Fourcade-Figueroa galaxy: A clearly disrupted superthin edge-on galaxy

J. Saponara\textsuperscript{1,2}, P. Kamphuis\textsuperscript{3}, B. S. Koribalski\textsuperscript{4,5}, and P. Benaglia\textsuperscript{1}

\textsuperscript{1} Instituto Argentino de Radioastronomía, CONICET-CICPBA-UNLP, CC5 (1897) Villa Elisa, Prov. de Buenos Aires, Argentina  
\textsuperscript{2} Facultad de Ciencias Astronómicas y Geofísicas, UNLP, Paseo del Bosque s/n, 1900 La Plata, Argentina  
\textsuperscript{3} Ruhr University Bochum, Faculty of Physics and Astronomy, Astronomical Institute, 44780 Bochum, Germany  
\textsuperscript{4} CSIRO Astronomy and Space Science, Australia Telescope National Facility, PO Box 76, Epping, NSW 1710, Australia  
\textsuperscript{5} Western Sydney University, Locked Bag 1797, Penrith, NSW 2751, Australia

Received 12 March 2021 / Accepted 4 June 2021

ABSTRACT

\textbf{Context.} Studies of the stellar and the $\text{H} \text{I}$ gas kinematics in dwarf and low surface brightness (LSB) galaxies are essential for deriving constraints on their dark matter distribution. Moreover, a key component to unveil in the evolution of LSBs is to determine why some of them can be classified as superthin.

\textbf{Aims.} We aim to investigate the nature of the proto-typical superthin galaxy Fourcade-Figueroa (FF) to understand the role played by the dark matter halo in forming its superthin shape and to investigate the mechanism that explains the observed disruption in the approaching side of the galaxy.

\textbf{Methods.} Combining new $\text{H} \text{I}$ 21 cm observations obtained with the Giant Metrewave Radio Telescope with archival data from the Australia Telescope Compact Array we were able to obtain sensitive $\text{H} \text{I}$ observations of the FF galaxy. These data were modelled with a 3D tilted ring model in order to derive the rotation curve and surface brightness density of the neutral hydrogen. We subsequently used this model, combined with a stellar profile from the literature, to derive the radial distribution of the dark matter in the FF galaxy. Additionally, we used a more direct measurement of the vertical $\text{H} \text{I}$ gas distribution as a function of the galactocentric radius to determine the flaring of the gas disk.

\textbf{Results.} For the FF galaxy, the Navarro-Frenk-White dark matter distribution provides the best fit to the observed rotation curve. However, the differences with a pseudo-isothermal halo are small. Both models indicate that the core of the dark matter halo is compact. Even though the FF galaxy classifies as superthin, the gas thickness about the galactic centre exhibits a steep flaring of the gas that agrees with the edge of the stellar disk. In addition, FF is clearly disrupted towards its north-west side, clearly observed at optical and $\text{H} \text{I}$ wavelengths. As suggested previously in the literature, the compact dark matter halo might be the main cause for the superthin structure of the stellar disk in FF. This idea is strengthened through the detection of the disruption; the fact that the galaxy is disturbed also appears to support the idea that it is not isolation that causes its superthin structure.

\textbf{Key words.} galaxies: groups: individual: ESO270-G017 – galaxies: interactions – radio lines: galaxies

1. Introduction

In 1993, Karachentsev, Karachentseva and Parnovskij published the Flat Galaxy Catalogue (FGC, Karachentsev et al. 1993). A revised version of it was released in 1999 (RFGC, Karachentsev et al. 1999). The catalogue contains disk-like edge-on galaxies with a major-to-minor stellar axis ratio $a/b > 7$. Superthin galaxies are a special type of flat galaxies with $a/b > 10$. These are gas-rich low surface brightness (LSB) galaxies, with little or no obvious bulge component, minimal dust absorption (Matthews & Wood 2001), blue optical colours (Dalcanton & Bernstein 2000), low metallicities (Roennback & Bergvall 1995), low current star formation, and a high ratio of dynamic to $H$ mass (de Blok & Bosma 2002). These characteristics suggest that these galaxies are some of the least evolved galaxies in the Universe. In addition, their high inclinations and simple structure allow us to study the effects produced by internal as well as external processes (Usón & Matthews 2003). All these characteristics make the superthin galaxies an ideal laboratory to for investigating the early stages of disk galaxy evolution.

The cosmological paradigm of hierarchical galaxy formation and evolution proposes that galaxies are subject to merging and interaction. Thus, the disk structure and thickness in galaxies are affected by the environment (Toth & Ostriker 1992; Odewahn 1994; Reshetnikov & Combes 1997; Schwarzkopf & Dettmar 2001). This suggests that flat-disk galaxy must remain isolated to persist as a superthin. However, some of these galaxies are found in groups of galaxies as well as in the field (Kautsch 2009). Therefore the question arises how the pure disk survives? A possible explanation is the presence of a massive dark matter (DM) halo that stabilises their disks against perturbations (Zasov et al. 1991; Gerritsen & de Blok 1999); moreover, Mosenkov et al. (2010) found a correlation between the thickness of stellar disks and relative mass of the DM halo. Banerjee & Jog (2013) showed that the determination of the superthin disk distribution in low-luminosity bulge-less galaxies is ruled by the compactness of the DM. This idea is supported by the studies of

\* The reduced ATCA+GMRT data cube (FITS file) are only available at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsarc.u-strasbg.fr/viz-bin/cat/?A+A/652/A108

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four superthin and proto-typical superthin galaxies UGC 7321 (O’Brien et al. 2010; Banerjee & Bapat 2017), IC 2233, IC 5249 (Banerjee & Bapat 2017), and FGC 1540 (Kurapati et al. 2018). As this sample is still extremely small, any single addition to it can still provide significant new insights or strengthen the current ideas about the nature of superthin galaxies.

Studies of the stellar and the H\textsc{i} gas kinematics in dwarf and LSB galaxies are essential for deriving constraints on the DM distribution (Rubin et al. 1978; McGaugh & de Blok 1998; Banerjee et al. 2010). Moreover, understanding why some LSBs are superthin can contribute to the overall understanding of LSBs and DM in general. In this paper we focus on the prototypical superthin Fourcade-Figueroa (FF) galaxy. By combining new Giant Metrewave Radio Telescope (GMRT) data with archival Australia Telescope Compact Array (ATCA) data, we obtained a high-resolution sensitive H\textsc{i} observation of the galaxy. After modelling the gas distribution, we use the derived rotation curve to determine the DM distribution in the FF galaxy.

The FF galaxy, also known as ESO 270–G017, was discovered in 1970 (Fourcade 1970) as an elongated and diffuse object, see Fig. 1, located approximately at 2° 32′ south-east of the core of the radio galaxy Centaurus A (Cen A; NGC 5128). The galaxy was initially thought to be part of the Centaurus A group (Colomb et al. 1984; Tully et al. 2013; Karachentsev & Kudrya 2014). However, recent distance estimates place it just beyond Centaurus A at a distance of 7 Mpc (Karachentsev et al. 2015). Karachentsev et al. (1999) reported a stellar axial ratio of $a/b = 9.1$ (or $b/a = 0.1$). The ratio $b/a$ is a strong parameter to determine the flatness of a galaxy because typical $b/a$ measurements of flat galaxies (between 0.04 to 0.14, Karachentsev et al. 1999) are quite different from the usual values found in the literature regarding all types. The major and minor axes can also be used to derive the galaxy inclination $i$ as a first approximation, as $\cos(i) = b/a$.

We list the main optical properties of the FF galaxy in Table 1. From WISE observations, Wang et al. (2017) obtained the two-dimensional structural surface brightness decomposition of FF. This profile has a scale length of 4.4 kpc. From their cleaned 3.4 µm WISE image, we determine an inner ($r < 2.8$ kpc) scale height of 0.47 kpc. This results in a ratio $h_r/h_z \sim 9.4$, again confirming that the FF galaxy can be considered a superthin galaxy (see also Kregel et al. 2002). FF is a good candidate on which to perform mass-modelling and thereby determine its DM halo. Despite its superthin structure, the FF galaxy shows an asymmetry towards its north-west side (Fourcade 1970), like a shred or disruption, which is observed in

![Fig. 1. FF three-colour image composites from the B, V, and I bands published by Ho et al. (2011).](image-url)
both optical and HI images. The origin of this disruption remains unclear.

The paper is organised as follows: in Sect. 2 we describe the observations and data reduction, including the combination process between data sets from very different radio interferometers; in Sect. 3 we present the HI distribution and kinematics; in Sect. 4 we describe the mass models; in Sect. 5 we present the mass-modelling results and the discussion; in Sect. 6 we present the shred and in Sect. 7 the summary.

2. HI Observations and data reduction

The FF galaxy has been observed at 1420 MHz with the Australia Telescope Compact Array (ATCA). The data were downloaded from the Australia Telescope Online Archive (ATOAI). The data were published by Koribalski et al. (2018) and are part of the Local Volume H I Survey (LVHIS) project. Notwithstanding the existence of previous observations, new ones were carried out at the same frequency with the GMRT, which provides a better angular and velocity resolution. Additionally, it has better coverage of the $w$-plane, which can be further improved upon by using observations from both telescopes. In the following subsections we describe the observations and data calibration for both ATCA and GMRT as well as the combination process.

2.1. Australia Telescope Compact Array data

The ATCA 21cm observations were carried out in January 1993, June and July 1993, as well as November 2008 using the 750, 6A, and EW367 array configurations, respectively. The total integration time on-source was 27 h 40 min. The 8 MHz bandwidth was used with the GMRT-Software backend. We selected the line-free channels on either side of the detected HI emission.

2.2. Giant Metrewave Radio Telescope data

The GMRT data were observed for a total time of $\sim$14 h (project 28_069, PI P. Benaglia). The observations were carried out during June-July 2015 and January 2016 in the spectral zoom mode with the GMRT-Software backend. We used a 4.16 MHz bandwidth with 512 channels, which results in a spectral resolution of 8.13 kHz, equivalent to $\sim 1.7 \text{ km s}^{-1}$ per channel. The flux calibrator was observed at the beginning and end of each observing run for 10 min, after which a phase calibrator was observed between the target scans every 45 min; see Table 2 for more details.

Data reduction and analysis were performed with the MIRIAD software (Sault et al. 1995) using standard procedures. We calibrated each data set separately, using PKS 0407–658 (750/6A array) and PKS 1934–638 (EW367 array) as primary flux and bandpass calibrators. PKS 1320–446 (750/6A array) and PKS 1421–490 (EW367 array) served as the phase calibrators. We used the MIRIAD task UVLIN to subtract the continuum. With a bandwidth of 8 MHz (see Table 2), we were able to select the line-free channels on either side of the detected HI emission.

2.3. Combining ATCA and GMRT radio interferometer data

The benefits of combining the GMRT with ATCA data are the improvement of the signal-to-noise ratio by $\sim 15\%$, a better $w$-plane coverage that should improve the quality of the final images, and a better angular resolution. In this manner, we will get the most out of observations; we can map the extended structures with excellent angular resolution.

As the GMRT is a non-coplanar array, we should in principle account for this when imaging the data, that is, a $w$-projection is required. However, for our current observations, we estimated that the shift introduced by ignoring this effect would lead to a shift of $2.25''$ at the first null of the primary beam over a 12h observation. This leads to a 10% error on the synthesised beam if we limit our baselines to be $< 28 \text{ k}$.

We carried out the data combination in the $uv$ domain using the MIRIAD software. Both data sets need to have the same velocity system reference and channel increment organised in the same way; the tasks CVEL, SPLIT and BLOAT from AIPS were used to arrange the visibilities of the different observations on the same frequency grid. We implemented the MIRIAD routine INVERT to perform a linear mosaic of these 21 cm GMRT and ATCA data. The INVERT task optimises the signal-to-noise ratio using the system temperature. For this, after we loaded the GMRT data sets into MIRIAD, we had to add the value of the system temperature in the header. This parameter was gathered from the GMRT user’s manual. The deconvolution process was carried out using the maximum entropy deconvolution, MOSMEM task, for a mosaiced image. The final synthesised beam was created with the task MOSSPSF and applied during restoration.

To summarise, the final HI cube was made using baselines up to $28 \text{ k}$ and natural weighting. The synthesised beam is $20'' \times 20''$, which results in a physical resolution of $673 \text{ pc} \times 673 \text{ pc}$ at the adopted FF distance. The corresponding r.m.s. noise is 2 mJy beam$^{-1}$.

3. HI distribution and kinematics

To ensure that our combined data set was free from systematic biases, we first extracted the line spectrum and compared it to the individual datasets and an archival single-dish observation. The results are shown in Fig. 2. The total line flux obtained from the combination data cube is $F_{\text{HI}} = 197 \pm 0.4 \text{ Jy km s}^{-1}$, which agrees with the value in the H1 Parkes All-Sky Survey (HIPASS), $F_{\text{HI}} = 199.4 \pm 15.1 \text{ Jy km s}^{-1}$ (Koribalski et al. 2004).

1. https://atoa.atnf.csiro.au/
2. http://gmrt.ncra.tifr.res.in
Table 2. ATCA and GMRT observing parameters.

|                      | ATCA configuration | GMRT          |
|----------------------|--------------------|---------------|
|                      | 750A               | 6A            | EW367        | 28.069 |
| Project              | C245               | C245          | C1341        | 29-06, 04-07-15/ |
| Date(s)              | 28-01-93/29-01-93  | 28-06-93/16-07-93 | 15-11-08     | 07-07-15/26-01-16 |
| Time on source [min] | 474.9              | 588/544       | 597.0        | 195/501/196    |
| Centre frequency [MHz]| 1417               | 1417          | 1417         | 1414          |
| Bandwidth [MHz]      | 8                  | 8             | 8            | 4.16          |
| Number of channels   | 512                | 512           | 512          | 512           |
| Channel width [km s⁻¹]| 3.3                | 3.3           | 3.3          | 1.8           |
| Velocity resolution [km s⁻¹] | 4                 | 4             | 4            | 1.8           |
| Primary beam ["]    | 33                 |               | 26.6         |               |

Fig. 2. Comparison of the FF global H I profile obtained using ATCA (light blue), GMRT (orange), Parkes (green, Koribalski et al. 2004), and the combination of ATCA and GMRT data (red).

and LVHIS (Koribalski et al. 2018) with the LVHIS F_{HI} = 224.7 Jy km s⁻¹.

The global H I profile of the FF galaxy is shown in Fig. 2. For the profile derived from the combined cube (ATCA+GMRT data), the flux along the velocity axis remains mostly equal to or below that derived from Parkes data alone, as expected.

The H I diameter is D_{HI} = 20′. The H I emission was detected from ~720 to 920 km s⁻¹. At a distance of 6.95 Mpc, this corresponds to a total H I mass of M_{HI} = 2.2 \times 10^9 M_\odot, which means that M_{HI}/L_B = 1.04. The systemic velocity of FF is 828 km s⁻¹. The profile widths of 20% and 50% levels are 142 km s⁻¹ and 120 km s⁻¹.

3.1. H I distribution

Figure 3 shows the channels where the FF galaxy contains detectable H I emission. A visible disruption is observed in the channels covering the velocity ranges from 770 to 810 km s⁻¹. The shred (Fourcade 1970; Thomson 1992) is clearly seen as a disruption in the distribution as well as the kinematics of the gas, and corresponds to the shred as seen in the optical. The disruption is at a projected radial distance ~5 kpc from the centre, at the same position in which the H I distribution bends away from the major axis to the north, see Fig. 4. The H I is distributed over a diameter of ~20′, almost twice the optical diameter (~11.3′), see Fig. 4 top panels. The velocity field of FF is not regular, as shown in the bottom left panel in Fig. 4. The velocity dispersion varies between 5 and 15 km s⁻¹, see the bottom right panel in Fig. 4. Because we study a (nearly) edge-on galaxy, the measured dispersion indicates the spread in coherent rotation along any line of sight, rather than a physical gas velocity dispersion.

3.2. Vertical gas thickness

Considering the H I gas distribution in FF is asymmetric, we derived the thickness of the H I disk as a function of the galactocentric radius. The method we implemented follows the procedures laid out in Olling (1995) and O’Brien et al. (2010). The vertical H I profile of FF exhibits a high degree of asymmetry of the gas thickness about the galactic centre. At the receding side of the galaxy, the H I flares from a full width half maximum (FWHM) of 2.5 kpc at 5 kpc out to 3.5 kpc at 18 kpc. The steep flaring of the gas agrees with the edge of the stellar disk. Between 5 kpc and 15 kpc, the H I thickness seems to remain constant, except for a bump at 8 kpc. At the approaching side, the vertical H I thickness shows an irregular flaring profile. From 3 kpc to 5 kpc, the H I thickness is roughly constant with an FWHM of about 2 kpc. In the range between 5 kpc to 10 kpc, the H I gas flare from 2.3 kpc to 3.6 kpc, which agrees with the location of the shred. The steep gas flare at the mentioned galactocentric distance is coincident with the radius at which the stellar disk becomes fainter. Additionally, the line width of the H I profiles (see Fig. 4) highly increases at this position. After 10 kpc (galactocentric radius), the H I disk thickness decreases at radii outside of 15 kpc; this agrees with the decrease in H I velocity dispersion. The linear size of the beam is ~700 pc, and Fig. 5 shows that variations in vertical gas thickness occur on a much larger scale (a few kiloparsec, thus including several beams), and therefore override or at least minimise beam-smearing problems. On average, z₀ is 32.6′′ ± 0.2′′ or z₀ = 1.1 ± 0.4 kpc at the assumed distance of 6.95 Mpc.

3.3. H I kinematics, 3D modelling and the rotation curve using FAT and TiRiFiC

The rotation curve was derived using the fully automatic TiRiFiC code (FAT, Kamphuis et al. 2015), which is a wrapper code around the tilted ring fitting code (TiRiFiC, Józsa et al. 2012), to perform a 3D modelling, and the source finder application (SoFiA, Serra et al. 2015) to estimate the initial parameters. We found that FAT is not capable of dealing with the varying
noise statistics that are due to the primary beam correction. The final FAT model did not cover the full extent of the H\textsc{i} disk. Therefore the outer parts of the galaxy were fitted manually with TiRiFiC itself. Performing a 3D modelling by fitting the 3D observations directly as TiRiFiC and FAT routines do guarantees that problems such as beam smearing and projection effects are overcome, according to Józsa et al. (2012) and Kamphuis et al. (2015). Because the FF galaxy is clearly warped and asymmetric, we created a two-disk model in which each disk represents one half of the galaxy. The inclination was the most problematic
parameter to fit; we attempted values between 80 and 90 degrees, and after the visual inspection of the results, we decided to fix it at 87 deg. From the vertical Hi distribution analysis, we obtained that $z_0$ is $1.1 \pm 0.4$ kpc on average. We therefore decided to fix this value in the model as well. To check the validity of the fits, visual comparisons between the data and models were performed in many different representations of the cubes, such as channel map by channel map, the velocity field, and the position velocity ($p_v$) diagram parallel to the minor and major axis. For the error bars on the final rotation curve, we used the difference between the approaching and receding side; a minimum realistic error of 2 km s$^{-1}$ was considered. Figure 6 shows that the rotation curve rises steeply in the innermost 4 kpc, then continues to rise slowly until the outermost radius. The maximum rotation speed is $\sim 72$ km s$^{-1}$. The de-projected Hi radial surface brightness profile derived by FAT shows the Hi surface density peak at $\Sigma_{\text{HI}} \sim 5 M_\odot$ pc$^{-2}$ in the centre but is mostly constant around $\sim 5, M_\odot$ pc$^{-2}$ (see Fig. 6). The $p_v$-diagram is shown in Fig. 7.

### 4. Mass models

#### 4.1. Visible matter contribution

The rotation velocities due to the gravitational potentials of the stellar and gaseous disks were determined separately using the task ROTMOD of the Groningen Image Processing System (GIPSY, van der Hulst et al. 1992). Because the old stellar population dominates the total stellar mass in late-type galaxies and mid-infrared emission is less susceptible to dust extinction and is also not affected by recent star formation, the stellar contribution ($V_*$) was derived using the stellar mass profile obtained by Wang et al. (2017) from WISE 3.4 $\mu$m infrared images. We assumed the vertical distribution as

$$D_*(z) = \frac{\exp\left(-\frac{|z|}{z_0}\right)}{z_0},$$

where $z_0$ is the disk scale-height ($z_0 = 0.47$ kpc), see for instance van der Kruit & Searle (1981a,b). The gaseous contribution ($V_{\text{gas}}$) was derived using the de-projected Hi radial surface density profile as derived by FAT and TiRiFiC. We considered a vertical density distribution given by the exponential law

$$D_{\text{gas}}(z) = \frac{-\exp\left(\frac{z}{z_0}\right)}{z_0},$$

where the value of $z_0 = 1.1 \pm 0.4$ kpc (see Sect. 3.2). The Hi gas surface density distribution was then multiplied by a factor of 1.4 to account for the primordial helium, but we did not consider
the presence of molecular H$_2$ in our models. For late-type LSB spiral galaxies the ratio H$_2$/HI is 10$^{-3}$ (Matthews et al. 2005).

4.2. Dark matter Halo

We used the so-called pseudo-isothermal halo (ISO) and the Navarro, Frenk & White (NFW) density profiles to model the DM halo of the FF galaxy. The simplest model for a DM halo density profile is the pseudo-isothermal halo (Begeman et al. 1991). Its density profile is given by

$$
\rho_{\text{ISO}}(R) = \frac{\rho_0}{1 + \left(\frac{R}{R_c}\right)^2},
$$

$$
V_{\text{ISO}}(R) = V_\text{inf} \sqrt{4\pi G \rho_0 (R_c)^2 \left[1 - \frac{R_c}{R} \arctan \left(\frac{R}{R_c}\right)\right]},
$$

where $\rho_0$ is the central core density and $R_c$ is the core radius of the halo. The rotational velocity expression at any radius $R$, due to an ISO DM halo, is $V_{\text{ISO}}$, and the asymptotic velocity of the halo is $V_{\text{inf}}$. Based on numerical simulations of DM halos, Navarro, Frenk & White (Navarro et al. 1996) described the radial density profile with the expressions:

$$
\rho_{\text{NFW}}(R) = \frac{\delta_c}{\rho_\text{crit}} \left(\frac{R}{R_s}\right)^2 \left[1 - \left(\frac{R}{R_s}\right)^2\right],
$$

$$
V_{\text{NFW}}(R) = V_\text{200} \sqrt{\ln(1 + cx) - \frac{cx}{1 + cx}}
$$

5.2. Minimum disk

The minimum disk model assumes that the rotation curve is entirely due to the presence of DM and therefore sets an upper bound on the DM density. We constructed two different minimum disk models: first, a minimum disk with gas. This model only considers the contribution of neutral hydrogen and helium to the rotation curve. In the upper panels of Fig. 9 we show the rotation curve decomposition with the minimum disk + gas, and in Table 3 we list the results. Second, by arbitrarily fixing $\Upsilon_\star$ to the maximum possible value, dominating the underlying gravitational potential. Both ISO and the NFW halo give higher values of reduced $\chi^2$ of all the fits. Previous studies of LSBs and some superthin galaxies indicate that most galaxies of this type do not have a maximum disk (de Blok et al. 2008; Banerjee & Bapat 2017), because the structure in the stellar disk is not seen in the rotation curve.

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5.3. Mass-modelling with MOND formalism

The modified newtonian dynamics (MOND) postulates that Newtonian dynamics breaks down at low acceleration (Milgrom 1983). This formalism rules out the presence of DM and takes into account the self-gravity of the stars and gas in galactic dynamics studies. There are two free parameters: the stellar mass-to-light ratio ($\Upsilon_\star$), and the acceleration per unit length ($a_0$).
Fig. 8. Modelling the H\textsubscript{i} rotation curve of the Fourcade-Figueroa galaxy. Upper panels: ISO and the NFW halo based mass model for the maximum disk with $\Upsilon_*=0.8$. Lower panels: ISO and the NFW halo based mass model for the maximum disk considering $\sim 75\%$ contribution to the peak of the rotation curve at $R=2.2r_s$. The orange line indicates the rotation curve due to the stellar disk, the blue line that due to the gas disk, the green line that due to the DM halo, and the red line shows the best-fitting model rotation curve.

Table 3. Results of the mass modelling of the FF galaxy for ISO and NFW DM halo profiles.

| Model                        | $\Upsilon_*$ | $\Upsilon_{\text{gas}}$ | $R_C$  | $R_C/R_D$ | $\rho_0$ $[10^{-3} M_\odot \text{pc}^{-2}]$ | $\chi^2$ |
|------------------------------|--------------|--------------------------|--------|-----------|--------------------------------------------|---------|
| Maximum disk fixed $\Upsilon_*$ | 0.8          | 1.0                      | 0.79 $\pm$ 0.11 | 0.2 | 131 $\pm$ 31 | 3.2 |
| Maximum disk                 | 4.13         | 1.0                      | 0.20 $\pm$ 0.06 | 0.05 | 7165 $\pm$ 405 | 3.0 |
| Minimum disk with gas        | 0            | 1.0                      | 0.8 $\pm$ 0.1  | 0.13 | 126 $\pm$ 25  | 3.2 |
| Minimum disk                 | 0            | 0                        | 0.9 $\pm$ 0.1  | 0.15 | 109 $\pm$ 18  | 2.7 |

| Model                        | $c$          | $R_{200}$  | $v_{200}$ $[\text{km s}^{-1}]$ |
|------------------------------|--------------|-----------|-------------------------------|
| Maximum disk fixed $\Upsilon_*$ | 0.8          | 1.0       | 7.1 $\pm$ 0.3  | 42 $\pm$ 1  | $\sim$ 30  | 1.0 |
| Maximum disk                 | 4.13         | 1.0       | 8.6 $\pm$ 1.1  | 26 $\pm$ 1  | $\sim$ 19  | 1.8 |
| Minimum disk with gas        | 0            | 1.0       | 7.1 $\pm$ 0.3  | 44.8 $\pm$ 0.6 | $\sim$ 32  | 0.9 |
| Minimum disk                 | 0            | 0         | 6.5 $\pm$ 0.2  | 47.3 $\pm$ 0.5 | $\sim$ 54  | 0.6 |

Notes. $R_C$ is the core radius of the ISO DM halo, $\rho_0$ is the central core density of the ISO DM halo, $c$ is the concentration parameter of the NFW DM halo, $R_{200}$ is the radius at which the average density of the NFW DM halo is $200\rho_{\text{crit}}$, and the parameters $\Upsilon_*$ and $\Upsilon_{\text{gas}}$ are the scaling factor from the stellar and gaseous disk were fixed in order to improve the results.

6. Shred

Despite its superthin structure, the FF galaxy shows an asymmetry towards its north-west side, clearly observed in optical and H\textsubscript{i} moment maps. A series of features appears at the approaching side of the galaxy: First, the iso-velocity contours start to exhibit distortions only a few kiloparsec away from the centre, and at the location of the kinematic anomalies, we can also see a thickening of the emission that is observed in the integrated moment map. However, because of the edge-on orientation of the galaxy, a more sophisticated analysis is required to determine at which radial location this occurs. Second, the H\textsubscript{i} gas steeply flares as the stellar component becomes fainter. This is indicative of a change in mass in the disk (Sancisi & Allen 1979; Olling 1995). Additionally, at the same location, the dispersion velocity is higher.

The de-projected H\textsubscript{i} peak surface density is $\Sigma_{\text{HI}} \sim 5 M_\odot \text{pc}^{-2}$, which is close to the mean value proposed by Cayatte et al. (1994) for Sbc galaxies ($\sim 6 M_\odot \text{pc}^{-2}$). This value also agrees with the results found by Kurapatli et al. (2018) and Banerjee & Bapat (2017) for similar superthin galaxies. Furthermore, in most of the gas disk of FF, the gas surface density seems to lie below that required for efficient star formation (Kennicutt 1989), and moreover, the overall density profile value is half of the peak surface density, see Fig. 6. Although the galaxy is forming some stars, this result is consistent with the very low star formation rate derived from optical observations.
Fig. 9. Modelling the H\textsc{i} rotation curve of the Fourcade-Figueroa galaxy. Upper panels: ISO and the NFW halo based mass model for the minimum disk + gas. Lower panels: ISO and the NFW halo based mass model for the FF galaxy for the minimum disk. The orange line indicates the rotation curve due to the stellar disk, the blue line that due to the gas disk, the green line that due to the DM halo, and red shows the best-fitting model rotation curve.

In 1992 Thomson (1992) proposed after the analysis of numerical simulations that the FF shred might arise because the FF galaxy undergoes a strong prograde interaction with the massive galaxy Cen A. This theory is currently ruled out. A recent more accurate distance estimate places FF just beyond Cen A (~7 Mpc, Karachentsev et al. 2015). Another possible explanation of the observed vertical thickness is the interaction with a companion dwarf galaxy, which enhances star formation in a small region in the western-most part of the disk, generating this and the higher dispersion observed. The available UV images from GALEX\textsuperscript{3}, although they partially cover the galaxy, provide an indication of this. Although the field of view is mostly filled with the galaxy, we visually searched for H\textsc{i} low-mass companions of the FF galaxy, but no recognisable companions were observed. However, Cen A appears to have an overabundance of the faintest dwarfs in comparison to its simulated analogues (Müller et al. 2019), indicating that interactions are likely, and the scenario of a dwarf galaxy accreted like the Sag dSph by the Milky Way turns very probable (Ruiz-Lara et al. 2020). This would be in contrast to superthin galaxies evolving in isolation. FF might be disturbed in such a way that it is evolving away from being a superthin galaxy, although the quiescent and thin approaching side appear to counter this idea. Most studies of superthin galaxies have so far presented this class as isolated objects, that is, devoid of interactions. An exception might be galaxy IC 2233, for which the authors explored the possibility of interaction with smaller nearby galaxies (Usón & Matthews 2003). That interactions do not destroy the superthin disks in these galaxies fits previous results (O’Brien et al. 2010; Banerjee & Bapat 2017; Kurapati et al. 2018), indicating that the compact DM halo is the main cause for the superthin structure of the stellar disk, not isolation.

7. Summary

We used the rotation curve, the H\textsc{i} surface density profile, and with the stellar profile obtained from the literature to construct mass models for the FF galaxy. The FF rotation curve, as well as its de-projected H\textsc{i} surface density profile, were derived by fitting a detailed 3D tilted ring model to the data. After assuming the ISO as well as a NFW DM halo, we found that both halos fit the observed rotation curve well, but the best reduced $\chi^2$ values were obtained with the minimum disk model considering an NFW halo. The results obtained from the mass modelling imply that the DM halo is compact. We derived the thickness of the H\textsc{i} (log(SFR) = $-1.0 M_\odot$ yr$^{-1}$) and the low radio continuum emission reported previously (Saponara et al. 2012); The evidence suggests that intense star formation activity is not the main cause of the observed disruption.

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\textsuperscript{3} https://archive.stsci.edu/missions-and-data/galex
disk as a function of the galactocentric radius. At the approaching side of the galaxy, the vertical $H_1$ thickness shows an irregular profile. The FF galaxy shows an asymmetry towards its north-west side, which is clearly observed in optical and $H_1$ images. The new distance establishes FF away from Cen A, which dismisses the hypothesis of past interaction between them. Even though we did not find $H_1$ low-mass companions for FF in our $H_1$ cubes, tidal interaction cannot be ruled out. Thus, the compact DM halo might be the main responsible for the superthin structure observed in the galaxy, not isolation.

Acknowledgements. J. S. is grateful to Arumina Banerjee for use full discussions and to Jing Wang for the mass profile. This paper is based on observations obtained with the Australia Telescope Compact Array (ATCA) and the Giant Metrewave Radio Telescope (GMRT). ATCA is part of the Australia Telescope National Facility (ATNF) which is funded by the Australian Government for operation as a National Facility managed by CSIRO. We acknowledge the Gomerors people as the traditional owners of the Observatory site. GMRT is operated by the National Centre for Radio Astrophysics of the Tata Institute of Fundamental Research. We thank the staff of both radio telescopes who made these observations possible. This research has made use of the NASA/IPAC extragalactic database (NED) that is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. This work was partially supported by FCAG-UNLP and ANPCyT project PICT 2017-0773. P. K. is partially supported by the BMBF project 05A17PC2 for D-MeerKAT.

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