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

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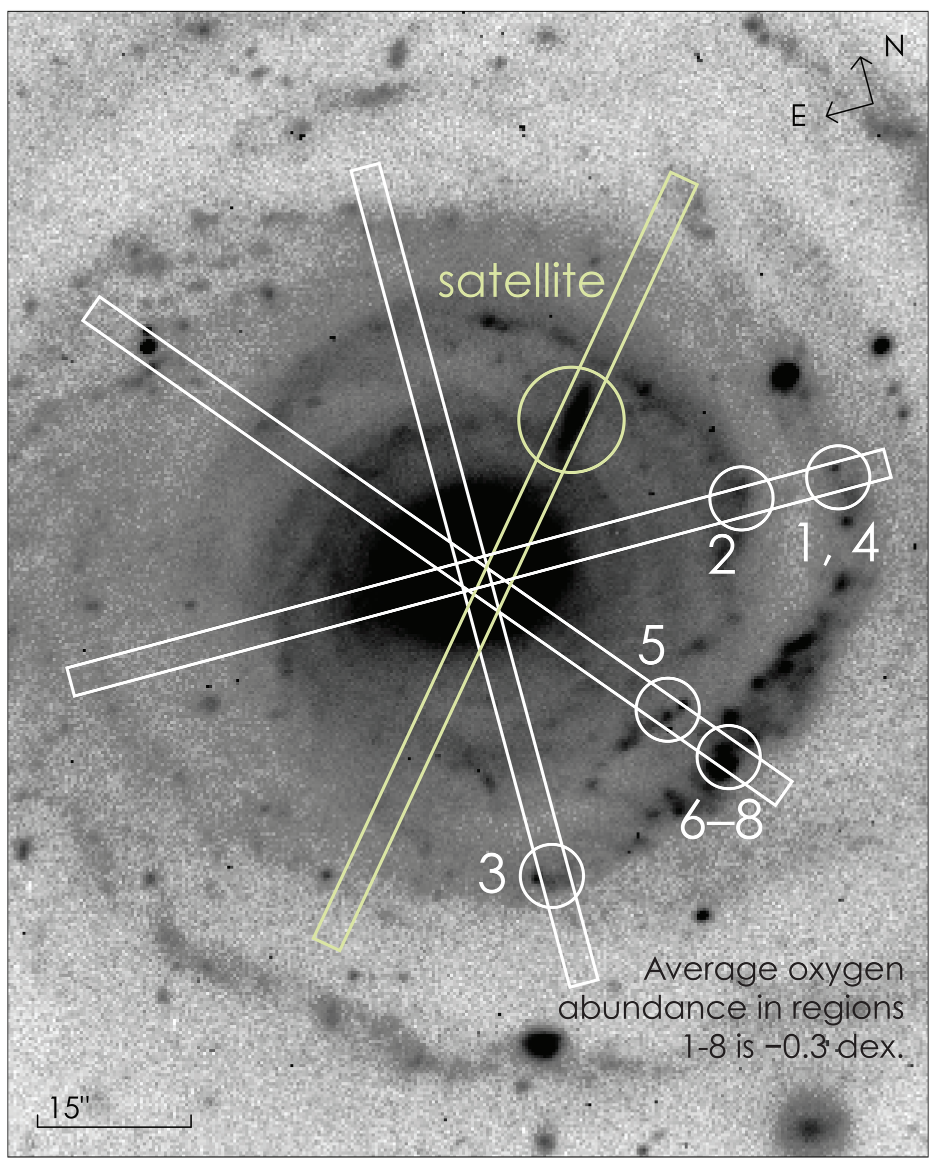
Observational data



Equatorial coordinates	$10^h39^m52^s.483$
(J2000.0)	$+20^{\circ}50'49''.36$
Distance	201 Mpc
Morphological type	Scd
Inclination angle	38 deg
Position angle	75 deg
R_{25}	45 kpc
M_B	− 21.38 mag
$(B - V)_0$	0.51 mag
$(V_{rot})_{max}$	~ 350 km/s
in g-band	
stellar disc central surf. brightness	~ 23 mag arcsec^{-2}
disc scalelength	~ 26 arcsec
B/T	0.45

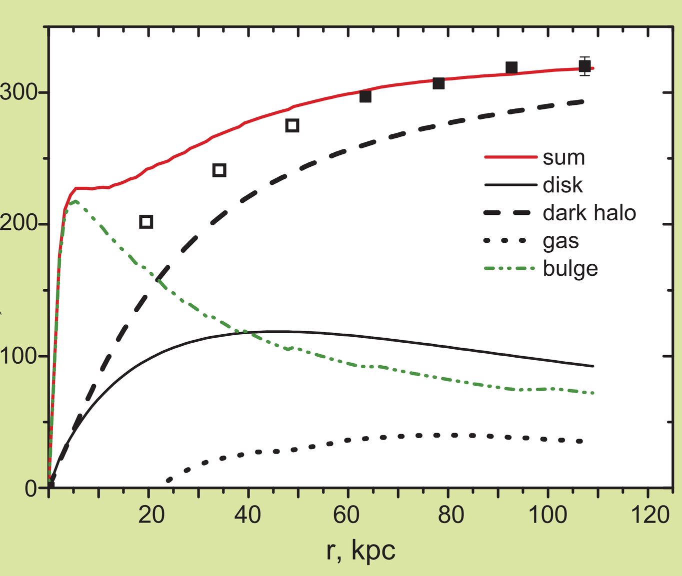
– BVR– and griz–images obtained with the 0.5-m telescope at the Apache Point Observatory (APO) and from SDSS and GMOS–N (Gemini) archives and UV from GALEX;

– Long–slit spectra of APO and GMOS–N (minor axis);

– Observations of gas components of the disc: HI (Pickering et al. 1997) and CO (Das et al. 2010).

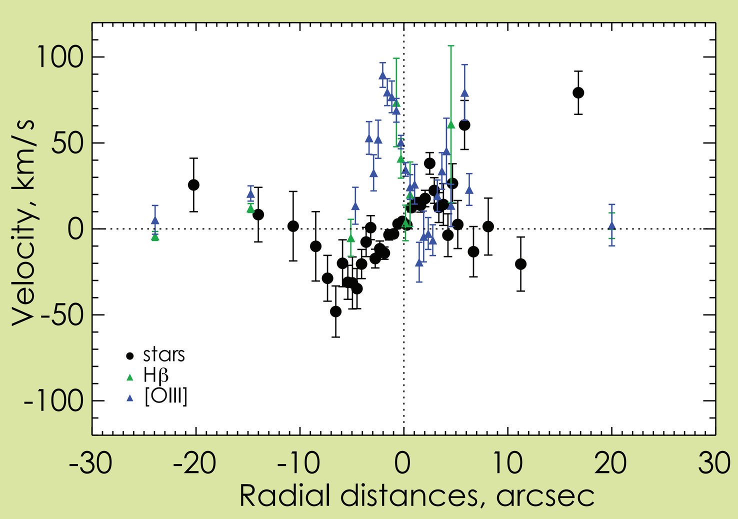
The low surface brightness (LSB) disc galaxy Malin 2 challenges the standard theory of galaxy evolution because of its enormous total mass ~$2 \cdot 10^{12}$ M_{sun}, which must have been formed without recent major merger events. The aim of our work is to create a coherent picture of this exotic object 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 ρ_0 ~ 0.003 M_{sun}/pc^3 and huge isothermal sphere core radius r_c = 27.3 kpc before the disc subsystem was formed. Our spectroscopic data analysis reveals complex kinematics of stars and gas in the very inner region (r = 5–7 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 HI 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.

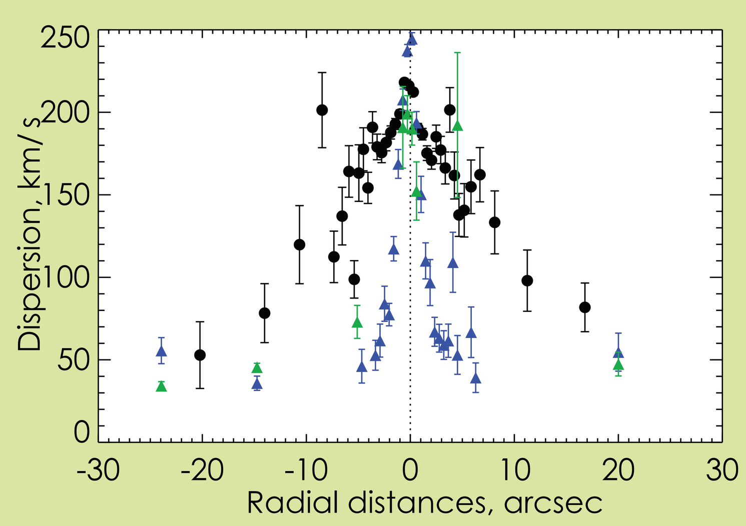
Mass model and kinematics in the inner region



Ratios of component-to-total mass of Malin 2 M_t within one and four disc scalelengths h = 25.3 kpc (in the g band)

	M_d/M_t	M_h/M_t	M_b/M_t	M_t $\times 10^{11} M_{\odot}$
r = h	0.2	0.43	0.30	3.13
r = 4h	0.12	0.81	0.0	22.4



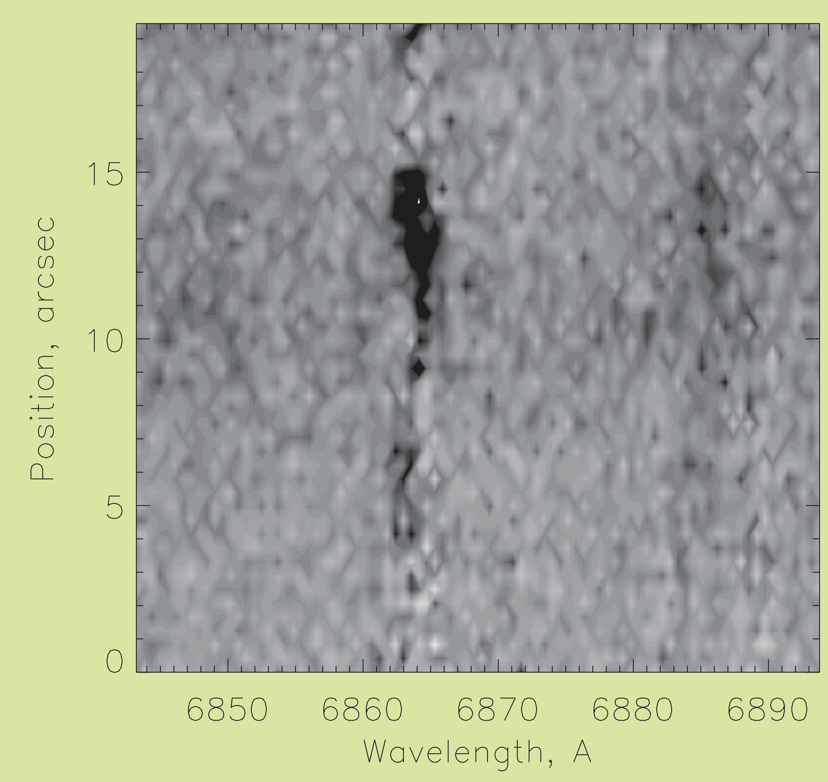


The line-of-sight velocity profile inferred from the Gemini GMOS-N long-slit spectra along the minor axis shows the decoupled kinematics of stars and gas in the very inner region (r ≈ 5–7 kpc). Such a feature in the stellar kinematics in the central bulge-dominated part of the galaxy can be related to the bulge triaxiality. The latter assumption is confirmed by moderate variation of the PA of internal isophotes with radius.

Spectroscopy at APO 3.5-m ARC telescope

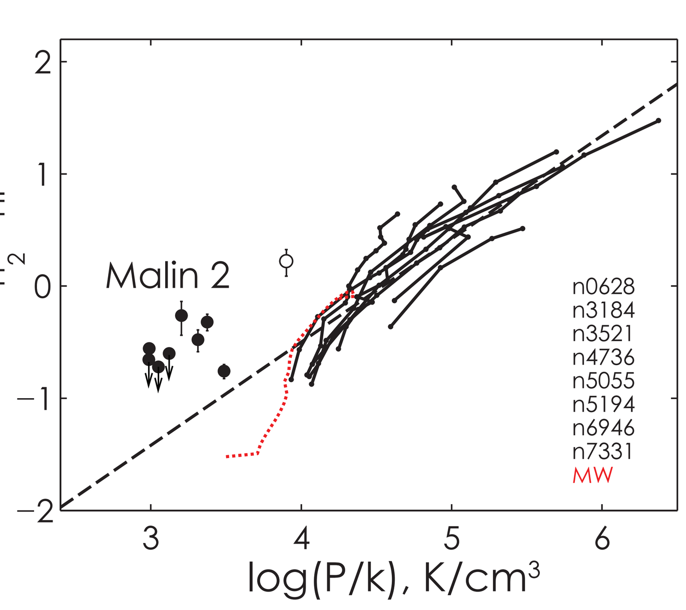
From our long-slit spectroscopic observations performed at the 3.5-m ARC telescope, we confirm a small satellite that is projected on to the main disc of Malin 2. The mass of the satellite is small, 1/500 of that of the main galaxy, and its radial velocity is very close to that of Malin 2.

The oxygen abundances estimated in HII regions 1-8 (top left panel) 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.



The position–wavelength diagram from the ARC 3.5-m spectra of the satellite 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.

Apparent gas imbalance and dark gas



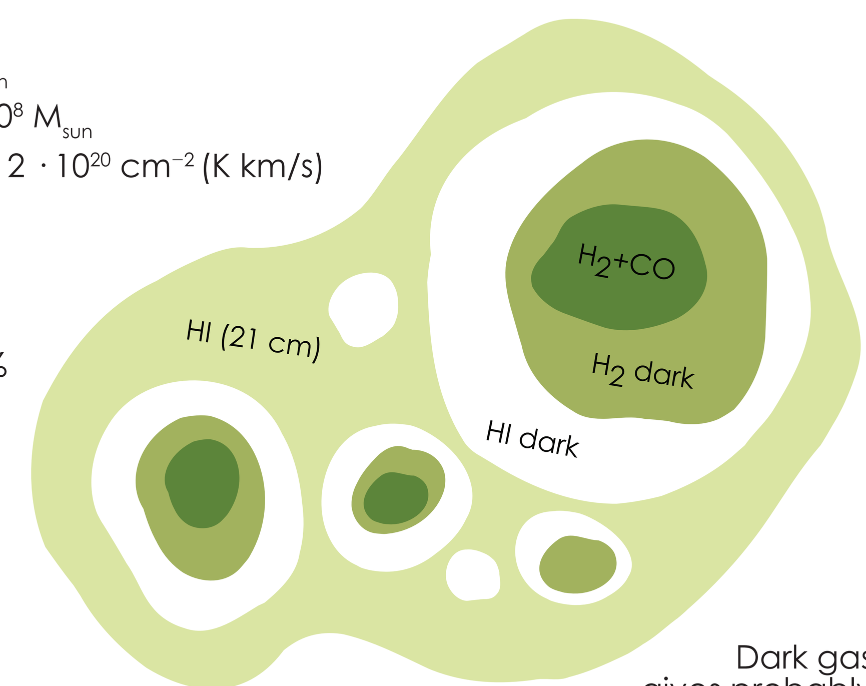
One of the unique properties of Malin 2 turned out to be the apparent imbalance of the interstellar media: the molecular gas is in excess with respect to the atomic gas for given values of the gas equilibrium turbulent pressure.

Such position of Malin 2 in the diagram can be explained neither by errors of pressure estimate or M/L nor by low conversion factor X_{CO} due to almost solar metallicity.

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 respective 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.

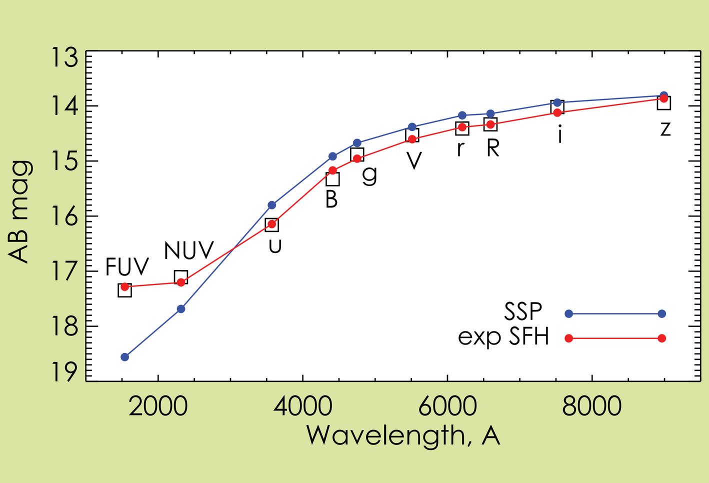
Total values:
MHI = $3.6 \cdot 10^{10}$ M_{sun}
MH2 = $4.9 - 8.3 \cdot 10^8$ M_{sun}
for $X_{CO} = N_{H2}/I_{CO} = 2 \cdot 10^{20}$ cm^{-2} (K km/s)
M_{H2}/M_{HI} = 1–2%

Local values:
Σ_{H2}/Σ_{HI} = 20 − 50%



Dark gas gives probably greater contribution to the ISM of Malin 2.

Star formation



We constructed a model of the spectral energy distribution (SED) and obtained mass-to-light ratio M/L in the V band for the disc and bulge 1.9 and 4 M_{sun}/L_{sun}, respectively. Our modelling of the ultraviolet-to-optical spectral energy distribution favours the exponentially declined star formation history of the disc over a single-burst scenario (see figure on the left);

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 Σ_{H2} observed by CO are normal.

Evolutionary models

In our work we argue that the most popular catastrophic formation scenarios for giant LSB galaxies are not suitable for Malin 2.

Neither the model of bygone head-on collision with a massive intruder (Mapelly+2008) nor the formation of extended low-density disc by tidally disrupted dwarf galaxies (Penarrubia+2006) are confirmed by observational data.

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 taking place during the disc formation. 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.

For more details see:
A. Kasparova, A. Saburova, I. Katkov, I. Chilingarian and D. Bizyaev,
The portrait of Malin 2: a case study of a giant low surface brightness galaxy, MNRAS, 437, 4, 3072, 2014