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The sequence of spiral arm classes: Observational signatures of persistent spiral density waves in grand-design galaxies

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Abstract. We investigate how the properties of spiral arms relate to other fundamental galaxy properties. To this end, we use previously published measurements of those properties, and our own measurements of arm-interarm luminosity contrasts for a large sample of galaxies, using 3.6µm images from the Spitzer Survey of Stellar Structure in Galaxies. Flocculent galaxies are clearly distinguished from other spiral arm classes, especially by their lower stellar mass and surface density. Multi-armed and grand-design galaxies are similar in most of their fundamental parameters, excluding some bar properties and the bulge-to-total luminosity ratio. Based on these results, we discuss dense, classical bulges as a necessary condition for standing spiral wave modes in grand-design galaxies. We further find a strong correlation between bulge-to-total ratio and bar contrast, and a weaker correlation between arm and bar contrasts.

Keywords. galaxies: evolution, galaxies: fundamental parameters, galaxies: photometry, galaxies: spiral, galaxies: stellar content, galaxies: structure

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1. Spiral arm classes

The spiral structure in disc galaxies exhibits a great variety in its properties, such as the number of spiral arms, their amplitudes, pitch angles and the overall level of symmetry. Based on this visual appearance, spiral galaxies are classified in three different classes: *flocculent*, *multi-armed* and *grand-design* galaxies. Spiral arms in flocculent galaxies (e.g. NGC 2841, NGC 7793) appear short, patchy and very irregular, suggesting that their spiral structure is mainly caused by local gravitational instabilities of the old stellar component, gas, and the resulting formation of new stars (see e.g. Elmegreen & Elmegreen 1984). On the contrary, the strongly bi-symmetric spiral arms of grand-design galaxies (e.g NGC 1566, M 51) might well be caused by density waves on global scales, as initially suggested by Lindblad (1959). While density waves can be driven by bars or satellites (Athanassoula 1980), they might as well form self-consistently by the swing amplification mechanism (Toomre 1981) or the density wave theory (Lin & Shu 1964). Multi-armed galaxies (e.g. NGC 0628, NGC 1232) share properties with both flocculent and grand-design galaxies, for instance by showing bi-symmetric spirals in the centre which become more and more irregular at larger radii. Therefore, these galaxies are usually considered an intermediate case (see e.g. Elmegreen & Elmegreen 1984, 1995).

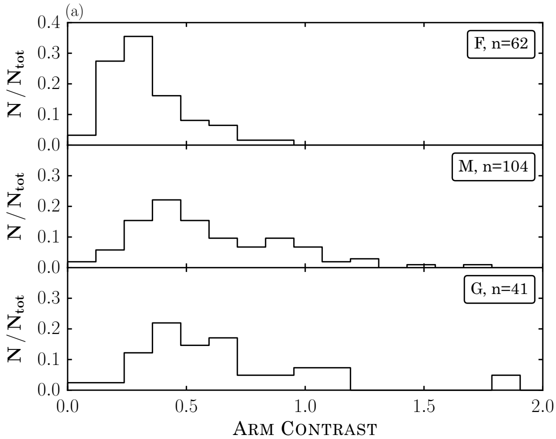

Figure 1. Distributions of arm contrasts for flocculent (*upper panel*), multi-armed (*middle panel*), and grand-design (*lower panel*) galaxies.

While the different processes that might trigger spiral structure are somewhat well understood, it still remains unclear why different mechanism dominate in different galaxies. In other words, how are the processes that cause the spiral structure related to the fundamental properties of their host galaxies? In Bittner *et al.* (2017) we perform a thorough comparison of the spiral arm strength and various fundamental galaxy properties, including bars and disc breaks. In the following, we summarise the main results, provide clear evidence that distinguishes flocculent galaxies from the other spiral arm classes, and present observational signatures consistent with long-lasting spiral density waves in grand-design galaxies.

2. Properties of discs in spiral galaxies

Spiral Arm Contrasts In order to quantify the visual classification in the spiral arm classes, we parametrize the strength of the spiral arms by their arm-interarm intensity contrast. To this end, we exploit a subsample of 288 galaxies obtained with the Spitzer Survey of Stellar Structure in Galaxies (S^4G; Sheth *et al.* 2010). In particular, we use 3.6μm observations, as these are less sensitive to dust emissions and highlight the old stellar component. All images are transformed into polar coordinates and the arm and interarm regions identified at various radii. By computing the ratio of the intensities, we obtain radial contrast profiles. The median of this profile in the radial range of the disc component, as determined by multi-component photometric decompositions (Salo *et al.* 2015), represents the resulting arm-interarm contrast.

In Fig. 1, we show the distributions of the spiral arm contrasts separated by spiral arm class. Surprisingly, the increase in spiral arm strength from flocculent to grand-design galaxies is not as significant as expected from the visual classification. In fact, only flocculent galaxies show lower spiral arm contrasts while the distributions of multi-armed and grand-design galaxies are not significantly different.

Fundamental Galaxy Properties In Fig. 2, we present the distributions of the total stellar mass and stellar mass surface densities, separated by spiral arm class. Here we find a similar behaviour as for the distributions of the arm-interarm contrast: flocculent galaxies are clearly distinguished by their lower masses and surface densities, while multi-armed and grand-design galaxies show very similar distributions. To further investigate these findings, we use the results of two-dimensional, multi-component decompositions, derived in pipeline 4 of the S^4G survey (Salo *et al.* 2015), as a parametrisation of the

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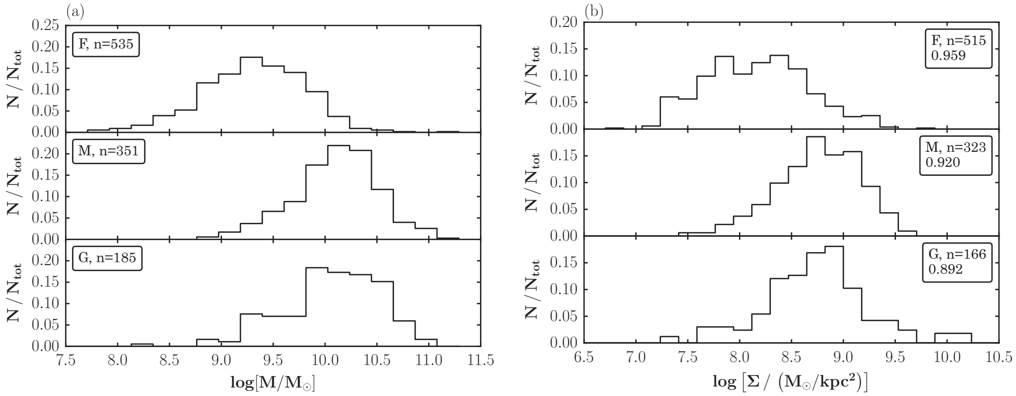

Figure 2. Distributions of total stellar masses (*left*) and stellar mass surface densities (*right*). The distributions of flocculent, multi-armed, and grand-design galaxies are displayed in the *upper*, *middle* and *lower* panels, respectively.

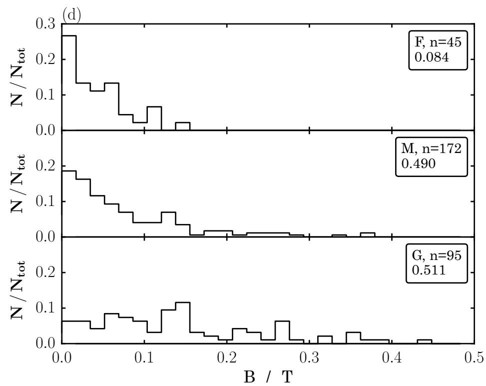

Figure 3. Distributions of the bulge-to-total luminosity ratio for flocculent (*upper panel*), multi-armed (*middle panel*), and grand-design (*lower panel*) galaxies.

fundamental galaxy properties. In fact, most of these considerations support the previous findings, except some bar properties and the bulge-to-total luminosity ratio (Fig. 3; see also Sect. 3 for a detailed discussion). Interestingly, we also find a strong correlation between bulge-to-total ratio and the bar contrast, and a weak correlation between arm and bar contrast (see Fig. 12 in Bittner *et al.* 2017) in multi-armed and grand-design, but not in flocculent galaxies. Therefore, we conclude that the three spiral arm classes do not represent a continuous sequence, but two distinct groups. While flocculent galaxies are hosted by a different type of discs, multi-armed and grand-design galaxies appear to be variants of each other.

3. The connection between dense bulges and spiral density waves

While multi-armed and grand-design galaxies appear vastly similar in most of their fundamental galaxy properties, one striking distinction remains. In Fig. 3 we present distributions of the bulge-to-total luminosity ratios. Grand-design galaxies appear to have significantly more massive bulges than multi-armed galaxies, while sharing similar bulge effective radii and Sérsic indices (see Fig. 4 in Bittner *et al.* 2017). Thus, the main difference we find in the fundamental galaxy properties of multi-armed and grand-design galaxies is the density of their bulge component.

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A possible explanation that reconciles the similarities of their host discs with the striking differences in their spiral pattern is related to the theory of spiral wave modes. Lindblad (1959) and Lin & Shu (1964) proposed that spiral structure might the caused by spiral density waves. However, the density waves in this theory do have an inward group velocity (Toomre 1969) and thus would eventually wrap up, unless reflected off a central component with a high Toomre-Q parameter. Such a reflection would result in a leading wave with an outward group velocity. Subsequently, this leading wave might be amplified at corotation by the swing amplification mechanism (Toomre 1981), thus producing a strong trailing wave with an inward group velocity. In this framework of a positive feedback loop a persistent, standing spiral wave mode can develop (Lin 1970; Mark 1976a,b,c; Bertin 1983; Lin & Bertin 1985; Bertin *et al.* 1989a,b). In summary, the main structural condition for long-lasting spiral density waves is the existence of a high Toomre-Q component in the centre of the galaxy.

Such a high Toomre-Q region might be provided by the dense and massive bulges in grand-design galaxies. If this was indeed the case, the spiral structure in grand-design galaxies would be caused by persistent spiral wave modes, which would naturally explain the very high level of bi-symmetry of their spiral pattern. On the contrary, multi-armed galaxies would be governed by transient spiral structure characterised by a lower level of symmetry, as their less dense bulges might simply not be able to reflect an incoming density wave.

In fact, these observational findings are consistent with recent numerical simulations. Saha & Elmegreen (2016) simulated a set of individual galaxies in a sequence of various bulge configurations. They find that in galaxies with intermediate bulge masses a long-lived, grand-design-like spiral pattern develops, well consistent with the theoretical framework and observational signatures presented above.

References

Athanassoula, E. 1980, *A&A*, 88, 184
Bertin, G. 1983, Internal Kinematics and Dynamics of Galaxies, 119
Bertin, G., Lin, C. C., Lowe, S. A., *et al.* 1989, *ApJ*, 338, 78
Bertin, G., Lin, C. C., Lowe, S. A., *et al.* 1989, *ApJ*, 338, 104
Bittner, A., Gadotti, D. A., Elmegreen, B. G., *et al.* 2017, *MNRAS*, 471, 1070
Elmegreen, D. M. & Elmegreen, B. G. 1984, *ApJS*, 54, 127
Elmegreen, D. M. & Elmegreen, B. G. 1995, *ApJ*, 445, 591
Lin, C. C. & Shu, F. H. 1964, *ApJ*, 140, 646
Lin, C. C. 1970, The Spiral Structure of Our Galaxy, 377
Lin, C. C. & Bertin, G. 1985, The Milky Way Galaxy, 513
Lindblad, B. 1959, Handbuch der Physik, 53, 21
Mark, J. W.-K. 1976, *ApJ*, 203, 81
Mark, J. W. K. 1976, *ApJ*, 205, 363
Mark, J. W.-K. 1976, *ApJ*, 206, 418
Mark, J. W.-K. 1977, *ApJ*, 212, 645
Toomre, A. 1969, *ApJ*, 158, 899
Toomre, A. 1981, Structure and Evolution of Normal Galaxies, 111
Sheth, K., Regan, M., Hinz, J. L., *et al.* 2010, *PASP*, 122, 1397
Saha, K. & Elmegreen, B. 2016, *ApJL*, 826, L21
Salo, H., Laurikainen, E., Laine, J., *et al.* 2015, *ApJS*, 219, 4

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