Mem. S.A.It. Suppl. Vol. 25, 17
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Memorie della
Supplementi

Thick disks and secular evolution

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Abstract. The detailed study of the different structural components of nearby galaxies can supply vital information about the secular, or internal, evolution of these galaxies which they may have undergone since their formation. We highlight a series of new studies on the thick and thin disk components of galaxies, based on the analysis of mid-infrared images of a sub-sample of the over 2000 local galaxies in the *Spitzer* Survey of Stellar Structure in Galaxies (S^4G). In particular, we show that the thick and thin disk components are roughly equally massive, and that their properties indicate that the thick disks mostly formed *in* situ, and to a much lesser degree as a result of galaxy-galaxy interactions. The occurrence of truncations and anti-truncations, studied separately in the thin and thick disk components, yields further constraints on the relative thin and thick disk masses, and on the evolutionary paths of their host galaxies.

Key words. Galaxies: evolution, Galaxies: formation, Galaxies: structure, Galaxies: spiral, Galaxies: kinematics and dynamics

1. Introduction

Two distinct concepts are nowadays considered within the overall context of galaxy evolution: early or cosmological evolution in the early stages of the Universe, which is fast and driven primarily by mergers and interactions, and secular or internal evolution, which is slower and happens under the influence of internal rather than external actors. It is important to investigate secular evolution because it allows us to understand the structure, dynamics, and properties of the galaxies, but also to test cosmological models of galaxy formation and early evolution. The detailed study of nearby galaxies is the most important approach in studying secular evolution.

Tracers of secular evolution in local galaxies include structural components of galaxies, such as bars, spiral arms, rings, or ovals, but also thick disks. In this short paper, we will briefly review new results on thick disks in edge-on galaxies, as obtained from new observations. Much more detailed reviews of the overall topic of galaxy evolution, and in particular secular evolution, can be found in Falcón-Barroso & Knapen (2012).

Thick disks in spiral galaxies are seen in edge-on disk galaxies as an excess of light, typically at a few scale heights of the traditional thin disk component. The existence of a thick disk component in external galaxies

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Send offprint requests to: J. H. Knapen has been known since the late 1970's (Burstein 1979; Tsikoudi 1979), and in the 1980's the thick disk of our own Galaxy (Gilmore & Reid 1983) has been discovered and characterised. We now know that thick disks are nearly ubiquitous among disk galaxies (Yoachim & Dalcanton 2006; Comerón et al. 2011a).

The origin of thick disks is not yet known, and is a matter of intense debate. There are three main classes of models to explain the formation of a thick disk component (see Comerón et al. 2011a, 2012 for references). The first is by the heating of the originally thin disk, which increases the stellar velocity dispersion. This heating can have an internal or external origin. The second is that the thick disk is a consequence of *in situ* star formation, or of star formation in very massive star clusters, with a high initial velocity dispersion. The third class of models predicts that the thick disk is formed through the accretion of stars from disrupted small galaxies during the build-up phase of the galaxy. Most of these models tie the origin of the thick disk very closely to the early cosmological evolution of galaxies, and many also imply significant evolution of the thick disk as a galaxy evolves secularly. This is the reason why thick disks are so interesting, and important to study in the context of both cosmological and secular galaxy evolution.

2. Edge-on galaxies in the Spitzer Survey of Stellar Structure in Galaxies

The *Spitzer* Survey of Stellar Structure in Galaxies (S^4G, Sheth et al. 2010) is an ambitious survey aimed at obtaining mid-infrared images of a large, representative sample of nearby galaxies. We use both archival and new images taken with the IRAC camera on the *Spitzer Space Telescope*, the latter obtained during the 'warm' phase of *Spitzer* operations. We obtained deep, wide-field images in the 3.6 and $4.5\,\mu$m bands of over 2000 large, nearby, and bright galaxies outside the Galactic plane ($v_{\rm radio} < 3000$ km/s which corresponds to $d <$ 40 Mpc for $H_0 = 75$ km/s/Mpc, Galactic latitude $|b| > 30^{\rm o}$, $m_{B,{\rm corr}} < 15.5$ and blue light isophotal diameter $D_{25} > 1.0$ arcmin).

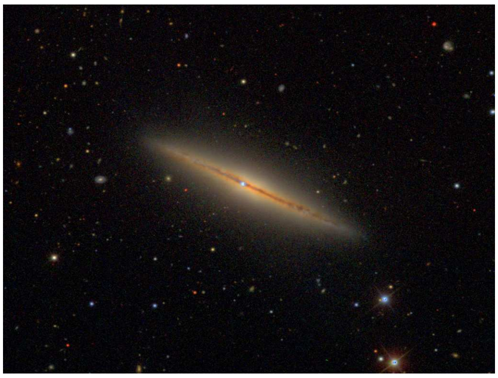

Fig. 1. Sloan Digital Sky Survey real-colour image of the highly inclined galaxy NGC 4013. Reproduced from NED, image by David W. Hogg, Michael R. Blanton, and the Sloan Digital Sky Survey Collaboration.

The S^4G sample is thus a representative selection of nearby galaxies across a wide range in mass and morphological type. The various S^4G data reduction pipelines deal with basic image reduction and mosaicing, masking of foreground stars and image defects, determining the residual background level and production of radial profiles and basic morphological parameters, multi-component decomposition, and the derivation of mass maps (see Sheth et al. 2010 for an overview).

For the study described here, we selected galaxies with morphological types $-3 \leq T < 8$ which appear edge-on, rejecting those galaxies which have distorted morphologies or extended envelopes, or which could for other reasons not be adequately fitted. To confirm the edge-on orientation of candidate sample galaxies, we referred wherever possible to real-colour images from the Sloan Digital Sky Survey, such as the one shown in Fig. 1.

Our final sample is of 70 galaxies. For these galaxies, we compare observed luminosity profiles perpendicular to the galaxy mid-plane with a grid of synthetic profiles, derived by modelling sets of coupled stellar and gaseous disks in equilibrium (see Comerón et al. 2011a, 2012 for details). This comparison allows us to define the properties and extent of the thick disk component, which in turn al-

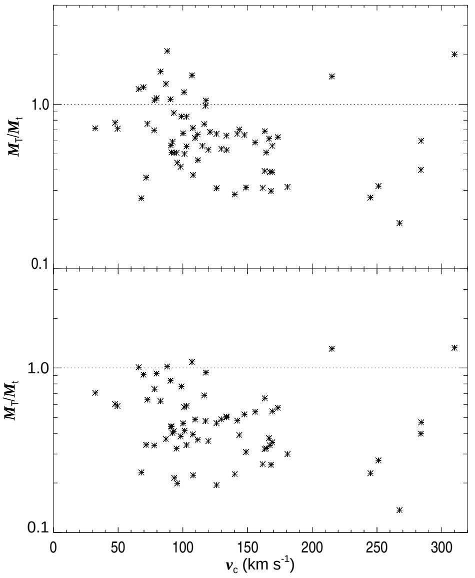

Fig. 2. Ratio of the thick and the thin disk mass, M_T/M_t, as a function of the circular velocity, v_c. Top panel: calculated using only stellar thin disk and thick disks; bottom panel: with a gas disk included in the thin disk. Reproduced with permission from Comerón et al. (2012).

lows us to study thin-disk and thick-disk dominated radial profiles of our sample galaxies (see Section 4).

3. Thick and thin disk masses

The advantages of using the imaging from the S^{4}G survey are that it provides a uniform data set, deep imaging, and a large parent sample. Our results so far include the characterisation of the subtle thick disk component in the galaxy NGC 4244, a galaxy which hitherto had appeared to be the exception to the rule that all disks had a thick component (Comerón et al. 2011b), and the finding of not just one, but two separate thick disk components in the galaxy NGC 4013 (Fig. 1; Comerón et al. 2011b).

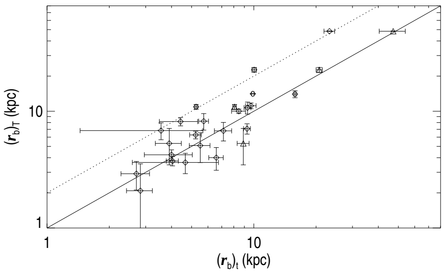

Fig. 3. Truncation radii of thick disks as a function of truncation radii for thin disks. The solid line traces a one-to-one relation between the thin and the thick disk truncation radius and the dotted lines indicates thick disks with a truncation radius two times larger than that of the thin disk. Triangles stand for the second truncation in profiles of certain galaxies. Error bars represent 2σ fitting errors. Reproduced with permission from Comerón et al. (2012).

But the most interesting and novel results come from the analysis of our sample of 70 edge-on galaxies (expanded from an original sample of 46 – Comerón et al. 2011a). Comparing our observed light profiles with a grid of models of coupled disks in equilibrium, we find that the mass of the thick disk component in many galaxies – especially low-mass ones – is comparable to that in the thin disk component (Fig. 2; Comerón et al. 2011a, 2012). The main reason for the increased thick disk mass as compared to previous works is our use of a physically based function, which assigns more mass to the thick disk than previously used *ad hoc* solutions such as the sech^2 function.

In general, high-mass galaxies have a thick disk with a low relative mass. These masses are compatible with the thick disk being formed secularly through the heating of a pre-existing thin disk. The thick disk mass is relatively higher in galaxies with low mass. In such galaxies, secular evolution mechanisms like dynamical heating are slower than in more massive counterparts and as a consequence have no time to build a thick disk in a Hubble-Lemaître time. So, their thick disk must have formed *in-situ*. In the context of this problem, the transition circular velocity between low- and high-mass galaxies is $v_c = 120\,\mathrm{km\,s^{-1}}$.

4. Thick and thin disk (anti-)truncations

We also used our sample of 70 inclined galaxies to study breaks in the radial profiles in the thick and thin disk components (Comerón et al. 2012). We are particularly interested in changes in the slopes of these profiles, which have been observed to become steeper (truncations) or shallower (anti-truncations) with radius (e.g., van der Kruit & Searle 1982; Erwin et al. 2005). It is still unclear to what extent these changes in slope are due to a threshold in the star formation, or a real drop in the stellar mass density of the disk associated with the maximum angular momentum of the stars (see also Martín-Navarro et al. 2012).

We find (Comerón et al. 2012) that thin disks truncate more often (77%) than thick disks (31%), but that when thick disks truncate, the radius at which the break occurs is comparable to that at which the break in the thin disk occurs, thus linking the origin and evolution of both disks.

About 40% of thin disks show an anti-truncation, or upward bending of their radial light profile. In most cases, however, these anti-truncations are artefacts, caused by the superposition of a thin and a thick disk, with the latter having a longer scalelength. We thus estimate the fraction of thin disks with a real anti-truncated radial profile to be less than 15% (Comerón et al. 2012).

5. Conclusions

The secular, or internal, evolution of galaxies which they may have undergone since their formation can be revealed by the detailed study of the different structural components of nearby galaxies. We have highlighted new studies of edge-on galaxies based on the analysis of mid-infrared images from the *Spitzer* Survey of Stellar Structure in Galaxies (S^4G). We have found that the thick and thin disk components of galaxies are roughly equally massive. Their properties indicate that thick disks mostly formed in situ, and to a lesser degree as a result of galaxy-galaxy interactions and secular evolution. The quality of the data allows us to study the occurrence of truncations and anti-truncations separately in the radial profiles of the thin and thick disk components, yielding further constraints on the relative thin and thick disk masses, and on the evolutionary paths of their host galaxies.

Acknowledgements. We thank our collaborators on the various projects described. Financial support by the European Commission through the DAGAL Network (PITN-GA-2011-289313) is gratefully acknowledged.

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