Distance and mass of the M 104 (Sombrero) group

Igor D. Karachentsev¹, Lidia N. Makarova¹, R. Brent Tully², Gagandeep S. Anand²,
Luca Rizzi³, and Edward J. Shaya⁴

¹ Special Astrophysical Observatory, The Russian Academy of Sciences, Nizhnij Arkhyz, Karachai-Cherkessian Republic 369167, Russia

e-mail: lidia.makarova@gmail.com

² Institute for Astronomy, University of Hawaii, 2680 Woodlawn Drive, Honolulu, HI 96822, USA

³ W. M. Keck Observatory, 65-1120 Mamalahoa Hwy, Kamuela, HI 96743, USA

⁴ Astronomy Department, University of Maryland, College Park, MD 20743, USA

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ABSTRACT

Aims. Distances and radial velocities of galaxies in the vicinity of the luminous early-type galaxy M 104 (Sombrero) are used to derive its dark matter mass.

Methods. Two dwarf galaxies: UGCA 307 and KKSG 30 situated near M 104 were observed with the Advanced Camera for Surveys on the *Hubble* Space Telescope. The distances $9.03^{+0.84}_{-0.51}$ Mpc (UGCA 307) and $9.72^{+0.44}_{-0.41}$ Mpc (KKSG 30) were determined using the tip of the red giant branch method. These distances are consistent with the dwarf galaxies being satellites of Sombrero.

Results. Using radial velocities and projected separations of UGCA 307, KKSG 30, and a third galaxy with an accurate distance (KKSG 29), as well as 12 other assumed companions with less accurate distances, the total mass of M 104 is estimated to be $(1.55 \pm 0.49) \times 10^{13} M_{\odot}$. At the *K*-band luminosity of the Sombrero galaxy of $2.4 \times 10^{11} L_{\odot}$, its total mass-to-luminosity ratio is $M_T/L_K = (65 \pm 20) M_{\odot}/L_{\odot}$, which is about three times higher than that of luminous bulgeless galaxies.

Key words. galaxies: dwarf – galaxies: distances and redshifts – galaxies: photometry – galaxies: individual: M 104 – galaxies: individual: UGCA 307 – galaxies: individual: KKSG 30

1. Introduction

The Local Volume of the Universe amounts to almost a thousand galaxies having distance estimates within 11 Mpc¹ (Karachentsev & Nasonova 2013). Near the far edge of this volume at a distance of 9.55 Mpc (McQuinn et al. 2016) there is a bright galaxy M 104 (also known as NGC 4594 or the Sombrero galaxy). With an apparent *K*-band magnitude of $m_K = 5^m0$ it has the luminosity of $L_K/L_{\odot} = 11.32$ dex, which is four times higher than the luminosity of the Milky Way (10.70 dex) or M 31 (10.73 dex). Thanks to its luminosity and, by inference, to its stellar mass the Sombrero is the most outstanding galaxy of the Local Volume.

Over recent years several attempts have been undertaken to determine the total (virial) mass of Sombrero using radial velocities and projected separations of its companions. Estimations of $M_T/M_{\odot}$ vary widely: 10.90 dex (Makarov & Karachentsev 2011), 13.17 dex (Karachentsev & Nasonova 2013), 13.45 dex (Karachentsev & Kudrya 2014), and 13.96 dex (Kourkchi & Tully 2017). The main reason of the scatter in estimates of the total mass is caused by the uncertainty on the gravitational binding of Sombrero with galaxies neighbouring in the projection. The Sombrero galaxy is located near the equator of the Local Supercluster where galaxies are concentrated in the filamental structure, the Virgo Southern Extension (VirgoSE; Tully 1982; Kourkchi & Tully 2017). Many galaxies in the VirgoSE have radial velocities similar to that of Sombrero, but lie at greater distances typical of the Virgo cluster (15–20 Mpc). At a distance

of 8 Mpc from the core of the Virgo cluster, the Sombrero galaxy lies at the edge of the zero velocity surface bounding the cluster infall domain, a property shared by other galaxies in the VirgoSE over an extended range in distances.

To reveal the true satellites of Sombrero among the neighbouring galaxies we need to measure their distances, preferably with an error $\Delta D < \sim 1$ Mpc. At present there is only one galaxy, KKSG 29, in the Sombrero vicinity with an accurately measured distance (9.82 ± 0.32 Mpc; Karachentsev et al. 2018), determined via the tip of the red giant branch (TRGB) method. This distance places the dwarf galaxy KKSG 29 as a physical satellite of the Sombrero galaxy.

In this work we present measurements of TRGB distances for two more dwarf galaxies, UGCA 307 (or DDO 153) and KKSG 30 (or LEDA 3097708) situated close to Sombrero. The distances of both the galaxies agree well with their belonging to the family of Sombrero satellites. The new distance measurements together with other less reliable distance estimates give us a possibility to make more precise value of the virial (orbital) mass of Sombrero.

2. TRGB distances to UGCA 307 and KKSG 30

The dwarf galaxies UGCA 307 ($12^h53^m56^s8-12^{\circ}06'21''$) and KKSG 30 ($12^h37^m35^s9-08^{\circ}52'01''$) have apparent *B* magnitudes of 14^m6 and 16^m3 , respectively, and projected separations of $\sim 3^{\circ}$ with respect to Sombrero. Their radial velocities in the Local Group rest frame, 731 km s^{-1} (UGCA 307) and 918 km s^{-1} (KKSG 30), are close to the radial velocity

¹ <http://www.sao.ru/lv/lvgdb>

Fig. 1. HST/ACS combined images of UGCA 307 and KKSG 30. The image size is $1'.6 \times 1'.4$. North is up and east is left.

of Sombrero, 892 km s^{-1} . The galaxies were observed with the Advanced Camera for Surveys (ACS) aboard the *Hubble* Space Telescope (HST) on December 5, 2019, and March 13, 2020, as a part of the SNAP project 15922 (PI R.B. Tully).

Two exposures for each object were made in a single orbit with the filters $F606W$ (750 s) and $F814W$ (750 s). The combined images of the galaxies are presented in Fig. 1. We used the ACS module of the DOLPHOT package by Dolphin (2002) to perform photometry of resolved stars based on the recommended recipe and parameters. Only stars with good quality photometry were included in the analysis. We selected the stars with a signal-to-noise ratio $S/N > 4$ in both filters, and with DOLPHOT parameters $\text{crowd}_{F606W} + \text{crowd}_{F814W} < 0.8$, $(\text{sharp}_{F606W} + \text{sharp}_{F814W})^2 < 0.075$. Artificial stars were inserted and recovered using the same reduction procedures to accurately estimate photometric errors. Subsequent analysis included only those image regions that contain stars of the galaxies themselves. We selected the region of 1.6×1.6 arcmin around UGCA 307 and 2.8×1.5 arcsec around KKSG 30. The resulting colour-magnitude diagrams in $F606W-F814W$ versus $F814W$ are plotted in Fig. 2. A maximum-likelihood method by Makarov et al. (2006) was applied to estimate the magnitude of the TRGB. We found $F814W(\text{TRGB})$ to be $25.76^{+0.19}_{-0.11}$ for UGCA 307 and $25.96^{+0.08}_{-0.07}$ for KKSG 30. Following the zero-point calibration of the absolute magnitude of the TRGB developed by Rizzi et al. (2007), we obtained $M(\text{TRGB})$ values of -4.09 (UGCA 307) and -4.08 (KKSG 30). Assuming values of foreground reddening, $E(B - V)$, 0.049 (UGCA 307) and 0.028 (KKSG 30) from Schlafly & Finkbeiner (2011), we derived the true distance modulus of $(m - M)_0 = 29.78^{+0.20}_{-0.12}$ or the distance $D = 9.03^{+0.84}_{-0.51}$ Mpc for UGCA 307 and $(m - M)_0 = 29.94^{+0.10}_{-0.09}$ or the distance $D = 9.72^{+0.44}_{-0.41}$ Mpc for KKSG 30.

3. Companions of Sombrero and background objects

Judging by the big stellar mass of the Sombrero galaxy, the virial radius of its halo can reach about 400 kpc. To search for assumed satellites of Sombrero we examined a region of radius $r_p = 6^\circ$ around it that corresponds to the linear projected radius of $R_p = 1.0$ Mpc at the distance of 9.55 Mpc. In this area there are 48 galaxies with radial velocities $V_{\text{LG}} < 1400 \text{ km s}^{-1}$. The data are presented in Table 1. The table columns contain (1) galaxy name; (2) equatorial coordinates J2000.0; (3) radial velocity in the Local Group rest frame (km s^{-1}); (4) morphological type; (5) apparent B magnitude from the Lyon Extragalactic Database (LEDa, Makarov et al. 2014) or NASA Extra-galactic Database (NED); (6) distance to the galaxy in Mpc; (7) method used for the distance estimate; (8) reference to the source of distance.

As seen from these data, 41 of the 48 galaxies have distance estimates. Most of them were made by the Tully-Fisher method, with uncertainties of 35–30% for these low luminosity galaxies. Accordingly, we consider only galaxies with distances $D < 12$ Mpc as probable members of the Sombrero group. The distance and radial velocity distribution of galaxies around Sombrero are given in Fig. 3. In total, 15 galaxies are probable satellites of Sombrero, with the luminosity of each of them more than an order of magnitude fainter than the luminosity of Sombrero. An empty volume (mini-void) is visible ahead of the group. The background galaxies have radial velocities substantially overlapping the Sombrero group velocities. Due to significant TF distance errors, ΔD of about 3–5 Mpc, the membership of some galaxies (UGCA 312, PGC 104868), whether in the group or background may be subject to revision.

The distribution of galaxies from Table 1 in supergalactic coordinates SGL, SGB is presented in Fig. 4. Indications of

Fig. 2. Colour–magnitude diagrams of UGCA 307 and KKSG 30. The TRGB position is indicated by the horizontal line.

galaxies with different symbols are the same as in the previous figure. Sombrero’s satellites, as well as background galaxies, are distributed asymmetrically. In both subsamples there is a noticeable increase in galaxy number towards the supergalactic equator and towards the Virgo cluster centre ($SGL = 103^\circ$, $SGB = -2^\circ$). The reason for this asymmetry in the case of Sombrero group members remains unclear to us.

Figure 5 presents the distribution of assumed satellites of Sombrero (solid circles) and background galaxies (open circles) according to angular projected separation, r_p , and absolute value of radial velocity difference, $|\Delta V|$. Sombrero satellites dominate within $r_p < 2.4^\circ$ (i.e. 400 kpc), and at larger distances assumed Sombrero satellites are lost among the numerous background galaxies. Such a confusion of two categories of galaxies makes it difficult to estimate the virial mass of the Sombrero galaxy.

4. Total (orbital) mass of Sombrero

The list of 15 assumed satellites of Sombrero with known radial velocities is presented in Table 2. The galaxies are ranked according to their projected separation from Sombrero. The average linear projected separations of the satellites is $\langle R_p \rangle = 431$ kpc, the mean difference of their radial velocities with respect to the principal galaxy is $+62 \pm 54$ km s $^{-1}$, and the dispersion of radial velocities is $\sigma_v = 204$ km s $^{-1}$.

We estimated the virial (orbital) mass of the Sombrero galaxy assuming Keplerian motion of satellites, as test particles, around the massive central body. At random orientation of the satellite orbits with the mean eccentricity of $\langle e^2 \rangle = 1/2$

(Barber et al. 2014) the estimate of orbital mass can be written (Karachentsev & Kudrya 2014) as

$$M_{\text{orb}} = (16/\pi)G^{-1}\langle \Delta V^2 R_p \rangle, \quad (1)$$

where G is the gravitational constant. If R_p is expressed in kpc and ΔV expressed in km s $^{-1}$, then

$$\log(M_{\text{orb}}/M_\odot) = \log\langle \Delta V^2 R_p \rangle + 6.07. \quad (2)$$

Using all 15 assumed satellites from Table 2 we obtain the mean value of orbital mass to be $(17.2 \pm 6.1) \times 10^{12} M_\odot$. For three satellites with accurate TRGB distances this quantity is $(15.3 \pm 8.1) \times 10^{12} M_\odot$, while for five dwarfs with TRGB and SBF distances the average orbital mass drops to $(10.3 \pm 5.4) \times 10^{12} M_\odot$. Attributing to 15 satellite galaxies different weights ($w = 1$ for TRGB distances, $w = 1/2$ for SBF distances and $w = 1/4$ for TF and mem distances), we derive the weighted mean $(15.5 \pm 4.9) \times 10^{12} M_\odot$. We adopt this quantity as the optimal estimate of the total mass of the Sombrero group.

As seen from Table 2, the early-type galaxies are concentrated towards Sombrero much more tightly than spiral and irregular galaxies. Apart from the S0 galaxy NGC 4802, all other E-companions reside in the central zone $R_p < 200$ kpc. The known effect of morphological segregation is more pronounced if probable Sombrero satellites without radial velocities are taken into account. Table 3 lists 12 dwarf galaxies of low and very low surface brightness have been detected near Sombrero by different authors (Karachentsev et al. 2000, 2020; Javanmardi et al. 2016; Carlsten et al. 2020a,b). None of them is detected in the

Table 1. Galaxies around Sombrero with $r_p < 6^\circ$ and $V_{LG} < 1400 \text{ km s}^{-1}$.

Name	RA Dec	V_{LG}	Type	B_T	D	meth.	Ref.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
DDO116	121628.6–113141	959	Sm	16.02	23.28	TFb ⁽¹⁾	(1)
DDO118	121711.9–114041	1064	Irr	16.2	14.22	TFb	(1)
PGC104765	122143.7–123957	1221	Irr	16.92			
KKSG27	122205.7–094801	1128	Im	17.70	6.64	TFb	(1)
UGCA278	122310.4–135644	942	Irr	16.20	18.2	TF	(1)
PGC970571	122549.4–110305	1134	BCD	16.33			
PGC157820	123001.8–114731	909	S0	16.13			
NGC 4487	123104.5–080314	847	Sc	11.76	20.1	SN	(2)
NGC 4504	123217.4–073348	812	Sc	12.12	17.5	TF	(3)
UGCA287	123355.4–104047	852	Sm	15.36	20.5	TF	(4)
UGCA289	123537.8–075236	800	Sd	14.46	14.6	TF	(3)
PGC970397	123539.4–110402	928	Irr	16.87	10.00	TF	(1)
KKSG29	123714.1–102952	562	Irr	16.54	9.82	TRGB	(5)
KKSG30	123735.9–085201	918	Irr	16.30	9.72	TRGB	(8)
dw1239-1143	123915.3–114308	1171	dE	16.80	7.9	SBF	(6)
PGC1024539	123944.7–070519	744	Irr	17.90	15.6	TFb	(1)
NGC 4594	123959.4–113723	892	S0a	9.00	9.55	TRGB	(7)
SUCD1	124003.1–114004	1109	dE	18.40	9.55	mem	(1)
NGC 4597	124012.9–054757	866	Sm	12.87	10.10	TF	(4)
dw1240-1140	124017.6–114046	1097	dSph	19.50	9.55	mem	
PGC042730	124248.9–122327	829	dEn	14.78	9.55	mem	
UA295	124453.9–090731	1197	Sm	15.10	22.9	TF	(1)
DDO146	124541.4–060408	1304	Sm	13.01	17.3	TF	(3)
NGC 4674	124603.5–083920	1318	Sab	13.96			
PGC1003283	124750.9–082816	860	S0	15.89			
PGC104868	124854.1–114042	1171	BCD	15.0	11.17	TF	(1)
NGC 4700	124908.1–112435	1219	Sd	12.60	7.30	TF	(4)
PGC043345	124923.6–100712	1124	Sdm	12.79	16.6	TF	(4)
PGC1019240	124955.9–072527	1236	Sm	15.52			
NGC 4731	125101.4–062339	1323	SBC	11.88	13.6	TF	(3)
NGC 4723	125103.0–131413	1109	Sm	15.38	15.3	TF	(4)
PGC043526	125113.3–063334	1327	Im	13.26	13.6	mem	
NGC 4742	125148.0–102717	1088	E	12.11	15.8	SBF	(9)
NGC 4757	125250.1–101836	664	S0	14.54			
UGCA 307	125356.8–120621	731	Im	14.60	9.03	TRGB	(8)
NGC 4781	125423.7–103214	1080	Scd	11.39	15.5	TF	(4)
NGC 4790	125451.9–101452	1175	Sc	12.41	16.9	TF	(4)
UGCA308	125531.1–102350	1140	Irr	16.30	16.6	TFb	(4)
NGC 4802	125549.6–120319	843	S0	12.39	11.5	SBF	(10)
IC3908	125640.6–073346	1127	Scd	13.33	23.9	TF	(4)
NGC 4818	125648.9–083131	892	Sab	11.99	11.3	TF	(3)
UGCA311	125746.8–093802	1306	Scd	14.00	19.8	TF	(4)
PGC044460	125828.3–103437	1173	Sdm	14.70	8.70	TF	(4)
UGCA312	125906.5–121340	1121	Irr	15.88	12.0	TFb	(4)
NGC 4856	125921.3–150232	1145	S0a	11.44	24.0	TF	(4)
UGCA314	130017.2–122048	1397	Im	14.64	24.8	TF	(4)
PGC936912	130107.0–133106	1120	Im	15.40	14.6	TF	(4)
NGC 4920	130204.2–112243	1155	Im	14.15	18.2	TF	(4)

Notes. (1) Kashibadze et al. (2018), (2) Pejcha & Prieto (2015), (3) Tully et al. (2016), (4) Karachentsev & Nasonova (2013), (5) Karachentsev et al. (2018), (6) Carlsten et al. (2020a,b), (7) McQuinn et al. (2016), (8) present paper, (9) Blakeslee et al. (2001), (10) Tonry et al. (2001). ⁽¹⁾“TRGB” – the luminosity of tip of the red giant branch, “SBF” – surface brightness fluctuations, “TF” and “TFb” – the classic Tully & Fisher (1977) relation or its baryonic version; “SN” – the luminosity of supernova; “mem” – assumed membership in a group with the known distance.

HI line, and all are classified as spheroidal dwarfs. These objects with quenched star formation have projected separations $R_p < 200 \text{ kpc}$, increasing the segregation effect.

5. Concluding remarks

Radial velocities and projected separations of 15 assumed satellites of Sombrero yield the weighted estimate of its total mass ($M_T/M_\odot = (1.55 \pm 0.49) \times 10^{13}$). At $M*/L_K = 1 M_\odot/L_\odot$ (Bell et al. 2003) the stellar mass of Sombrero is $2.1 \times 10^{11} M_\odot$. Accounting for the luminosity of all the satellites increases

Fig. 3. Distribution of assumed members of the Sombrero group (filled circles) and background galaxies (open circles) according to their distance and radial velocity in the Local Group rest frame. The galaxies satisfy the conditions $V_{LG} < 1400 \text{ km s}^{-1}$ and projected separation $r_p < 6^\circ$ with respect to Sombrero (asterisk).

Fig. 4. Distribution of assumed Sombrero satellites (filled circles) and background galaxies (open circles) in supergalactic coordinates. All galaxies have $V_{LG} < 1400 \text{ km s}^{-1}$.

the stellar mass of the group to $M* = 2.4 \times 10^{11} M_\odot$. Therefore, the Sombrero halo has a total-mass-to-stellar-mass ratio of $M_T/M* = 65 \pm 20$, which is much higher than the cosmic baryonic ratio, $M_{\text{halo}}/M_b = 6$.

Karachentseva et al. (2011) undertook a search for faint companions around 2MASS Isolated Galaxies (2MIG). They found 214 faint neighbours around 125 2MIG galaxies with radial velocity differences of $|\Delta V| < 500 \text{ km s}^{-1}$ and projected separations of $R_p < 500 \text{ kpc}$. For 60 companions around E,S0-galaxies the median ratio of $M_{\text{orb}}/M*$ turns out to be 63, while for the remaining 154 spiral galaxies the median ratio is only 17. A similar search for companions around late-type spiral galaxies without bulges was performed by Karachentsev & Karachentseva (2019). Based on 43 companions

Fig. 5. Radial velocity difference and angular projected separation for assumed members of the Sombbrero group (filled circles) and background galaxies (open circles) taken with respect to the Sombbrero galaxy.

Table 2. Satellites of Sombbrero with known radial velocities.

Name	Type	r_p , (°)	R_p , (kpc)	ΔV (km s ⁻¹)
SucD1	dE	0.04	7	217
dw1240-1140	dSph	0.09	15	205
dw1239-1143	dE	0.22	37	279
PGC042730	dE	1.03	171	-63
PGC970397	Irr	1.21	201	36
KKSG29	Irr	1.32	220	-330
PGC104868	BCD	2.18	362	279
NGC 4700	Sd	2.24	372	327
KKSG30	Irr	2.84	471	26
UGCA 307	Im	3.45	573	-161
NGC 4802	S0	3.89	646	-49
PGC044460	Sdm	4.64	770	281
KKSG27	Im	4.78	794	236
NGC 4818	Sab	5.17	858	0
NGC 4597	Sm	5.85	971	-26

around 30 Sc-Scd-Sd galaxies, they found the mean ratio $M_{\text{orb}}/M_* = 20 \pm 3$. The factor of three difference in halo-mass-to-stellar-mass ratio between early-type and late-type luminous galaxies attests to their different dynamical histories.

In the vicinity of Sombbrero there are still more than a dozen galaxies with unreliable or even unknown distance estimates. Measurements of their TRGB distances with HST would help us to study the structure and dynamics of this group.

Table 3. Assumed satellites of Sombbrero without radial velocities.

Name	RA (2000.0) Dec	Type	D, Mpc	meth
dw1237-1125	123711.6–112559	dSph	7.5	SBF
KKSG31	123833.7–102925	dSph	9.55	mem
dw1239-1152	123909.0–115237	dSph	8.2	SBF
dw1239-1159	123909.1–115912	dSph	11.3	SBF
N4594-DGSAT-3	123932.8–111338	dSph	7.9	SBF
Sombbrero DwA	123951.5–112029	dSph	9.7	SBF
KKSG32	123955.0–114448	dSph	9.0	SBF
KKSG33	124008.9–122153	dSph	9.55	mem
dw1240-1118	124009.4–111850	dSph	8.8	SBF
dw1241-1131	124102.8–113144	dSph	7.2	SBF
Sombbrero DwB	124112.0–115333	dSph	11.2	SBF
KKSG34	124118.9–115539	dSph	9.0	SBF

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