 425
Young J.S., Knezek P.M. 1989, *ApJ* 347, L55
Zaritsky D., Kennicutt R.C., Huchra J.P. 1994, *ApJ* 420, 87