Malin 1: interacting galaxy pair?*

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Accepted 2010 May 27. Received 2010 May 27; in original form 2010 February 11

ABSTRACT
Malin 1 is a unique, extraordinarily large low-surface brightness galaxy. The structure and the origins of the galaxy are poorly understood. The reason for this is the absence of detailed observational data, especially of high-resolution kinematics. In this Letter, we study the stellar kinematics of the inner part (r ≤ 15 kpc) of Malin 1.

We present spectroscopic arguments in favour of a small galaxy – Malin 1B – being a companion probably interacting with the main galaxy – Malin 1. This object is clearly seen in many published images of Malin 1 but is not mentioned in any astronomical data bases. Malin 1B is located at a projected distance of 14 kpc from Malin 1’s nucleus and has small – 65 ± 16 km s⁻¹ – relative velocity, which we determined for the first time. We suggest that the ongoing interaction with Malin 1B can explain the main morphological features of Malin 1’s central region – two-armed spiral structure, a bar and an external one-armed spiral pattern.

We also investigated the large-scale environment of Malin 1 and postulated that the galaxy SDSS J123708.91 + 142253.2 might be responsible for the formation of an extended low-surface brightness envelope by means of head-on collision with Malin 1 (in the framework of the collision scenario proposed by Mapelli et al.). To test the collisional origins of Malin 1’s global structure, more observational data and new numerical models are needed.

Key words: galaxies: individual: Malin 1 – galaxies: interactions – galaxies: kinematics and dynamics – galaxies: structure.

1 INTRODUCTION
Malin 1 is one of the most unusual galaxies known to date. The galaxy was accidentally discovered in the course of a systematic survey of the Virgo cluster region designed to detect extremely low-surface brightness (LSB) galaxies (Bothun et al. 1987). According to observational characteristics, Malin 1 remains unique among other known galaxies.

The radial extent of Malin 1’s stellar disc in the V passband is ≈60 arcsec or ≈90 kpc [adopting distance D_v = 366 Mpc and a scale of 1.51 kpc/1 arcsec from the NASA/IPAC Extragalactic Database (NED)] and the disc scalelength is about 45 arcsec or 68 kpc (Bothun et al. 1987). Deep R-band data show a larger radial size of the disc – about 80 arcsec or 120 kpc – and a somewhat smaller scalelength value – 33 arcsec or 50 kpc (Moore & Parker 2006). Therefore, Malin 1 possesses the largest stellar disc of any known spiral galaxy. The disc is of extremely LSB – the extrapolated central surface brightness is μ₀(V) ≈ 25.5 mag arcsec⁻² (Bothun et al. 1987) and μ₀(R) ≈ 24.7 mag arcsec⁻² (Moore & Parker 2006). Malin 1 has a very low brightness, but due to its enormous size the galaxy’s total optical luminosity is high: M_V ≈ −22.9 mag (Pickering et al. 1997). Based on these characteristics, Malin 1 is often considered as a prototypical giant LSB galaxy.

Malin 1 is among the most gas-rich galaxies known to date: M(H_I) ≈ 7 × 10¹⁰ M_☉ (Pickering et al. 1997) or ≈5 × 10¹⁰ M_☉ (Matthews, van Driel & Monnier-Raingane 2001). The H_I disc of the galaxy demonstrates strong non-circular motions and is strongly warped (Pickering et al. 1997; Lelli, Fraternali & Sancisi 2010).

Recent analysis of a Hubble Space Telescope (HST) I-band image suggests that Malin 1 has a normal barred inner spiral disc embedded in a huge diffuse LSB envelope (Barth 2007). Based on previously published photometric characteristics and H_I kinematics, Seigar (2008) derived a possible mass profile for Malin 1. He concluded that the galaxy is baryon dominated in the centre (out to ~10 kpc) and, probably, has parameters typical of normal galaxies (of course, excluding the giant LSB envelope). Recently, Lelli et al. (2010; see also Sancisi & Fraternali 2007) presented similar results using their re-analysis existing H_I data. The models by Seigar (2008) and Lelli et al. (2010) are based on published H_I observation by Pickering et al. (1997). But these H_I data are strongly affected by

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beam smearing and, as a result, no reliable kinematics inside the central 15 kpc are currently available.

In order to investigate the stellar kinematics of Malin 1, we have performed a spectroscopic study of the galaxy with the Russian 6-m telescope. Detailed discussion and results of the modelling will be published later. In this Letter, we present the most surprising result of our observations – the discovery of the galaxy (Malin 1B) that probably interacts with Malin 1.

2 SPECTRAL OBSERVATIONS
The spectroscopic data were obtained with the 6-m telescope of the Special Astrophysical Observatory of Russian Academy of Sciences on 2009 March 30/31. We observed Malin 1 with the multimode focal reducer SCORPIO (Afanasiev & Moiseev 2005) in the long-slit mode with a spectral resolution of about 2.5 Å in the wavelength range of 5500–6550 Å that corresponds to 5080–6050 Å in the galaxy rest frame. The spectral range studied contains numerous absorption features (Mg I, Fe, etc.) produced by old stellar population. The possible contribution of weak emission lines was insignificant. The slit, whose length is about 6 arcmin, has been placed on the galaxy nucleus at position angle [P.A. = 55°] (see Fig. 1). The slit width was 1 arcsec with a spatial sampling of 0.35 arcsec pixel$^{-1}$. We took in total an exposure of 7200 s under an atmospheric seeing of 2 arcsec.

For data reduction and analysis, we used programmes and algorithms briefly described in Zasov et al. (2008). The line-of-sight velocity and stellar velocity dispersion profiles for the stellar components have been estimated by cross-correlating galactic spectra binned along the slit with template star HD 10380 (K3 III) spectra from the library MILES (Sanchez-Blazquez et al. 2006). We applied 2–3 pixels binning along the slit to provide a sufficient signal-to-noise ratio; the resulting sampling was 0.70 arcsec for the inner part of the galaxy and 1.05 arcsec for several external points.

![Figure 1. I-band contour map of the central part of Malin 1. The faintest contour is about 23.7 mag arcsec$^{-2}$, the isophotes step is 0.75 mag arcsec$^{-2}$. The red lines mark the position of the long-slit (1 arcsec in width). The F814W Wide Field Planetary Camera 2 image was extracted from the Hubble Legacy Archive.](https://academic.oup.com/mnrasl/article-abstract/406/1/L90/1041392)

The results are presented in Fig. 2. At $r \approx 9$ arcsec, the slit crosses the nucleus of a small companion galaxy (Malin 1B). Fig. 2 shows that this region is kinematically decoupled from Malin 1’s rotation curve: it has an invert radial velocity gradient and a distinct peak at the velocity dispersion profile.

3 RESULTS AND DISCUSSION
3.1 Characteristics of Malin 1
From our spectrum, we determined the following parameters of the main galaxy (Malin 1): the heliocentric systemic velocity $V_{sys} = 24775 \pm 10$ km s$^{-1}$ and the central velocity dispersion $\sigma_0 = 192 \pm 13$ km s$^{-1}$. Both values are in good agreement with previously published results (Table 1).

The companion galaxy – Malin 1B – has coordinates $\alpha(2000) = 12^h36^m58^s89$ and $\delta(2000) = +14^\circ19'43''9$ and is located about 9 arcsec south-west from the main galaxy nucleus (Fig. 1). The systemic radial velocity of the companion is $V_{sys} = 24840 \pm 12$ km s$^{-1}$, the velocity difference with Malin 1 is $65 \pm 16$ km s$^{-1}$ and the projected distance is 14 kpc.

The outer elliptical isophotes of Malin 1B are disturbed and elongated to the north–north-east (Fig. 3). The mean axial ratio of the isophotes is $b/a = 0.76 \pm 0.07$, the P.A. of the major axis is $79^\circ \pm 3^\circ$ and the major axis is about 3 arcsec or 4.5 kpc.

The surface brightness distribution of Malin 1B looks usual for early-type spiral galaxies (Fig. 3). In the framework of the two-component model, the bulge-to-disc ratio is $\approx 1$. This value is typical for the S0-Sa galaxies (e.g. Simien & de Vaucouleurs 1986).

The observed luminosity of Malin 1B measured within $\mu(I) = 23$ mag arcsec$^{-2}$ is about one-tenth of the luminosity of Malin 1.
Table 1. General characteristics of the galaxies.

| Parameter                         | Malin 1 | Malin 1B | SDSS J123708.91+142253.2 | Ref.       |
|-----------------------------------|---------|----------|--------------------------|-----------|
| \(\alpha\) (2000)                | 12\(^{h}\)36\(^{m}\)59\(^{s}\)36 | 12\(^{h}\)36\(^{m}\)58\(^{s}\)89 | 12\(^{h}\)37\(^{m}\)08\(^{s}\)92 |           |
| \(\delta\) (2000)                | 14\(^{\circ}\}19\,\prime\,49\,\prime\,41 | 14\(^{\circ}\}19\,\prime\,43\,\prime\,91 | 14\(^{\circ}\}22\,\prime\,53\,\prime\,3 |           |
| Projected separation from Malin 1 | 0       | 9 arcsec (14 kpc) | 3.855 arcmin (350 kpc) |          |
| Apparent magnitude               | 17.6 (g) | 18.6 (g) |                          | SDSS     |
| Heliocentric systemic velocity\(^a\) (km s\(^{-1}\)) | 24775 ± 10 | 24840 ± 12 | 24907 ± 27 | Present work |
|                                  | 24800 ± 17 |            | 24840 ± 12 | SDSS     |
|                                  | 24819 ± 65 |            |              | SDSS     |
|                                  | 24767 ± 4  |            |              | Lelli et al. (2010) |
|                                  | 24784 ± 15 |            |              | Matthews et al. (2001) |
|                                  | 24755 ± 10 |            |              | Pickering et al. (1997) |
|                                  | 24705, 24745 |          |              | Impey & Bothun (1989) |
|                                  | 24750 ± 10 |            |              | Bothun et al. (1987) |
| Central velocity dispersion (km s\(^{-1}\)) | 192 ± 13 | 65 ± 16 | Present work | Barth (2007) |
|                                  | 196 ± 15 |            |              |          |

\(^a\) Conventional radial velocity obtained as \(cz\).

Figure 3. Top: contour map of Malin 1B from the HST I-band image. Orientation of the figure is the same as in Fig. 1. Isophotes are separated by a factor of 1.5; the faintest contour is 22.3 mag arcsec\(^{-2}\). Axes are in arcsec. Bottom: photometric profile for Malin 1B along the apparent major axis (dots). The solid line represents the approximation of the profile by a standard two-component model (de Vaucouleurs’ bulge and exponential disc).

within the same isophote. The total luminosity of the companion \(M_I \approx -20\) or \(M_I \approx -18.7\) (assuming \(V-I = 1.3\) for an S0 galaxy).

The observed central velocity dispersion of Malin 1B is \(\sigma_0 = 97 \pm 20\) km s\(^{-1}\) and the galaxy parameters satisfy the Faber–Jackson relation.

Figure 4. Distribution of galaxies within an RA range of \(160\,\circ \leq \alpha(2000) \leq 220\,\circ\) (from top to bottom) and a redshift of \(z \leq 0.15\) in a polar plot according to the NED. Malin 1’s position is indicated by a red arrow. The Dec. range of \(13\,\circ 1 \leq \delta(2000) \leq 15\,\circ 6\) is projected on to the plane.

The ratio \(V_{\text{max}}/\sigma_0 > 0.7\) is typical for the rotationally supported disc galaxies, as it follows, for instance, from Binney’s diagnostic \((v/\sigma - \epsilon)\) diagram (e.g. Kormendy 1993).

3.2 Malin 1 as an interacting galaxy

Fig. 4 shows the large-scale spatial environment of Malin 1. As one can see, the galaxy is located in a relatively low-density region, near the end of an elongated structure, that is probably a filament of the large-scale structure (LSS). Therefore, Malin 1 is within the environment typical for LSB galaxies. For example, Rosenbaum & Bomans (2004) and Rosenbaum et al. (2009) concluded that the LSB galaxies appear to favour the edges of filaments. This conclusion supports the idea that LSB galaxies were formed in the voids of the LSS without many galaxy interactions. It is only in this case that the low-density primordial fluctuations could have survived. If this
would have been the case, then galaxy would have migrated to the edges of the filaments due to gravitational infall.

There is another point of view about the origins of LSB galaxies. Some authors suggested a possible link between giant LSB galaxies and ring galaxies formed as a result of a head-on collision with a massive flyby intruder (e.g. Mapelli et al. 2008). Smoothed shell-like structures at large radii can also be produced by mergers between a disc-like galaxy and an elliptical one (Pierani et al. 2010).

The collisional scenario is very attractive because Malin 1 has a normal inner stellar disc and a normal bulge (Barth 2007). Moreover, its extended stellar and gaseous discs can be considered as collisional rings at the late stage of their evolution. Mapelli et al. (2008) presented a model that matches in general the global photometry of Malin 1. Unfortunately, such a model needs an intruder with mass that is comparable with the total mass of the main galaxy or only a few times less. Malin 1B looks too small and insufficiently massive to produce an extended ring-like structure. It could have been more massive originally but has been tidally stripped during the interaction with Malin 1. But we know that its position and relative velocity favour a close orbit rather than a flyby at escape speed that is commonly presumed when one considers a collisional origin of ring-like galaxies (Lynds & Toomre 1976; Hernquist & Weil 1993; Horellou & Combes 2001).

Nevertheless, Malin 1B could cause the appearance of a single dusty spiral arm in Malin 1 that has been recently revealed (Moore & Parker 2006). This type of structure is often considered as the result of an interaction with a satellite on a retrograde orbit (Athanassoula 1978).

Malin 1B could also produce two-armed structure and trigger a bar instability in the inner disc of Malin 1. The inner spiral structure is definitely seen in the HST I-band image (figs 1 and 2 of Barth 2007) and the bar can be clearly recognized by analysing the surface brightness distribution of Malin 1 (fig. 3 of Barth 2007). But we definitely need a more massive companion to support the scenario by Mapelli et al. (2008).

The nearest bright galaxy with known redshift is SDSS J123708.91+142253.2 with \( V_{hel} = 24907 \pm 27 \) (Table 1). The galaxy is located at a projected distance of 3.9 arcmin or 350 kpc far from Malin 1 and has an apparent magnitude \( g_{(SDSS)} = 18.6 \). The velocity difference between this galaxy and Malin 1 is rather small – \( 132 \pm 29 \) km s\(^{-1}\).

We can use parameters of the collisional model presented by Mapelli et al. (2008) to check the galaxy SDSS J123708.91+142253.2 as a candidate for being a possible intruder. The ratio of Malin 1 to ‘intruder’ optical luminosities (that is about 1/2.5 in the g band) is in agreement with the value of the mass ratio of target to intruder galaxies in the model under discussion.

The collisional model (Mapelli et al. 2008) suggests an impact at an inclination angle of \( \sim 14^\circ \) with respect to the angular momentum axis of the target (Malin 1 in our case). According to Moore & Parker (2006), the inclination angle of a stellar disc of Malin 1 is \( \sim 45^\circ \). Then the direction of intruder motion would have an inclination angle to the line of sight between \( \theta \sim 30^\circ \) and \( \theta \sim 60^\circ \). Let us choose the largest value of the angle for further estimates. The initial position and the velocity (with respect to the centre of mass of the progenitor of the ring galaxy) for the intruder adopted by Mapelli et al. (2008) are \( r \approx 33 \) kpc and \( v_{hel} \approx 900 \) km s\(^{-1}\), respectively. It implies that the intruder radial velocity would be \( v = v_{hel} \cos \theta \sqrt{r_{true} / r} \approx 130 \) km s\(^{-1}\) at the projected distance \( r_{proj} = r \sin \theta = 350 \) kpc. Both estimates mean that it takes the intruder about 1 Gyr \( (t \approx \frac{r}{v} / v) \) to get there, providing a very small impact parameter and a flyby as suggested by Mapelli et al. (2008).

Our simple velocity estimate for the intruder is in agreement with the data presented here. Moreover, the current location of the galaxy SDSS J123708.91+142253.2 maintains the idea for the closest passage to happen 1 Gyr ago that is also in accordance with the model by Mapelli et al. (2008). But this otherwise attractive scenario has one serious drawback.

The model by Mapelli et al. (2008) predicts the existence of strong non-circular motions that could be associated with the expansion velocity of the old ring and/or with the fallback of a part of the ejected matter towards the centre. The strength of non-circular motions can be quantified by the ratio of radial to tangential velocities of gas. Simulations show that there is a region in the outer part of the galaxy (\( \sim 70–80 \) kpc far from the centre) where radial velocities are comparable with tangential ones (fig. 12 of Mapelli et al. 2008). However, the analysis of H I data (to be discussed in a forthcoming paper) shows that possible radial motions are smaller (see also Lelli et al. 2010). Namely, the radial component of non-circular gas motions in the galaxy outskirts has a maximal value of about 0.3–0.4 of rotation velocities. Moreover, the azimuthal distribution of non-circular motions is more complex than a simple inflow/expansion pattern predicted by numerical simulations.

In any case, the structure of Malin 1 seems more complex than that predicted from the Mapelli et al. (2008) model because the real situation should include two events: a possible strong head-on collision with a massive companion (SDSS J123708.91+142253.2) and a current interaction with a smaller Malin 1B galaxy.

Thus, we do not reject the collisional model of Malin 1 but it definitely needs to be refined, as far as, new observational data are urgently needed.

## 4 CONCLUSIONS

In this Letter, we present the results of spectroscopic observations of the Malin 1 galaxy and its newly discovered companion Malin 1B. Our main conclusions are as follows.

(i) Malin 1 is currently undergoing a minor merger with a relatively small companion galaxy. This galaxy is at a projected distance of 14 kpc and shows a small velocity difference with Malin 1’s systemic velocity (\( \Delta V = 65 \) km s\(^{-1}\)).

(ii) An accreting companion might be responsible for the main morphological features in the central part of Malin 1. It could produce a two-armed inner structure and trigger the bar instability (Fig. 1). Also, one can relate this companion to the one-armed spiral pattern in the Malin 1 disc (see fig. 4 in Moore & Parker 2006).

(iii) Malin 1 is in a relatively low-density large-scale spatial environment that is typical for LSB galaxies.

(iv) We discuss the possible origins of Malin 1’s global structure due to a bygone head-on collision with a massive intruder (mechanism proposed by Mapelli et al. 2008). Available data do not contradict this scenario (for instance, we even identified a possible intruder galaxy SDSS J123708.91+142253.2), but more detailed simulations and new observational data are needed for definite conclusions.

## ACKNOWLEDGMENTS

The research is partly based on observations made with the NASA/ESA Hubble Space Telescope, and obtained from the Hubble...
Legacy Archive, which is a collaboration between the Space Telescope Science Institute (STScI/NASA), the Space Telescope European Coordinating Facility (ST-ECF/ESA) and the Canadian Astronomy Data Centre (CADC/NRC/CSA). Funding for the Sloan Digital Sky Survey (SDSS) and SDSS-II has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Science Foundation, the U.S. Department of Energy, the National Aeronautics and Space Administration, the Japanese Monbukagakusho, and the Max Planck Society, and the Higher Education Funding Council for England. The SDSS Web site is http://www.sdss.org/. AVM thanks the grant of the Russian Foundation for Basic Researches number 09-02-00870 and also the Dynasty Fund.

We thank an anonymous referee for helpful comments on the Letter.

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