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Structures in galaxies: nature versus nurture. Input from theory and simulations

E. Athanassoula

LAM/OAMP, UMR6110, CNRS/UP, Technopôle de Marseille Etoile, 38 rue Frédéric Joliot Curie, 13388 Marseille Cédex 20, France

Abstract. Galaxies, in particular disc galaxies, contain a number of structures and substructures with well defined morphological, photometric and kinematic properties. Considerable theoretical effort has been put into explaining their formation and evolution, both analytically and with numerical simulations. In some theories, structures form during the natural evolution of the galaxy, i.e. they are a result of nature. For others, it is the interaction with other galaxies, or with the intergalactic medium – i.e. nurture – that accounts for a structure. Either way, the existence and properties of these structures reveal important information on the underlying potential of the galaxy, i.e. on the amount and distribution of matter – including the dark matter – in it, and on the evolutionary history of the galaxy. Here, I will briefly review the various formation scenarios and the respective role of nature and nurture in the formation, evolution and properties of the main structures and substructures.

1. General introduction

What do we mean by "nature versus nurture"? To some degree, all galaxies have one or more neighbours and/or are influenced by their surroundings. So in the absolute sense of the word, there is no such thing as an isolated galaxy, except in computer simulations. On the other hand, even though a given structure may be triggered by an interaction, it will evolve within its galaxy potential, which, together with the remaining characteristic properties of the galaxy, will influence its evolution. Thus, no structure is 100% due to nature, or 100% due to nurture. It is, nevertheless, useful to ask which of the two has mainly influenced the formation and evolution of a given structure, and, therefore, in the following I will assign the origin of a structure to one of these two alternatives.

In fact, as will be seen below, more than one scenario is possible for each structure, and, very often, some mixture of nature and nurture can be involved. Hence, one can only reason in terms of probabilities and propose this or that agent as the most probable cause for a given feature. Time comes into play as well: if one goes sufficiently far back, all galaxies have experienced important interactions with their surroundings. If, however, the time elapsed since the last interaction is longer than the time necessary for a given structure to form, one can safely argue that this structure is due to nature rather than to nurture (see also a discussion in Hopkins (2009b)).

After these introductory remarks, let me review what models and simulations can tell us. Since the subject is very broad, I will discuss here only certain aspects, necessarily reflecting my own preferences, without me wanting to belittle in any way work which I cannot mention for lack of time and space. The list of references given is likewise far from complete. Finally, I will only discuss the formation of structures and not their destruction, although the latter could also be due either to nature or to nurture.

2. Discs

Formation of galactic discs is one of the major still unsolved astronomical problems. Very schematically, one can distinguish two families of theories, both with important implications for the evolution and development of structures and stellar populations in disc galaxies.

The first one explains disc formation as due to gas inflow, which can come either in the form of a gradual accretion, or of minor gas-rich mergers (White & Rees 1978; Fall & Efstathiou 1980; Mo, Mao & White 1998; Dekel & Birnboim 2006; Heller et al. 2007; Genzel et al. 2008; Agertz, Teyssier & Moore 2009; Bournaud & Elmegreen 2009; Epinat et al. 2009; Law et al. 2009, etc.).

More recently, however, a second alternative has been proposed, which, if confirmed, would make discs the result of major mergers. Since the pioneering work of Toomre & Toomre (1972) and Toomre (1977), many arguments, mainly based on simulations, have shown that a dry major merger will result in an elliptical galaxy. The outcome of wet major mergers has been relatively less well studied and is more complex, since it can result in a disc plus spheroid. The mass ratio of these two components depends not only on the gas fraction in the progenitors and their mass ratio, but also on the encounter orbit, the relative orientation of their discs and even on the properties of their gaseous component (particularly its feedback). A merging of present day spirals, even late types, will fall short of the necessary gaseous content (Barnes 2002). At higher z, however, progenitors are much more gas rich, and the final merger can be a disc galaxy (e.g. Springel & Hernquist 2005; Robertson et al. 2006; Governato et al. 2008; Hopkins 2009a; Stewart et al. 2009).

More work is needed before the formation of discs by mergers can be considered as established. Nevertheless, it is interesting to point out that this second formation scenario, which has considerable support from observations (Hammer et al. 2005, 2009), would result in younger discs. Furthermore, present day discs, and therefore their structures and substructures, would then be of a second generation following the ones formed initially in their progenitors.

3. Bulges

Bulges are a very inhomogeneous class of objects (Kormendy & Kennicutt 2004). Athanassoula (2005a) reviews the various definitions of bulges and distinguishes three types. **Classical** bulges form mainly by mergings, have a spheroidal shape and a very centrally concentrated mass distribution. **Boxy/Peanut** bulges are parts of bars that stick well out of the disc equatorial plane. They form from vertical instabilities of the bar material. Finally, **discy** bulges have the shape of a disc, but are not necessarily axisymmetric. They are due to disc material that has been pushed inwards either by interactions/mergers, or by the torques due to a bar. Thus boxy/peanut bulges can be primarily assigned to nature, classical bulges primarily to nurture and discy bulges to both.

4. Bars

N-body simulations have shown that stellar bars form naturally in galactic discs (for recent reviews see Athanassoula 2005b; Binney & Tremaine 2008) and that their growth rate depends on the halo-to-disc mass ratio – measured in the inner parts of the galaxy – and the velocity dispersion in the disc (Athanassoula & Sellwood 1986). Thus, stellar bars grow faster in relatively more massive and colder discs. They then evolve by redistributing the angular momentum within the galaxy. This is emitted mainly from near-resonant material in the bar region and absorbed mainly by near-resonant material in the halo and the outer disc, so that the bar strength correlates well with the amount of angular momentum exchanged (Athanassoula 2002, 2003). The pattern speed of such bars decreases with time and its evolution is followed by a number of morphological, kinematic and photometric changes, the most spectacular of which is the formation of a boxy/peanut bulge from the vertical instability of the bar (Combes et al. 1990; Raha et al. 1991; Debattista & Sellwood 2000; Athanassoula & Misiriotis 2002; Valenzuela & Klypin 2003; O'Neill & Dubinski 2003; Athanassoula 2003, 2005a; Debattista et al. 2006; Martinez-Valpuesta et al. 2006). For the formation and evolution of bars in gas rich systems see e.g. Bournaud et all. (2005), Berentzen et al. (2007), Romano et al. (2008) and references therein.

Thus, bar formation and evolution can be explained as totally due to nature. Nevertheless, interactions also can trigger bars, or can strongly influence bar properties (e.g. Gerin et al. 1990; Miwa & Noguchi 1998; Berentzen et al. 2003, 2004). For example, impacts by small companions can produce off-centred bars, which are generally shorter and less elongated than their centred precursors (Athanassoula, Puerari & Bosma 1997).

5. Spirals

In cases like M51, it is clear that the spiral has been triggered by an interaction (Toomre & Toomre 1972; Toomre 1981). This, however, is not true in all cases and several mechanisms have been proposed to form spirals in isolation.

The SWING mechanism (Toomre 1981) relies on the amplification of a spiral as it swings from leading to trailing in the corotation region of a shearing galactic disc. It involves an outwards travelling and swinging leading wave and two trailing waves, one travelling outwards from corotation to the outer Lindblad resonance and the other inwards. If the latter is reflected at the centre of the galaxy or at a sharp edge, the cycle can close. Thus, this mechanism could explain both grand design and flocculent spirals.

In the case of barred galaxies the spirals can also be due to material guided by the manifolds emanating from the unstable Lagrangian points at the ends of the bar (Romero-Gómez et al. 2007; Athanassoula et al. 2009a,b). This theory explains why grand design spirals in barred galaxies are trailing and have preponderantly two arms. It also reproduces well the shape of the arms.

Thus, although interactions can link spirals to nurture, other mechanisms explain them a result of nature.

6. Rings

Like bulges, rings are also an inhomogeneous class of objects (Athanassoula & Bosma 1985). A small companion, hitting a disc in a direction not too far from perpendicular to its equatorial plane and not too far from its centre, will create a density wave in the form of a ring, propagating outwards (Lynds & Toomre 1976). These rings are not common, in agreement with the fact that they require particular impact parameters. Often a second ring is visible. The most spectacular case is the Cartwheel galaxy, which, besides the first and second rings, has also spokes between the two. Such rings can be clearly attributed to nurture.

A different type of rings, not due to a collisional encounter, is often observed in barred galaxies. Depending on their location within the galaxy, these can be classified as nuclear, when they are in the innermost parts of the disc, inner rings, which have roughly the size of the bar, and outer ones, which have roughly twice that size (Buta 1995). The inner and outer rings can be due to material guided by the manifolds emanating from the unstable Lagrangian points at the ends of the bar (Romero-Gómez et al. 2006, 2007; Athanassoula et al. 2009a,b), i.e. they can be explained by the same theory that explains spiral arms in such galaxies. This theory predicts the correct sizes and orientations for both inner and outer rings. In particular, inner rings are elongated along the bar and outer ones either along it or perpendicular to it, as observed. This theory also explains the rings found in gas response simulations as those of Schwarz, Salo, Byrd, Laurikainen, Rautiainen, etc., whose results agree very well with observations.

Polar rings are yet a third type of rings. They are external to the disc with a size of the order of twice the disc radius and their plane makes usually an angle of roughly 90° with that of the disc. For this reason, they are generally believed to be due to the accretion of a companion galaxy, or to mass transfer during encounters, i.e. due to nurture.

7. Other features

7.1. Thick discs

Disc galaxies often have a second disc, aligned with the standard, well-known thin disc, with the same equatorial plane, but much thicker (Tsikoudi 1979; Burstein 1979, etc.). Its existence has been, directly or indirectly, attributed to mergings with small companions, or satellites captured by the disc. The material that constitutes it would then be either from the pre-existing thin disc, which has been puffed up by the merging, or directly from the companion, which is disrupted and adopts the orientation of the initial thin disc, or from both (e.g. Walker 1996; Penarrubia 2006). Either way, thick discs are attributed to nurture.

7.2. Shells

Shells around an elliptical galaxy can be well explained as due to the disruption of a small companion falling in the elliptical (see Athanassoula & Bosma 1985, for a review). Similarly, small central discs in such galaxies can be due to gas-rich infalling companions.

7.3. Warps

Although several attempts have been made to explain warps as due to nature, I will here focus on the nurture origin, which is more generally followed. Two such possibilities have been mainly considered. The first possibility (Ostriker & Binney 1989; Quinn & Binney 1992; Debattista & Sellwood 1999; Jiang & Binney 1999; Shen & Sellwood 2006) is that warps are due to cosmic infall. If this reorientates the outer parts of the halo by several degrees per Gyr, the disc will develop a warp with properties similar to those observed.

The second and most straightforward way of producing warps is through the tidal interaction with a close companion, as has been witnessed in a large number of simulations. If this alternative is generally true, i.e. if this is the way that all warps are formed, then we should be able to observe around all warped discs a companion whose mass and orbit can account for the warp. NGC 4013 was for a long time believed to be a counterexample to this possibility. Yet deep imaging in Martinez-Delgado et al. (2009) showed the debris of a past companion, so that even in this case the warp could be tidally generated.

7.4. Bridges and tails

Spectacular examples of such structures can be seen in M51, or the antennae. After the pioneering work of Toomre & Toomre (1972) and the many other studies that followed it, it has become clear that these structures are due to gravitational interactions, i.e. are due to nurture.

8. Summary

I discussed the possible formation mechanisms of structures and substructures in galaxies, focusing on whether their origin is due to nature or to nurture. In most cases, there is more than one alternative. A few structures can be explained only by a mechanism relying on nurture, but none uniquely only to nature.

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