SCIENCE RESULTS

The central region of the enigmatic Malin 1

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Abstract. Malin 1, being a class of giant low surface galaxies, continues to surprise us even today. The HST/F814W observation has shown that the central region of Malin 1 is more like a normal SB0/a galaxy, while the rest of the disk has the characteristic of a low surface brightness system. The AstroSat/UVIT observations suggest scattered recent star formation activity all over the disk, especially along the spiral arms. The central 9" (~14 kpc) region, similar to the size of the Milky Way’s stellar disk, has a number of far-UV clumps—indicating recent star-formation activity. The high resolution UVIT/F154W image reveals far-UV emission within the bar region (~4 kpc)—suggesting the presence of hot, young stars in the bar. These young stars from the bar region are perhaps responsible for producing the strong emission lines such as Hα, [OII] seen in the SDSS spectra. Malin 1B, a dwarf early-type galaxy, is interacting with the central region and probably responsible for inducing the recent star-formation activity in this galaxy.

Keywords. Galaxies: structure—galaxies: evolution—galaxies: interaction.

1. Introduction

Since its discovery (Bothun et al. 1987), Malin 1 continues to surprise us. Malin 1 belongs to the class of giant low-surface brightness (GLSB) galaxies and probably, is one of the largest disk galaxies with spiral arms extending up to 130 kpc in radius at the distance of Malin 1 (Moore & Parker 2006; Boissier et al. 2016). Most of the stars in the outer disk of Malin 1 follows an exponentially declining surface brightness profile. The outer disk is so faint, that when extrapolated to the centre, it has a central surface brightness of 25.5 mag arcsec⁻² in the v-band (Impey & Bothun 1989). Using the deep images in the six photometric bands from the NGVS and GUViCS surveys, Boissier et al. (2016) have shown that the extended low-surface brightness disk has a long and low star-formation history. However, the central region has a complex structure—with a bulge and a bar as revealed by the Hubble Space Telescope (HST) observation (Barth 2007). In other words, the morphology of the central region is similar to the high surface brightness (HSB) galaxies with SB0/a morphology. This, in turn, makes Malin 1 a classic example of a hybrid galaxy with central HSB-like and outer LSB-like envelope. The central HSB-like structure is also manifested in terms of the inner steeply rising rotation curve (Lelli et al. 2010). Several questions arise here—is Malin 1 a galaxy in transition from LSB to HSB? What drives such a transformation? In addition to stars, the galaxy contains plenty of neutral hydrogen gas (Pickering et al. 1997) as in typical late-type spirals. Even then, it appears that the galaxy may not be forming stars efficiently as it lacks CO molecules (Braine et al. 2000), although, the non-detection of CO may also be
attributed to the low temperature of molecular gas compounded with sub-solar metallicity (Braine et al. 2000). Nevertheless, the central region appears to have recent star formation activity—based on the strong emission lines such as Hα, Hβ, [OⅡ], [OⅢ] from the SDSS central 3′′ fibre spectra and much recently from a detailed spectroscopic study by Junais and Epinat (2020). Such an activity is probably induced by an external perturber.

Indeed, Malin 1 is interacting with another galaxy called Malin 1B which an early type galaxy at a distance of only 9″ (14 kpc) from the centre. Recently, Reshetnikov et al. (2010) suggest that Malin 1 is also probably interacting with another galaxy SDSSJ123708.91+142253.2 at a distance of about 358 kpc away. Such an interaction can lead to the formation of the central bar (Miwa & Noguchi 1998; Lang et al. 2014; Lokas et al. 2014). Accretion of smaller galaxies like Malin 1B or giant clumps could enhance star-formation, increase the central concentration—in other words, grow the central bulge (Aguerri et al. 2001; Eliche-Moral et al. 2018). One might expect to see the induced star-formation activity in the UV emission and indeed, this is evident from the far-UV (FUV) and near-UV (NUV) emission in the FUV band from the bar region of Malin 1 with the Ultra-Violet Imaging Telescope (UVIT) on-board AstroSat, simultaneously in far-UV (F154W; 1250–1750 Å) and near-UV (N263M; 2461–2845 Å) filters by the UVIT during February 2017 (PI: Kanak Saha; proposal id: G06-016). The observations were carried out in the photon counting mode (frames taken every 34 millisecond during each orbit) resulting in about ~45000 frames accumulation in a typical good dump orbit. The orbit-wise L1 dataset was processed using the official L2 pipeline. The pipeline throws away the cosmic-ray affected frames during data reduction process and these frames were excluded in the final science-ready images in FUV and NUV bands and the subsequent calculation of the photometry. The final science-ready images had a total exposure time of \( t_{\text{exp}} = 9850 \text{ s} \) in F154W (bandwidth = 380 Å) and \( t_{\text{exp}} = 9600 \text{ s} \) in N263M (bandwidth = 275 Å).

2. UVIT observation and data analysis

The giant low-surface brightness galaxy Malin 1 (at a redshift of \( z = 0.0827 \)) was observed simultaneously in the far-UV (F154W; 1250–1750 Å) and near-UV (N263M; 2461–2845 Å) filters by the UVIT during February 2017 (PI: Kanak Saha; proposal id: G06-016). The observations were carried out in the photon counting mode (frames taken every 34 millisecond during each orbit) resulting in about ~45000 frames accumulation in a typical good dump orbit. The orbit-wise L1 dataset was processed using the official L2 pipeline. The pipeline throws away the cosmic-ray affected frames during data reduction process and these frames were excluded in the final science-ready images in FUV and NUV bands and the subsequent calculation of the photometry. The final science-ready images had a total exposure time of \( t_{\text{exp}} = 9850 \text{ s} \) in F154W (bandwidth = 380 Å) and \( t_{\text{exp}} = 9600 \text{ s} \) in N263M (bandwidth = 275 Å).

Astrometric correction was performed using the GALEX and CFHT \( u \) band images as the reference images. We have used an IDL program which takes an input set of matched xpixel/ypixel from UVIT images (F154W and N263M) and RA/Dec from GALEX and CFHT \( u \) band images. We then perform a TANGENT-Plane astrometric plate solution similar to ccmp task of IRAF (Tody 1993). The astrometric accuracy in NUV was found to be ~0.15″ while for FUV, the RMS was found to be ~0.22″, approximately half a (sub) pixel size. Note that the absolute astrometric accuracy for GALEX based on QSOs data is about 0.5″ (Morrissey et al. 2007). It is also known that there is systematic offset between SDSS and GALEX ~0.1–0.3″.

The photometric calibration is performed with a white dwarf star Hz4; the photometric zero-points are 17.78 and 18.18 for F154W and N263M respectively (Tandon et al. 2017). Once photometric calibration and astrometric correction are successfully applied, we extract an image of size 600″ × 600″ as shown in Fig. 1. The morphology and color of the galaxy are discussed in Section 3. We run SExtractor (Bertin & Arnouts 1996) on this cutout image of size 600″ and extract the 3σ sources. After removing the 3σ sources, we place a large number of random apertures of 7 × 7 pixel boxes avoiding the location of the extracted sources. This was repeated with boxes of size 11 pixels. We use the mean of the resulting histogram (nearly symmetric) as the background. For F154W, the background is \( B_f = 9.5 \times 10^{-6} \text{ cts}^{-1} \text{ pix}^{-1} \) with a
\[ \sigma_f = 3.94 \times 10^{-5} \text{ cts}^{-1} \text{ pix}^{-1} \]. In N263M filter, the sky background is \( B_n = 7.24 \times 10^{-5} \text{ cts}^{-1} \text{ pix}^{-1} \) with a \( \sigma_n = 6.48 \times 10^{-5} \text{ cts}^{-1} \text{ pix}^{-1} \). Note that the sextractor background from the FUV image is even lower and it is \( B = 1.15 \times 10^{-8} \text{ cts}^{-1} \text{ pix}^{-1} \) with an rms of \( 1.9 \times 10^{-5} \text{ cts}^{-1} \text{ pix}^{-1} \). We did not consider this in our subsequent calculation.

### 2.1 PSF modeling

FUV modelled PSF is shown in Fig. 2. To model the PSF and estimate the FWHM, we have chosen a bright star (RA: 189.2595, Dec:14.2518) right at the bottom of Malin 1 (see Fig. 1). We used IRAF (Tody 1993) to obtain the surface brightness profiles (SBP) of the star in FUV band. The star in NUV is heavily saturated, so we have avoided a discussion of the NUV PSF here. Instead, we have considered a circular symmetric PSF from the recent calibration paper (Tandon et al. 2020) for NUV modelling. The SBP reveals long wing outside the core in FUV (see the star’s image in the upper panels of Fig. 2). The FUV star profile is fitted with two components: a Moffat profile for the core, and an exponentially declining profile for the wing as follows:

\[
I_{PSF}(r) = I_{m0} \left[ 1 + \left( \frac{r}{\alpha} \right)^{2} \right]^{-\beta} + I_{o0} e^{-\frac{r}{\sigma}}, \tag{1}
\]

where \( I_{m0} \) and \( I_{o0} \) denote the central intensity values of the inner Moffat and outer exponential profiles respectively. For the Moffat, the FWHM = \( 2\alpha V \sqrt{2\beta - 1} \); where \( \beta \) and \( \alpha \) are the free parameters, \( \beta \) determining the spread of the Moffat function. Note the Gaussian function is a limiting case of Moffat function (\( \beta \rightarrow \infty \)).

The best fit model was obtained with two components (Moffat and exponential). With the Moffat fit, the estimated PSF obtained is \( 1.67'' \) with \( \beta = 1.4 \). We discuss the wing of the PSF separately below.
2.2 PSF wing

The wing of the PSF in F154W follows an exponential fall-off. This is also true for the N263M band where the exponential profile extends up to $\sim 35''$ or $\sim 84$ pixels (not shown here). In F154W, the wing has been modelled till $\sim 14''$ or $\sim 34$ pixels. In F154W, the scale-length of the exponential profile is $h_0 = 3.5''$ or 8.4 pixels. Accurate estimation of the faint emission from the galaxy will require a thorough knowledge of the PSF wing which reflects amount of the scattered light in the same wavelength. We found that the wing of the PSF contains about 19% of the total flux while 81% is in the core in accordance with recent UVIT calibration (Tandon et al. 2020).

2.3 Dust correction

Both FUV and NUV fluxes are susceptible to both foreground and internal dust extinction. Schlegel et al. (1998) full-sky 100 μm map provides us with the foreground dust reddening $E(B - V)$ along a given line of sight. The mean $E(B - V) = 0.038$ along the direction of Malin 1. The values of foreground extinction parameter for the FUV and NUV bands are then derived using $A_j = k_jE(B - V)$; where $k_j$ is obtained following Calzetti extinction law (Calzetti et al. 2000). For F154W, $A_{F154W} = 0.39$ mag with $k_{F154W} = 10.18$ while for N263M, $A_{N263M} = 0.29$ mag with $k_{N263M} = 7.57$.

The nebular colour excess can be estimated using the method of Balmer decrement (Osterbrock and Ferland 2006) assuming case B recombination, temperature $T = 10^4$ K and electron density $n_e = 100$ cm$^{-3}$ as

$$E(B - V) = 1.97 \log \left( \frac{\langle H\alpha/H\beta \rangle_{\text{obs}}}{2.86} \right),$$

where $H\alpha$ and $H\beta$ are the observed line fluxes. Based on the SDSS spectra of the central 3'' region, the observed $H\alpha$ and $H\beta$ fluxes are $224.5 \pm 5.8 \times 10^{-17}$ and $67 \pm 4.6 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$ respectively. The internal color excess $E(B - V)_{\text{nebular}} = 0.1323$. In the subsequent calculation, we use the Calzetti relation (Calzetti et al. 2000) for stellar continuum color excess $E(B - V)_{\text{star}} = 0.44 \times E(B - V)_{\text{nebular}} = 0.058$—suggesting low extinction in the central region of the galaxy (Junais & Epinat 2020). This is in-sync with general trend found in LSB galaxies which are often devoid of dust and molecular gas compared to their HSB counterparts (Rahman et al. 2007; Das et al. 2006). In the rest of the calculation, we use these values of extinction for the full galaxy.

2.4 Comparison with GALEX observation

The FUV image from GALEX has an exposure time of 3154 s while in UVIT/F154W band, it is 9850 s. Compared to GALEX NUV, our NUV band N263M is narrower and avoids the 2175 Å bump in the extinction curve. In Fig. 3, we show a one-to-one comparison between the GALEX and UVIT observation of Malin 1. Rectangular regions marked 1 and 2 along the spiral arms of Malin 1 in the GALEX images are resolved into clumps in the UVIT images. With the UVIT FUV image, it is thus possible to study the young star-forming clumps along the spiral arms. The region 2 in GALEX FUV image resolves into four clear clumps (marked by a, b, c, and d) in UVIT F154W image. We have measured their aperture magnitudes and the corresponding signal-to-noise ratio.
ratios. The faintest of the four far-UV clumps ‘b’, has a background subtracted magnitude of 24.27 AB mag with a S/N $= 4.2$. While the brightest among them is the clump ‘c’ having a magnitude of 23.3 AB mag and S/N $= 7.3$. One of the clumps marked by cyan circle in region 1 (bottom right panel of Fig. 3) in the N263M band has been detected at S/N $= 7.2$ and has a magnitude of 23.65 AB mag within a circular aperture of radius 1.6$''$.

Due to the improved image resolution and sensitivity of UVIT, we are able to measure the far-UV flux from Malin 1B, marked by magenta circle, located at a distance of 9$''$ from the centre (see Figures 3 and 4). Within an aperture of radius 2$''$, Malin 1B has a magnitude of 24.9 AB mag (and 24.5 AB mag after foreground correction) with S/N $= 3.3$. In comparison, Malin 1B is completely blended in the GALEX FUV as well as in the NUV images (see the left panels of Fig. 3). The inner regions (denoted by green circle with radius = 9$''$) in the GALEX images are also not resolved. Whereas in their UVIT counterpart, it is possible to locate a few clumps in the FUV F154W band and N263M band—indicating recent star-forming activity. A closer inspection of the central region of the F154W image shows that there is an elongated structure in FUV; when zoomed into this, we found two clumps aligned to give an impression of a bar-like structure. We discuss this structure in detail in the following section. Interestingly, the bar-like structure is also seen in the N263M (relatively dust-free); although it appears like an elliptical blob.

In Fig. 4, we compare the UVIT/FUV morphology with the CFHT u-band image. The better resolution and depth of the CFHT observation (Boissier et al. 2016) makes it possible to compare both regions 1 and 2 in considerable detail. The star-forming far-UV clumps (a, b, c, d) marked in Fig. 3 are clearly visible in the CFHT u, g and i bands. The observation of these clumps in the optical bands, in particular the i-band, alongside the far-UV, indicates that they are older than 100 Myr. In other words, the spiral arms in Malin 1 although appear bluer, are not as young as a few 100
Myr. The combination of optical and far-UV emission suggests that there is a mixture of both young and old stellar populations along the spirals arms, e.g., see regions 1 and 2 as well as the color-map in Fig. 5.

3. Morphology and colormap

The bottom panel of Fig. 1 shows a color composite of Malin 1 in CFHT g-band and the two UVIT filters. The spiral arms extend to large radii—it is possible to trace it clearly up to a radius of \( 60'' = 93 \) kpc, perhaps even larger radii Boissier et al. (2016). Interestingly, the spiral arms are not wide open, like in NGC 1566 (Gouliermis et al. 2017). The CFHT g-band image reveals more of a tightly wound type, although it is believed to be interacting with an external galaxy SDSS J123708.91+142253.2 (Reshetnikov et al. 2010) located at a distance of about 358 kpc away. Apart from the spiral arms, the disk in the outer part is nearly invisible—in other words, even with the deepest CFHT image (Ferrarese et al. 2012), we see just the spiral arms. These spiral arms are asymmetric (Moore & Parker 2006), both in radii and azimuths; the asymmetry is prominent along the North-East and South-West direction (Fig. 1). One can easily trace the F154W light (in blue) along the same direction. However, as one moves inward, the galaxy morphology changes, rather dramatically. There is clearly a brighter component in the central \( 9''.14 \) kpc region. Interestingly, this central region is nearly the same size as that of the stellar disk of the Milky Way. As revealed in the HST observation, this central region harbours a bar (Barth 2007). In Fig. 5, we show the 2D \( g-i \) color map of the galaxy using the CFHT deep observation and the FUV–NUV color from AstroSat/UVIT. Globally, the galaxy has a clear color gradient with bluer outskirts, see Boissier et al. (2016). By comparing with Fig. 3, one can easily trace the regions 1 and 2 with bluer \( g-i \) color. However, the central \( 9''.14 \) region is comparatively redder with \( g-i \sim 1-1.5 \), except the central bulge. The color map reveals the central bar very clearly with \( g-i \sim 1.29 \). The central bulge is red with \( g-i \sim 2 \)—suggesting old stellar population. The comparative bluer \( g-i \) color of the bar in Malin 1 suggest triggering of star formation in the bar region given the Malin 1 seems to be interacting with the neighbour Malin 1B (Barway & Saha 2020). The evidence of star-formation activity in the bar region is also clear from the FUV contours.

Figure 4. A comparison between the CFHT \( u \)-band and AstroSat/UVIT FUV image. The radius of the blue circle centred on Malin 1 is \( 60'' \) and that of the inner green one is \( 9'' \). The magenta circle marks the location of Malin 1B.

Figure 5. CFHT \( g-i \) color map of Malin 1 and its central \( 9''.14 \) region. The unit of the color bar is in magnitude. Inset figure highlights the central disk with F154W contour of the bar region overlaid on the \( g-i \) color map. A part of the FUV emission appears misaligned with respect to the bar.
shown on the optical $g - i$ color map. The FUV–NUV color map of Malin 1 is noisy. There are several pixels with zero count/s in the FUV observation. On a visual inspection, it appears that the overall FUV–NUV $\sim 0$, although the very central part is redder. In the subsequent analysis, we do not use this FUV–NUV color map to draw any inference.

4. Multi-component decomposition

In the following, we obtain the surface brightness profile (SBP) using the IRAF ellipse task on the CFHT $g$-band image (Fig. 6). We model this SBP using a combination of the standard Sersic profile (Sersic 1968) for the bulge and exponential profile (Freeman 1970) for the stellar disk. We also use the Sersic profile to model the central bar as in Pahwa & Saha (2018). The Sersic + exponential profiles are convolved with a Gaussian PSF of FWHM 0.7” (in CFHT $g$-band) and the resulting model is fitted to the observed $g$-band SBP using profiler (Ciambur 2016).

4.1 Faint exponential envelope

The 1D profile decomposition (Fig. 6) shows that there is a very faint low-surface brightness exponential disk whose central surface brightness is $\mu_{0,g} = 26.7$ mag arcsec$^{-2}$ and a large scale length $h_0 = 30.2^\prime \sim 47$ kpc. The origin of such a faint and diffuse stellar disk is elusive. Could it be due to the interaction with the SDSS galaxy (Reshetnikov et al. 2010) or due to the accretion of Malin 1B, a dwarf early-type galaxy which in-spiraled towards the central region as a result of the dynamical friction? The outer region beyond 20” has spiral arms as can be seen by two kinks on the radial light profile—one at $\sim 22^\prime$ and another at $\sim 35^\prime$. From the nature of the spiral arms (more or less like a tightly wound), it might be possible to infer that Malin 1B might have excited it during its inward in-spiraling movement. Interestingly, the spiral arms do not extend all the way to the central region; it stops around $8 - 10^\prime$ from the center and this is apparently the high surface brightness region of the galaxy with a morphology of SB0/a. It might be possible that this hotter inner region is acting like a Q-barrier for sustaining the spiral structure in the outer disk (Saha & Elmegreen 2016).

4.2 Intermediate exponential disk

The slope of the SBP changes significantly at radii below 20”. We fit the intermediate region (from about 6–20”) with an exponential profile motivated by the nature of the profile in this region. The central surface brightness of this disk is 21.79 mag arcsec$^{-2}$ in $g$-band and has a scale length of 2.51” = 3.9 kpc. Considering the B-band $\mu_0 = 22.5$ mag arcsec$^{-2}$ and the same in $r$-band as 21 mag arcsec$^{-2}$ as the definition of LSB disk (Pahwa & Saha 2018), we obtain $\mu_0 = 21.9$ mag arcsec$^{-2}$ in the $g$-band for the definition of LSB disk. According to this and the comparatively larger scale-length, the intermediate disk is also an LSB disk or a marginal LSB disk. The best-fit parameter reveals a compact pseudo-bulge at the central region with an effective radius $r_e = 1.08^\prime = 1.6$ kpc and Sersic index $n = 0.66$.

![Figure 6. CFHT $g$ band surface brightness profile fitted with a sersic function for the bulge (dashed red line), and two exponential components (dashed purple and blue lines) and spiral arms and non-uniformities fitted by Gaussians (dashed cyan lines). The black solid line shows the best-fit model.](image-url)
However, the central region is better modelled with the higher resolution images from HST as Malin 1 has been observed in the HST/WFPC2/F300W and F814W bands (see Barth 2007). Before we discuss the central region and the bar in detail, it is useful to understand the global UV surface brightness profile (especially the central region) and cold neutral hydrogen gas distribution in the galaxy.

5. UV surface brightness profile and H I

Boissier et al. (2016) have performed a detailed modelling of the FUV and NUV surface brightness profiles using GALEX observation. Although they exclude the central $20''$ region from their analysis, measurements of FUV and NUV surface brightness levels are shown at $10''$ and they are about $27$ mag arcsec$^{-2}$. Whereas at a radius of $20''$ from the centre the FUV and NUV surface brightness levels are $28.7$ and $28.5$ mag arcsec$^{-2}$ respectively.

In Fig. 7, we show the surface brightness profile (SBP) of Malin 1 in F154W and N263M bands. Since the galaxy is extremely diffuse in FUV and NUV, we have not run the IRAF ellipse task to derive its SBPs. Instead, the SBPs are derived by placing concentric circular apertures on the galaxy and reading the counts within each aperture. Both the F154W and N263M SBPs are corrected for the foreground dust extinction as mentioned in Section 2.3. It is useful to compare our UV SBPs with that from GALEX. At $10''$ from the centre, the F154W surface brightness level is $\sim 27.5$ mag arcsec$^{-2}$ and in N263M band, it is about $\sim 28.4$ mag arcsec$^{-2}$. At a radius of $20''$, the N263M SB level is $\sim 29.5$ mag arcsec$^{-2}$ while the FUV SBP stays flat at $\sim 28$ mag arcsec$^{-2}$ except at the location of the spiral arms. When comparing these with the previous studies (Boissier the central region is better. 2016), we find that the UVIT probes deeper in surface brightness level at $10''$ radius while at $20''$ the N263M filter goes $1$ mag arcsec$^{-2}$ deeper than GALEX NUV.

At smaller radii, i.e., within $10''$ radius, the surface brightness level rises steeply both in FUV and NUV and this has become possible because of the better image resolution in UVIT. From the UV surface brightness profiles, we find that the FUV − NUV $\approx 0$ in the central region consistent with previous result (Boissier et al. 2016). However, at radii $>10''$, the FUV SBP flattens out and FUV − NUV $\approx -1$—indicating young, bluer stellar population in the outskirts. Since Malin 1 is interacting with two other galaxies—one is in-spiraling, i.e., Malin 1B and another, SDSS J123708.91−142253.2 (Reshetnikov et al. 2010), currently at a larger distance, might be responsible for the excitation of star-formation activity in the overall galaxy and might have elevated the FUV flux in the whole galaxy. This is not so unlikely as the galaxy Malin 1 has a huge reservoir of neutral hydrogen gas.

The most validated 21-cm emission from VLA observations of Malin 1 by Pickering et al. (1997) shows an extended H I disk up to $\sim 60''$ radius (see Fig. 8). The total H I mass of this huge disk was estimated by them to be $6.8 \times 10^{10} M_\odot$ corresponding to

![Figure 7](image-url)

**Figure 7.** Surface brightness profiles in near and far-UV bands of AstroSat/UVIT. The galaxy has extremely low surface brightness level outside the central region.
an integrated flux of 2.5 Jy km/s (with a $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$). They also found a slowly rising rotation curve that flattened to 210 km s$^{-1}$ at $\sim 40''$. However, Lelli et al. (2010) note that the slow rise in the central region could well be an effect of beam smearing (which affects only the central parts). On a re-analysis of Pickering et al. (1997) data with a technique that reduces beam smearing, they find that the circular velocity touches 237 km s$^{-1}$ at 8$''$ itself. This implies that Malin 1 has a steeply rising rotation curve, which is a unique feature of an HSB disk. Based on this, Lelli et al. (2010) argue that Malin 1 has an inner early-type HSB disk followed by an extended LSB disk. As mentioned earlier, the outcome from the rotation curve analysis is in accordance with findings from HST observation which describes the central region of Malin 1 as a normal SB0/a galaxy surrounded by a huge LSB disk (Barth 2007).

As evident in Fig. 8, the apparent distribution in the extended HI disk is far from centrally concentrated. Pickering et al. (1997) conclude that the HI disk is very strongly warped from the twisted contours seen in their individual channel maps. A strong northern warp (towards us) coupled with the inclination of 38$^\circ$ may well explain the observed non-axisymmetry in HI distribution. Yet, it is unclear whether the warp alone is sufficient to explain it or the disk is also lopsided to an extent which could be a result of the ongoing tidal-interaction (Yozin & Bekki 2014; van Eymeren et al. 2011). From Fig. 8, it also clear that the central 9$''$ region which harbours a bar has a lopsided HI distribution. This is interesting as well as exciting given the morphology of the central region. Normally, galaxies with S0 morphology are gas-poor (Chamaraux et al. 1986; Haynes et al. 1990; Masters et al. 2012) and if there is a bar, one expects to find HI holes (van Driel & van Woerden 1991; Athanassoula et al. 2013; Newham et al. 2020). In the following section, we discuss the implications and possible connection between the bar, far-UV emission and the HI observation.

6. Central disk and the bar

The high resolution HST image has revealed a central bar (Barth 2007) in the heart of Malin 1 within 9$''$ radius. Here for the sake of completeness, we model the surface brightness profile of the central 9$''$ region observed in HST/F814W band (see Fig. 9). The central region has three components—a bulge, a bar and an exponential disk. We have used profiler (Ciambur 2016) to model the inner surface brightness profile taking into account the HST PSF. The bulge is a compact pseudobulge with sersic index $n = 1.4$ and $r_e = 0.56'' = 0.87$ kpc in the F814W band. The exponential disk has a central surface brightness of $\mu_0 = 17.64$ mag arcsec$^{-2}$ and a scale-length of 4.8 kpc (in F814W). This disk is clearly a high surface brightness disk like our own Galaxy and our analysis confirms previously findings in this regard (Barth 2007; Lelli et al. 2010; Boissier et al. 2016). The lower panels of Fig. 9 show the radial variation of the ellipticity and position angle (PA) of the central region. The ellipticity has a peak at around 2.6$''$ (= 4 kpc) which is considered here as the radius of the bar (Erwin 2005). Beyond this region, i.e., outside the bar ($\sim 3'' - 5''$), the PA changes abruptly and there is a hint of faint spiral arm (on the East-ward direction, see the CFHT $u$-band image in Fig. 4) which might have been driven by the bar itself (Saha et al. 2010; Saha & Elmegreen 2016). Otherwise, the inner part resembles S0 galaxies with a bar and pseudo-bulge (Vaghmare et al. 2015, 2018). If we consider the optical color $g - r = 1.16$ for this 9$''$ central region, we find the mass-to-light ratio is 9.1 following Bell & de Jong (2001) and a stellar mass of $M_* = 8.9 \times 10^{11} M_\odot$—this is about 17 times more

![Figure 8. HI 21 cm map of Malin 1 (reproduced here with permission from T. Pickering). The HI extends up to 60'' (white circle). The blue circle corresponds to the size of Malin 1’s central 9'' region. A rough estimate of the HI mass within the blue circle could be $M_{\text{HI}} = 2.6 \times 10^9 M_\odot$. Pickering et al. (1997) find evidence for a strong warp, which may explain all or part of the apparent non-axisymmetric HI distribution seen here.](image)
massive than the Milky Way’s stellar mass, although the size is similar. Using our rough estimate of the HI mass within this region, we find $M_{\text{HI}}/M_* = 0.003$—pushing the central region of Malin 1 close to one of the most gas-poor galaxies (Haynes et al. 1990; Masters et al. 2012). Note that the galaxy contains a significant amount of cold HI gas but because of the huge stellar mass ($\sim 1.8 \times 10^{12} M_\odot$), the overall gas fraction is only about $\sim 4\%$.

Figure 10 shows the central morphology of Malin 1 in HST/F814W, CFHT $g$-band, and UVIT/F154W bands. The bar is most prominent in the HST/F814W but not so prominent in the CFHT optical images. However, as we saw earlier, the CFHT $g - i$ color map reveals the bar mostly clearly (see Fig. 5). In Fig. 10, we also show the far-UV emission morphology in the central region alongside other bands. The central region has a few clumps in far-UV suggesting young, recent star-formation. But most of the FUV emission is originating from the bar region. The optical contours and the position angle show that the bar is oriented along the south-east to north-west direction with a position angle of $63^\circ$ for the optical bar. We also see emission from the bar region in the near-UV N263M band (see the bottom right panel of Fig. 3). The background subtracted far-UV flux within the bar region is $S = 0.008775$ ct/s corresponding to 22.92 AB mag. After the aperture and foreground dust extinction correction using Schlegel et al. (1998), the bar region has 22.64 AB mag in F154W band. In the N263M band, the background subtracted flux within the bar region (same aperture) is 0.018219 ct/s corresponding to 22.53 AB mag which after aperture and foreground correction becomes 22.28 AB mag. Within the same aperture (of 2.6" radius), we have computed the bar magnitudes in CFHT $u$, $g$, and $i$ bands and they are 19.65, 17.98 and 16.69 AB mag respectively (all mags are foreground dust corrected). The FUV–NUV (F154W–N263M) color of the bar region is 0.36—suggesting extremely blue and the presence of hot, young O, OB stars. While the $g - i = 1.29$ color of the bar suggest red and older stellar population. The same is reflected in other UV-optical colours such as FUV $- i = 5.7$, NUV $- g = 4.27$—indicating recent star formation activity (Schawinski et al. 2009) in the bar region. The broad-band colours and the central strong emission lines such as H$_\alpha$ and [OII] suggest mixed stellar population with very young stars. Contrary to quenching due to the bar (George et al. 2019), we see rejuvenation of the bar (Barway & Saha 2020) probably induced by the companion galaxies but this remains to be investigated with more detailed IFU-like observation. Overall, it appears that the gigantic Malin 1 has a massive Milky Way size stellar disk at its heart.

6.1 Central star formation activity

The central region of Malin 1 shows both absorption and emission lines. The strong absorption lines are
due to metals in the stellar atmospheres of mostly low-luminosity stellar population. It has several absorption lines e.g., Mg, Na, g-band, Ca(H/K)—suggestive of metal-rich environment or old evolved stars. We use the O3N2 relation (Pettini & Pagel 2004) to estimate metallicity of the galaxy to be 8.69 which is close to solar abundance. We find the metallicity is 5.0 ± 0.6 × 10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ Å}^{-1} (3.9 ± 1.2 × 10^{-29} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ Hz}^{-1}) and luminosity = 6.74 ± 2.1 × 10^{30} \text{ erg s}^{-1} \text{ Hz}^{-1}. Further we estimate the SFR using the following relation (Kennicutt 1998):

\[ \text{SFR}(M_{\odot} \text{ yr}^{-1}) = 1.4 × 10^{-28} L_{\text{FUV}}(\text{erg s}^{-1} \text{Hz}^{-1}). \]  

The estimated FUV SFR within the central 2.6′ (i.e., the bar region) is 0.094 ± 0.03 M_{\odot} \text{ yr}^{-1}. In deriving the above relation, Kennicutt (1998) uses the Salpeter Initial Mass Function (IMF) with mass limits of 0.1 to 100 M_{\odot} and stellar population models with solar abundance.

We also estimate the SFR within 2.6 arcsec using the recent empirical relation by Karachentsev and Kaisina (2013):

\[ \log \text{SFR}(M_{\odot} \text{ yr}^{-1}) = 2.78 − 0.4 \times m_{\text{FUV}} + 2 \log(D), \]

where D is in Mpc and m_{\text{FUV}} refers to the FUV magnitude. The estimated FUV SFR is 0.094 ± 0.008 M_{\odot} \text{ yr}^{-1} in good agreement with that obtained using (Kennicutt 1998). The specific star formation rate sSFR = 1.00 × 10^{-13} \text{ yr}^{-1}—placing the central region of the galaxy in the quenched category marked by log sSFR = −11.8 (Barway & Saha 2020). Even if the star formation rate jumps by a factor of 10, the central region of Malin 1 would be classified as...
quenched. Nevertheless, the detailed process of quenching remains unclear (van den Bosch et al. 2008; Martig et al. 2009; Peng et al. 2015). The strong emission lines from the central region (Junais & Epinat 2020) and our UV observation suggest that there is recent star-formation activity and the presence of hot blue stars. Together, we seem to arrive at a complex scenario of the central region of Malin 1. Whatever might the case, it would be interesting to investigate in detail the central region of this galaxy.

7. Discussion and conclusions

Malin 1 is a classic example of a giant low-surface brightness galaxy (Impey & Bothun 1989; Moore & Parker 2006; Boissier et al. 2016) which is currently undergoing tidal interaction with two external galaxies (Reshetnikov et al. 2010). The central region (i.e., within 14 kpc) of Malin 1 has a HSB stellar disk with a compact, central pseudobulge, and a bar. The bar has a radius of 4 kpc. This central region is equivalent to ~17 Milky Way size stellar disks put together within this 9” region. The central disk has a few FUV clumps (S/N = 3)—indicating hot, young stars but only a hint of faint spiral structure. So the emerging picture of Malin 1 is that at the heart it, has a star-forming HSB Milky Way size stellar disk surrounded by an intermediate LSB exponential disk extending up to about 30 kpc. Beyond this lies the extremely low-surface brightness stellar envelope. The apparently simpler giant LSB galaxy has a complex layered structure—might hold important clues to the true complexity of galaxy formation yet to be unfolded (Cole et al. 2000; Martin et al. 2019; Kulier et al. 2020).

The star-forming bar in Malin 1 is surprising because of the central S0-like morphology. Our UVIT observation shows FUV emission from the bar region - indicating ongoing star formation. In addition, the SDSS central 3” fibre shows strong emission lines such as Hα and [OIII] indicating again the most recent (maybe 10 Myr old) star formation activity in the bar; a similar scenario has been observed in NGC 2903 (George et al. 2020). The bar appears to play a dual role in the star-formation activity in galaxies. It can funnel gas inwards (Combes 2004) and ignite star-formation activity in the central region of a galaxy and lead to the formation of a pseudobulge (Athanassoula 1992; Kormendy & Kennicutt 2004; Jogee et al. 2005; Lin et al. 2017). On the other hand, a bar can also lead to the star-formation quenching (James et al. 2009; James & Percival 2016; Khoperskov et al. 2018; George et al. 2019, 2020). The bar in Malin 1 has induced star-formation, probably due to the ongoing interaction; especially due to the in-spiraling Malin 1B. In addition, the strong lopsidedness of the atomic hydrogen gas might also lead to inward movement of gas due to outward angular momentum transport (Saha & Jog 2014).

Our primary conclusions from this work are:

- Using the high resolution UVIT observation, we show that there is scattered star formation all over the disk up to about 93 kpc. The FUV emission is clearly seen to follow the large scale spiral arms of Malin 1.
- We perform multi-component decomposition of the light profile of Malin 1 in - HST/F814W and CFHT g-band. The CFHT deep image in the g-band reveals that Malin 1 has a very faint low-surface brightness outer disk, and an intermediate LSB disk. Both disks follow exponential profile—the outer one has a scale-length of 47 kpc while the intermediate one has a scale-length of 3.9 kpc.
- The central 14 kpc region is modelled using F814W bands. Our decomposition shows that the central region has three components namely a compact pseudobulge, a bar and a HSB exponential stellar disk.
- The high resolution UVIT imaging data shows FUV emission from the bar region - indicating ongoing star-formation activity. The FUV-NUV colour of the bar is 0.36—indicating the presence of hot, young stars. Based on the extinction corrected FUV flux of the bar region, we estimate an SFR = 0.09 M⊙ yr⁻¹. Whereas the SFR based on the central Hα line flux is = 0.45 M⊙ yr⁻¹.
- The better PSF and sensitivity of UVIT have allowed us to detect FUV fluxes within the Malin 1B. The galaxy Malin 1B has a magnitude of 24.9 ± 0.32 AB mag.
- The surface brightness profiles in FUV and NUV up to about 77 kpc shows that FUV is flatter than NUV in the outer region—suggesting bluer population and scattered star-formation till the end of the disk.

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