Formation and Evolution of Galaxy Outskirts
Proceedings IAU Symposium No. 321, 2016
A. Gil de Paz, J.H. Knapen & J.C. Lee, eds.

doi:10.1017/S1743921316008796

The spectacular 200 kpc-wide disk of the Malin 1 giant low surface brightness galaxy

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Abstract. Malin 1 is the best example among giant low surface brightness galaxies. New observations of this object in 6 broad-bands allow us for the first time to perform a pan-chromatic study of the stellar population in its 200 kpc wide disk. We observe a spiral structure revealing a star forming disk. The colors indicate a long history with a low efficiency of star formation. It is well reproduced by a model of disk galaxy making it similar to the disk of the Milky Way or other nearby spirals, except for its extremely large angular momentum.

Keywords. galaxies: individual (Malin 1), galaxies: structure, galaxies: stellar content

1. Introduction

Giant Low Surface Brightness Galaxies (LSBGs) are *massive* galaxies with a disk central surface brightness well below the 21.65 mag arcsec^{-2} value of Freeman (1970), typical of usual disk galaxies. Even if they are relatively rare, we know several of these galaxies in the nearby universe (see e.g. the sample of large HI mass galaxies studied in Boissier *et al.* 2008, on the basis of GALEX UV observations). The origin of such galaxies is unclear and has been debated. For instance, Mapelli *et al.* (2008) proposed that head-on collisions produce rings of star formation that fade while expanding, producing giant LSBGs after a time-scale of 1 Gyr. Jimenez *et al.* (1998) proposed instead that LSBGs correspond to the queue in the distribution of angular momentum of galaxies. Boissier *et al.* (2003) made generic models for giant LSBGs under this assumption, modeling them exactly as the Milky Way and usual spirals, but with larger angular momentum.

Malin 1 is a very well known example of LSBGs, and is may be the largest known galaxy. The surface brightness profiles of Bothun *et al.* (1987) revealed a very extended LSBGs disk around a central part that they considered as a bulge. Barth (2007) using HST showed this central part could be instead a normal galaxy, making the rest of the galaxy an extreme case of anti-truncated disk. Modern instrumentation allows us to rediscover Malin 1. The galaxy was recently observed by Galaz *et al.* (2015) with the Magellan telescopes in g and r band. They showed that the extended disk exhibits a spiral arm structure, and they found some diffuse regions, possibly of tidal origin. Independently, we have obtained deep images in 6 bands (FUV, NUV, u, g, i, z) in the context of the NGVS survey (Ferrarese *et al.* 2012) and GUViCS survey (Boselli *et al.* 2011) with respectively Megacam at CFHT and the GALEX telescope.

In this proceeding we discuss preliminary results based on our data. A more complete analysis will be presented in details in Boissier *et al.*, in preparation.

† Based on data of the NGVS Survey, GUViCS survey; and with the help of collaborators: A. Boselli, L. Ferrarese, P. Côté, Y. Roehlly, S.D.J. Gwyn, J.-C. Cuillandre, J. Roediger, Juan Carlos Muños Mateos, J. Koda, B. Madore

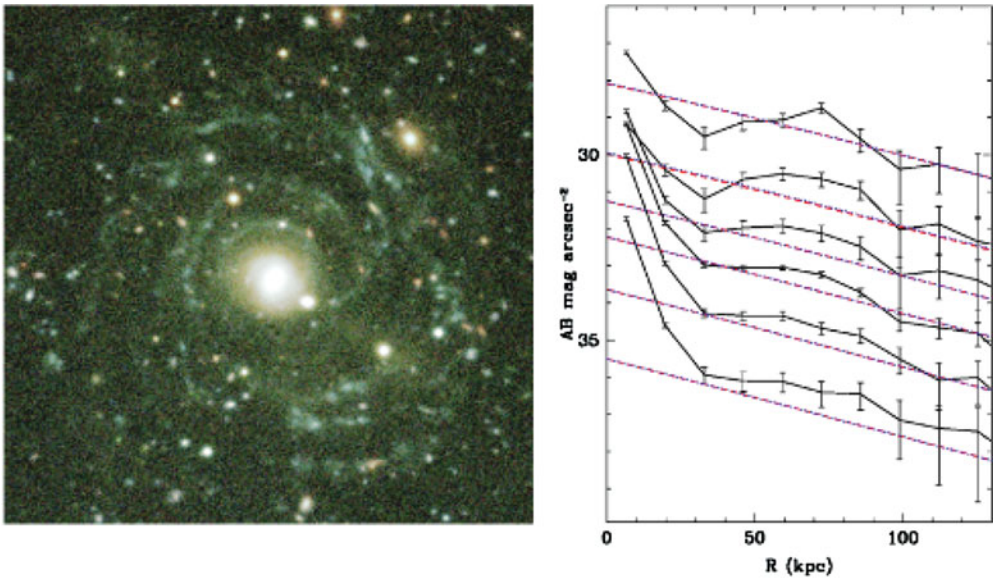

Figure 1. Left: combination of NGVS u, g, i, z images of Malin 1. Right: surface brightness profiles. From top to bottom: μ_{FUV}, $\mu_{NUV}+2$, μ_u+4, μ_g+6, μ_i+8, μ_z+10. Points with error-bars are the observations. The dotted/dashed lines correspond to a model fitting all the profiles with a simple large angular momentum evolutionary model. This model fits well the disk globally, excluding the central 20 kpc (a bulge or galaxy within the galaxy), and a region around 70 kpc, where a bump typical of the presence of spiral arms can be seen.

2. Analysis of our observations

Fig. 1 shows some of our new images of Malin 1, and the surface brightness profiles in our 6 bands, allowing us to perform a pan-chromatic analysis of Malin 1 for the first time and to obtain constraints on its stellar population. The profiles were measured in ellipses with constant inclination and position angle, and de-projected to a face-on orientation. Our images confirm the structures found by Galaz *et al.* (2015), i.e. a well developed spiral structure. We also detect the diffuse regions in the north, and some diffuse emission between the arms.

The profiles show a red central (20 kpc) region, corresponding to the bulge (or the inner galaxy, following Barth 2007), surrounded by a blue very extended disk. The color gradient in the disk is relatively flat, contrary to what is expected for a head-on collision. Indeed, in this case, the inner part of the disk should be red as star formation proceeded there more than 1 Gyr ago according to Mapelli *et al.* (2008), and the outer disk should be bluer as the ring of star formation has extended outwards.

On the contrary, we fitted well the surface brightness profiles with the models of Boissier *et al.* (2003) for normal galaxies, but allowing for large angular momentum. This grid of models calibrated in the Milky Way and in nearby star forming galaxies has only 2 free parameters: the circular velocity V and the spin parameter λ (a measure of the specific angular momentum). In these models, the star formation law is universal and depends on the local gas density. The accretion history is such that massive galaxies (high V) and dense regions accrete their material early-on on short-time scale, while low-mass galaxies and low-density regions form on a long time-scale.

A model with V=430 km/s and λ=0.57 produces a good fit to the observed profile, excluding the central part considered as a bulge by Bothun *et al.* (1987), and a region producing a blue bump around 70 kpc, typical of spiral arms crossing our ellipses. The

https://doi.org/10.1017/S1743921316008796 Published online by Cambridge University Press

spin parameter we need to fit this extended disk is incredibly large (of the order of 20 times the one of the Milky Way!). The velocity is also very large but such high values, although rare, are still found in the velocity functions of Gonzalez *et al.* (2000) or Zwaan *et al.* (2010). A HI velocity map was analyzed in Lelli *et al.* (2010), from which they derived a much lower velocity than ours (220 km/s). However, the observed velocity is sensitive to the inclination. They assumed an inclination of 40 degrees for the galaxy. Our images (especially in the bluest bands) are consistent with a smaller inclination. An inclination of 18 degrees is consistent with our images, and would make the two estimates of the circular velocity consistent.

The chemical evolution of the model providing the best fit suggests a relatively low metallicity (0.06 to 0.1 solar) that could be tested with future observations, and a long history during which the stellar disk has been build by a low efficiency star formation (the low efficiency results from the low density of the gas and its radial distribution). In Boissier *et al.* (2008), the UV colors of giant LSBGs suggested star formation proceeds by quiescent and active periods in these galaxies. Analyzing a number of regions detected in UV or u bands, we do find regions of various ages confirming this non continuous regime.

3. Conclusion

New data allows the study of the extremely extended disk of Malin 1, the most extreme case of giant LSBGs. We extracted surface brightness profiles in 6 bands, allowing for the first time to put constraints on the stellar population within this disk. We found that the color profiles are consistent with a long standing star formation history with low efficiency. They are well fitted by a model assuming LSBGs evolve in a similar way as usual galaxies such as the Milky Way, the main difference being their much larger angular momentum. How galaxies can acquire and sustain such a very high spin disk may be a challenge for cosmological models.

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