Angular Momentum across the Hubble sequence from the CALIFA survey

Jesús Falcón-Barroso[1,2], Mariya Lyubenova[3,4], Glenn van de Ven[4] and the CALIFA collaboration

[1]Instituto de Astrofísica de Canarias, Vía Láctea s/n, La Laguna, Tenerife, Spain
[2]Departamento de Astrofísica, Univ. de La Laguna, E-38205 La Laguna, Tenerife, Spain.
email: jfalcon@iac.es
[3]Kapteyn Astronomical Institute. University of Groningen Postbus 800, 9700 AV Groningen,
The Netherlands. email: lyubenova@astro.rug.nl
[4]Max Planck Institute for Astronomy, Königstuhl 17, 69117 Heidelberg, Germany. email:
glenn@mpia.de

Abstract. We investigate the stellar angular momentum of galaxies across the Hubble sequence from the CALIFA survey. The distribution of CALIFA elliptical and lenticular galaxies in the $\lambda_{Re} - \epsilon_e$ diagram is consistent with that shown by the Atlas[3D] survey. Our data, however, show that the location of spiral galaxies in this diagram is significantly different. We have found two families of spiral galaxies with particularly peculiar properties: (a) spiral galaxies with much higher λ_{Re} values than any elliptical and lenticular galaxy; (b) low-mass spiral galaxies with observed λ_{Re} values much lower than expected for their apparent flattening. We use these two families of objects to argue that (1) fading alone cannot explain the transformation of spiral to lenticular galaxies, and (2) that those low-mass spiral galaxies are in fact dark matter dominated, which explains the unusually low angular momentum.

Keywords. galaxies: elliptical and lenticular, cD - galaxies: evolution - galaxies: formation

1. The CALIFA survey

The CALIFA survey (Sánchez *et al.* 2012) provides a morphologically unbiased and statistically well defined view of the stellar and ionised gas properties of up to 600 galaxies in the redshift range $0.005 < z < 0.03$. The long wavelength coverage (3400–7300 Å) allows an accurate determination of the stellar population and ionised gas properties (Marino *et al.* 2013, Pérez *et al.* 2013).

In the work we present here we use the dedicated set of high-spectral resolution observations over 3750–4550 Å with the PPAK V1200 grating to derive high-quality stellar kinematics for a sample of 300 galaxies from elliptical E to spiral Sd morphological types. The wide field-of-view of the PMAS/PPAK instrument routinely covers well beyond the effective radius of the observed galaxies.

2. Angular momentum across the Hubble sequence

The combination of the apparent specific stellar angular momentum λ_{Re} and the ellipticity ϵ_e (Fig. 1) is an often used diagnostic tool to constrain the dynamical structure and evolution of galaxies. If all galaxies would be simple oblate isotropic rotators they should follow the red curve or lie to the left of it when viewed away from edge-on. The green curve indicates the demarcation line between fast rotator (FR, circles) and slow rotator (SR, squares) galaxies as inferred from the Atlas[3D] survey of elliptical (E) and lenticular (S0) galaxies (grey symbols, Emsellem *et al.* 2011).
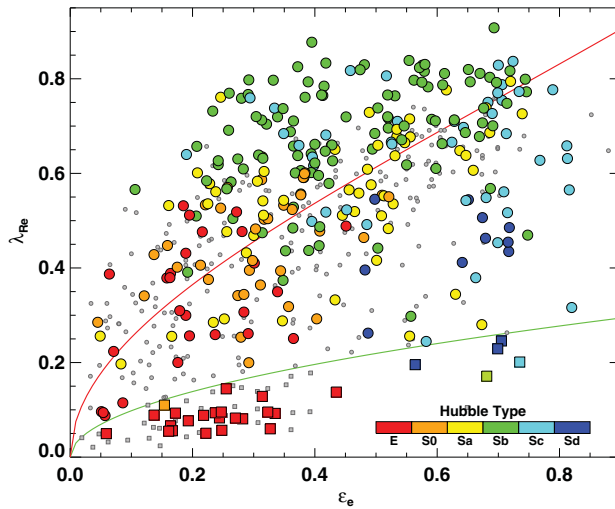
Figure 1. Apparent stellar angular momentum λ_{Re} as function of the ellipticity ϵ_e for 300 CALIFA galaxies color-coded by their morphological type. The green curve indicates the demarcation line between slow-rotator (squares) and fast- rotator galaxies (circles) as inferred from the Atlas^{3D} survey of elliptical (E) and lenticular (S0) galaxies, which are plotted as grey symbols (Emsellem *et al.* 2011). The red curve indicates the location in case galaxies were simple isotropic oblate rotators viewed edge-on.

With the CALIFA survey we are exploring for the first time in a homogeneous way all Hubble types. Spiral galaxies, as expected, are nearly all fast rotator galaxies. However, in comparison with E and S0 galaxies, especially the Sb galaxies reach very high λ_{Re} values, while several Sc and Sd galaxies exhibit low λ_{Re} values and fall just inside the slow rotator regime, in both cases having interesting consequences as discussed in the following sections.

3. Are lenticular galaxies faded spirals?

The angular momentum is set very early on in the life of galaxies, providing an important tool to distinguish between different scenarios of galaxy evolution. For example, a possible explanation of the observed morphology-density relation is the transformation of spiral into fast rotating lenticular galaxies through fading of the stellar populations (e.g. Cappellari *et al.* 2011). Under this scenario the light concentration and the angular momentum are not expected to change significantly.

We measured the apparent specific stellar angular momentum within the half-light radius λ_{Re} (left axis in Fig. 2) for our sample of 300 CALIFA galaxies. The light concentration based on SDSS r-band Petrosian radii (bottom axis) is a proxy for the relative flux in a spheroid (bulge+bar) and disk component (indicated in the top axis, following Gadotti 2009). We observe that Sa galaxies indeed overlap with S0/FR galaxies. Sc and Sd galaxies also have low λ_{Re} values, but their concentrations are too small, which taken together with their large gas supplies, makes it difficult to transform them into red sequence S0/FR galaxies by fading alone. Most of the Sb galaxies are in the green valley and hence their gas may have already been quenched. However, their λ_{Re} values are twice as large and light concentrations significantly smaller than S0/FR galaxies today. This hints to a picture in which the red sequence is being built over time from galaxies that contain disks that are substantially larger and have higher angular momenta.
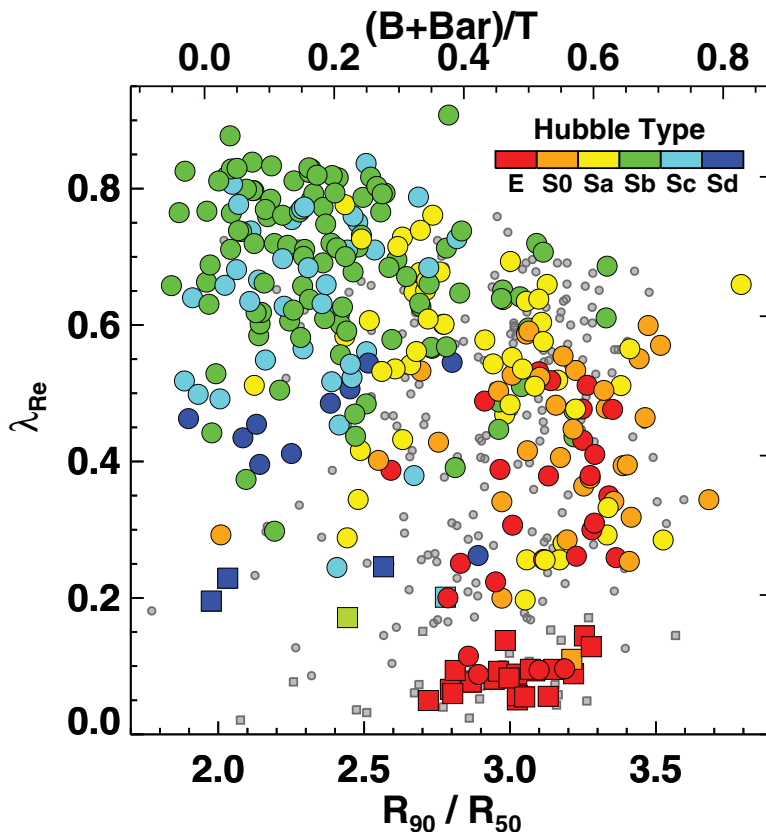
Figure 2. Apparent stellar angular momentum λ_{Re} versus light concentration R_{90}/R_{50} based on SDSS r-band Petrosian radii (bottom axis) as a proxy for the relative flux in a spheroid (bulge+bar) and disk component (top axis). Symbols and colors as in Fig.1.

4. Are low-mass spiral galaxies dark matter dominated?

The intrinsic mass distribution of a galaxy is one of the most consequential properties when it comes to its structure and evolution. However, the interplay between baryons and dark matter content is still under heated debate. We inferred the total mass of the 300 CALIFA galaxies of all morphological types by constructing axisymmetric dynamical Jeans models that fit the observed motions of their stars. The stellar mass was derived by fitting the galaxy spectra to stellar population models under the assumption of a Chabrier initial stellar mass function (IMF; González-Delgado *et al.* 2014). The resulting ratio of total-to-stellar mass inside the effective radius (R_e) is shown in Fig. 3 (vertical axis), with arrows indicating the approximate contribution of gas to the baryonic mass (Papastergis *et al.* 2012). On the high-mass end, the upturn above unity could be due to the presence of dark matter or a change toward an IMF even bottom-heavier than the Salpeter IMF as claimed in previous studies (e.g., Cappellari *et al.* 2012, La Barrera *et al.* 2013). However, for low-mass Sc-Sd galaxies there are no indications of a significant deviation from a Chabrier IMF, so that the high total-to-stellar mass ratios are believed to be the result of a high dark matter fraction even within R_e. This is further supported by their observed low λ_{Re} values, as the presence of a relatively large dark matter halo would support a dynamically hot but geometrically thin stellar disk.
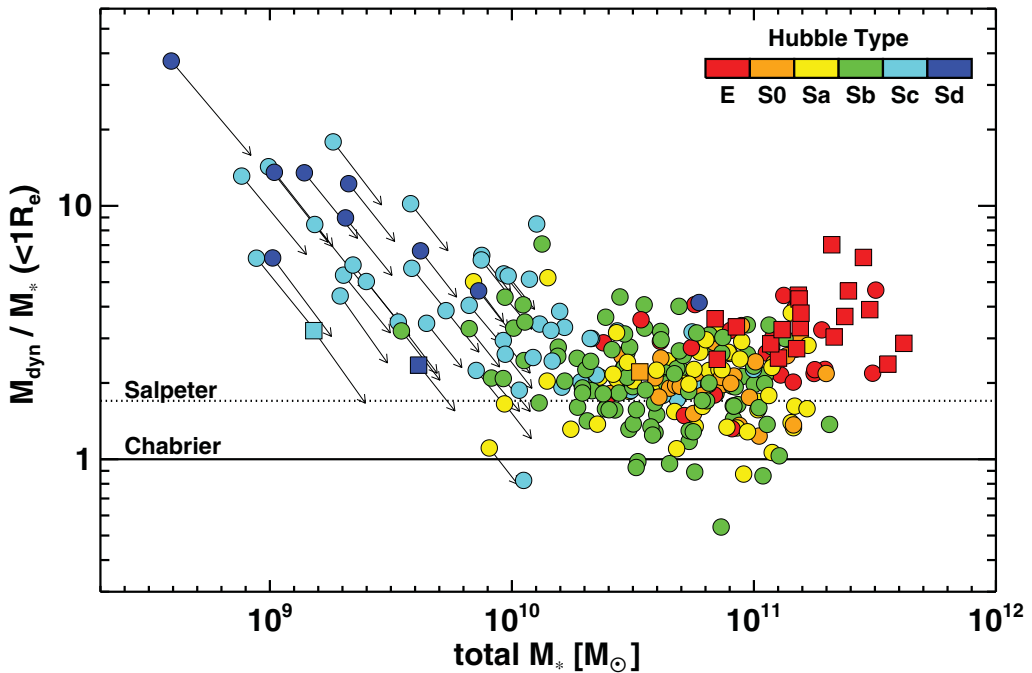
Figure 3. Ratio of total dynamical mass over stellar mass within the half-light radius versus total stellar mass for our sample of CALIFA galaxies. Horizontal lines mark normalizations for different stellar initial mass functions. Symbols and colors as in Fig.1.

Acknowledgements

References

Cappellari, M., *et al.*, 2011, *MNRAS*, 413, 813
Cappellari, M., *et al.*, 2012, *Nature*, 484, 485
Emsellem, E., *et al.*, 2011, *MNRAS*, 414, 888
Gadotti, D. A., 2009, *MNRAS*, 393, 1531
González Delgado, R. M., *et al.*, 2014, *A&A*, 562, A47
La Barbera, F., Ferreras, I., Vazdekis, A., de la Rosa, I. G., de Carvalho, R. R., Trevisan, M., Falcón-Barroso, J., & Ricciardelli, E., 2013, *MNRAS*, 433, 3017
Marino, R. A., *et al.*, 2013, *A&A*, 559, A114
Papastergis, E., Cattaneo, A., Huang, S., Giovanelli, R., & Haynes, M. P., 2012, *ApJ*, 759, 138
Pérez, E., *et al.*, 2013, *ApJ*, 764, L1
Sánchez, S. F., *et al.*, 2012, *A&A*, 538, A8
Walcher, C. J., *et al.*, 2014, *A&A*, 569, A1