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

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VOLGA
View On the Life of GAlaxies

Low surface brightness galaxy (LSB)

- Central B-band surface brightness values are below 22.5 mag arcsec^{-2};
- This class includes a significant subset of the galaxy population, in particular among dwarfs (Bothun+1997, O'Neil & Bothun 2000, Zhong+2008);
- Disc radial scales are larger than that for normal galaxies of similar luminosity;
- The most of LSB galaxies have not bulges and AGNs (excepted the giants, such as Malin 1, Malin 2, UGC 6614 and others).

Low surface brightness galaxy (LSB)

They are interesting from two points of view:

1. In most LSB galaxies, dark matter is assumed to dominate at all distances from the centre (Bothun+1997),
   $\longrightarrow$ which conducive to studying dark haloes *directly*.

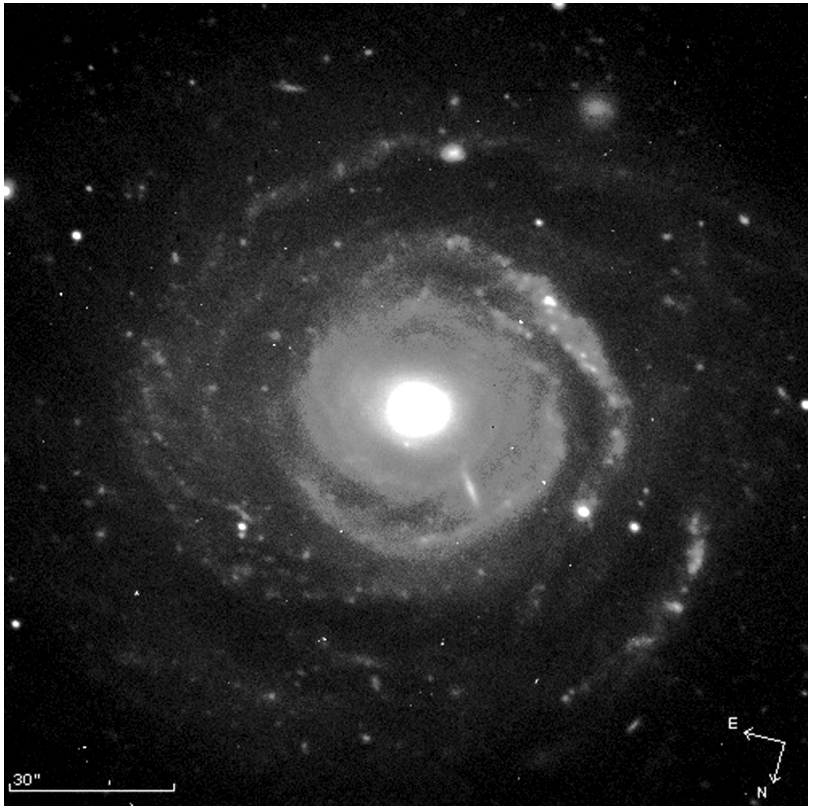
2. Many particularities of LSB galaxies like to ones **at the periphery of normal galaxy discs** (e.g. Abramova & Zasov 2011):
   - The observed gas surface density is too low for large-scale gravitational instability (e.g. Bothun+1997, Pickering+1997);
   - The observed low star formation rate (SFR) is usually associated with insufficient conditions for the formation of molecules H_2 (O'Neil+2003, Krumholz+2009).

$\longrightarrow$ The study of both aspects can give the key to understanding of galaxy evolution ways.

Malin 2

F 568-06
PGC 086622

Equat. coord.	10h 39m 52.483s
J2000.0	$+20^{o}50'49.36''$
Dist.	201 Mpc
Morph. type	Scd
R_{25}	45 kpc
M_B	-21.38^{m}
$\langle \log(O/H) + 12 \rangle$	8.64
M_{H_2}	$4.9 - 8.3 \cdot 10^{8}$ $M_{\odot}$
M_{HI}	$3.6 \cdot 10^{10}$ $M_{\odot}$



$R \approx 100$ kpc and $V_{rot} \approx 350$ km/s

The aim of work:
to create a coherent picture of Malin 2 evolution explaining its features of structure, gas and star formation properties.

Used observational data

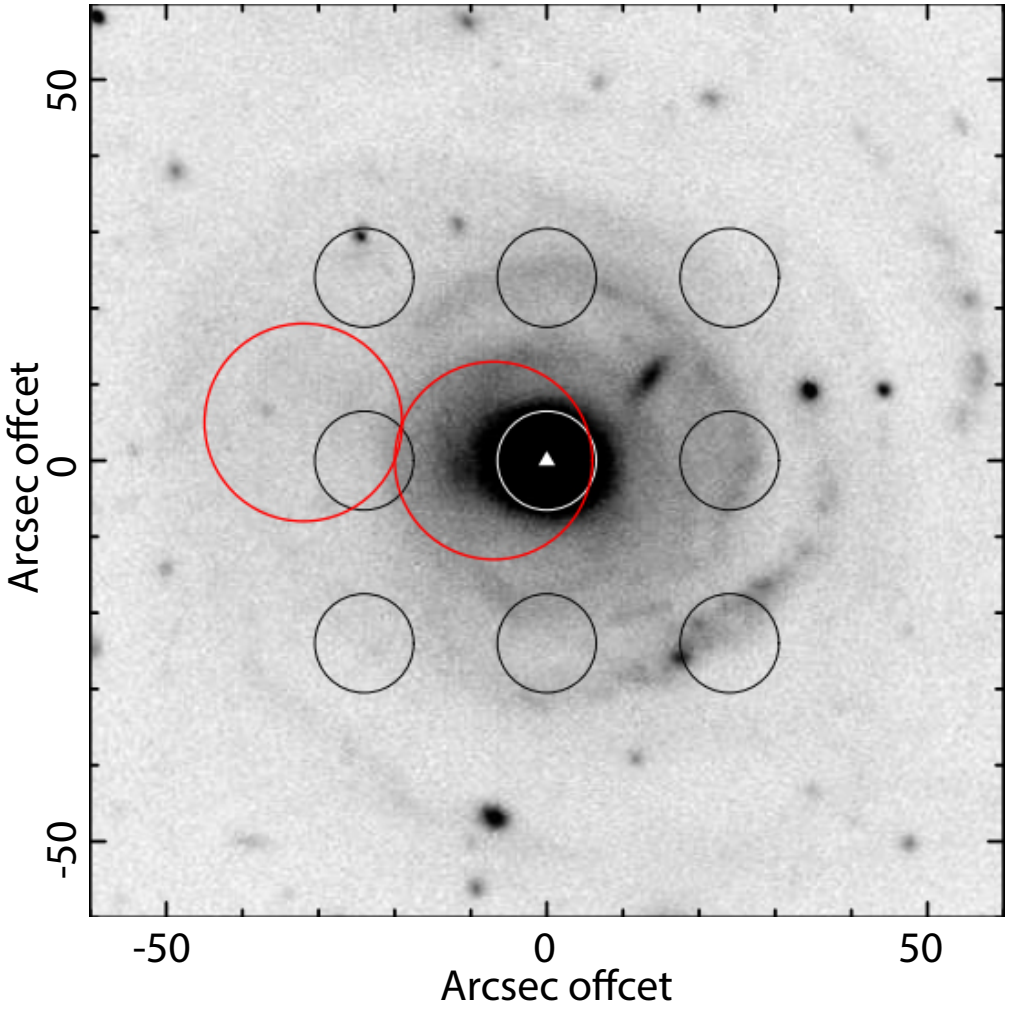
- BVR— and griz–images obtained with the 0.5-m telescope at the Apache Point Observatory (APO) and from SDSS and GMOS–N (Gemini) archives and UV from GALEX;
- Long–slit spectra of APO and GMOS–N (minor axis);
- Emission lines from HII areas in extended disc of Malin 2 (DIS, 3.5-m telescope ARC APO);
- Observations of disc gas components:
  HI (Pickering+1997) and CO (Das+2010);
- Star formation data from different sources (Wyder+2009, Boissier+2008, Lee+2004).

Gas components of disc

- $\mathrm{M_{HI}} = 3.6 \cdot 10^{10}\ \mathrm{M_\odot}$
- $\mathrm{M_{H_2}} = 4.9 - 8.3 \cdot 10^{8}\ \mathrm{M_\odot}$
  Standard conversion factor:
  $\mathrm{X} = \mathrm{N_{H_2}}/\mathrm{I_{CO}} =$
  $2 \cdot 10^{20}\ \mathrm{cm^{-2}}$(K km/s)

$\downarrow$

- Total ratio
  $\mathrm{M_{H_2}}/\mathrm{M_{HI}} = 1 - 2\%$
- "Local" ratio
  $\Sigma_{\mathrm{H_2}}/\Sigma_{\mathrm{HI}} = 20 - 50\%$



Balance of gas components HI$\longleftrightarrow$H$_2$

The ratio of molecular to atomic hydrogen surface density $\eta = \Sigma_{\rm H_2}/\Sigma_{\rm HI}$ depends mainly on:

1. Total gas surface density and metallicity — $\eta(\Sigma_{\rm gas}, {\rm Z})$ (Krumholz+2009).

   In case of Malin 2 H$_2$ have to be destroyed by UV:
   - $\Sigma_{\rm gas}({\rm R}) = \Sigma_{\rm HI} + \Sigma_{\rm H_2} \lesssim 5$ M$_\odot$/pc^2 (at all distances)
   - Gas metallicity decreases from the solar value in the centre to a half of that at $20 - 30$ kpc

2. Gas turbulent pressure — $\eta({\rm P})$ (Blitz & Rosolowsky 2006)

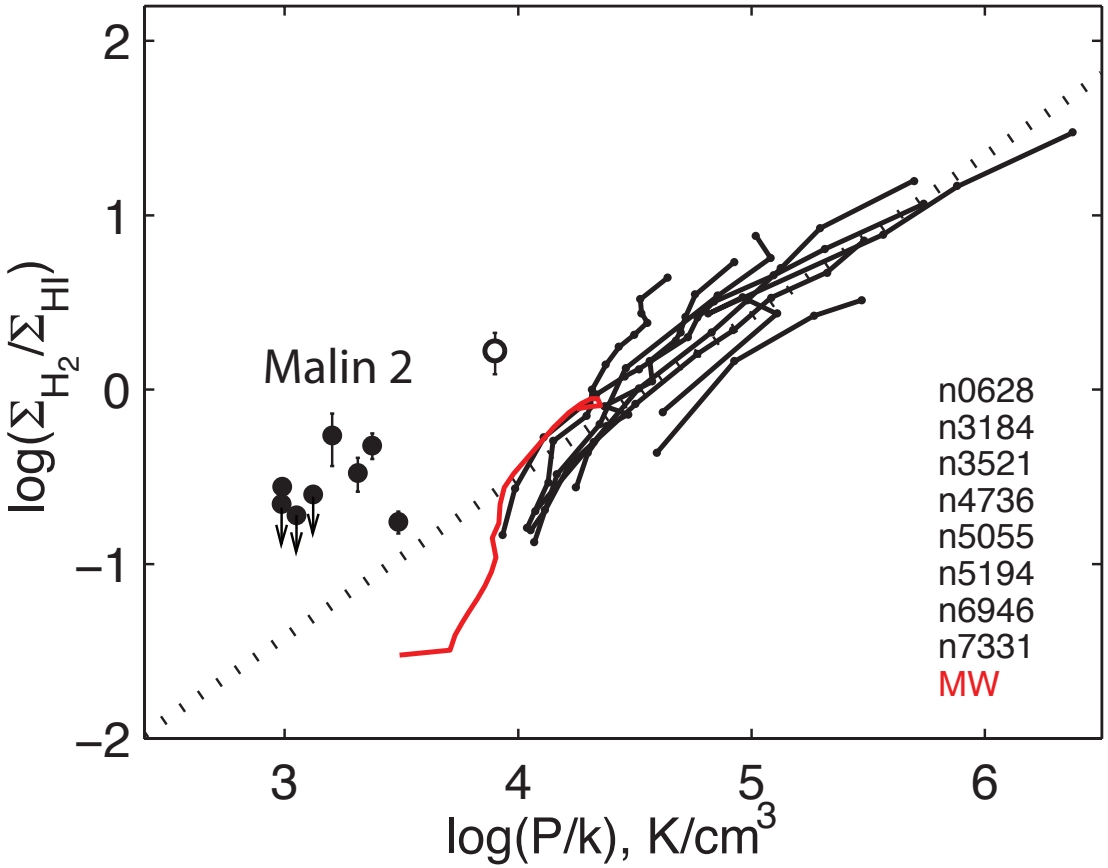
Gas turbulent pressure

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

$$\longrightarrow P = \rho_{HI} \times \sigma_{HI}^2 + \rho_{H_2} \times \sigma_{H_2}^2$$

Kasparova & Zasov 2008:
Poisson's and hydrostatic equations
+ gas self-gravity
+ radial profile of the stellar disc thickness
+ dark matter halo

The portion of molecular gas is ten times higher than the expected one for given values of pressure.



Why can the apparent gas imbalance occur?

1. Underestimation of the pressure?

- The model of a marginally gravitationally stable disc gives the upper limit of stellar volume densities and pressure.
- Errors in M/L (non-standard IMF, f.e.) lead to errors in $\Sigma_{\rm star}$, but do not significantly affect value $\rm P$ (Abramova & Zasov 2011).
- There isn't influence of the environment ($\rm P_{ram}$ и $\rm P_{stat}$) in the case of Malin 2, probably.

2. Errors in the molecular gas density estimate?

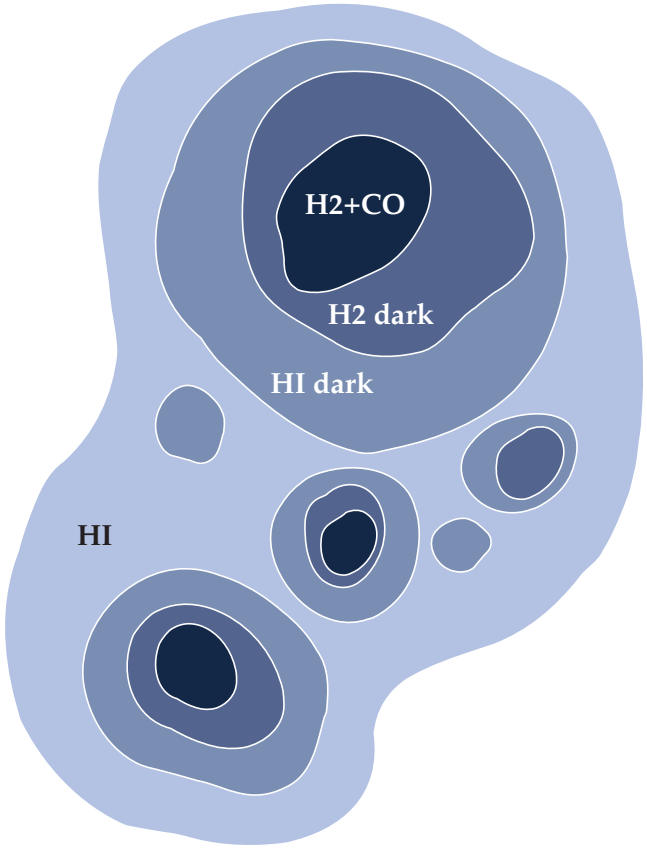
- In order to get 10 times more H_2 we need one order higher metallicity $\rm X \propto Z^{-1}$. But Malin 2 has a sub-solar metallicity.

3. Different structure of gas media. **The dark gas**

- The dark gas is discovered by the observed excess in γ-rays and also in IR excess from the dust (*Grenier+2005, PLANK*).
- CO-dark gas: CO molecules are destroyed by UV more effectively, than H_2
  $\rightarrow$ the part of molecular gas is invisible in CO.
- Dark HI: for $\mathrm{T} < 90$ K HI clouds are opaque (*Peters+2013*), but HI mass in $\lambda = 21$ cm is estimated by assuming $\tau \ll 1$.

$\longrightarrow$ The relative contribution of the dark gas drops from small to massive clouds (f.e. PLANK).

$\longrightarrow$ The greater transparency of the interstellar medium, the greater the portion of dark gas (*Wolfire+2010*).



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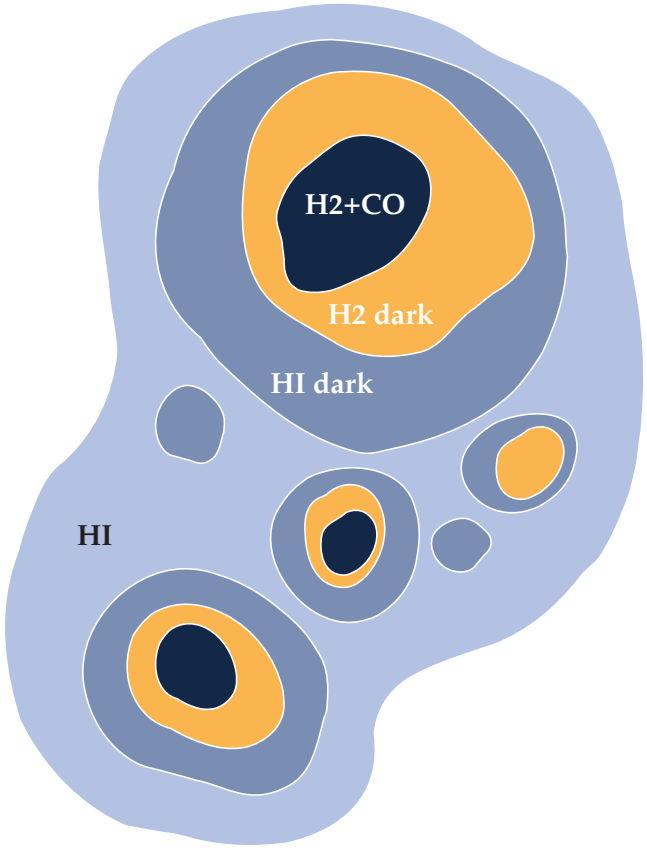

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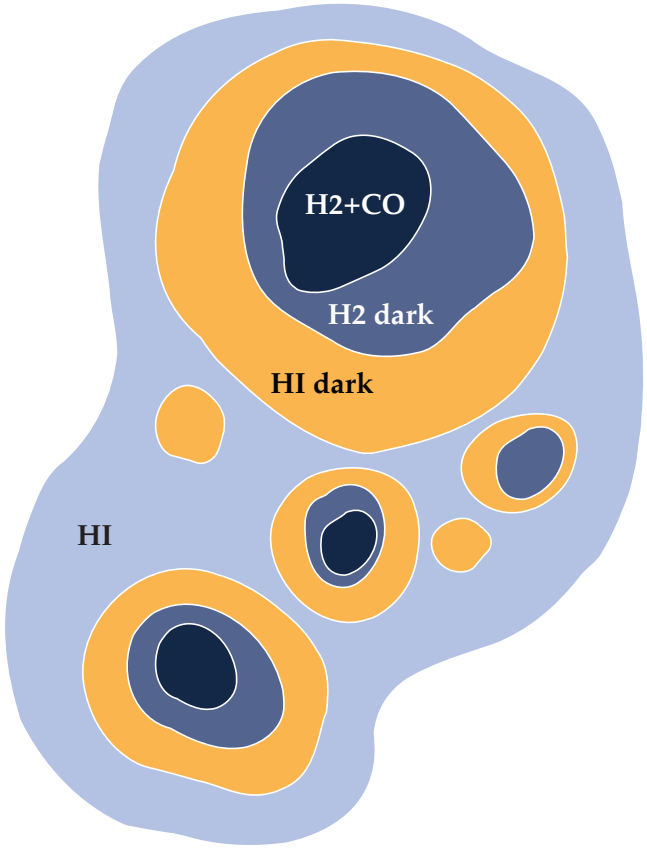

3. Different structure of gas media. **The dark gas**

- In the solar neighbourhood dark gas adds $\sim 30\%$ to HI by weight, observed in 21 cm, and $\sim 120\%$ to H_2, observed in CO.
- There are reasons to assume that the part of dark gas can vary depending on the conditions in the gas disc of the galaxy.

  $\longrightarrow$ In LMC accounting dark gas doubles the mass observed in 21 cm (*Galliano+2011, Bernard+2008*).

The assumption about higher portion of dark gas in Malin 2 disc solves two problems simultaneously:
$\longrightarrow$ It returns gas balance.
$\longrightarrow$ It leads the surface density to the threshold value.

Evolutionary models

1. Formation of giant LSB galaxies in collision with a massive companion and after the "ring" stage (Mapelli+2008).
   - Required massive companion (1:1.7) often destroys the disc.
   - Galaxy-progenitor is already giant and LSB.
   - This model reproduces slowly grow rotation curve.
   - Inability to obtain spirals.
2. The giant disc from the dwarf satellites (Penarrubia+2006):
   - We will observe a decrease of the rotation curve or the remnants of interaction.
   - What metallicity will a disc have?

3. Grounds for non-catastrophic scenario for Malin 2.
   - Major mergers usually destroy the disc subsystem or overheat it strongly (Wilman+2013, Chilingarian+2010).
   - The dark halo of Malin 2 is rarefied and the potential well is shallower than that in normal galaxies ($\rho_{\rm o} = 0.004$ M$_\odot$/pc^3 and $\rm R_c = 22.4$ kpc).
   - Shallow potential well of dark halo indicates a small number of mergers (Wechsler+2004).

$\longrightarrow$ Unique dark halo already existed before the formation of the disc subsystem.

   - LSB galaxies tend to be located at the edges of the large-scale structure filaments (Rosenbaum & Bomans 2004). Were they formed in the regions lacking the intergalactic medium?

$\longrightarrow$ Possible difficulties with the accretion related with halo parameters and poor gas environment may explain the large scale and low central surface density.

Summary

- Accounting of additional dark gas can explain the high portion of H_2 in Malin 2 that leads ISM surface density to a threshold value and explains the ongoing star formation.
- Dark halo parameters and the density of the gas environment can completely determine the accretion rates and features of Malin 2. There is no need to assume catastrophic scenario of this galaxy formation.

$\longrightarrow$ Can similar processes act both in LSB galaxies and in the disc periphery of normal spiral galaxies?

A. Kasparova, A. Saburova, I. Katkov, I. Chilingarian and D. Bizyaev, MNRAS, 2014, 437, 3072.