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Secular evolution in disk galaxies

Johan H. Knapen[1,2]

[1] Instituto de Astrofísica de Canarias, E-38200 La Laguna, Spain
[2] Departamento de Astrofísica, Universidad de La Laguna, E-38205 La Laguna, Tenerife, Spain

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 based on the analysis of mid-infrared images of over 2000 local galaxies which we are collecting within the *Spitzer* Survey of Stellar Structure in Galaxies (S^4G). In particular, we discuss new results on the thick and thin disk components of galaxies, which turn out to be roughly equally massive, and whose properties indicate that the thick disks mostly formed *in situ*, and to a lesser degree as a result of galaxy-galaxy interactions and secular evolution. We then briefly review recent research into rings in galaxies, which are common and closely linked to secular evolution of galaxies. Finally, we report on the research into local galaxy morphology, kinematics and stellar populations that we will perform over the coming four years within the EU-funded initial training network DAGAL (Detailed Anatomy of GALaxies).

1 Introduction

Galaxy evolution starts at an early stage in the young Universe, and we now understand that the early, or cosmological, evolution of galaxies is fast and to a significant extent driven by interactions and mergers. Once galaxies have been formed, they continue to evolve but more slowly and under the influence of internal rather than external actors. We refer to this slow evolution of galaxies as secular evolution. Understanding secular evolution from the detailed study of nearby galaxies is important not only 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.

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 two of these: thick disks and rings, 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 [10].

2 The *Spitzer* Survey of Stellar Structure in Galaxies

The *Spitzer* Survey of Stellar Structure in Galaxies (S^4G, [13]) is an ambitious survey aimed at obtaining mid-infrared images of a large, representative sample of nearby galaxies. We use the IRAC camera on the *Spitzer Space Telescope* for this, combining archival images obtained during the initial cooled phase of operation of the telescope with new images we obtained during the "warm" phase. We obtained deep, wide-field imaging in the 3.6 and 4.5 μm bands of over 2300 galaxies selected to be large, nearby, bright, and outside the Galactic plane ($v_{\rm radio} < 3000$ km s^{-1} which corresponds to $d < 40$ Mpc for $H_0 = 75$ km s^{-1} Mpc^{-1}), Galactic latitude $|b| > 30^{\rm o}$, $m_{B,\rm corr} < 15.5$ and blue light isophotal diameter $D_{25} > 1.0$ arcmin).

The S^4G sample contains galaxies across a wide range in mass and morphological type. A description of the various S^4G data reduction pipelines is given in [13]. These 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. All these different steps will be described in a series of technical papers. The images and various data products will soon be released publicly, starting with a first data release at the start of 2013.

3 Thick disks

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 has been known since the late 1970's [1, 14], and in the 1980's the thick disk of our own Galaxy [11] has been discovered and characterised. We now know that thick disks are nearly ubiquitous among disk galaxies [15, 5].

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. 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.

Our team is using the deep mid-infrared images from the S^4G survey to shed new light on the formation and evolution of thick disks. The advantages of this survey are that it

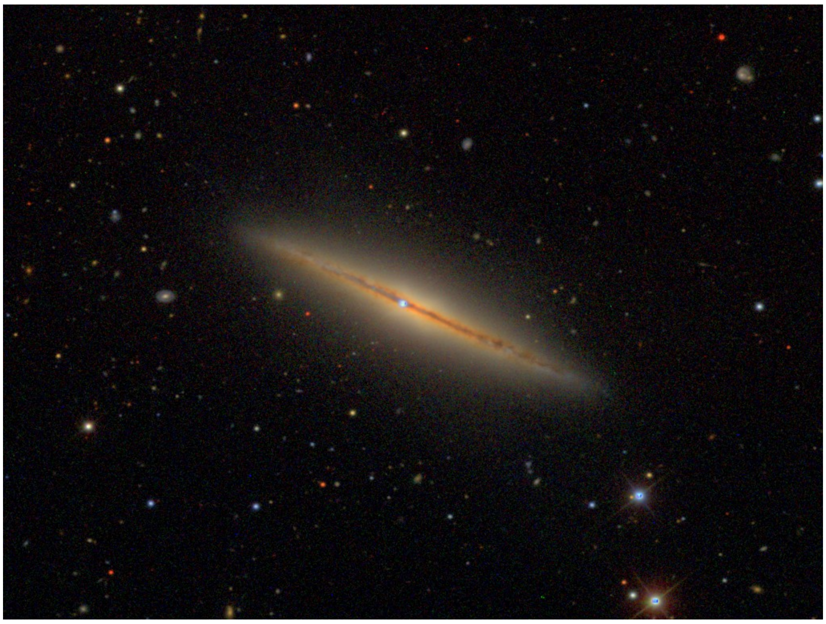

Figure 1: Sloan Digital Sky Survey real-colour image of the highly inclined galaxy NGC 4013. Reproduced from NED, image by David W. Hogg, Michael R. Blanton, and the Sloan Digital Sky Survey Collaboration.

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 [5], and the finding of not just one, but two separate thick disk components in the galaxy NGC 4013 (Fig. 1; [6]).

But the most interesting and novel results come from our study of a sample of 70 highly inclined galaxies (expanded from an original sample of 46 [7]). From a comparison of observed light profiles with a grid of models of coupled disks in equilibrium, we find that the mass of the thick disk component is comparable to that in the thin disk component [7, 8]. This implies that the most likely origin of the thick disk component is through *in-situ* star formation, starting at high redshifts. The thick disk mass is relatively higher in galaxies of lower mass, indicating a slower dynamical evolution which causes stellar thin disks to be younger and less massive than those in higher-mass galaxies. 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.

We also used our sample of 70 inclined galaxies to study breaks in the radial profiles in the thick and thin disk components [8]. We find 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 thin disk break 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% [8].

4 Rings

Rings are common in galaxies. Several kinds of rings are known: collisional, polar, and resonance rings, of which the latter is by far the most common. Resonance rings are prime tracers of the underlying dynamical structure of disk galaxies, in particular of orbital resonances and of manifolds. Rings are also indicators of angular momentum transport, and this is a key factor in secular evolution (see the various reviews in [10]).

Resonance rings come in three flavours, primarily defined by their size, namely nuclear, inner, and outer rings. From studies like those of [3, 2, 12] and [4, 9] we know that the radii of nuclear rings range from a few tens of parsec to some 3.5 kpc, while inner rings and outer rings have typical radii of 1.2 and 2.5–3 times the length of the bar. Many host galaxies of rings are barred, but so are most galaxies in general. Some 20% of all rings occur in non-barred galaxies, which implies that rings do not, or hardly, occur preferentially in barred galaxies [12, 4, 9]. In most non-barred ringed galaxies an oval, a past interaction, or even prominent spirals arms lie at the dynamical origin of the ring, but this needs additional scrutiny.

From an inventory of all known *nuclear* rings, the following conclusions was reached by [4]. Star-forming nuclear rings occur in $20 \pm 2\%$ of disk galaxies with $-3 < T < 7$; 18/96 occur in disk galaxies without a bar (19%); they are found in S0 to Sd galaxies, peaking in types Sab−Sb; when nuclear rings occur in barred galaxies, the ring radius is limited to one quarter of the bar radius; and stronger bars host smaller rings [12].

We are now using the *Spitzer* Survey of Spiral Structure in Galaxies (S^4G; [13]) to expand our survey to inner and outer rings [9]. We aim to study the relations between ring and host properties – as we did before for nuclear rings. We will use the S^4G sample size and image depth to reach further insight into the secular evolution of galaxies by measuring structural properties of rings, as well as those of components like bars and disks. We will then be able to tackle outstanding questions such as the origin of rings in non-barred galaxies, and how exactly ring properties are determined by the bar.

5 The Detailed Anatomy of GALaxies network

DAGAL (Detailed Anatomy of GALaxies) is an EU-funded Initial Training Network (ITN) in which we aim to exploit the combination of the very deep mid-infrared imaging of over 2300 local galaxies provided by S^4G with ground- and space-based UV, optical, and radio data. This combination should allow us to trace the distribution and motions of old and young stars, and gas, and hence to reveal the interplay between galactic dynamics, current star formation and star formation history. Detailed numerical modelling is an integral part of our work plan, and will allow us to relate the present structure and dynamics of galaxies to their formation and subsequent evolution.

Our network is comprised of the academic nodes Instituto de Astrofísica de Canarias (coordinating node), the University of Oulu, the Max Planck Institut für Astronomie in Heidelberg, the University of Groningen, the Laboratoire d'Astrophysique de Marseille, and the Universidad Autónoma de Madrid, and the private sector companies Springer, FRACTAL, and Specim. DAGAL has just hired a number of PhD students and postdocs, and will organise a series of events over the coming four years. Most of these summer and winter schools, training courses, and international conference will be open to participants from outside the network, and will be advertised in due course across the astronomical community.

6 Summary

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. In this short paper, we have highlighted a series of new studies based on the analysis of mid-infrared images of over 2000 local galaxies which form the sample of the *Spitzer* Survey of Stellar Structure in Galaxies (S^4G). We have found that 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. Rings in galaxies are common, and are closely linked to the properties of their host galaxies and bars, and thus to the secular evolution of galaxies. Finally, we report on the research into local galaxy morphology, kinematics and stellar populations that we will perform over the coming four years within the EU-funded initial training network DAGAL (Detailed Anatomy of GALaxies).

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