A SPECTROSCOPIC STUDY OF THE GIANT LOW SURFACE BRIGHTNESS GALAXY MALIN 1

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Abstract. Low Surface Brightness galaxies (LSBs) represent a significant fraction of galaxies in the nearby universe. However, despite their large fraction, the structure and origin of this class of galaxies is still poorly understood, especially due to the lack of high-resolution kinematics and spectroscopy.

Malin 1 is the largest known low surface brightness galaxy to date, the archetype of so-called giant LSBs. We present new results based on spectroscopic observations of Malin 1, using the Hα and $[\mathrm{OII}]_{3727}$ emission lines in order to bring new constraints on the internal dynamics of this galaxy. We have extracted a total of 16 spectra from different regions of Malin 1 and calculated the inner rotational velocities using the observed shift in the emission line wavelengths.

We show for the first time a steep rise in the rotation curve of Malin 1 up to ∼400 km s^{-1} (within r $<$ 10 kpc), which had not been observed in any of the previous works on this galaxy. We will discuss the implications of this result in comparison with existing works on Malin 1 and also the possibility for making a new mass model for this galaxy.

Keywords: Low surface brightness galaxy, Rotation curve, Dynamics

1 Introduction

Low Surface Brightness galaxies (LSBs) can be historically defined as the galaxies with a central disk surface brightness (μ_0) fainter than the typical Freeman (1970) value for disk galaxies ($\mu_{0,B}$ = 21.65 mag arcsec^{-2}). LSBs may account up to a total of 50% of all galaxies in the universe according to O'Neil & Bothun 2000; 40% for Galaz et al. 2011. So it is really important to study this large population of galaxies in order to have an unbiased view of galaxy formation and evolution scenarios.

Malin 1 is an extreme example of an LSB galaxy with a disk central surface brightness $\mu_{0,V} \approx 25.5$ mag arcsec^{-2} (Impey & Bothun 1997) and a diameter of ∼240 kpc (Moore & Parker 2006). Therefore Malin 1 can be clearly considered as a prototype for the study of LSBs and giant LSBs (GLSBs) in general.

In the recent years with the advancement in our technology and the advent of powerful imaging instruments, there has been a new interest in Malin 1 and other similar GLSBs (e.g. Galaz et al. 2015; Boissier et al. 2016; Hagen et al. 2016; Mishra et al. 2017; Zhu et al. 2018; Saburova et al. 2018). However the origin and evolution of this class of galaxies is still poorly understood, mainly due to the lack of good quality spectroscopic data. So we present here an on-going work on a new spectroscopic study of Malin 1 from Junais et al. (in preparation).

2 Data and reduction

We obtained some long-slit spectroscopic data for Malin 1 using the IMACS-Magellan spectrograph of the 6.5m Magellan Baade telescope in the Las Campanas Observatory, Chile. We initially used observations made in 2016 of 4 slit positions each of slit-width 2.5″, out of which we extracted spectra from 12 different regions within 3 slits where it was possible to obtain a clear signal. This includes a region at ∼26 kpc which is relatively far from the center of Malin 1. In 2019 we obtained new data for Malin 1 using the same instrument and a relatively smaller slit-width of 1.2″, from which we extracted a total of 4 spectra (see Fig.1). The orientation of the wider slits (2.5″ slits) was chosen on the basis of UV images from Boissier et al. (2008) and the smaller slit (1.2″ slit)

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was placed passing through the major axis of the galaxy. All the data reduction processes to extract the spectra were done using standard IRAF procedures.

Within the extracted spectra, we focused on the Hα and $[\mathrm{OII}]_{3727}$ emission lines (Hα was observed in the wider slits and $[\mathrm{OII}]_{3727}$ observed in the narrower slit) which was the strongest of all. The emission line fitting was done using Python routines implementing a Markov Chain Monte Carlo (MCMC) method in order to obtain the peak wavelengths and the associated errorbars of each emission line. Various constraints were also applied on the emission lines during the fitting procedure, including a fixed line ratio for the [NII] and [OII] doublets (Ludwig et al. (2012); Comparat et al. (2013)) and a fixed line separation using the laboratory wavelengths. The results of this fitting procedure will be used for our further analysis.

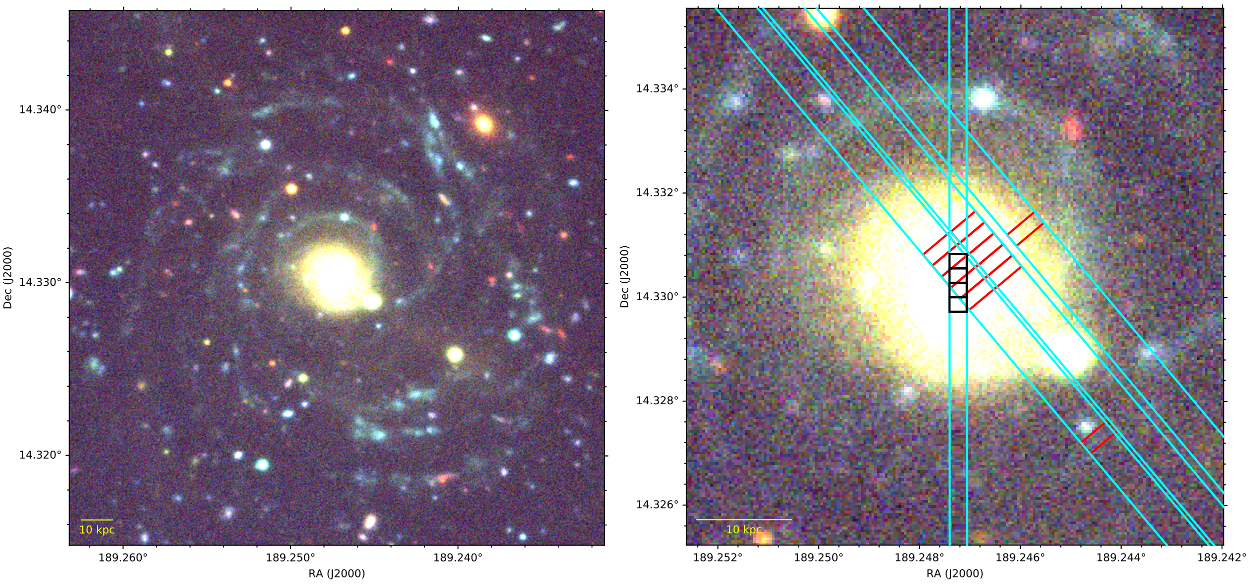

Fig. 1. Left: Colour composite image of Malin 1 from the CFHT-Megacam Next Generation Virgo cluster Survey (NGVS, Ferrarese et al. 2012) u, g and i band images. **Right:** The slit positions of our observations are shown (in blue) along with the 16 apertures (in red and black for the Hα and $[\mathrm{OII}]_{3727}$ data respectively) in which we could extract a spectrum.

3 A new Rotation Curve for Malin 1

The observed wavelength shift with respect to their laboratory wavelengths of the Hα and $[\mathrm{OII}]_{3727}$ emission lines in our extracted spectra was used to calculate the circular velocities on Malin 1 galaxy plane as a function of radius. We also applied a correction for the galaxy inclination angle, PA and systemic velocity (V_{sys}) using the values adopted from the HI study of Lelli et al. 2010. A few data points which are too close to the minor axis of the galaxy with a large correction for the intrinsic rotational velocity values (points with the azimuth in the galaxy plane $> 70°$) were eliminated considering to be unrealistic for the rotation curve. Moreover we have also done a 3 pixel re-binning of the two outermost data points (the ones at 10 kpc and 26 kpc) in order to obtain a better signal-to-noise in these regions.

Fig.2 shows the extracted rotation curve for Malin 1 along with the data points from Lelli et al. 2010 using low resolution HI data. We observe for the first time a steep rise in the rotational velocity for the inner regions of Malin 1 (inside $\sim$10 kpc) up to $\sim$ 400 km s^{-1}, and a subsequent decline to reach the plateau observed on large scales with HI. The implications of this new result and its future prospects are discussed in Section 4.

4 Discussions

A steep rise in the rotation curve is not typical for an LSB galaxy. Therefore the observed steep rise in the newly extracted rotation curve for Malin 1 could imply that in its central regions Malin 1 shows a behaviour different from an LSB galaxy, despite the presence of its huge LSB disk. This is also in accordance with the observation

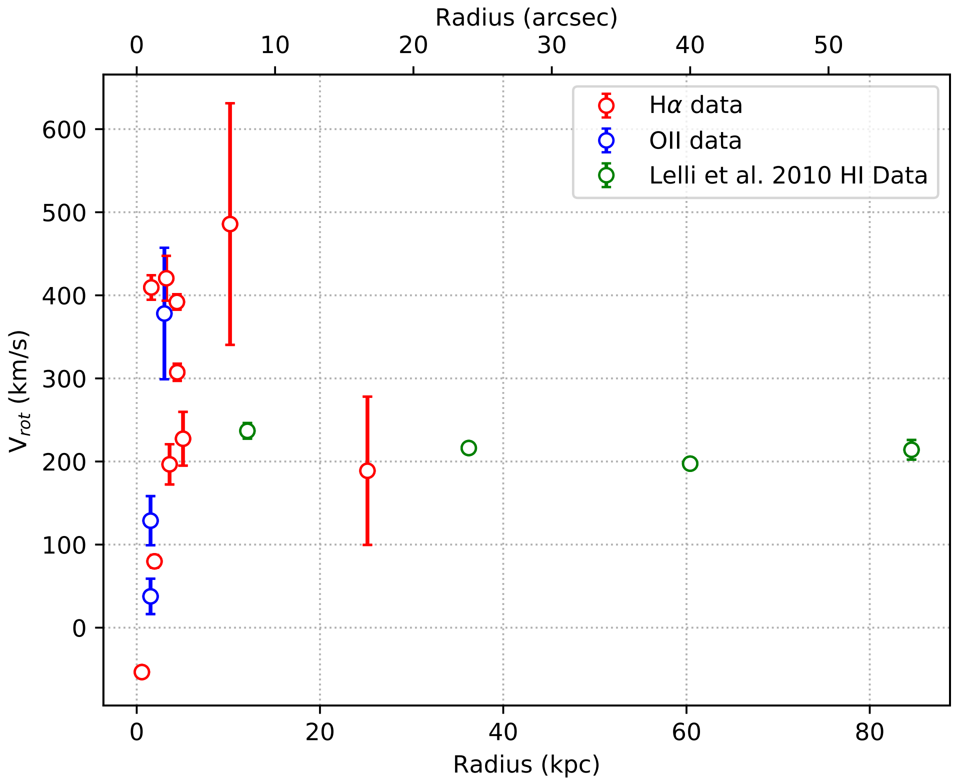

Fig. 2. Rotation curve for Malin 1. The red and black points indicate the Hα and $[OII]_{3727}$ data respectively from this work along with the Lelli et al. (2010) HI data points (green).

from Barth (2007) that described Malin 1 as an early type SB0/a galaxy with a central bulge, surrounded by a huge LSB disk.

Lelli et al. (2010) provides a rotation curve and mass model for Malin 1 using HI data, and observes that Malin 1 has a steep rising rotation curve in contrast with the slowly rising rotation curve from Pickering et al. (1997). He also indicates that from the observation of surface photometry and gas dynamics of Malin 1, it tends to have a double HSB-LSB structure. However the poor resolution of HI data used in the analysis of Lelli et al. (2010) (a resolution of $\sim 21''$ corresponding to ~ 32 kpc) makes it hard to bring strong constraints on the internal dynamics of the galaxy ($r < 10$ kpc).

Therefore this work, with a better resolution than any of the previous works on Malin 1, could be crucial in bringing new constraints on the dynamics and mass distribution in the inner regions of Malin 1. We are currently in the final stages of preparation of a mass model for Malin 1 using the constraints from our new rotation curve in combination with the HI measurements from Lelli et al. (2010) and Hubble Space Telescope (HST) I-band photometry from Barth (2007). With a new mass model we expect to have a better understanding of the overall matter distribution within Malin 1, especially the dark matter distribution which is often debated for LSB galaxies (de Blok & McGaugh 1997).

Reshetnikov et al. (2010) also provides yet another spectroscopic study of the internal dynamics of Malin 1 using stellar absorption lines. However they only provide a single slit of observation with a position angle of 55° and relatively poor sampling. The rotational velocities from their data, when converted to the rotational velocity in the galaxy plane using the same geometrical approximations we did in this work, are in good agreement with our data (within $r \sim 10$ kpc) considering their huge errorbars. This suggest that the stellar and gas kinematics are coherent in the central regions of Malin 1.

A recent IllustrisTNG simulation result from Zhu et al. (2018) also produces some interesting results similar to our observations in this work. They were able to produce a Malin-like galaxy in their simulations with similar observed features of Malin 1 and a rotation curve with a maximum rotational velocity of ~ 430 km s^{-1}, close to the value we observed for Malin 1 in this analysis. However they do not observe a rotation curve with a steep rise followed by a decline to ∼200 km s^{-1}, contrary to what we observe in this work. This comparison of our observational data with that of a simulation indicates that our work can offer more constraints for future simulations like this regarding Malin 1 like galaxies or GLSBs in general.

It will be important in the future, however, to obtain better quality data for the proper understanding of the formation and evolution of Malin 1 like galaxies. Recently we have obtained a LAM grant for the purchase of a new Hα filter at the redshift of Malin 1, which will provide us with the possibility to obtain an Hα emission map of the galaxy, crucial for the study of the dynamics and star formation within Malin 1.

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