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S0 Galaxies Are Faded Spirals: Clues from their Angular Momentum Content

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Abstract. We study the stellar specific angular momentum of the disc components for a sample of ten field/group unbarred lenticular (S0) galaxies from the CALIFA survey. The location of these discs in the $j_\star$-$M_\star$ plane allows us to obtain clues on the physical processes that lead to the formation of S0s from spirals. We found that eight of our S0 discs have a distribution in the $j_\star$-$M_\star$ plane that is fully compatible with that of spiral discs, while only two have values of $j_\star$ lower than the spirals. These two outliers show signs of recent merging. Our results suggest that merger and interaction processes are not the dominant mechanisms in S0 formation in low-density environments. Instead, S0s appear to be the result of secular processes and the fading of spiral galaxies after the shutdown of star formation.

Keywords. galaxies: elliptical and lenticular, cD, galaxies: evolution, galaxies: formation, galaxies: fundamental parameters (classification, colors, luminosities, masses, radii, etc.), galaxies: kinematics and dynamics

1. Introduction

S0 galaxies are characterized by properties that encompass multiple distinct classes of galaxies (Kormendy & Bender 2012). Their main features are that they have a bulge and a disc, like spiral galaxies, but lack cold gas and, as a consequence, star formation. The formation of S0 galaxies in clusters is well understood (e.g. Gunn & Gott 1972, Larson, Tinsley, & Caldwell C. N. 1980). There is not, instead, a general consensus on the physical mechanisms that lead to the formation of S0s in galaxy groups and in the field. This is the main motivation that prompted us to study group and field S0s. In low density environments, the numerous S0 formation mechanisms belong to two main categories: passive, in which the cold gas of the progenitor disc galaxy is slowly removed because of star formation (e.g. Armillotta, Fraternali, & Marinacci 2016, Bellstedt, *et al.* 2017), or violent, in which, as a result of mergers (Querejeta *et al.* 2015) or tidal interactions (Bekki & Couch 2011), the galaxy cold gas is rapidly consumed. These two scenarios cause distinctive changes to the properties of a spiral galaxy, in addition to quenching its star formation. Therefore, some of the structural properties that characterize S0 galaxies could provide a record of the physical mechanisms that have triggered their evolution.
Most previous work has focused on structural and morphological properties of S0s (Laurikainen *et al.* 2010; Head *et al.* 2014). In our analysis, we focused on the distribution of the S0 discs in the plane of specific angular momentum ($j_\star$) versus stellar mass ($M_\star$). Observations obtained with a number of techniques and instruments (e.g. Fall 1983; Romanowsky & Fall 2012, RF12 hereafter; Posti *et al.* 2018) show that different morphological types follow different relations between their $j_\star$ and $M_\star$. This allowed us to compare the distribution of our S0 discs in the $j_\star$-$M_\star$ plane with the relations and distributions that characterize spiral discs and ellipticals. This comparison gives important

Table 1. For each galaxy in our sample (column 1) we report the morphological types taken from visual classification by the CALIFA group (Walcher *et al.* 2014) (column 2) and the environment indication taken from NED (column 3). In column 4 we show the values of the angular momentum estimator, $j_{\star,\mathrm{RF}}$, as defined by RF12, while in column 5 we show the values of disc stellar masses, calculated under the assumptions of RF12.

Galaxy	Type	Environment	$j_{\star,\mathrm{RF}}$	$\log(M_{\star\mathrm{d,RF}}/M_{\odot})$
NGC 7671	S0	Pair	1359^{+120}_{-140}	10.91±0.05
NGC 7683	S0	Isolated	2048^{+186}_{-183}	10.81±0.03
NGC 5784	S0	Group	1408^{+283}_{-283}	11.22±0.02
IC 1652	S0a	Group	1003^{+81}_{-95}	10.63±0.10
NGC 7025	S0a	Isolated	3824^{+304}_{-512}	11.30±0.08
NGC 6081	S0a	Field	1979^{+113}_{-188}	11.03±0.02
NGC 0528	S0	Group	1470^{+166}_{-100}	10.78±0.07
UGC 08234	S0	Field	1833^{+167}_{-149}	10.97±0.27
UGC 10905	S0a	Field	3284^{+346}_{-378}	11.18±0.26
NGC 0774	S0	Field	535^{+101}_{-92}	10.92±0.02

clues to the formation of S0s, since the position of a galaxy in this plane is subject to a characteristic change with respect to its progenitors depending on the physical mechanisms associated to the two formation scenarios (passive or violent). A violent scenario should result in a distribution of S0s similar to that of ellipticals, while a passive scenario (consumption of cold gas) should give a distribution similar to that of spirals.

2. Sample and data

The sample of galaxies studied in this work is drawn from the CALIFA (Calar Alto Legacy Integral Field Area) Survey (Sanchez *et al.* 2012). We selected all the unbarred S0 or S0a galaxies from the CALIFA Second Public Data Release (Garcia-Benito *et al.* 2015). We selected only unbarred galaxies because both the photometric and spectroscopic decomposition are easier if only two components, bulge and disc, are included in the analysis. However, since the barred galaxies studied in RF12 do not show any systematic difference in the $j_\star$-$M_\star$ plane from the unbarred ones, we do not expect that an analysis of barred S0s results in significant deviations from the results found in this work. In Table 1, for each galaxy (column 1) we report the indication of the galaxy environment (column 3), taken from NED.

3. Bulge-disc decomposition

The estimation of the stellar angular momentum can be obtained from observations by measuring two quantities: the surface brightness and the rotation velocity.

Photometric bulge-disc decomposition. The galaxy decomposition in bulge and disc components is performed using the 2D fitting routine GALFIT (version 3.0.5, Peng *et al.* 2010). The surface-brightness distribution of each galaxy of the sample is modelled using a Sersic function for the bulge and an exponential function for the disc. Beside the parameters that define these two components, this decomposition method provides an estimate for the bulge-to-disc luminosity ratio, B/D, in each spatial pixel.

Kinematic bulge-disc decomposition. To derive the kinematics of bulge and disc components of our galaxy sample separately we devised a method that fits the galaxy spectrum at each location using a Markov Chain Monte Carlo routine (Rizzo, Fraternali & Iorio 2018). The main assumption of our fitting method is that the observed line-of-sight velocity distribution (LOSVD) is produced by the contribution of bulge and disc components that are, in principle, characterized by different kinematics. In order to describe these different kinematics, we model the LOSVD at each point of the galaxy with two Gaussians that have amplitudes fixed by the B/D given by our photometric decomposition and different means ($V_{\rm b}$, $V_{\rm d}$) and dispersions ($\sigma_{\rm b}$, $\sigma_{\rm d}$). The disc velocity fields, resulting from the application of our kinematic-decomposition software, are then analysed using the tilted-ring model (Begeman 1987), that allows to obtain the rotation curves for each of the disc of our sample.

4. Specific angular momentum and stellar masses

In order to compare the distribution of our S0 discs in the $j_\star$-$M_\star$ plane to the relations found by RF12 for all morphological types, we have estimated the values of $j_\star$ using their angular momentum estimator ($j_{\star,\rm RF}$), and their assumptions on the derivation of the stellar masses for the disc components ($M_{\star\,\rm d,RF}$).

5. Results and discussion

The derivation of $j_{\star,\rm RF}$ and of disc stellar masses $M_{\star\,\rm d,RF}$ allows us to compare the distribution of our S0 discs with the relation between these two quantities derived by RF12 for different morphological types. In Fig. 1 we show the best-fit found by these authors for different subtype spiral discs, S0 and elliptical galaxies. The relation shown for spirals (blue line) in Fig. 1 refers to their disc components, while the dashed black and

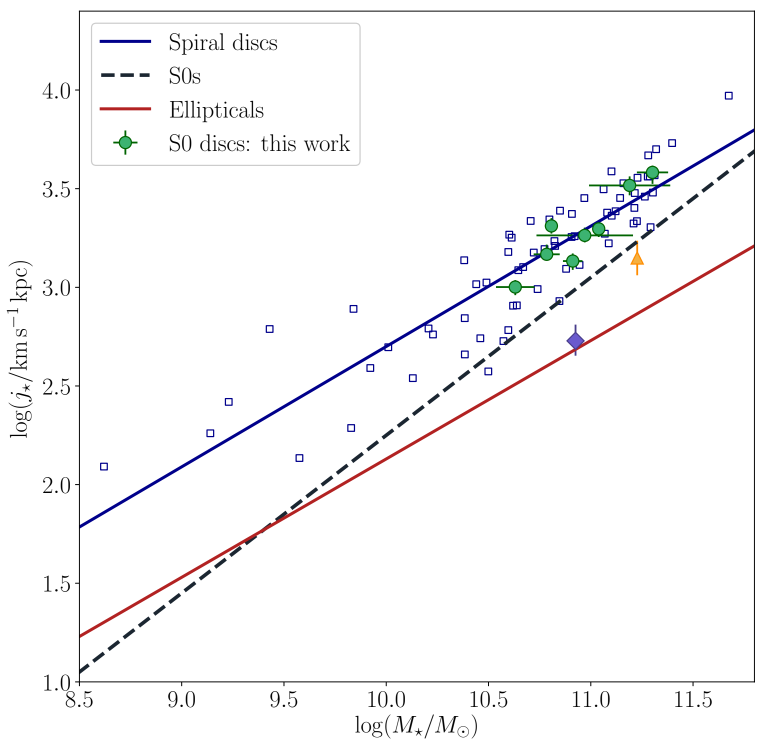

Figure 1. Distribution of the ten S0 discs of our sample in the $j_\star$-$M_\star$ log-space. Eight of our galaxies are represented by green circles, while for the two problematic cases we use an orange triangle (NGC 5784) and a violet diamond (NGC 0774). The lines represent the best-fit relation for $j_\star$-$M_\star$ found by RF12. The blue line, with a slope of ~ 0.6, refers to all spiral discs (Sa, Sb, Sc, Sd, Sm); the black dashed line, with a slope of ~ 0.8, was found for S0s (without separation of their bulge and disc components), while the red line, with a slope of ~ 0.6, is the best-fit for elliptical galaxies. The blue empty squares represent the spiral discs from RF12.

red lines for S0s and ellipticals refer to the best-fits for total $j_\star$-$M_\star$, without taking into account the decomposition in disc and bulge. From Fig. 1 we can see that eight of our ten S0 discs have a distribution in the $j_\star$-$M_\star$ plane that is in full agreement with those of spiral discs. Furthermore, their scatter is fully compatible with the intrinsic scatter $\sigma_{\log j_\star} = 0.17$ found by RF12, as showed also by the blue squares in Fig. 1 that represent the spiral discs in RF12. This result implies that spiral and S0 discs are dynamically similar, differing more in their morphological features mostly related to the presence or absence of star formation activity. The absence of a systematic shift towards lower values of $j_\star$, that would be caused by tidal interactions or mergers, suggests that the violent processes are not the dominant mechanisms that transform spirals into S0s. The position of our S0 discs in $j_\star$-$M_\star$ diagram, indeed, is fully compatible with the kinematic properties of the discs of spiral galaxies. Eight of our ten S0s can be considered as faded spirals, namely as a result of the quenching of their star formation and of the consecutive fading of the spiral arms. This passive fading appears as the most likely mechanism that does not change the disc $j_\star$ and $M_\star$ values. Only two galaxies, NGC 5784 and NGC 0774, are located systematically below the others. These two outliers are the only two galaxies that show signs of interaction/merger (see Rizzo, Fraternali & Iorio 2018 for further details). Our results on the position of S0 discs in $j_\star$-$M_\star$ diagram suggest that a passive scenario for the transformation from spiral galaxies to S0s is the most plausible. In this passive evolutionary scenario a spiral galaxy is transformed into an S0 because of the consumption of the cold gas reservoir. The exhaustion of the fuel for sustaining the star formation causes the fading and reddening of the disc, as well as the disappearance of its spiral arms. As a result, this quenched spiral galaxy is classified as an S0 and ends up on the red sequence.

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