Distance and Mass of the NGC 253 Galaxy Group

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Abstract

Two dwarf galaxies, WOC2017-07 and PGC 704814, located in the vicinity of the nearby luminous spiral galaxy NGC 253 were observed with the Advanced Camera for Surveys on the Hubble Space Telescope. Their distances of $3.62 \pm 0.18$ Mpc and $3.66 \pm 0.18$ Mpc were derived using the tip of the red giant branch method. These distances are consistent with the dwarf galaxies being members of the NGC 253 group. Based on the radial velocities and projected separations of seven assumed dwarf companions, we estimated the total mass of NGC 253 to be $(8.1 \pm 2.6) \times 10^{11} M_{\odot}$, giving a total-mass-to-$K$-luminosity ratio of $M_{\text{tot}}/L_K = (8.5 \pm 2.7) M_{\odot}/L_{\odot}$. A notable property of NGC 253 is its declined rotation curve. NGC 253 joins four other luminous spiral galaxies in the Local Volume with declined rotation curves (NGC 2683, NGC 2903, NGC 3521, and NGC 5055) that together have the low average total-mass-to-luminosity ratio, $M_{\text{tot}}/L_K = (5.5 \pm 1.1) M_{\odot}/L_{\odot}$. This value is only $\sim 1/5$ of the corresponding ratio for the Milky Way and M31.

Unified Astronomy Thesaurus concepts: Galaxy distances (590); Galaxy groups (597); Dwarf galaxies (416); Hertzsprung Russell diagram (725)

1. Introduction

Bright spiral galaxies in the Sculptor constellation form a diffuse association marked by de Vaucouleurs (1959) and Arp (1985). According to Jerjen et al. (1998) and Karachentsev et al. (2003), these galaxies, NGC 24, NGC 45, NGC 55, NGC 247, NGC 253, NGC 300, and NGC 7793, and their dwarf companions are located in a filamentary structure that extends along the line of sight from the Local Group to a distance of $D \sim 7$ Mpc. The Sculptor filament itself lies in the Local Sheet (Tully 1988), residing also in the Local Supercluster plane. The central part of the filament is the group of dwarf galaxies around the luminous spiral NGC 253. At the apparent magnitude of $K_s = 3^{\text{m}} 80$ (Jarrett et al. 2003) and the distance of $3.70$ Mpc (G. S. Anand et al. 2021, in preparation), the luminosity of NGC 253 corrected for Galactic and internal extinction is $L_K/L_{\odot} = 10.98$ dex, which exceeds the luminosity of the Milky Way or M31.

In the vicinity of NGC 253 within a radius of $15^{\circ}$ ($\sim 1$ Mpc) there are a dozen dwarf galaxies with radial velocities close to the radial velocity of NGC 253 of $V_{\text{LG}} = 276 \pm 2$ km s$^{-1}$ (Koribalski et al. 2004). Accurate distances for most of them have been measured via the luminosity of the tip of red giant branch (TRGB; Cannon et al. 2003; Karachentsev et al. 2003; Sand et al. 2014; Toloba et al. 2016). Only two assumed dwarf satellites of NGC 253, WOC2017-07 (Westmeier et al. 2017) and 2DFGRS-S431Z = PGC 704814 (Colless et al. 2003), have not had reliable distance estimates. In Section 2 we present estimates of their distances, made by the TRGB method from the images of these galaxies obtained with the Advanced Camera for Surveys (ACS) on the Hubble Space Telescope (HST). The distances measured by us confirm the association of both galaxies with the NGC 253 group. In Section 3, updated information on the group membership is used to evaluate the mass of the NGC 253 group.

2. TRGB Distances to WOC2017-07 and PGC 704814

We obtained HST ACS imaging of WOC2017-07 and PGC 704814 in both the F606W and F814W bands (760 s each) as part of the Every Known Nearby Galaxy survey (SNAP-15922; PI: R. Tully). Color cutouts of these two galaxies produced with this data are shown in Figure 1. Both galaxies contain visible young and older stellar populations. WOC2017-07 is irregular and lacks clear definition, whereas PGC 704814 is roughly spherical in shape with at least one very prominent young star cluster. The image for PGC 704814 contains numerous artifacts (figure-eight ghosts) that are caused by an extremely bright foreground star located in the ACS field of view (but not shown in the cutouts in Figure 1). For each galaxy, we used DOLPHOT (Dolphin 2000, 2016) to produce point-spread function (PSF) photometry with the $flux$ images, using the drizzled F814W image as the alignment reference frame. We cull these photometric catalogs to ensure that only resolved sources of the highest quality remain. For this work, we use the quality cuts modified from McQuinn et al. (2017), selecting stars with a signal-to-noise ratio $\geq 5$ in both bands, type $\leq 2$ (good or faint star), an error flag = 0 (well-recovered stars), $(Crowd_{F606W} + Crowd_{F814W}) \leq 0.8$, and $(SharF606W + SharF814W)^2 \leq 0.075$. Since the two dwarf galaxies only take up a small portion of the ACS field of view, we isolate the dwarfs to produce a color–magnitude diagram (CMD) that has reduced contamination from background objects.

It is seen in Figure 2 that the main feature present in both of the CMDs is the red giant branch (RGB). Both galaxies also have a small population of upper main-sequence stars, indicating there is some ongoing star formation present in both targets. To determine the location of the TRGB, we use the methods described in detail by Makarov et al. (2006) and Wu et al. (2014). Briefly, we perform artificial star experiments with DOLPHOT to quantify the levels of photometric errors, bias, and completeness present in the measured photometry.
The results from these experiments allow us to fit the observed luminosity function of RGB and brighter asymptotic giant branch (AGB) stars with a broken power law, with the break signifying the location of the TRGB. The physical reason for this parameterization lies in the fact that after undergoing the helium flash and leaving the TRGB, these stars immediately drop down on to the horizontal branch where they are significantly less luminous. This leaves a sharp break on the observed luminosity function at the location of the TRGB. An in-depth explanation of the method can be found in the original references (Makarov et al. 2006; Wu et al. 2014). We find $m_{\text{TRGB}} = 23.71 \pm 0.03$ for WOC2017-07, and $m_{\text{TRGB}} = 23.74 \pm 0.02$ for PGC 704814. The TRGB in the F814W band is slightly sensitive to the metallicity and age of the underlying stars, so we adopt the absolute magnitude and color calibration of the TRGB presented by Rizzi et al. (2007). Taking into account the (small) foreground extinction (Schlafly & Finkbeiner 2011), we find $D = 3.62 \pm 0.18$ Mpc for
WOC2017-07, and $D = 3.66 \pm 0.18$ Mpc for PGC 704814. The reduced photometry, full-field CMDs, and list of underlying parameters are available in the CMDs/TRGB catalog of the Extragalactic Distance Database\(^6\) (EDD; Jacobs et al. 2009; G. S. Anand et al. 2021, in preparation).

### 3. The Total Mass of the NGC 253 Group

A summary of data on 18 galaxies belonging to the NGC 253 group and its vicinity is presented in Table 1. Its columns contain: (1) galaxy name; (2) supergalactic coordinates; (3) morphological type on the de Vaucouleurs scale; (4) radial velocity in km s\(^{-1}\) relative to the Local Group centroid; (5) galaxy distance in megaparsecs from the EDD\(^7\); (6) method used to determine the distance; (7) log of $K_s$-band luminosity of the galaxy in the units of solar luminosity; (8) projected separation from NGC 253 in degrees; (9) projected separation in kiloparsecs; (10) the tidal index $\Theta_1$; (11) name of the main disturber; and (12) orbital mass estimate via the given satellites units of $10^{11}$ Msun.

| Name             | SGL SGB | $T$ | $V_{LG} \pm e$ | $D$   | Method | log$_{10}L_{Ks}$ | $r_p$ | $R_p$ | $\Theta_1$ | MD | $M_{orb}$ |
|------------------|---------|-----|----------------|-------|--------|------------------|------|-------|------------|----|-----------|
| NGC 253          | 271.57−05.01 | 5   | 276 ± 2        | 3.70  | trgb   | 10.98           | 0    | 0     | 0.1        | N 247 | ...       |
| ScI-MM-Dw2       | 272.25−05.47 | −2  | ...            | 3.12  | trgb   | 7.36            | 0.82 | 53    | 0.7        | N 253 | ...       |
| ScI-MM-Dw1       | 270.50−05.30 | −2  | ...            | 3.94  | trgb   | 6.77            | 1.11 | 72    | 1.8        | N 253 | ...       |
| WOC2017-07       | 274.06−06.12 | 10  | 288 ± 5        | 3.62  | trgb   | 6.17            | 2.73 | 176   | 2.1        | N 253 | 0.3       |
| DDO 226          | 274.23−03.21 | 10  | 412 ± 2        | 4.92  | trgb   | 7.71            | 3.21 | 207   | −0.3       | N 253 | ...       |
| SculptorSR       | 268.28−02.75 | 10  | ...            | 3.70  | mem    | 6.36            | 3.99 | 258   | 1.2        | N 253 | ...       |
| DDO 6            | 275.84−04.40 | 10  | 347 ± 2        | 3.43  | trgb   | 7.08            | 4.31 | 278   | 1.3        | N 253 | 16.5      |
| NGC 247          | 275.92−03.73 | 7   | 210 ± 2        | 3.71  | trgb   | 9.50            | 4.53 | 293   | 1.6        | N 253 | 15.1      |
| Sc 22            | 270.62+00.31 | −3  | ...            | 4.29  | trgb   | 7.15            | 5.40 | 349   | 0.5        | N 253 | ...       |
| ESO 540-032      | 276.95−04.24 | 10  | 285 ± 7        | 3.63  | trgb   | 6.83            | 5.43 | 351   | 1.4        | N 247 | 0.3       |
| KDG 2            | 278.66−03.52 | 10  | 290 ± 7        | 3.56  | trgb   | 6.85            | 7.24 | 468   | 1.0        | N 253 | 1.1       |
| NGC 59           | 273.13+03.16 | −3  | 431 ± 2        | 4.90  | trgb   | 8.66            | 8.32 | 537   | −0.4       | N 253 | ...       |
| PGC 704814       | 262.42+03.35 | 10  | 299 ± 8        | 3.66  | trgb   | 6.90            | 12.39| 800   | 2.1        | N7793| (4.2)     |
| ESO 349-031      | 260.18−00.40 | 10  | 234 ± 3        | 3.21  | trgb   | 7.12            | 12.61| 814   | 0.2        | N 253 | 17.0      |
| NGC 7793         | 261.30+03.12 | 10  | 250 ± 2        | 3.71  | trgb   | 9.70            | 13.10| 846   | 0.2        | N 253 | 6.7       |
| UGCA 442         | 260.78+06.11 | 8   | 300 ± 6        | 4.36  | trgb   | 8.03            | 15.49| 1000  | −0.3       | N 253 | ...       |
| NGC 625          | 257.27−17.34 | 8   | 320 ± 6        | 4.02  | trgb   | 8.96            | 18.88| 1219  | −0.3       | N 253 | ...       |
| ESO 245-005      | 255.13−19.74 | 9   | 307 ± 2        | 4.57  | trgb   | 8.53            | 24.39| 1575  | −0.7       | N 253 | ...       |

Note: (1) galaxy name; (2) supergalactic coordinates; (3) morphological type on the de Vaucouleurs scale; (4) radial velocity in km s\(^{-1}\) relative to the Local Group centroid; (5) galaxy distance in megaparsecs from the EDD; Jacobs et al. 2009; G. S. Anand et al. 2021, in preparation.

where $L_i$ is a luminosity of the neighboring galaxy in the $K$ band and $D_i$ is its separation from the neighbor, ranking the surrounding galaxies by the magnitude of their tidal force, $F_t \sim L_i/D_i^3$. The most significant neighbor is the main disturber (MD), where the constant $C$ is chosen so that a galaxy with $\Theta_1 = 0$ is located at the zero-velocity sphere relative to its MD. Consequently, the unrelated galaxies with a negative $\Theta_1$ are referred to as the population of the general field. Column (11) in Table 1 contains the name of the MD and column (12) contains the orbital mass estimate via the given satellite, described below. All galaxies in Table 1 are ranked according to their angular separation from NGC 253.

As seen from Table 1, the luminosity of principal galaxy NGC 253 exceeds the luminosity of its neighbors by more than one order of magnitude. In a case when a group is dominated by one massive galaxy surrounded by a set of light test particles, one can use the orbital mass estimate (Karachentsev & Kudrya 2014)

$$M_{orb} = (32/3\pi)(1 - 2e^2/3)^{-1}G^{-1}\langle\Delta V_i^2 R_{pi}\rangle.$$ 

where $G$ is the gravitation constant, $e$ is the prevailing orbit eccentricity, and $\Delta V$ is the radial velocity difference of a companion $i$ at the projected separation $R_{pi}$ relative to the principal galaxy. Basing on $N$-body simulations, Barber et al. (2014) estimated the typical eccentricity value of $\langle e_i \rangle \approx 1/2$ that yields

$$M_{orb} = (16/\pi)G^{-1}\langle\Delta V_i^2 R_{pi}\rangle$$

and

$$\langle M_{orb}/M_0 \rangle = 1.18 \times 10^6 \langle\Delta V_i^2 R_{pi}\rangle,$$

where $\Delta V$ and $R_{pi}$ are expressed in km s\(^{-1}\) and kiloparsecs, respectively. Individual values of $M_{orb}$ derived via different

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5 http://edd.ifa.hawaii.edu/

6 http://leda.univ-lyon1.fr

7 http://www.sao.ru/bv/lvgdb
companions are given in the last column of Table 1 in units of $10^{11} M_\odot$.

The distribution of galaxies in the vicinity of NGC 253 is presented in Figure 3 in supergalactic coordinates. Assumed satellites of NGC 253 with measured radial velocities are shown with solid symbols and assumed companions without radial velocities are indicated with open circles. The field galaxies with $\Theta_1 < 0$ are shown with crosses. For a galaxy with the luminosity of $L_K/L_\odot = 10^{10.98}$, the typical virial radius is $R_v \approx 300$ kpc, and the radius of the zero-velocity sphere is $R_0 \approx 3.5 R_v$ (Tully 2015b). The minor and the major circles in Figure 3 corresponds to $R_v = 4^\circ.65$ and $R_0 = 16^\circ.3$. In the sphere of the gravitational dominance of NGC 253 (i.e., inside $R_0$) there are eight satellites with measured radial velocities. For one of them, PGC 704814, the velocity error is too large and we ignore this galaxy. For the seven remaining companions of NGC 253, the mean radial velocity difference is $\langle \Delta V \rangle = -4 \pm 17$ km s$^{-1}$, the radial velocity dispersion is $\sigma_v = 42$ km s$^{-1}$, and the mean projected separation is $\langle R_v \rangle = 465$ kpc. The average estimate of orbital mass via the seven satellites is $M_{\text{orb}} = (8.1 \pm 2.6) \times 10^{11} M_\odot$, which yields the mass-to-luminosity ratio of $M_{\text{orb}}/L_K = (8.5 \pm 2.7)M_\odot/L_\odot$. The latter value is four times less than the ratios of $(27 \pm 9)M_\odot/L_\odot$ for the Milky Way and $(33 \pm 6)M_\odot/L_\odot$ for M31 (Karachentsev & Kudrya 2014).

With such a low halo mass for NGC 253, the expected virial radius should not be 300 kpc, but rather $\sim 200$ kpc (Tully 2015a). Then only five satellites are inside of the sphere of a radius $R_0 \sim 700$ kpc. For them, the dispersion of radial velocities, $\sigma_v = 44$ km s$^{-1}$, and the orbital mass estimate, $M_{\text{orb}} = (6.7 \pm 3.7) \times 10^{11} M_\odot$, is little changed, although the average projected separation of the five satellites drops to $\langle R_v \rangle = 313$ kpc. It should be noted that the location of these satellites appears to be very asymmetric with respect to the principal galaxy.

Interestingly, the field galaxies with $\Theta_1 < 0$ around NGC 253 follow the cold unperturbed Hubble flow with the Hubble parameter $H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$ and $\sigma_v = 40$ km s$^{-1}$. According to Karachentsev et al. (2003), the Hubble flow around NGC 253 is characterized by the zero-velocity radius $R_0 = 0.7$ Mpc, which corresponds to the total mass of the group $M_f(R_0) = 6.7 \times 10^{11} M_\odot$ in agreement with the mass estimate via internal (orbital) motions.

Lucero et al. (2015) performed H I observations of NGC 253 with the Karoo Array Telescope and determined its rotation curve $V(R)$ out to the projected separation of $\sim 20$ kpc from the galaxy center. These observations show that the rotation velocity reaches a maximum of $V_m = 214$ km s$^{-1}$ at $R \sim 12$ kpc, and then decreases systematically down to $\sim 185$ km s$^{-1}$. A similar result was obtained earlier by Hlavacek-Larrondo et al. (2011) from observations in the H\alpha and [N II] lines using Fabry–Perot interferometry. The declining rotation curve of NGC 253 can serve as an independent indication of a small size for the halo of this galaxy.

NGC 253 is not the only case of a luminous spiral galaxy with a falling rotation curve at the periphery. Casertano & van Gorkom (1991) and Zobnina & Zasov (2020) identified four more such galaxies in the Local Volume: NGC 2683, NGC 2976, NGC 3132, and NGC 3139.
NGC 2903, NGC 3521, and NGC 5055. All of these are located in areas of low cosmic density and have a small number of dwarf satellites. Karachentsev et al. (2020) estimated orbital masses of these galaxies, using radial velocities and separations of their companions. Data on five galaxies in the Local Volume with declined rotation curves are presented in Table 2. As one can see, all these spirals are characterized by high luminosities and low relative masses of their dark halos. The average dispersion of radial velocities of their satellites is 46 km s\(^{-1}\) at the average projected separation of 225 kpc. The low average value of \((M_{\text{orb}}/L_K) = (5.5 \pm 1.1)M_\odot/L_\odot\) is comparable to the cosmic baryon abundance, \(M_{DM}/M_{\text{bar}} \approx 6\), at the stellar mass-to-\(K\)-luminosity ratio of \(M_\text{stellar}/L_K \approx 1M_\odot/L_\odot\) (Bell et al. 2003).

It is implied that the galaxies with a declined rotation curve form a special category among the spiral galaxies of high luminosity. In the Local Volume with the distance \(D < 11\) Mpc there are 19 spiral galaxies with the luminosity \(\log(L_K/L_\odot) > 10.5\). If we exclude the five galaxies seen nearly face-on with indefinite rotation curves, NGC 628, IC 342, NGC 3184, M101, and NGC 6946, then the relative number of cases with quasi-Keplerian \(V(R)\) is \(\sim 36\%\).

Zobnova & Zasov (2020) noted that spiral galaxies with a declined rotation curve do not deviate from the general Tully–Fisher relation, \(\log(L_K) \propto \log(V_m)\), if \(V_m\) used as an argument, and not \(V(R_{\text{max}})\). Consequently, the identification of galaxies with relatively low-mass dark halos is a nontrivial observational problem, requiring data on the kinematics of their distant periphery.

### Table 2

Luminous Galaxies in the Local Volume with Declined Rotation Curves

| Name     | Type | \(D\)  | \(\log L_K\) | \(n_r\) | \(\sigma_r\) | \(\langle R_p \rangle\) | \(\log M_{\text{orb}}\) | \(M_{\text{orb}}/L_K\) |
|----------|------|-------|--------------|--------|-------------|----------------|----------------|----------------|
| NGC 253  | 5    | 3.70  | 10.98        | 7      | 42          | 465            | 11.91          | 8.5 \pm 2.7 |
| NGC 2683 | 3    | 9.82  | 10.81        | 2      | 43          | 49             | 11.09          | 1.9 \pm 1.3 |
| NGC 2903 | 4    | 8.87  | 10.82        | 4      | 45          | 198            | 11.68          | 7.3 \pm 6.4 |
| NGC 3521 | 4    | 10.70 | 11.09        | 2      | 46          | 198            | 11.77          | 4.8 \pm 4.0 |
| NGC 5055 | 4    | 9.04  | 11.00        | 4      | 54          | 216            | 11.71          | 5.1 \pm 1.8 |
| Mean     | 4    | 8.43  | 10.94        | 4      | 46          | 225            | 11.63          | 5.5 \pm 1.1 |

Note: (1) Galaxy name; (2) morphological type on the de Vaucouleurs scale; (3) galaxy distance in megaparsecs; (4) \(\log K_s\)-band luminosity of the galaxy in the units of solar luminosity; (5) number of companions with measured velocities; (6) velocity dispersion of companions in \(\text{km s}^{-1}\); (7) mean separation of companions in kiloparsecs; (8) \(\log\) mass of a group from orbital dynamics in solar masses; and (9) ratio of orbital mass to \(K\)-band luminosity in solar units.

NGC 2903, NGC 3521, and NGC 5055. All of these are located in areas of low cosmic density and have a small number of dwarf satellites. Karachentsev et al. (2020) estimated orbital masses of these galaxies, using radial velocities and separations of their companions. Data on five galaxies in the Local Volume with declined rotation curves are presented in Table 2. As one can see, all these spirals are characterized by high luminosities and low relative masses of their dark halos. The average dispersion of radial velocities of their satellites is 46 km s\(^{-1}\) at the average projected separation of 225 kpc. The low average value of \((M_{\text{orb}}/L_K) = (5.5 \pm 1.1)M_\odot/L_\odot\) is comparable to the cosmic baryon abundance, \(M_{DM}/M_{\text{bar}} \approx 6\), at the stellar mass-to-\(K\)-luminosity ratio of \(M_\text{stellar}/L_K \approx 1M_\odot/L_\odot\) (Bell et al. 2003).

It is implied that the galaxies with a declined rotation curve form a special category among the spiral galaxies of high luminosity. In the Local Volume with the distance \(D < 11\) Mpc there are 19 spiral galaxies with the luminosity \(\log(L_K/L_\odot) > 10.5\). If we exclude the five galaxies seen nearly face-on with indefinite rotation curves, NGC 628, IC 342, NGC 3184, M101, and NGC 6946, then the relative number of cases with quasi-Keplerian \(V(R)\) is \(\sim 36\%\).

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### 4. Concluding Remarks

We measured accurate TRGB distances of 3.62 Mpc and 3.66 Mpc for WOC2017-07 and PGC 704814, respectively, two dwarf galaxies in the vicinity of the bright spiral galaxy NGC 253, confirming their physical association with NGC 253 at 3.70 Mpc. Basing on the data on radial velocities and separations of seven satellites of NGC 253, we determined its ratio of the total (orbital) mass to \(K\)-band luminosity, \(M_{\text{orb}}/L_K = 8.5 \pm 2.7M_\odot/L_\odot\), which is 3–4 times less than the analogous ratio for the Milky Way or M31. A notable feature of NGC 253 is the presence of a descending rotation curve at the periphery. This feature is shown by four more galaxies in the Local Volume: NGC 2683, NGC 2903, NGC 3521, and NGC 5055. All of them are characterized by a low radial velocity dispersion of satellites, \(\sigma_r = (42–54)\text{ km s}^{-1}\), and a low mass of dark halo, \(\log(M_{\text{orb}}/M_\odot) = 11.09–11.91\). The mean total-mass-to-\(K\)-luminosity ratio for them is \((5.5 \pm 1.1)M_\odot/L_\odot\) on the scale of \(\sim 225\) kpc.

It is suggested that there is a special population of galaxies with quasi-Keplerian rotation curves, which are found mainly in regions of low cosmic density. In the Local Volume, their relative number is \(\sim 1/3\) among luminous spiral galaxies. The dark halos of these galaxies appear to be restricted in mass to an extent.

Recently, Correa & Schaye (2020) and Seo et al. (2020) studied the dark-to-stellar mass ratio, \(M_{DM}/M_\star\), depending on the morphology of galaxies from Sloan Digital Sky Survey. Both teams reported systematically lower values of \(M_{DM}/M_\star\) for disk-dominated (blue) galaxies than bulge-dominated (red) ones. A similar effect was found for Two Micron All-Sky Survey isolated galaxies by Karachentseva et al. (2011). Correa & Schaye (2020) explain this difference by the assumption that the stellar disks are more massive because they had more time for gas accretion and star formation. Also, according to Seo et al. (2020, p. 1), “the system velocity dispersion of satellite galaxies show a remarkably tight correlation with the central velocity dispersion of their primary galaxies for both red and blue samples.” The study of the relationship between the kinematics of satellites and inner kinematics of isolated luminous galaxies seems to be an important observational problem.

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