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THE FORMATION OF LARGE GALACTIC DISKS: REVIVAL OR SURVIVAL?

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Abstract. Using the deepest and the most complete set of observations of distant galaxies, we investigate how extended disks could have formed. Observations include spatially-resolved kinematics, detailed morphologies and photometry from UV to mid-IR. Six billion years ago, half of the present-day spiral progenitors had anomalous kinematics and morphologies, as well as relatively high gas fractions. We argue that gas-rich major mergers, i.e., fusions between gas-rich disk galaxies of similar mass, can be the likeliest driver for such strong peculiarities. This suggests a new channel of disk formation, e.g. many disks could be reformed after gas-rich mergers. This is found to be in perfect agreement with predictions from the state-of-the-art ΛCDM semi-empirical models: due to our sensitivity in detecting mergers at all phases, from pairs to relaxed post-mergers, we find a more accurate merger rate. The scenario can be finally confronted to properties of nearby galaxies, including M31 and galaxies showing ultra-faint, gigantic structures in their haloes.

Keywords: galaxies; galaxy formation; spirals; M31

1 Introduction

Seventy two percent of local galaxies with $M_{stellar} > 2\times 10^{10}$ $M_\odot$ are disk-dominated. Thin disks are fragile to collisions with other galaxies that can easily destroy them (Toth & Ostriker 1992). ΛCDM predicts a high level of merger activity on all scales and this makes it difficult for the corresponding simulations to reproduce such a large number of large disks with small bulge fraction. This is illustrated by the tidal torque theory (Peebles 1976; White 1984), which assumes that the angular momentum of disk galaxies had been acquired by early interactions: related simulations provide too small disks with too small angular momentum, compared to observations.

What do we learn from observations? The situation seems somewhat confused with discordant results on the real impact of mergers, either minor or major. Thus, the role of mergers in the evolution of disk galaxies remains uncertain. Discordant results can be attributed to the following reasons:

- differences between galaxy sample selection, for example various stellar/baryonic mass ranges;
- different methodologies to characterize a merger (pair technique, automatic classification methods such as concentration-asymmetry and GINI-M20, decision tree methods, etc.);
- different methodologies to classify "normal" galaxies, especially disk galaxies: either automatic classification or systematic comparison to local templates and use of spatially-resolved kinematics to verify the presence of rotation;
- the depth and spatial resolution of the images to which the above methodologies have been applied.

In this paper, we present the results of the IMAGES survey that encompasses the deepest and the most complete set of measurements of galaxies at z=0.4-0.8. The explicit goal of IMAGES is to gather enough constraints z=0.4-0.8 galaxies to directly link them to their descendants, the local galaxies. Its selection is limited by an absolute J-band magnitude ($M_J(AB) <$ -20.3), a quantity relatively well linked to the stellar mass (Yang et al. 2008, hereafter IMAGES-I), leading to a complete sample of 63 galaxies with $M_{stellar} > 1.5$ 10^{10} $M_\odot$, and with an average value similar to the Milky Way mass. The set of measurements includes:

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- ACS imagery from GOODS (3 orbits in b, v, i and z) to recover color-morphology comparable to the depth and resolution (<400 pc) of the SDSS (Delgado-Serrano et al. 2010);
- spatially-resolved kinematics from FLAMES/GIRAFFE (from 8 to 24hrs integration) to sample gas motions at $\sim$ 7 kpc resolution scale (IMAGES I);
- deep VLT/FORS2 observations (3hrs with two grisms at R=1500) to recover the gas metal abundances (Rodrigues et al. 2008, hereafter IMAGES-IV);
- Spitzer 24μm observations of the GOODS field to estimate the extinction-corrected star formation rates as well as Spitzer IRAC and GALEX deep observations of the field to provide photometric points to constraint the spectral energy distribution.

Taken together, these measurements ensure that the IMAGES sample is collecting an unprecedented amount of data with depth and resolution comparable to what is currently obtained for local galaxies. For example IMAGES is hardly affected by cosmological dimming, because 3 HST/ACS orbits ensure the detection of the optical disk of the Milky Way after being redshifted to z $\sim$ 0.5. In section 2 we present the morphological and kinematical properties of distant galaxies, and propose a scenario to relate them to their present-day mass analogues. In section 3 we discuss these results in the context of the ΛCDM model. In section 4 we verify whether this link is robust when compared to the detailed observations of nearby spirals and their haloes.

2 What is the past history of giant spiral galaxies?

Progenitors of present-day giant spirals are similar to galaxies having emitted their light $\sim$ 6 Gyr ago, according to the Cosmological Principle. The IMAGES sample is then unique to sample these progenitors: Fig. 1 presents the results of a morphological analysis of 116 SDSS galaxies (top) and of 143 distant galaxies including those from IMAGES (bottom) for which depth, spatial resolution and selection are strictly equivalent (Delgado-Serrano et al. 2010). Methodology for classifying the morphologies follows a semiautomatic decision tree, which uses as templates the well known morphologies of local galaxies that populate the Hubble sequence, including the color of their sub-components (Delgado-Serrano et al. 2010, see their Fig. 4). Such a conservative method is the only way for a robust morphological classification, and indeed, the Delgado-Serrano et al. (2010) results are similar to those of experts in the field (e.g., van den Bergh 2002). The second step in classifying the nature of distant galaxies is to compare the morphological classification to the spatially-resolved kinematics. The latter provides a kinematical classification of velocity fields ranging from rotation, perturbed rotation or complex kinematics (Flores et al. 2006; Yang et al. 2008). Neichel et al. (2008) robustly established that peculiar morphologies coincide well with anomalous kinematics and vice versa: 95% and 86% of galaxies with complex kinematics and perturbed rotations have peculiar morphologies, respectively. On the other hand 80% of galaxies with robust rotation show spiral morphologies.

Neichel et al. (2008) also verified whether such a situation is preserved when using automatic classification methods such as concentration-asymmetry and GINI-M20. The answer is negative, and these methods overestimate the number of spirals by a factor of two, a problem already identified by Conselice et al. (2005). Such methods are interesting because they can be applied to a much larger number of galaxies than the 143 galaxies studied by Delgado-Serrano et al. (2010). However their limitations in distinguishing peculiar from spiral morphologies lead to far larger uncertainties than the Poisson statistical noise in Delgado-Serrano et al. (2010).

Fig. 1 presents the global evolution of the Hubble sequence during the past 6 Gyr. The link between the two Hubble sequences (past and present-day) is marginally affected by very recent mergers (number density evolution) or by stellar population evolution (luminosity or stellar mass evolution). While the former is limited by the expected decrease of mergers at recent epochs, the latter is precisely compensated by the evolution of the $M_{stellar}/L_K$ ratio (Delgado-Serrano et al. 2010, see their sect. 5.3). As a results the fraction of E/S0 has not evolved, while half of the spirals were not in place 6 Gyr ago, or in other words, half of the spiral progenitors have either peculiar morphology and/or anomalous kinematics.

The remarkable agreement between morphological and kinematical classifications implies that dynamical perturbations of the gaseous component at large scales are linked to peculiar morphological distribution of the stars. This indicates a common process at all scales for gas and stars in these galaxies. Which physical processes may be responsible of this morpho-kinematic behavior? Most anomalous galaxies reveal peculiar large-scale gas motions that cannot be caused by minor mergers: although they can affect locally the dispersion map they do not affect the large scale rotational field over several tens of kpc (Puech et al. 2007). Internal fragmentation

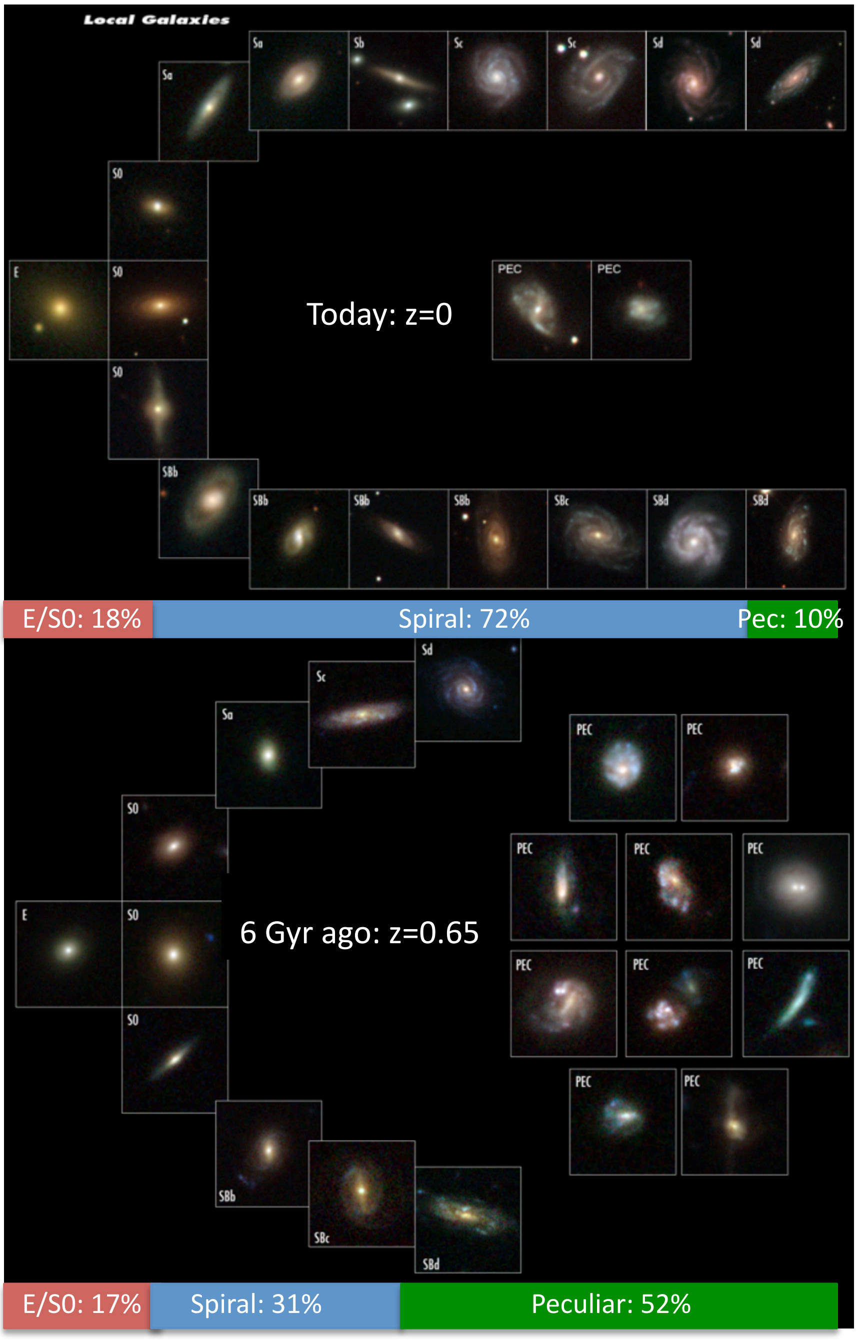

Fig. 1. An adaptation of the Delgado-Serrano et al. (2010) Figure 5: Present-day Hubble sequence derived from the local sample (top) and past Hubble sequence derived from the distant sample (bottom). Each stamp represents approximately 5% of the galaxy population. Galaxy fractions are given in percentage.

is limited because less than 20% of the sample show clumpy morphologies according to Puech (2010) while associated cold gas accretion tends to vanish in massive halos at z<1, with $<1.5\ M_{\odot}$/yr at z$\sim$ 0.6 (Keres et al. 2009; Brooks et al. 2009). Finally perturbations from secular and internal processes (e.g. bars or spirals) are too small to be detected by the "large-scale" spatially resolved spectroscopy of IMAGES. Major mergers appear to be the most likely mechanism to explain the above properties of anomalous galaxies and indeed it is the only way to explain the strong redshift evolutions of the scatter of the Tully-Fisher relation (Puech et al. 2008, 2010) and of the scatter of the luminosity-metallicity relation (Hammer et al. 2001; Liang et al. 2006; Rodrigues et al. 2008).

This has led our team to test and then successfully model five of the IMAGES galaxies as consequences of major mergers (Peirani et al. 2009; Yang et al. 2009; Hammer et al. 2009b; Puech et al. 2009; Fuentes-Carrera 2010) using hydrodynamical simulations (GADGET2 and ZENO). However the amount of data to be reproduced per galaxy is simply enormous, leading to 21 observational constraints to be compared to 16 free model parameters in the specific case of Yang et al. (2009). We have then limited our subsequent analysis to the 33 galaxies belonging to the CDFS for reasons of data homogeneity. A comparison of their morpho-kinematics properties to those from a grid of simple major merger models based on Barnes (2002), provided convincing matches in about two-thirds of the cases. This implies that a third of z=0.4-0.75 spiral galaxies are or have been potentially involved in a major merger. Since major mergers can easily destroy thin rotating disks, this creates an apparent tension between the large fraction of present-day disks and their survival within the ΛCDM (e.g., Stewart et al. 2009). On the other hand this appears consistent with expectations from Maller, Dekel, & Somerville (2002) i.e., that: "the orbital angular momentum from major mergers may solve the spin catastrophe".

3 Are disks surviving or reviving after a merger?

Barnes (2002) described the re-formation of disks after major mergers, assuming a Milky Way gas fraction (12%) in the progenitors. With larger gas fraction the rebuilt disk can be more prominent and in case of extremely high gas fraction, could dominate the galaxy (Brook et al. 2004; Springel & Hernquist 2005; Robertson et al. 2006). After a gas-rich merger a prominent gaseous disk can form, which could be the progenitor of some present-day disks. These models could appear to be of relatively limited significance given the very large assumed gas fractions (up to 90%). In fact observations of distant galaxies indicate gas fractions that may exceed 50% at z∼ 1.5-2 (Daddi et al. 2010; Erb et al. 2006), and it is unclear whether or not higher gas fractions may be common at those redshifts. It could be possible to circumvent this difficulty, perhaps through tuning some physical ingredients in the models, e.g. a feedback more efficient within the central region (Governato et al. 2009), or a star formation less efficient at earlier epochs (Hammer et al. 2010). Such methods are not necessarily wrong, but their additional value is limited since they have been designed intentionally to preserve the gas before the merger or to remove the gas from the central regions to redistribute it to the newly formed disk.

Important progress is expected on both observational and theoretical sides: a confirmation/infirmation of the IMAGES result has to be done by an independent team, although it needs to avoid automatic procedures that often degrade the significance of astrophysical data. With this, the so numerous unstable, anomalous progenitors of present-day spirals, with behavior so similar to major mergers will be the major constraint for disk galaxy formation theories. Why IMAGES is finding so many galaxies (a third to half of the spiral progenitors) that can be attributed to a major merger phase? In fact the morpho-kinematic technique used in IMAGES is found to be sensitive to all merger phases, from pairs to post-merger relaxation. Puech et al. (2011) has compared the merger rate associated with these different phases, and found a perfect match with predictions by state-of-the-art ΛCDM semi-empirical models (Hopkins et al. 2010) with no particular fine-tuning. Thus, both theory and observations predict an important impact of major mergers for progenitors of present-day spiral galaxies: the Hubble sequence made of elliptical and spiral galaxies could be just a vestige of merger events (Hammer et al. 2009b).

Athanassoula (2010) described the different physical processes leading to the formation of elliptical and spiral galaxies. Since the "merger hypothesis" by Toomre &Toomre (1972), it is often accepted that elliptical galaxies may be the product of a major merger between two gas-poor spiral galaxies. It appears more and more plausible that some spiral galaxies could also result from a gas-rich merger of two smaller spiral galaxies. An increasing number of cosmological simulations lead to the formation of late-type disk galaxies after major mergers (Font et al. 2011; Brook et al. 2011). There are still some important questions on precisely how galaxies dominated by thin disks can be generated by such violent processes. We also need to examine whether this scenario can be reconciled with observations of large disks in present-day spiral galaxies.

4 Can a rich merger history be reconciled with observations of nearby spirals?

Having a tumultuous merger history 6 Gyr ago should have left some imprints in many present-day spiral galaxies. Let us consider our nearest neighbour, M31. Quoting van den Bergh (2005): "Both the high metallicity of the M31 halo, and the $r^{1/4}$ luminosity profile of the Andromeda galaxy, suggest that this object might have formed from the early merger and subsequent violent relaxation, of two (or more) relatively massive metal-rich ancestral objects." In fact the considerable amount of streams in the M31 haunted halo could be the result of a major merger instead of a considerable number of minor mergers (Hammer et al. 2010). This alternative provides a robust explanation of the Giant Stream discovered by Ibata et al. (2001): it could be made of stars returning from a tidal tail that contains material previously stripped from the lowest mass encounter prior to the fusion. In fact stars in the Giant Stream (Brown et al. 2007) have ages older than 5.5 Gyr, which is difficult to reconcile with a recent collision that is expected in a case of a minor merger (e.g., Font et al. 2008). This constraint has let Hammer et al. (2010) to reproduce the M31 substructures (disk, bulge & thick disk) as well as the Giant Stream after a 3:1 gas-rich merger for which the interaction and fusion may have occurred 8.75 ± 0.35 and $5.5\ \pm0.5$ Gyr ago, respectively. Besides this, the Milky Way may have had an exceptionally quiet merger history (e.g., Hammer et al. 2007).

Further away from the Milky Way, Martínez-Delgado et al. (2010) conducted a pilot survey of isolated spiral galaxies in the Local Volume up to a low surface brightness sensitivity of ~ 28.5 mag/arcsec^2 in the V band. They found that many of these galaxies have loops or streams of various shapes. These observations are currently considered as evidencing the presence of minor mergers in spiral galaxies. For example, NGC5907 is showing the most spectacular loops thar have been modelled by a very minor merger (mass ratio is 4000:1) by Martínez-Delgado et al. (2008). Instead of that, Wang et al. (2011) recently succeed to model the NGC5907 galaxy and their associated loops by assuming a 3:1 gas-rich major merger during the past 8-9 Gyr, for which the loops are caused by returning stars from tidal tails.

There is still a considerable work to do to establish firmly which process is responsible for the tumultuous history of nearby spirals that is imprinted into their haloes. In most cases (Martínez-Delgado et al. 2010), there is no hint of the residual of the satellite core that is responsible of the faint structures discovered in the nearby spiral haloes. If confirmed, this may be problematic for the minor merger scenario. On the other hand, the major merger alternative still faces the problem of reconstructing thin disks that are consistent with the observed ones. However, numerical simulations are rapidly progressing, and AREPO-like simulations (Keres et al. 2011) provide much higher resulting angular momentum when compared to GADGET, and thus thin disks that could resemble much more to the observed ones. Another important advance is provided by Spitzer observations of edge-on spirals (Comerón et al. 2011), indicating more massive thick disks than previously reported, these structures being naturally expected in the case of major mergers.

5 Conclusion

The first proposition that major mergers could be responsible of the re-formation of $\sim 70\%$ of present-day galactic disks (Hammer et al. 2005), was at that time only based on the coeval evolution of morphologies, star formation density and merger rate. Subsequent morpho-kinematic analyses are providing a much more robust confirmation and accuracy to this scenario. It now receives much more attention from both the theoretical side – with an impressive number of articles aiming at reforming spiral galaxies after a collision – and from the observational side – with a large number of papers discussing the influence of mergers in galaxy formation.

Here we plead for the use of a complete set of (observationally), well-determined parameters to characterize distant galaxies. Galaxies are made of hundred billions of stars and distant galaxies contain an equivalent amount of mass of gas. As such they are complex objects and, to be relevant, analyses should include detailed characterizations of their morphologies, kinematics, star formation and gas and stellar masses. Very large surveys are very powerful in gathering huge number of galaxy spectra, although they often lead to oversimplifications related to automatic procedures in characterizing galaxies.

Having characterized distant galaxies with unprecedented details through the IMAGES project, this supports that a third to a half of spiral progenitors were in a merger phase at z=[0.4-0.75]. This can potentially reconcile the ΛCDM scenario, predicting a large fraction of mergers, with the very large fraction of large disks in present-day galaxies with masses similar to that of the Milky Way. Consequences of a disk reformation after a merger episode could have important impacts in modern cosmology.

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