A portrait of Malin 2: a case study of a giant low surface brightness galaxy

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ABSTRACT

The low surface brightness (LSB) disc galaxy Malin 2 challenges the standard theory of galaxy evolution because of its enormous total mass $\sim 2 \times 10^{12} \text{ M}_\odot$, which must have been formed without recent major merger events. The aim of our work is to create a coherent picture of this exotic object by using new optical multicolour photometric and spectroscopic observations at the Apache Point Observatory as well as archival data sets from Gemini and wide-field surveys. We have performed Malin 2 mass modelling, we have estimated the contribution of the host dark halo and we have found that it acquired its low central density $\rho_0 \simeq 0.003 \text{ M}_\odot \text{ pc}^{-3}$ and huge isothermal sphere core radius $r_c = 27.3 \text{ kpc}$ before the disc subsystem was formed. Our spectroscopic data analysis reveals complex kinematics of stars and gas in the very inner region ($r = 5\text{–}7 \text{ kpc}$). We have measured the oxygen abundance in several clumps and we have concluded that the gas metallicity decreases from the solar value in the centre to a half of that at 20–30 kpc. We have found a small satellite projected on to the galaxy disc at 14 kpc from the centre and we have measured its mass (1/500 of the host galaxy) and gas metallicity (similar to that of the Malin 2 disc at the same distance). One of the unique properties of Malin 2 turned out to be the apparent imbalance of the interstellar media: the molecular gas is in excess with respect to the atomic gas for given values of the gas equilibrium turbulent pressure. We explain this imbalance by the presence of a significant portion of the dark gas not observable in CO and the H I 21-cm lines. We also show that the depletion time of the observed molecular gas traced by CO is nearly the same as in normal galaxies. Our modelling of the ultraviolet-to-optical spectral energy distribution favours the exponentially declined star formation history over a single-burst scenario. We argue that the massive and rarefied dark halo which formed before the disc component describes all the observed properties of Malin 2 well and we find that there is no need to assume additional catastrophic scenarios (such as major merging) proposed previously in order to explain the origin of giant LSB galaxies.

Key words: galaxies: haloes – galaxies: individual: Malin 2 – galaxies: ISM.

1 INTRODUCTION

A challenging task in contemporary extragalactic astrophysics is the development of a general theory of galaxy evolution consistent with modern cosmological concepts. With the advances in observational methods, numerous phenomena have been revealed, which become hard to explain within the existing and presently accepted evolutionary models. Therefore, eliminating contradictions between theory and observations has now become crucially important. For this purpose, it is useful to study in detail some peculiar objects that could have formed under unusual conditions 'on the edge of the parameter space': because of these, we can perform critical tests to constrain the theories of galaxy formation.

One such prominent class of peculiar galaxies is low surface brightness (LSB) galaxies that possess discs with central $B$-band surface brightness values remaining below 22.5 mag arcsec$^{-2}$. This class includes a significant subset of the galaxy population, in particular among dwarfs (Bothun, Impey & McGaugh 1997; O’Neil & Bothun 2000; Zhong et al. 2008). Moreover, we have to keep in mind that their numbers are likely to be underestimated as a result of selection effects because they are difficult to observe. However, in most LSB galaxies, dark matter is assumed to dominate at all distances from the centre (Bothun et al. 1997), which makes them
very attractive targets for studying dark haloes directly and gives some clues to the verification of different galaxy formation models (e.g. Macciò et al. 2007).

However, this galaxy class is not entirely homogeneous in observational properties. For example, there are both metal-poor LSB dwarfs and giant galaxies with redder colours and nearly solar values of [O/H]. The latter subclass includes objects such as Malin 1, Malin 2,UGC 6614 and some others.

LSB galaxies are believed to have thinner discs (Matthews 2000; Bizyaev & Mitronova 2002, 2009; Khoperskov et al. 2010) with larger exponential scalelengths (Bothun et al. 1997; Bergvall et al. 1999; Zhong et al. 2008) than normal galaxies. Bulges occur very rarely in LSB galaxies and are smaller in size than those in classical spirals. Typically, the bulge mass correlates with the metallicity (Galaz et al. 2006) and LSB galaxies follow this trend. From the dynamic modeling of rotation curves, it turns out that dark haloes contribute significantly to the total mass of LSB galaxies and that they are described by the pseudo-isothermal sphere rather than by the cuspy profile (Pickering et al. 1997; Satters et al. 2003; Kuzio de Naray et al. 2006). Cosmological simulations show that LSB galaxies reside preferentially in the relatively less concentrated and fast-rotating dark haloes (Mo, Mao & White 1998; Bullock et al. 2001; Macciò et al. 2007; Kim & Lee 2013).

When studying the physical conditions in LSB discs, the main points we need to understand are (i) whether the stellar disc surface density is low or (ii) whether the stellar mass-to-light ratio (M/L) is high. The assumption of low disc density requires low star formation rates (SFRs) and, hence, results in slow evolution. The second scenario involves the heavy baryon disc probably because of an unusual bottom-heavy stellar initial mass function (IMF; Fuchs et al. 2002; Lee et al. 2004; Saburova 2011), which reduces the dark matter fraction estimates for these galaxies. In both cases, the most important subject of the study is the structure of the interstellar medium (ISM) in LSB galaxies.

The properties of gas in LSB galaxies are often considered to be similar to those at the periphery of normal galactic discs (e.g. Abramova & Zasov 2011). In particular, the observed gas surface density is too low for large-scale gravitational instability (e.g. Bothun et al. 1997; Pickering et al. 1997). Hence, the common point of view is that LSB galaxies lack molecular gas H$_2$ (see Abramova & Zasov 2011; O’Neil, Schinnerer & Hofner 2003, and references therein). Therefore, the detection of H$_2$ in the discs of some LSB galaxies was a surprise (Das et al. 2006; Das, Boone & Viallefond 2010). Because we observe the ultraviolet (UV) radiation of LSB discs (e.g. Boissier et al. 2008), we query how they can form stars under conditions of H$_2$ shortage. What type of non-gravitational instability does play a key role here? Is it possible for stars to form directly from atomic gas?

The observed features of LSB galaxies are often connected with their poor environment (Rosenbaum & Bomans 2004) and are considered to be the result of a slow evolution (Bothun et al. 1997), thus explaining the observed unutilized atomic gas (O’Neil 2000). The wide range of colours of LSB galaxies indicates that they might be observed at various evolution stages. The question is whether there is a single key mechanism responsible for the formation of LSB discs for all subtypes of LSB galaxies.

The subject of our study is Malin 2, which is a member of the giant LSB galaxy family and possesses a number of peculiar properties. Despite its enormous total mass ~2 × 10$^{12}$ $M_{\odot}$ and its size of ~100 kpc, Malin 2 has an extended disc with a clear spiral structure (the plateau of its rotation curve is about 350 km s$^{-1}$). There are some difficulties in placing this object within the hierarchical clustering concept in which the dark haloes hosting disc galaxies do not experience major mergers. So, the dark halo of Malin 2 could not have undergone any significant transformation. However, in order to form a giant LSB disc, at some moment its progenitor, supposedly a normal-sized galaxy, should have experienced a catastrophic scenario of interaction with a companion (Mapelli et al. 2008; Peñarrubia, McConnell & Babul 2006). Although, in most cases, such interaction overheat and destroys the disc (e.g. Wilman et al. 2013), there can be a narrow range of parameters under which it can lead to the formation of a LSB disc with a large scalelength (such as those observed in giant LSBs). However, the central surface density in such interaction scenarios is difficult to change (e.g. O’Neil, Bothun & Schombert 1998). The result is a very questionable picture in which an unusual progenitor, already an LSB galaxy with a peculiar giant halo, experienced a rare catastrophic scenario.

In this work, we attempt to create a self-consistent portrait of the galaxy Malin 2, taking into account new observing data. The paper is organized as follows. In Section 2, we present an overview of the photometric and kinematical observations and the data reduction procedures. In Section 3, we present the modelling of the spectral energy distribution (SED). In Section 4, we describe the mass distribution model of Malin 2. In Section 5, we analyse the balance of gas components and estimate the turbulent pressure of the ISM. In Section 6, we discuss possible reasons for the high fraction of molecular gas observed in the galaxy. We also review the star formation history (SFH) and the evolutionary scenarios suitable for Malin 2. We present our conclusions in Section 7.

### 2 OBSERVATIONS AND DATA REDUCTION

To provide a basic comparison of Malin 2 with normal galaxies, we briefly discuss its position on known scaling relations of disc galaxies. The basic properties of Malin 2 are given in Table 1.

| Malin 2 | Ref. |
|--------|-----|
| F 568-06 | |
| PGC 086622 | |

| Parameter | Value |
|-----------|-------|
| Equatorial coordinates | 10°39′52′′83 |
| (J2000.0) | +20°50′49′′36 |
| Distance | 201 Mpc |
| Morphological type | Scd |
| Inclination angle | 38 deg |
| Position angle | 75 deg |
| $R_{25}$ | 45 kpc |
| $r_{eff}$ | 2.8 kpc |
| $h_d$ | 19.5 kpc |
| $M_b$ | $-21.38$ mag |
| $(B-V)_0$ | 0.51 mag |
| $(\log (O/H) + 12)$ | 8.64 |
| $M_{HI}$ | $4.9-8.3 \times 10^8 M_{\odot}$ |
| $M_{HI}$ | $3.6 \times 10^{10} M_{\odot}$ |

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Table 1. Basic properties of Malin 2. The references are as follows: 1, NED* (http://ned.ipac.caltech.edu); 2, HYPERLEDA (http://leda.univ-lyon1.fr; Paturel et al. 2003); 3, Pickering et al. (1997); 4, McGaugh (1994); 5, Das et al. (2010). $R_{25}$ is the radius of the $B$-band 25 mag arcsec$^{-2}$ isophote, $r_{eff}$ is the effective $R$-band radius of the bulge, $h_d$ is the stellar disc $R$-band radial scalelength, $M_b$ is the absolute $B$-band magnitude, $(\log (O/H) + 12)$ is the gas metallicity, $M_{HI}$ is the molecular gas mass and $M_{HI}$ is the atomic gas mass.

*The NASA/IPAC Extragalactic Database (NED) is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.
Table 2. Observations of Malin 2 at the 0.5-m Apache Point Observatory telescope in 2011 May.

| Date    | 05/05 | 06/05 | 07/05 | 08/05 | 09/05 |
|---------|-------|-------|-------|-------|-------|
| Band    |       |       |       |       |       |
|         | Exposition time (s) | Seeing (arcsec) |
|         | 2 \times 900 | 4 \times 900 | 5 \times 900 | 4 \times 900 | 3 \times 900 | 2.2 |
| B       | 900   | 3 \times 900 | 4 \times 900 | 4 \times 900 | 3 \times 900 | 2.0 |
| V       | 900   | 3 \times 900 | 4 \times 900 | 4 \times 900 | 3 \times 900 | 2.1 |

2.1 Photometric observations

To add constraints on the disc and bulge surface densities and radial scales to our dynamical modelling, we performed surface photometry of Malin 2 in the BVR bands using the observations collected with the 0.5-m telescope at the Apache Point Observatory (see Table 2). In addition, we incorporate the archival griz photometry from the Sloan Digital Sky Survey (SDSS) Data Release 7 (Abazajian et al. 2009) and archival g-band photometry from the Gemini multi-object spectrograph at the Gemini North telescope (GMOS-N). The photometric data were reduced in a standard way using the IRAF\(^1\) and MIDAS\(^2\) software packages. To calibrate our BVR images, we observed photometric standard stars from Landolt (1992, 2009) during the same nights. The archival images from SDSS and GMOS-N were calibrated according to the information available at the official web sites\(^3\) and the FITS file headers. The foreground stars were removed from all galactic images and replaced by the mean fluxes of surrounding regions before further analysis.

Using tools from MIDAS, we calculated the radial profile of the position angle (PA) in all photometric bands (see Fig. 1). We obtained the azimuthally averaged radial light and colour profiles (Fig. 2) using ellipses with radially constant flatness and position angle PA = 75 deg. We corrected them for Galactic extinction according to Schlafly & Finkbeiner (2011) but not for internal extinction and disc inclination.

The bump clearly seen in the surface brightness profiles at \(r \approx 35\) arcsec (Figs 2a and b) is a result of the prominent spiral arm patch located at this galactocentric distance. The colour profiles show significant gradients (Fig. 2c). The same colour gradient was found earlier by Bothun et al. (1990), but their \((B - V)\) values are 0.3 mag bluer than those obtained in our study. In order to verify our \((B - V)\) colours, we compared two types of photometric calibrations: that from the Landolt stars and another using the stars with available SDSS photometry located in our galaxy images. Both calibration types yielded the same colour index values.

In order to construct the dynamical model of Malin 2 (Section 4), we need to estimate the structural parameters of its bulge and disc. For this purpose, we performed the two-dimensional (2D) decomposition of the images into the following components: a disc with an exponential radial brightness distribution \(\mu_d(r) = \mu_0 + 1.086 \ r/h\) and a Sérsic bulge \(\mu_b(r) = \mu_e + c_{1}[(r/r_c)^{1/n} - 1]\). We used the BUDDA code,\(^4\) version 2.2 (de Souza, Gadotti & dos Anjos 2004).

The 2D decomposition results are presented in Fig. 3, where the best-fitting model and the observed Gemini g-band images are shown next to the residuals. The images have the same scale and contrast. The panel on the left also shows the slit positions for our spectroscopic observations (see Section 2.2). The structural parameters of the disc and bulge of Malin 2 are provided in Table 3.

2.2 Gemini-North spectroscopy

The spectroscopic data for Malin 2 were collected using GMOS-N on the 8-m Gemini-North telescope under science programme GN-2006B-Q-41 (PI: C. Onken) in 2007 January. The data were obtained using the long-slit set-up (0.5-arcsec wide slit) with the B1200+G5301 grating providing a wavelength coverage between 4800 and 6200 Å with the spectral resolving power of \(R = 3800\). The six 1800-s long exposures (a total of 3 h) were obtained for the slit position \(PA_{\text{slit}} = 345\) deg, which corresponds to the minor axis of the Malin 2 disc (see the horizontal dashed lines in Fig. 1). We retrieved this publicly available data set from the GEMINI science archive\(^5\) in order to study the central region of Malin 2.

\(^1\) IRAF is distributed by the National Optical Astronomical Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

\(^2\) MIDAS is developed and maintained by the European Southern Observatory.

\(^3\) See http://www.gemini.edu/ and http://www.sdss.org/.

\(^4\) http://www.sc.eso.org/~dgadotti/budda.html

\(^5\) http://www.cadc-ccda.hia-iha.nrc-cnrc.gc.ca/sga/
through the rest of the data reduction steps: flat-fielding, wavelength calibration, sky subtraction with the Kelson (2003) technique and flux calibration using a spectrophotometric standard star.

The uncertainty frames were computed from the photon statistics and the readout noise values, and processed through exactly the same data reduction steps in order to estimate the flux uncertainties.

### 2.2.2 Data analysis

We used the NBURSTS full spectral fitting technique of Chilingarian et al. (2007a,b) with the stellar population models based on the ELODIE.3.1 (Prugniel et al. 2007) empirical stellar library in order to determine the internal kinematics, ages, metallicities and mass-to-light ratios of stars.

The NBURSTS full spectral fitting package implements a pixel-to-pixel fitting algorithm. Generally, an observed spectrum is approximated by a linear combination of stellar population models broadened with the galaxy’s parametric line-of-sight velocity distribution, whose parameters (e.g. SFH, metallicity, IMF) are determined inside the same minimization loop as the internal kinematics. The fitting procedure includes a multiplicative polynomial continuum aimed at absorbing possible flux calibration issues in both observations and models.

For the spectral fitting, we use two sets of stellar population models with different SFHs: the exponentially declining model, exp-SFH, and a single instantaneous burst, simple stellar population (SSP). Both are computed with the PEGASE.HR code (Le Borgne et al. 2004) based on the ELODIE.3.1 empirical stellar library. The SSP models are characterized by metallicity and age, and the exp-SFH models are characterized by metallicity and the exponential decay time-scale $\tau$. The starting epoch of the star formation in the exp-SFH model is set at the big bang (13.7 Gyr minus the light travel time). The model grids were computed with the PEGASE.HR evolutionary synthesis code at the intermediate spectral resolution ($R = 10000$) in a wavelength range 3900–6800 Å for the Salpeter (1955) and Kroupa (2001) stellar IMFs for the SSP and exp-SFH models, respectively. We used the 25th-order multiplicative polynomial continuum. The model grids were pre-convolved with the spectral line spread function of the GMOS-N, which was determined from strong airglow lines in the spectra. The mean instrumental dispersion is $\sigma_{\text{instr}} = 35 \text{ km s}^{-1}$. In order to achieve the required signal-to-noise ratio ($S/N = 10$) per spatial bin, we performed adaptive binning of the spectra in the spatial direction.

An emission-line spectrum of every spatial bin was obtained by subtracting the stellar contribution (i.e. the best-fitting stellar population model) from the observed spectrum. This step provided a pure emission spectrum uncontaminated by absorption lines of the stellar component, which is especially important for the Balmer lines. Then, we fitted emission lines with Gaussians pre-convolved with the instrumental resolution in order to determine the line-of-sight velocities of the ionized gas and emission-line fluxes.

Fig. 4 shows the best-fitting values of radial velocity, velocity dispersion, metallicity of the stellar component as well as kinematics of ionized gas and emission-line ratios. Despite the orientation of the long slit along the minor axis of the galaxy, the stellar radial velocity profile reveals a solid-body rotation with amplitude up to 40 km s$^{-1}$ in the central 5–7 arcsec. This kinematic feature in the central part of the galaxy can be related to the bulge triaxiality, confirmed indirectly by the variation of PAs of isophotes with radius (see Fig. 1). Alternatively, the noticeable rotation along the minor axis could be supported by either a bar or a nuclear polar ring, but none of these structures is detected in the residual image after the 2D photometric analysis.

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**Figure 2.** Surface brightness profiles of Malin 2 in the $griz$ (a) and $BVR$ bands (b), and the colour indices (c).

**2.2.1 Data reduction**

We reduced the data using our own GMOS data reduction pipeline constructed on top of the universal long-slit and IFU data reduction toolbox implemented in IDL. The data reduction was performed independently for every science exposure (including spectrophotometric standard stars). The data reduction was identical to that of long-slit GMOS spectra presented by Francis et al. (2012), except for the object extraction step, which was skipped here because we were dealing with the extended galaxy. The GMOS-N detector is a three-chip mosaic and we performed primary data reduction steps on a per-chip basis, which included bias subtraction, bad/hot pixel masking, cosmic ray rejection and modelling the diffuse light in the spectrograph by using the flux in two slit bridges and outside the slit. Then, the individual chips were mosaiccked together, and processed...
model subtraction. The strong asymmetrical non-circular motions in the central region are seen in both stellar and ionized gas components. The peculiar gas kinematics within ~5–7 kpc cannot be explained by the weak nuclear activity detected by Ramya, Prabhu & Das (2011). The weak active galactic nucleus (AGN) activity is also supported by our measurements of the log[O/III]/Hβ line ratio (all H II regions reside below log[O/III]/Hβ = 0.8) on the BPT diagram (Baldwin, Phillips & Terlevich 1981; Kewley et al. 2006). Beyond the central 7 arcsec, the gaseous and stellar kinematics indicate negligible rotation, which is expected along the minor axis.

Our estimates of gas and stellar metallicities reveal that the gradient decreases from almost solar value in the centre to [Z/H] = −0.4 to −0.3 dex outside the bulge-dominated region. Measurements of the stellar metallicity outside the bulge area are very uncertain because of the low signal-to-noise and are not suitable for satisfactory chemical analysis of the galactic disc.

The SSP-equivalent measurements of metallicity in the bulge-dominated region indicate a very old stellar population, T_{SSP} \approx 15 \text{ Gyr}, while the exponential decay time-scale \tau values are at the lower limit of our exp-SFH model grid (\tau = 10 \text{ Myr}).

### 2.3 Spectroscopy at the Apache Point Observatory 3.5-m ARC telescope

#### 2.3.1 Observations and data reduction

We observed Malin 2 with the dual imaging spectrograph (DIS) at the Apache Point Observatory in the low-resolution set-up during the nights of 2011 December 26 and 2012 January 21. Table 4 presents the observing log. The standard night-time dome calibrations (bias, He–Ne–Ar arc lamp and quartz flat-field lamp) were obtained. We observed the spectrophotometric white dwarf standards Feige 34 and GD 153 in order to perform the flux calibration.

We reduced the spectra in the standard way within IRAF using the CCDRED, CRUTIL, ONEDSPEC and TWODSPEC packages. We used sky lines in order to correct the distortion in 2D spectral frames. Our spectra from 2012, where the red and blue spectral ranges overlap, suggest that the accuracy of the relative flux calibration between the red and blue parts is better than 8 per cent.

The spectra at slit positions crossing the bright parts of the spiral arms in Malin 2 exhibit very visible emission lines. Unfortunately, our 2011 set-up did not allow us to observe the [O II]3727Å line, although we were able to observe it in 2012. As a result, we were only able to apply the oxygen abundance estimator R_{23} (Pagel et al. 1979; Pilyugin & Thuan 2005) to our 2012 data. The spectral range in all spectra from both 2011 and 2012 enables us to estimate the oxygen abundance from the N2 and O3N2 indicators (in calibration by Storchi-Bergmann, Calzetti & Kinney 1994; Marino et al. 2013; Alloin et al. 1979; Pettini & Pagel 2004). Table 5 summarizes our oxygen abundance estimates [in terms of 12+log(O/H)]. The average value of 12+log(O/H) through the disc of Malin 2 is 8.54 \pm 0.10 dex (the internal uncertainty, whereas the calibration uncertainty is at least 0.2 dex), which corresponds to the metallicity [M/H] = −0.4 dex. The latter value is in agreement with the result of the chemical analysis for the central regions of the galaxy.
good agreement with the value of 8.59 found by McGaugh (1994). Table 5 also suggests that the abundance gradient is consistent with that estimated from Gemini spectroscopy.

One of our slits in the 2011 observing run passed through a concentration at ∼14 arcsec (13.7 kpc) to the north-west of the nucleus of Malin 2 (see the S1 object in Fig. 3). Although we suspect that this object is a satellite galaxy, it also resembles a foreground or background edge-on galaxy, or a concentration in the spiral arm of the main galaxy. Thus, we analysed the spectra to identify the nature of this object. Fig. 5 shows the spectra of the clumps in the candidate satellite galaxy near Hα. These suggest that the candidate has a −110 km s$$^{-1}$$ radial velocity difference with Malin 2, and hence probably resides at the same distance as the main galaxy. It is difficult to decide from the spectra if the satellite is above or below the galactic plane of Malin 2.

The images we have presented show that the satellite looks like quite a flattened galaxy. Our spectra indicate that the satellite has an amplitude of rotation curve of about 65 km s$$^{-1}$$, although the rotation curve inferred from Fig. 5 looks far from regular. We estimate the size of the satellite as 8.3 arcsec (8.1 kpc) from the photometry and spectroscopy. Its mass derived from the amplitude of the rotation curve and size given above is 4$$\times$$10$$^9$$ M$$\odot$$, or 1/500 from Malin 2 (see Fig. 7); that is, this is a small galaxy or a remnant of a larger progenitor. It is worth mentioning that the estimate of the stellar mass of this satellite, made from the K-band photometry (i.e. 1/600 of the mass of Malin 2), is fully consistent with the dynamical

Table 4. Summary of spectroscopic observations with the 3.5-m ARC telescope. The columns give the following: (1) position angle of the slit; (2) exposure time; (3) and (5) spectral range covered by the blue and red spectrographs, respectively; (4) and (6) dispersion of the blue and red spectra, respectively.

| Date             | Slit PA (deg) (1) | Exp. time (2) | Blue sp. range (3) | Blue disp. (4) | Red sp. range (5) | Red disp. (6) |
|------------------|------------------|--------------|-------------------|---------------|------------------|--------------|
| 26 December 2011 | Slit 1 90        | 80 min       | 4600–5600 Å       | 0.6 Å pix$$^{-1}$$ | 6015–7190 Å     | 0.6 Å pix$$^{-1}$$ |
|                  | Slit 2 0         | 60 min       | 4600–5600 Å       | 0.6 Å pix$$^{-1}$$ | 6015–7190 Å     | 0.6 Å pix$$^{-1}$$ |
|                  | Slit 3 40        | 80 min       | 4600–5600 Å       | 0.6 Å pix$$^{-1}$$ | 6015–7190 Å     | 0.6 Å pix$$^{-1}$$ |
| 21 January 2012  | Slit 4 90        | 120 min      | 3500–5600 Å       | 1.8 Å pix$$^{-1}$$ | 5250–9100 Å     | 2.3 Å pix$$^{-1}$$ |
|                  | Slit 5 40        | 120 min      | 3500–5600 Å       | 1.8 Å pix$$^{-1}$$ | 5250–9100 Å     | 2.3 Å pix$$^{-1}$$ |

Table 5. Oxygen abundances 12 + log(O/H) in different regions of the Malin 2 disc estimated using different abundance indicators. The R$_{23}$ method is applied in calibration by Pilyugin & Thuan (2005). The bottom line in the table shows the abundance in the S1 candidate satellite. The positions of the clumps in the galaxy are shown in the left panel of Fig. 3.

| Clump                   | r (kpc) | $R_{23}$ | N2 | O3N2 |
|-------------------------|---------|----------|----|------|
| Clump 1                 | 32.8    | –        | 8.36| 8.42 |
| Clump 2                 | 25.1    | –        | 8.64| 8.60 |
| Clump 3                 | 32.2    | –        | 8.63| 8.51 |
| Clump 4                 | 31.9    | 8.49     | 8.46| 8.46 |
| Clump 5                 | 21.5    | 8.57     | 8.65| 8.68 |
| Clump 6                 | 24.6    | 8.18     | 8.70| 8.71 |
| Clump 7                 | 26.6    | 8.61     | 8.55| 8.58 |
| Clump 8                 | 28.1    | 8.67     | 8.56| 8.58 |
| Candidate satellite S1  | 13.2    | –        | 8.64| –    |
estimate within uncertainties. The oxygen abundance in this satellite is close to that in the spiral arms of the main galaxy.

2.3.2 Closed-box model of chemical evolution

Our abundance estimations, together with the results of the mass modelling (see Section 4), can be used to determine the effective oxygen yield \( Y_{\text{eff}} \). The effective yield is defined in a closed-box model, where the system is supposed to be isolated and to have zero metallicity at the beginning of evolution. The gas is assumed to be chemically homogeneous at a given galactocentric distance, and the IMF does not change with time. The instant recycling approximation is implied. In this model, we can define the metallicity \( Z \) in the following way (e.g. Edmunds 1990)

\[
Z = Y \ln(1/\mu),
\]

where \( \mu(r) = (\Sigma_{\text{HI}} + \Sigma_{\text{H}_2})/\Sigma_{\text{tot}} \) is the ratio of gas (taking helium into account) to total (gas + stars) surface density at a given radius. If accretion or outflow of gas occurs in the disc, the value of \( Y_{\text{eff}} \) will be lower than the real yield \( Y \) (see Edmunds 1990). Here, we can use the effective oxygen yield

\[
Y_{\text{eff}} = \frac{12(\text{O}/\text{H})}{\ln(1/\mu)},
\]

where \( 12(\text{O}/\text{H}) \) is the oxygen to total mass fraction, used to test the closed-box model for Malin 2. We have obtained the following effective oxygen yield \( Y_{\text{eff}}^{(1)} = 0.00478 \) and \( Y_{\text{eff}}^{(2)} = 0.00174 \) for the oxygen abundances reported above. At the same time, Pilyugin, Thuan & Vílchez (2007) obtained \( Y_{\text{eff}} = 0.0035 \) for the inner parts of luminous spiral galaxies. The former value of the effective yield is higher than that from Pilyugin et al. (2007), which could indicate that the corresponding oxygen abundance is overestimated, and that the second value is more realistic. This provides us with some evidence that accretion of metal-poor gas perhaps took place in Malin 2 during its evolutionary history.

3 SPECTRAL ENERGY DISTRIBUTION MODELLING

In comparison with the central region of the galaxy, the outer regions have very low signal-to-noise and hence we cannot precisely model the disc stellar population there. Using the disc contribution revealed by the 2D decomposition derived from broad-band images and adding Galaxy Evolution Explorer (GALEX) UV colours, we consider the SED of the disc component of Malin 2. We fitted it using stellar population synthesis models computed with the PEGASE.2 code (Fioc & Rocca-Volmerange 1997), with the low-resolution BaSeL synthetic stellar library (Lejeune, Cuisinier & Buser 1997).

In order to determine the best-fitting photometric model, we performed the \( \chi^2 \)-minimization of residuals between the observed SED of the disc and that of the stellar population models using a special version of the NBURST+PHOT technique (Chilingarian & Katkov 2012). The default mode in this technique is the simultaneous fitting of the spectral and photometric distributions with \( \chi^2 \) computed as a sum of the spectral and photometric contributions. The latter term is added with certain weight \( \alpha \). In order to fit the photometric SED, we chose weight \( \alpha = 1 \), which corresponds to the negligible spectral contribution. The dust attenuation is not included with the model parameters because only a small amount of dust is observed in giant LSB galaxies (Hinz et al. 2007).

For the spectral fitting, we apply two sets of stellar population models with different SFH and IMF: the exponentially declining SFH for the Kroupa IMF and the SSP models with the Salpeter IMF. The best-fitting models for both exponentially declining SFH and SSP models are shown in Fig. 6. We can see that the exponentially declining model is preferred over the SSP model because it fits the UV photometric points much better.

4 MASS MODELLING

Pickering et al. (1997) obtained the 21-cm \( ^1\text{H} \) rotation curve of Malin 2. Because of the beam smearing effect leading to low angular resolution (∼20 arcsec), these data are not suitable for detailed modelling of the central part of the galaxy, but they can still be used to constrain the mass of its main components. Pickering et al. (1997) utilized identical mass-to-light ratios for the bulge and disc components and did not take into account any spectrophotometric information in the rotation curve modelling presented in their paper. We construct a more elaborate model using our new photometric and spectral data. We decompose the rotation curve into four

![Figure 5](https://example.com/image5.png)

**Figure 5.** The position–wavelength diagram from the ARC 3.5-m spectra of the satellite S1 of Malin 2. The spectral range is clipped to show the [N II] and Hα emission lines only. The vertical solid line marks the position of the Hα emission line in the main galaxy.

![Figure 6](https://example.com/image6.png)

**Figure 6.** Results of the photometric SED modelling. The squares denote the observed broad-band SED of the disc component of Malin 2. The curves designate the best-fitting SED models based on the SSP model (dashed line) and the model with the exponentially declining SFH (solid line), respectively.
components: pseudo-isothermal halo, exponential stellar disc, Sérsic bulge and gaseous disc. We use the gaseous disc surface density derived by Pickering et al. (1997). The $M/L$ ratios for the bulge and disc were obtained from our spectra and SED modelling, respectively. We chose the pseudo-isothermal dark halo density profile instead of the cosmologically predicted Navarro, Frenk & White (1996) (NFW) profile because the central parts of the rotation curves of LSB galaxies are better described by the cored pseudo-isothermal halo than by the cuspy profile (e.g. Kuzio de Naray, McGaugh & de Blok 2008). It is worth mentioning that the poor spatial resolution of the $\text{H}_1$ rotation curve does not allow us to distinguish between these two profiles.

We assume that mass follows light in the stellar disc and bulge radial profiles. The $M/L$ ratios of the disc and bulge were calculated from the SED and spectral fitting using the exponential SFH and the Kroupa stellar IMF. We obtain $(M/L)_\text{disc} = 1.7$, $(M/L)_\text{bulge} = 3.25 \, M_\odot/L_\odot$ and $(M/L)_\text{bulge} = 1.98$, $(M/L)_\text{bulge} = 5 \, M_\odot/L_\odot$ for the $R$ and $g$ bands, respectively. At the same time, the observed colour profiles and stellar population models of Bell & de Jong (2001) give the mean mass-to-light ratios of the disc and bulge, $(M/L)_\text{disc} = 2.3$ and $(M/L)_\text{bulge} = 4.3 \, M_\odot/L_\odot$, which are higher than expected from spectral and SED fitting. We cannot fully explain this difference by the choice of different IMFs – Bell & de Jong (2001) used the scaled Salpeter IMF, whereas we utilized the Kroupa IMF – because according to Portinari, Sommer-Larsen & Tantalo (2004) the $M/L$–colour relationship obtained for the scaled Salpeter IMF is practically identical to that based on the Kroupa IMF. The Bell & de Jong (2001) models do not account for variations in the SFH in the galaxies, which are known to have a strong effect on stellar $M/L$ ratios. As demonstrated by Chilingarian & Zolotukhin (2012), stellar populations with exponentially declining and instantaneous burst (SSP) SFHs might have $B$-band $M/L$ ratios that are different by a factor of 3, while the observed $g - r$ colours will be identical.

Fig. 7 shows a comparison between the observed rotation curve and its model. The discrepant visible in the central part of the rotation curve could be a result of the unaccounted beam-smearing effect, which makes the rotation curve shallower in the centre (see Lelli, Fraternali & Sancisi 2010).

Our results of the mass modelling are provided in Table 6. Our model shows that the dark halo is not dominating in the inner region, but its mass fraction is approximately 80 per cent within four disc scalelengths. The obtained photometrical model is close to the ‘maximum disc’ model. This conclusion is in good agreement with that made by Lelli et al. (2010), who considered two giant LSB galaxies (Malin 1 and NGC 7589) and concluded that the maximum disc assumption produces stellar mass-to-light ratios in the range typical for HSB galaxies.

We obtain the following parameters for the dark halo in Malin 2: asymptotic velocity $v_\text{as} = 347 \, \text{km} \, \text{s}^{-1}$ and core radius $r_c = 27.3 \, \text{kpc}$. These correspond to the central density of the dark halo $\rho_0 = 0.0029 \, M_\odot \, \text{pc}^{-3}$ (for comparison, the Milky Way’s dark halo has $\rho_0 = 0.036 \, M_\odot \, \text{pc}^{-3}$ and $r_c = 5.0 \, \text{kpc}$, taken from Mera, Chabrier & Schaeffer 1998). These parameters indicate that Malin 2 possesses a low-density dark halo with a large core radius, in contrast to the galaxies from the $\text{H}_1$ Nearby Galaxy Survey (THINGS; de Blok et al. 2008), which have smaller core radii and higher densities. The peculiar parameters of the dark halo of Malin 2 might give us a clue to understanding its formation history (see Section 6).

Another important conclusion is that the masses of the stellar bulge and disc, obtained by applying the mass-to-light ratio from SED and spectral modelling to the surface photometry data, are close to the maximum values that could be compatible with the rotation curve. Increasing the masses significantly would lead to a discrepancy between the model and the observed rotation curves. Therefore, the disc cannot contain a large fraction of unseen dark matter because, in this case, its stellar mass should be much less than the maximum allowed for a given rotation curve.

### Table 6. Ratios of component-to-total mass of Malin 2 $M_t$ within one and four disc scalelengths $h = 25.3 \, \text{kpc}$ (in the $g$ band) obtained with our dynamical modelling. The masses of the disc, bulge, gas, and dark halo are designated as $M_d$, $M_b$, $M_g$ and $M_h$, respectively.

| $r = h$ | $M_d/M_t$ | $M_b/M_t$ | $M_g/M_t$ | $M_h/M_t$ | $M_t \times 10^{11} M_\odot$ |
|---------|------------|------------|------------|------------|-------------------------------|
| 0.25    | 0.43       | 0.30       | 0.02       | 3.13       |
| 0.12    | 0.81       | 0.04       | 0.02       | 22.4       |

Fig. 7. Decomposition of the $\text{H}_1$ rotation curve of Malin 2 (squares). The curves designate the stellar and gaseous discs, bulge and pseudo-isothermal dark halo. The open squares denote untrustworthy values, which are unreliable because of the beam-smearing effect.

5 TURBULENT GAS PRESSURE AND MOLECULAR GAS FRACTION

Malin 2 belongs to the class of LSB galaxies that is expected to have unique properties of the ISM. For a long time, their low brightness has been thought to go hand-in-hand with the lack of necessary conditions to form molecular clouds. The observed atomic surface density of LSB discs is below the threshold of gravitational instability (e.g. Bothun et al. 1997; Pickering et al. 1997). Therefore, the significant amount of molecular gas recently detected in the discs of giant LSB galaxies is striking (Das et al. 2006). Das et al. (2010) obtained maps of Malin 2 in the CO($J = 2 - 1$) line and estimated the total molecular mass (within $R < 40$ arcsec) in the range of $4.9 - 8.3 \times 10^8 M_\odot$, adopting the standard conversion factor $X = N_{\text{H}_2}/I_{\text{CO}} = 2 \times 10^{20} (\text{K} \, \text{km} \, \text{s}^{-1}) \, \text{cm}^{-2}$.

In our paper, we use the local values of the $\text{H}_2$ surface density $\Sigma_{\text{H}_2}$ in nine areas presented by Das et al. (2010) (these areas cover, in addition to the centre, the ring from 24 to 40 kpc by radius). We have taken the information about atomic hydrogen from Pickering et al. (1997). According to their results, there is a hole in the $\text{H}_1$ distribution in the central region of the disc that is probably associated with the AGN feedback (see Fig. 8). Outside 60 kpc, the atomic gas is distributed slightly asymmetrically with respect to the galactic
centre (the northern HI semimajor axis is longer than the southern one). Pickering et al. (1997) also found high-velocity gas to the south-west of the centre, which corresponds to the star-forming spiral arm (the mass of this gas is about $10^6$ $M_\odot$). The total HI mass estimated by Pickering et al. (1997) is $3.6 \times 10^9$ $M_\odot$, which implies that the contribution of the molecular gas is 1–2 per cent if $H_2$ does not extend beyond 40 arcsec. Moreover, its local$^6$ density contribution in the disc can reach 20–50 per cent, typical for normal spiral galaxies. The local observed total gas surface density $\Sigma_{gas}(r) = \Sigma_{HI} + \Sigma_{H_2}$ is less than $5 M_\odot$ pc$^{-2}$. The one-dimensional velocity dispersion of the atomic and molecular gas is found to be $\sigma_{HI} = 10$ km s$^{-1}$ and $\sigma_{H_2} = 13$ km s$^{-1}$, respectively (Pickering et al. 1997; Das et al. 2010). It is worth mentioning that the velocity dispersion of molecular gas, which is higher than that of atomic gas, looks unrealistic, and is most likely a result of beam smearing because of the low spatial resolution of observations. However, if we decrease this value by a factor of 1.5–2 (to make it closer to that of normal galaxies) it will not affect our further conclusions significantly.

The balance of the gas components $H_1=H_2$ in galactic discs is closely related to the total gas surface density and metallicity (Krumholz, McKee & Tumlinson 2009) and the equilibrium turbulent gas pressure $P$ (Blitz & Rosolowsky 2006). For normal spiral galaxies, the dependences $\eta(P)$ and $\eta(\Sigma_{gas}, Z)$, where $\eta = \Sigma_{HI}/\Sigma_{H_2}$ is the ratio of the surface densities of $H_2$ and $H_1$, behave similarly. However, these key correlations are broken when considering unusual objects, such as low-metallicity dwarf galaxies (Fumagalli, Krumholz & Hunt 2010) or members of galactic clusters exposed to environmental effects (Kasparova 2012), which significantly complicate their interpretation.

In this paper, we investigate the reason for the high fraction of molecular gas in the disc of Malin 2 in terms of pressure (although these arguments can be extended to the $\eta(\Sigma_{gas}, Z)$ relation). We calculate the gas pressure from the gas volume density in the disc mid-plane under the assumption of a constant turbulent velocity dispersions $\sigma_{HI}$ and $\sigma_{H_2}$, but taking into account the gas self-gravity, the radial profile of the stellar disc thickness and the dark matter halo contribution to the galactic gravitational potential. The volume density is found through a self-consistent solution of the equations describing the vertical structure of the stellar, atomic and molecular disc components. This approach was proposed by Narayan & Jog (2002) for our Galaxy and was developed and applied by Kasparova & Zasov (2008), Abramova & Zasov (2011) and Kasparova (2012) for other galaxies.

The key equation is obtained from the condition of the vertical hydrostatic equilibrium and the Poisson equation:

$$\frac{d^2 \rho_i}{dz^2} = \frac{\rho_i}{\langle \sigma_i^2 \rangle} \left[ -4\pi G \sum_{i=1}^{3} \rho_i \frac{\partial^2 \phi_0}{\partial z^2} + \frac{1}{\rho_i} \left( \frac{d \rho_i}{dz} \right)^2 \right].$$

Here, the index $i$ denotes each of the disc components (stars, HI, H$_2$), $\rho_i$ is the volume density and $\sigma_i$ is the turbulent velocity (effective speed of sound) along the $z$-axis. The term in brackets corresponds to the total potential of the disc and $\phi_0$ is the pseudo-isothermal spherical dark matter halo. The system of equations for the stellar disc and the gas subsystems was solved numerically using the fourth-order Runge–Kutta method with boundary conditions in the disc mid-plane $z = 0$; $\rho_i = (\rho_i^0)$, and $d\rho_i/dz = 0$ (for more details, see Kasparova & Zasov 2008).

To solve equation (1) in the nine areas with the measurements of $H_2$ and HI surface densities, we specify the surface density of the stellar disc and the dark matter halo parameters obtained from our mass model (see Section 4). The stellar velocity dispersion is determined from the rotation curve modelling and the surface density of the disc under the assumption of its marginal stability. As shown by Kennicutt (1989), Zasov, Khoperskov & Tyurina (2004) and Zasov, Khoperskov & Saburova (2011), the discs of most spiral galaxies are close to the marginal gravitational stability. Besides, there is no reason to believe that LSB discs are overheated.

The solutions of equation (1) are the volume densities in the disc mid-plane and the scaleheights of stellar, atomic and molecular components for the considered nine areas. These values are in good agreement with those obtained for Malin 2 by Abramova & Zasov (2011) in a similar manner but using slightly different stellar profile and halo parameters and without taking into account the $H_2$ components.

In Fig. 9, we compare the position of Malin 2 (circles) on the molecular gas fraction $\eta$ versus turbulent gas pressure $P$ diagram with those of normal spiral galaxies (solid lines). It is worth mentioning that the centre of Malin 2 (the open circle) has an unreliable position because of nuclear activity effects and because we neglect the bulge’s gravitational potential. The dashed line corresponding to the Milky Way shows a sharp decrease of $\eta$ at low pressure values associated with the gas self-gravity and the dark halo influence. The calculations of pressure for normal spiral galaxies in the THINGS sample from Leroy et al. (2008) and for the Milky Way have been presented by Kasparova (2012) and Kasparova & Zasov (2008), respectively. The molecular gas fraction in Malin 2 is higher by a factor of 10 than that from the fitting of the simplified pressure estimates from Blitz & Rosolowsky (2006) for normal galaxies, as marked by the dotted line. The contrast is even more

$^6$Here, the averaging is done in areas with a diameter of about 11 arcsec, as shown in Fig. 8.

$^7$In the models by Krumholz et al. (2009), there is a similar downturn of the molecular fraction for the total gas density less than $10 M_\odot$ pc$^{-2}$.
prominent in comparison to the periphery of the Milky Way. If the values of \( \eta \) correspond to the real properties of the ISM of Malin 2, what is the scenario for obtaining such a high fraction of molecules? Fig. 9 indicates that the observed H\( \text{II} \) density is too high and/or the H\( \text{I} \) density is too low in Malin 2.

This might happen if the atomic hydrogen was removed from the disc via ram pressure stripping and/or gravitational harassment, for example, which takes place in galaxy clusters and groups. In this case, the H\( \text{2} \) gas does not dissociate over the times comparable with the H\( \text{I} \) depletion time. However, it seems questionable that a significant portion of H\( \text{I} \) left the disc of such a massive galaxy as Malin 2 (see below).

Otherwise, we can assume that the molecular gas was formed at earlier stages of the evolution of Malin 2 and for some reason H\( \text{2} \) neither turned into H\( \text{I} \) nor was transformed into stars. With regard to the transition of molecular gas into stars, the depletion time for Malin 2 is nearly the same as for normal galaxies (see Section 6.2).

It is important to emphasize that in both cases the lifetime of molecular clouds is high and it is longer than the time of the H\( \text{I} \) stripping or depletion, as argued earlier by Kasparova & Zasov (2012). This is true despite the fact that, presumably, H\( \text{2} \) must be efficiently destroyed at low gas densities \( \Sigma_{\text{gas}} < 10 \, \text{M}_\odot \, \text{pc}^{-2} \) and solar metallicity (Krumholz et al. 2009). Thus, we need to find an additional factor of stabilization of molecular clouds and/or the reasons that could lead to errors in the estimates of values of \( \eta \) and \( P \) (see Section 6.1).

6 DISCUSSION

6.1 Why can the apparent gas imbalance occur?

In this section, we consider what particular properties of Malin 2 can lead to the apparent disruption of gas balance manifested in the high values \( \eta = \Sigma_{\text{H}_2}/\Sigma_{\text{H}I} \) for given turbulent ISM pressure \( P \) (see Section 5). Notably, this might be because of an underestimation of \( P \) or an incorrect estimate of the conversion factor \( X = N_{\text{H}_2}/I_{\text{CO}} \) transforming the intensity of the CO line to the molecular density along the line of sight. The reason for the high value of \( \eta \) could be either one or a combination of the factors described in the following. In addition, we discuss the possibility of dark gas in the galaxy disc.

6.1.1 Underestimation of the pressure?

To estimate the gas turbulent pressure, we use the model of a marginally gravitationally stable disc, giving the upper limit for stellar volume densities (and hence maximum gas volume densities) in the galaxy mid-plane. The galactic disc will be stable only if the stellar velocity dispersion exceeds the adopted value of \( \sigma_{st} \). This means that the pressure can only be overestimated in our model (if for some reason the disc is overheated). Therefore, the position of Malin 2 on the \( \eta(P) \) diagram (Fig. 9) cannot be explained in terms of the violation of the marginal gravitational stability.

Suppose that our estimates of the stellar surface density based on the photometry are wrong because of a non-standard stellar IMF (see also Section 6.2). However, increasing \( \Sigma_{st} \) does not change \( P \) significantly because in our approach the resulting stellar volume density, to the first approximation, depends only on the local epicyclic frequency but not on the stellar surface density (see the appendix in Abramova & Zasov 2011).

The effect of additional pressure is known because of the environmental impact from, for example, the intergalactic medium or tidal interaction with companions. For example, Virgo cluster galaxies have a high H\( \text{2} \) fraction at disc peripheries, which is similar to what we observe in Malin 2, because they are influenced by ram and static pressure from the intergalactic medium (Kasparova 2012). Although our spectroscopy revealed one companion projected on the main disc, and possibly interacting with the massive main galaxy, its mass is a fraction of a per cent of that of Malin 2, so we do not expect intense interaction with it.

6.1.2 Errors in the molecular gas density estimate?

When analysing the molecular hydrogen content, we should keep in mind that H\( \text{2} \) was not observed directly in Malin 2; instead, we rely on CO(\( J = 2 - 1 \)) line observations. The molecular gas has a complex structure. First, it can form giant molecular clouds (GMCs) as well as diffuse medium. GMCs are chemically inhomogeneous and tracers are shielded and destroyed by the UV radiation generally in a different way than H\( \text{2} \) molecules. There are two obvious reasons for the possible deviation from the standard conversion factor.

One reason could be a non-solar metallicity. In most galaxies, the relationship between the metallicity and the conversion factor \( X_{\text{XZ}^{-1}} \) proposed by Boselli, Lequeux & Gavazzi (2002) is most likely valid. Hence, extremely high metallicity is needed in order to explain the values of \( \eta \) a factor of 10 higher than expected for normal galaxies. However, our measurements of metallicity in the H\( \text{II} \) regions of the Malin 2 disc show ordinary values, half-solar to solar (see Table 1 and Section 2.3).

The disc in Malin 2 has low density \( \langle \Sigma_{\text{H}_2} \rangle \sim 1 \, \text{M}_\odot \, \text{pc}^{-2} \) and molecular scaleheight \( h_{\text{H}_2} \sim 500 \, \text{pc} \) whereas for the solar neighbourhood these values are 2.3 \( \text{M}_\odot \, \text{pc}^{-2} \) and 100 pc, respectively (e.g. Kasparova & Zasov 2008). For the Galaxy, even at its disc periphery (\( R \sim 15 \, \text{kpc} \) and \( \Sigma_{\text{H}_2} \sim 0.2 \, \text{M}_\odot \, \text{pc}^{-2} \)) the scaleheight of H\( \text{2} \) does not exceed 250 pc. Thus, we can hardly expect that conditions in the molecular gas are identical to those in the Milky Way, including the solar neighbourhood. It is not unusual to assume, on average, a thinner H\( \text{2} \) disc for Malin 2 or, for example, that the predominant form is not a GMC, but a combination of smaller clouds and diffuse H\( \text{2} \). The CO-to-H\( \text{2} \) conversion factor should be different.
in this case. In this context, we have to keep in mind that the stellar IMF might depend on the mass spectrum and the density profile in the molecular clouds or, more exactly, in the dense cores of the clouds (see Section 6.2; Williams & McKee 1997; Girichidis et al. 2011).

6.1.3 The dark gas?

Another opportunity to explain the high values of $\eta$ is the additional fraction of gas invisible in the CO (2.6 mm and others) and neutral hydrogen (21 cm) lines. The idea of the presence of some dark gas fraction in galaxy discs emerged long ago (e.g. Pfenniger, Combes & Martinet 1994; Revaz et al. 2009) and now it is confirmed for our Galaxy by the observed excess in $\gamma$-rays from cosmic ray interactions with the gas (Grenier, Casandjian & Terrier 2005) and also far-infrared excess from the dust (Ade et al. 2011). The dark gas is detected at intermediate hydrogen column densities and it is likely to be a key link in the evolution between the diffuse atomic media and molecular clouds. There is no consensus about what the dark gas is: H$_2$ or H$_i$. On the one hand, in the outer layer of a molecular cloud, the CO molecules are destroyed by UV photodissociation more efficiently than H$_2$, which is self-shielded and also protected by dust (Wolfire, Hollenbach & McKee 2010). On the other hand, we can expect that up to a half of the dark gas is atomic because of variations in the H$_i$ optical thickness (Ade et al. 2011; Fukui et al. 2012). The atomic clouds become opaque at $T < 90$ K (Peters et al. 2013), but the estimate of the H$_i$ mass from the 21-cm line is based on the assumption of small optical depth $\tau \ll 1$. In the solar neighbourhood, after accounting for the dark gas, the estimate of H$_i$ increases by one-third and the molecular gas content becomes at least twice as high (Grenier et al. 2005; Ade et al. 2011; Paradis et al. 2012). Besides, the relative contribution of the dark gas drops from small to massive clouds and becomes lower with the opacity increase. There is a reason to suspect that the dark gas fraction is higher at the low-density disc periphery in normal galaxies than in the solar neighbourhood.

As we have already mentioned, the structure of the gas medium in Malin 2 must be more rarefied than that in normal galaxies. It would be more appropriate to compare this galaxy with the Large Magellanic Cloud (LMC), where an excess of dust radiation is also detected (Bernard et al. 2008; Galliano et al. 2011). Moreover, in the LMC, the dark gas could be twice that observed at 21 cm.

Because of the uncertainty in the relative contribution of H$_i$ and H$_2$, we cannot say by how much the presence of additional dark gas will change $\eta$. Nevertheless, we can consider some possibilities. If the dark gas of Malin 2 consists mainly of molecular hydrogen, it would lead to the offset of points along the dotted line in Fig. 9. In this case, the reason for the apparent gas imbalance is not in its dark component. However, the pressure reaches the expected value (towards the dotted line) if we only double the total amount of gas adding the dark gas, more than half of which is in atomic form (i.e. $\eta$ decreases). In any case, the spatial distribution of the dark gas (regardless of its chemical composition) has to follow that of molecular clouds, but is not expected to correlate with the atomic gas. We note that the additional gas will not affect our dynamical modelling because of the small relative contribution compared to the stellar disc component. Moreover, the presence of the dark gas provides additional support for the observable H$_2$, shielding it from UV radiation, which helps to explain why H$_2$ molecules do not dissociate.

![Figure 10. A plot of $\Sigma_{SFR}$ versus $\Sigma_{H_2}$ from Bigiel et al. (2011), showing each measurement individually on a common angular scale of 1 kpc as a black dot (the sample of normal galaxies). The filled circles indicate running medians and the error bars show the 1σ log scatter in each $\Sigma_{H_2}$ bin. The dashed lines indicate the H$_2$ depletion time in years. The open circles mark Malin 2.](https://academic.oup.com/mnras/article-abstract/437/4/3072/997705)

Although the observed total gas surface density is below the gravitational stability threshold (e.g. Kennicutt 1989; Martin & Kennicutt 2001) in Malin 2 (see fig. 10 in Pickering et al. 1997), the total gas density would reach the threshold value taking into account the dark gas, and therefore can explain the ongoing star formation in the present-day disc of Malin 2 (see Section 6.2).

Resuming, the most likely reason for the apparent disruption of the gas balance is the particular structure of the ISM of Malin 2. It can be manifested in a greater proportion of the unobserved dark gas than in normal galaxy discs (e.g. because of the lower temperatures of the ISM of Malin 2). Far-infrared observations of the dust and some other tracers of molecular hydrogen beyond CO are needed in order to investigate this possibility.

6.2 Star formation and initial mass function

Malin 2 possesses an extended UV disc with a well-observed spiral structure (Boissier et al. 2008). Wyder et al. (2009) have estimated the total SFRs using far-ultraviolet (FUV)$^8$ (average over time $\sim 10^8$ yr) as

$$\log \Sigma_{SFR} = 7.413 - 0.4 \mu_{UV},$$

where $\Sigma_{SFR}$ is the SFR surface density in $M_\odot$ yr$^{-1}$ kpc$^{-2}$ and $\mu_{UV}$ is the UV surface brightness in mag arcsec$^{-2}$. They obtained SFR values several times lower than those predicted by the Kennicutt–Schmidt law $\Sigma_{SFR} \propto \Sigma_{gas}^{1.4}$ for Malin 2 and other LSB galaxies. In the galaxy centre, the local SFR values are slightly higher because of the additional UV flux probably coming from the AGN.

$^8$ Wyder et al. (2009) assumed a zero contribution of H$_2$ to the total mass of gas for LSB galaxies and neglected the UV absorption by dust, which presents in a small amount even in giant LSB galaxies (such as Malin 1 and UGC 6614) according to the Spitzer Space Telescope infrared data (Hinz et al. 2007). Thus, it is likely that they do not significantly underestimate the SFR.
There are two ways to assess the star formation efficiency (SFE). In the first case, \( \text{SFE}_{\text{gas}} = \frac{\text{SFR}}{\Sigma_{\text{gas}}} \) is low for Malin 2, and is consistent with values for other LSB discs and the outer regions of normal galaxies (Abramova & Zasov 2012). The low values of \( \text{SFE}_{\text{gas}} \) for LSB galaxies are often associated with the impossibility of forming molecules at the low total gas surface density \( \Sigma_{\text{gas}} < 10 \, M_{\odot} \, \text{pc}^{-2} \) (Krumholz et al. 2009). Evidently, for Malin 2 this explanation is not true because the H$_2$ fraction in the disc is high (see Section 5).

We can also consider the SFE estimated as \( \text{SFE}_{\text{HI}} = \frac{\text{SFR}}{\Sigma_{\text{HI}}} \). The average values of \( \text{SFE}_{\text{HI}} \) for the nine areas with known H$_2$ densities in Malin 2 (see Fig. 8) is \( (2.8 \pm 1.4) \times 10^3 \, \text{yr}^{-1} \), which agrees well with the value for normal galaxies, \( 2.35 \times 10^3 \, \text{yr}^{-1} \). For the sake of clarity, in Fig. 10, we present a plot from Bigiel et al. (2011) on which open circles mark Malin 2. Thus the molecular gas depletion time is nearly the same everywhere, even at the extremely low observed gas density. In other words, the CO intensity closely correlates with the number of clumps that give birth to massive stars. However, the amount of the gas that is not observed by tracers can probably be different from that in normal galaxies.

Now we discuss the IMF and the possible SFH, which might be the key to understanding the evolution of such an unusual object as Malin 2. Although, perhaps, there is no close connection of the ongoing SFR with the general SFH,\(^9\) we try to choose the most probable scenario.

There are several reasons to believe that the IMF for LSB galaxies is unusual. First, the high disc mass-to-light ratio \( M/L \) found from the dynamical disc mass estimates (e.g. Fuchs 2003; Saburova 2011) can be partly explained by the large contribution of low-mass stars. Another reason is that LSB galaxies have smaller numbers of supernovae (Weidner & Kroupa 2005) and a high proportion of diffuse H II radiation estimated from H$_2$ imaging (O’Neil et al. 2007). However, it must be kept in mind that the class of LSB galaxies is not very uniform and we must consider whether there is a reason to believe that the SFH and the IMF of Malin 2 are also so unusual.

Indeed, the role of older stars in Malin 2 is more significant than in other LSB galaxies because their colour indices \( \text{NUV} - r \)\(^{10} \) are about \( \sim 3.5 \) and \( \sim 2 \), respectively (Wyder et al. 2009). Lee et al. (2004) have tried to explain the presumably high \( M/L \) ratio in the discs of several LSB galaxies using the single burst model of the stellar population, taking into account their colour indices. The single burst model with a high fraction of low-mass stars reproduces the observed colours in the metal-poor LSB galaxies. However, this model is not suitable for Malin 2 (which has nearly solar metallicity) with the disc mass-to-light ratio estimates \( (M/L)_{\text{disc}} \) either 10.3 \( M_{\odot}/L_{\odot} \) from Fuchs (2002) compared to 1.7 \( M_{\odot}/L_{\odot} \) found by us.

Another reason to question the presence of a non-standard bottom-heavy IMF in Malin 2 is that the photometric model of the rotation curve that we obtain is close to the maximum disc model with the highest possible contribution of the disc to the rotation curve. Thus, we cannot increase the density of the disc so that it has a mass-to-light ratio that is significantly higher than that expected from the photometry and models with the standard IMF.

The NUV colour is sensitive to stars with a wider range of ages than FUV, so the colour index \( \text{(FUV} - \text{NUV)} \) shows a very recent SFH. Boissier et al. (2008) modelled the colour indices \( \text{(FUV} - \text{NUV)} \) for a sample of LSB galaxies. For Malin 2, as well as for most LSB galaxies, the model of constant SFR with a normal IMF is not suitable.\(^{11} \) However, the observed red colour – total as well as for only the disc area \( \text{(FUV} - \text{NUV)} \) \( \pm 0.3 \) mag – can be explained by the model of constant SFR with a lack of massive stars (IMF truncated at 5 \( M_{\odot} \) or the post-starburst scenario (i.e. fading of star formation after the burst 10$^8$ yr ago) at any IMF (see fig. 6 of Boissier et al. 2008). It should be mentioned that the model with the truncated IMF contradicts the observed value of \( \text{SFR}_{\text{HI}} \) for Malin 2.

Our broad-band SED modelling indicates that an exponentially declining SFH (with the Kroupa IMF) is applicable in the case of Malin 2, while an instantaneous burst cannot explain the photometric SED, especially its UV excess. This result supports the previous study of observational spectrophotometric and chemical properties of a sample of LSB disc galaxies by van den Hoek et al. (2000), who concluded that the observed properties of LSB galaxies are best explained by models with exponentially declining SFH.

According to the data we have analysed, the values of SFR and \( \text{SFE}_{\text{gas}} \) are lower than those for normal galaxies. The stellar IMF is likely to be a standard Kroupa because the dynamic constraints do not allow us to add a substantial amount of low-massive stars and the efficiency of the massive star formation for a given value of \( \Sigma_{\text{HI}} \) (the dense regions observed by CO) is normal. The single burst scenario (SSP models) cannot explain the observed colour indices in Malin 2. In our view, most likely, this galaxy has an exponentially declining SFH.

### 6.3 Evolutionary models

Malin 2 challenges standard evolutionary models of disc galaxies in which one can hardly form such a huge mass \( \sim 2 \times 10^{12} \, M_{\odot} \) without recent major merger events. The dynamic and structural properties of galaxies are believed to be related closely to their host dark haloes whose properties cannot change significantly by minor mergers. Malin 2 must have had acquired some of its specific properties at the early epoch before the disc subsystem was formed. Therefore, we want to understand whether we can explain the low brightness and the large scalelength of the Malin 2 disc by an exotic evolutionary scenario (as fine-tuned interaction with companions at later evolutionary stages) or by unusual initial cosmological conditions.

Unlike most LSB galaxies, giant LSBs seem to require interaction event(s) with massive companions. Two formation scenarios for giant LSB galaxies have been proposed in recent years. Mapelli et al. (2008) suggested that the unusual structure of giant LSBs was formed by a bygone head-on collision with a massive intruder (the mass ratio should be 1:1.7). They considered ring galaxies as the progenitors of giant galaxies having a low-density disc with a large scalelength. Reshetnikov, Moiseev & Sotnikova (2010) discussed a possible formation scenario of another LSB giant, Malin 1 (many of its properties are similar to those of Malin 2), and concluded that the available observational data did not contradict the scenario proposed by Mapelli et al. (2008). We should mention that although there is a rise of the disc scalelength with time in this scenario, the central surface density does not change (see fig. 2 of Mapelli et al. 2008).

\( ^9 \) For instance, colour gradients do not correlate with the distribution of H$_2$ (Burkholder, Impey & Sprayberry 2001; O’Neil, Oey & Bothun 2007).

\( ^{10} \) The colour \( \text{(NUV} - r \) gives information about the ratio of SFR and total stellar mass and therefore the weighted average age of stars in a galaxy.

\( ^{11} \) A similar conclusion was made for some other giant LSB galaxies by O’Neil et al. (2007).
This means that the progenitor of Malin 2 must have been a galaxy not only with an initially peculiar giant dark halo but also with a low density of stars (i.e. it was also a large LSB galaxy).

We do not observe a candidate intruder around Malin 2 that is sufficiently massive to satisfy the conditions introduced by Mapelli et al. (2008). Malin 2 possesses four well-observed companions: SDSS J103947.19+204506.2, SDSS J104011.80+205451.6, SDSS J103951.56+205100.1 and S1. The most massive of these has ~four times lower luminosity than Malin 2. For that companion, the velocity difference with respect to Malin 2 is about 30 km s$^{-1}$ and the projected distance between the galaxies is 342 kpc.

We stress that the major merger scenario should be extremely rare for a disc galaxy because similar interactions in most cases overheat or destroy the disc subsystem. The unequal mass merger simulations (mass ratios 1:2 and 1:10) included in the GalMer data base (Chilingarian et al. 2010) suggest that even at the mass ratio 1:10 in the case of prograde encounters (i.e. when the co-aligned angular momentum of the gas-rich satellite galaxy with that of the host galaxy – only in this case the formation of a co-planar corotating star-forming ring – occurs), the stellar disc becomes significantly overheated and the merger remnant at the end resembles a lenticular galaxy with an outer large star-forming ring (see the discussion by Sil’chenko et al. 2011). However, the low velocity dispersion in Malin 2 suggests that the stellar disc is relatively thin. However, although minor mergers on retrograde non-coplanar orbits do not significantly heat the host galaxy disc; they do result in the accretion of the greater part of the infalling satellite’s ISM on to polar orbits (e.g. Chilingarian et al. 2009) in the very central region of the host galaxy. Therefore, these cannot explain the formation of an extended gaseous disc. So, taking into account the aforesaid lack of a good candidate for a collision and, in addition, the inability to form clear spirals, we conclude that the model of Mapelli et al. (2008) is not suitable for Malin 2.

The second scenario is that the extended low-density disc of Malin 2 could have been partially formed by tidally disrupted dwarf galaxies (Peharrubia et al. 2006). In these simulations, if the low-mass satellite falls at a quasi-circular orbit, we should expect a decrease of the rotation amplitude in the periphery of the galaxy by 30–50 km s$^{-1}$. In this case, the relaxation time of the external disc will be more than 14 Gyr. This is in contrast to the case of a massive companion on a highly eccentric orbit when the stellar debris disrupts within 2 Gyr, but the resulting rotational velocity must decrease by 100 km s$^{-1}$. In Malin 2, the uncertainties of the rotation curve do not contradict the fact that the velocity decreases by less than 30 km s$^{-1}$ (Pickering et al. 1997), but we do not observe significant distortions in the disc that could reveal a destroyed companion. The colour map of Malin 2 shows only blue spiral arms and a red bulge with no traces of recently accreted satellites. Another reason not to give large credibility to this scenario is that the satellites should have almost the same angular momentum to form the disc instead of a spherical system. Moreover, it is believed that the inner disc is not strongly affected by such accretion events (O’Neel et al. 1998; Peharrubia et al. 2006). Thus, in this scenario too, the progenitor of Malin 2 should already be a LSB galaxy.

Our measurements of the mass and metallicity in the small satellite of Malin 2 projected on to the main galaxy show that small accretion events are still going on, and that the events might have been more frequent in the past. The small mass, a few per cent of that of Malin 2 at most, and similar metallicity of the satellite support the second mild merging scenario of galaxy formation. Therefore, we now have the grounds to assume a less catastrophic evolutionary scenario for Malin 2.

Like other LSB galaxies, Malin 2 is in good agreement with the assumption of the constant surface density of dark matter (Kormendy & Freeman 2004). Thus, the dark halo of Malin 2 is rarefied and the potential well is shallower than that in normal galaxies. There are numerous cosmological simulations devoted to LSB galaxies because their dark haloes are believed to dominate the total mass, providing the possibility to almost directly detect the dark mass. In modern scenarios, it turns out that LSB galaxies reside in the host haloes with relatively low concentrations and possess fast rotation\footnote{It should be understood that the cosmological models normally use the NFW profile but in the observation analysis the pseudo-isothermal sphere is used.} in which the low-density discs are formed as a result of centrifugal equilibrium (Mo et al. 1998; Bullock et al. 2001; Kim & Lee 2013). Moreover, there are reasons to expect the correlation between the halo concentration, spin parameter and the environment (Macciò et al. 2007). In fact, LSB galaxies tend to be located at the edges of the large-scale structure filaments and some LSB galaxies are even found in void regions (Rosenbaum & Bomans 2004). It is likely that such galaxies were formed in the regions lacking the intergalactic medium. The matter distribution and concentration in a galaxy depend on the rate of accretion of the intergalactic gas. In addition, the later a halo formed, the lower its central density, because of the individual halo assembly history (Wechsler et al. 2002). However, we note that all these relationships are tighter for dwarf rather than giant LSB galaxies because of the much worse number statistics. In general, we think that comparing our results with the cosmological models is premature because the halo properties in simulations are quite sensitive to relatively small changes in the cosmological parameters (van den Bosch, Mo & Yang 2003; Macciò et al. 2007). However, the lack of obvious contradictions with present models allows us to consider that the main causes for the Malin 2 features are cosmological initial conditions. Together, the peculiarities of the dark halo and probably the poor gas environment (at the time when the disc subsystem was formed) imply difficulties with the formation of the high surface density disc and with the accretion of gas to Malin 2. Perhaps this might affect the temperature of the gas disc and elevate the dark gas fraction.

Finally, we conclude that there is no need to propose any exotic catastrophic scenario because the halo parameters of Malin 2 were initially unusual and they could not have been changed significantly by minor merger events.

7 SUMMARY

In this paper, we have attempted to construct a consistent evolutionary picture of the giant LSB galaxy Malin 2 based on new observations and on available data in the literature.

(i) We performed the surface photometry of Malin 2 in the $BVR$ and $griz$ bands using imaging from the 0.5-m Apache Point Observatory telescope and using archival data from the SDSS and from GMOS-N (Gemini). The photometric data were used to constrain our mass distribution model. The dynamical model of Malin 2 implies a massive and rarefied dark halo (the central density $\rho_0 \approx 0.003 \, M_\odot \, pc^{-3}$ and the core radius $r_c \approx 27.3$ kpc of the isothermal sphere), which dominates by mass within four disc radial scale-lengths, but whose dynamical signature is small in the inner regions (Table 6).
(ii) The line-of-sight velocity profile inferred from the Gemini GMOS-N long-slit spectra along the minor axis shows the decoupled kinematics of stars and gas in the very inner region ($r \approx 5$–$7$ kpc). Such a feature in the stellar kinematics in the central bulge-dominated part of the galaxy can be related to the bulge triaxiality. The latter assumption is confirmed by moderate variation of the PA of internal isophotes with radius.

(iii) From our long-slit spectroscopic observations performed at the 3.5-m ARC telescope, we confirm a small satellite that is projected on to the main disc of Malin 2. The mass of the satellite is small, 1/500 of that of the main galaxy, and its radial velocity is very close to that of Malin 2. The oxygen abundances estimated in several H II regions at intermediate distances to the galactic centre (20–30 kpc) suggest a metallicity of $-0.3$ dex, which is in good agreement with spectroscopic estimations from GMOS-N for the central region of the galaxy, slightly subsolar values for both gas and stars.

(iv) The observed ratio of molecular to atomic hydrogen surface density, $\langle \log (\Sigma_{\text{H}_2}/\Sigma_{\text{HI}}) \rangle \approx -0.5$, is significantly higher than that expected in normal galaxies, given a low value of the turbulent gas pressure, $\langle \log (P/k) \rangle \approx 3.25$ K cm$^{-3}$, and the total gas density in the galaxy. Most likely the reason for the apparent gas balance violation is a specific structure of the ISM in the Malin 2 disc. It can be an excess of low-mass molecular clouds and a higher fraction of unobserved dark gas with respect to normal galaxies. Once we assume the excess of the dark gas, the total gas surface density increases and reaches its critical value for the gravitation instability. This allows us to explain the observed ongoing star formation in the disc of Malin 2.

(v) The SFE per total gas mass is really low but not because of the lack of conditions for the formation of molecules. The stellar IMF is unlikely to be bottom heavy because our dynamic modelling does not allow us to add a substantial amount of low-mass stars, and the rates of the massive star formation for values of $\Sigma_{\text{HI}}$ observed by CO are normal.

(vi) We conclude that a single star formation burst scenario cannot explain the observed disc colour indices in Malin 2. In our opinion, the simplest model that describes Malin 2 well is an exponentially declining SFH.

(vii) There is no need to assume a catastrophic scenario for the formation of Malin 2. We conclude that the features of Malin 2 are different from those of non-giant LSB galaxies primarily because of the dark halo scale. The peculiar properties of this galaxy can be explained by the shallow potential well of the host dark halo and by a poor gas environment when the disc was formed. These factors should impose restrictions on the rate and efficiency of the accretion of intergalactic gas and they should affect the luminous matter distribution, which can lead to the formation of a low surface density disc with high scalelength.

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