New dwarfs around the curly spiral galaxy M 63

I.D. Karachentsev\textsuperscript{1} | F. Neyer, R. Späni, T. Zilch\textsuperscript{2}

\textsuperscript{1}Russian Academy of Sciences, Special Astrophysical Observatory, N.Arkhyz, KChR, Russia
\textsuperscript{2}Fachgruppe Astrofotografie, Tief Belichtete Galaxien group of Vereinigung der Sternfreunde e.V., PO Box 1169, D-64629, Heppenheim, Germany

Correspondence
*Russian Academy of Sciences, Special Astrophysical Observatory, N.Arkhyz, KChR, Russia Email: ikar@sao.ru

Present Address
*Russian Academy of Sciences, Special Astrophysical Observatory, N.Arkhyz, KChR, Russia

We present a deep (50 hours exposed) image of the nearby spiral galaxy M 63 (NGC 5055), taken with a 0.14-m aperture telescope. The galaxy halo exhibits the known very faint system of stellar streams extending across 110 kpc. We found 5 very low-surface-brightness dwarf galaxies around M 63. Assuming they are satellites of M 63, their median parameters are: absolute $B$-magnitude $-8.8$ mag, linear diameter 1.3 kpc, surface brightness $\sim 27.8$ mag/sq. arcsec and linear projected separation 93 kpc. Based on four brighter satellites with measured radial velocities, we derived a low orbital mass estimate of M 63 to be $(5.1 \pm 1.8) \times 10^{11} M_\odot$ on a scale of $\sim 216$ kpc. The specific property of M 63 is its declining rotation curve. Taking into account the declining rotation curves of the M 63 and three nearby massive galaxies NGC 2683, NGC 2903, NGC 3521, we recognize their low mean orbital mass-to-K-band luminosity ratio, $(4.8 \pm 1.1) M_\odot/L_\odot$, that is only $\sim 1/6$ of the corresponding ratio for the Milky Way and M 31.

**KEYWORDS:**
galaxies: dwarf - galaxies: haloes - galaxies: individual (M 63)

1 INTRODUCTION.

The large spiral Sbc galaxy M 63 (NGC 5055), known as the "sunflower" galaxy, has a radial velocity of $V_{LG} = +570 \pm 3$ km s$^{-1}$ relative to the Local Group centroid. Jacobs et al. (2009) and McQuinn et al. (2017) determined its distance to be 8.99 Mpc and 8.87 Mpc, respectively, using the luminosity of the tip of the red giant branch method. In the Extragalactic Distance Database (http://edd.ifa.hawaii.edu) the distance of M 63 is re-estimated as 9.04 $\pm$ 0.10 Mpc. We will use this value for our estimates below. According to Müller et al. (2017), the galaxy M 63 together with galaxies M 51 and M 101 and their companions form a chain of three groups. This filamentary structure may extend further towards the Local Void, including the spiral galaxy NGC 6503. The radial velocities and distances of principal galaxies in this filament increase smoothly from the northern to the southern edge: $297 \pm 13$ km s$^{-1}$ (NGC 6503 at 6.25 Mpc), $375 \pm 2$ km s$^{-1}$ (M 101 at 6.95 Mpc), $553 \pm 2$ km s$^{-1}$ (M 51 at 8.40 Mpc), and $570 \pm 3$ km s$^{-1}$ (M 63 at 9.04 Mpc). Hereinafter, the radial velocities and their errors are taken from HyperLEDA (Makarov et al. 2014, http://leda.univ-lyon1.fr). An angular extension of the filament reaches about 30 degrees.

At an apparent magnitude of $K_s = 5.60^{+0.03}_{-0.02}$ the M 63 galaxy has the extinction corrected luminosity of $L_K = 1.0 \times 10^{11} L_\odot$, i.e., 2 times higher than that of the Milky Way or M 31. In the zone of gravitational domination of M 63 there are 4 dwarf galaxies with similar radial velocities: UGC 8313 ($V_{LG} = +658 \pm 8$ km s$^{-1}$), KKH 82 = UGCA 337 ($+545 \pm 26$ km s$^{-1}$), CGCG 217-018 ($+608 \pm 33$ km s$^{-1}$) and SDSS1327+4348 = PGC 2229803 ($+529 \pm 39$ km s$^{-1}$), the luminosities of which are $(1/100 - 1/500)$ the luminosity of M 63. Karachentseva \& Karachentsev (1998) detected three dwarf galaxies of low surface brightness around M 63: KK 191, KK 193, and KK 194. Their radial velocities remain unmeasured. Using the data on Sloan Digital Sky Survey (SDSS), Müller et al. (2017) found three more assumed satellites of M 63: dw1308+40, dw1305+41, and dw1303+42. Recently Karachentsev et al. (2020) detected two new ultrafaint dwarfs near M 63: TBGdw1 and TBGdw2, inspecting a
deep image of M 63 obtained by O. Schneider with an exposure time of \( \sim 10 \) hours.

An impressive feature of the M 63 galaxy is the presence of multiple arches and "plumes" of low surface brightness on its periphery. This faint structure was first noticed by van der Kruit (1979). Staudaher et al. (2015) also found it on their mosaic of deep images of M 63 exposed in the K-band. The system of arches as assumed stellar streams is visible most detailed in the deep B- and R-images of M 63 presented by Chonis et al. (2011). According to their photometry, a surface brightness of the faintest arches and plumes reaches \( SB_B \sim (27 - 29) \) mag/sq. arcsec and the color of the streams are consistent with the color of stellar population in outer disk and halo of M 63. It is assumed that the observed system of streams is most probably a result of accretion of a dwarf satellite in the last few Gyr.

2 DEEP WIDE-FIELD IMAGE OF M 63.

The presented image of M 63 was acquired with the 0.14-m aperture refractor TEC140ED APO at f/7 focal ratio using a Moravian G3-16200 Monochrom CCD (KAF-16200) camera with Astrodon LRGB filters. The mounts used during imaging were an AstroPhysics 900 GoTo (Antares Observatory) and a 10micron GM4000 HPS II (Ceres Observatory). Guiding was performed using an active off-axis autoguiding system. Exposures with each filter: Lum (18 hours), red (10.7 h), green (9.7 h) blue (12.3 h) with 20-minutes sub-exposures were obtained by F. Neyer in Antares Observatory, Gossau, Switzerland and by R. Späni (for 9 hours) in Ceres Observatory, Urnasch AR, Switzerland. The total exposure time was 50.7 hours. Image calibration was carried out with standard calibration techniques, including: Overscan correction, Dark and Bias correction, Flat-fielding after each imaging session. A master luminance was created by combining all sub-frames of all filters. The total field of view is 120 by 80 arcminutes.

To address the effect of sky glow, the following procedure was used to calibrate the frames: an individual linear surface gradient (polynomial degree 1) was estimated for each image based on an autonomous distribution of several thousand background samples. The estimated gradients were subtracted from the images before image integration. Remaining low spatial frequency variations (\( > 20 \) arcmin) across the stacked image were reduced by a few well placed samples, i.e., outside areas with stellar stream features or galactic cirrus. Robust estimates of the individual background samples were used to build a model of low frequency background fluctuations. The model was carefully inspected for systematic artifacts due to galactic cirrus before it was applied.

Our five new candidates of M 63 satellites have the median parameters: absolute magnitude \( M_B = -8.8 \), linear diameter \( \sim 1.3 \) kpc and the mean surface brightness \( SB_B \sim 27.8 \) mag/ sq. arcsec, that are compatible with the parameters of faint satellites around the Milky Way and M 31.
FIGURE 1 A system of stellar streams around M 63. The image size is \(55 \times 44'\) or \(145 \times 116\) kpc. The scale \(10\) arcmin is \(26.4\) kpc. For reference, the optical image of the galaxy is shown in the central ellipse with the standard major diameter of \(32\) kpc. North is up and East is on the left. The image is taken by the authors, more details in the text.

3 | DARK HALO MASS OF THE M 63.

In the vicinity of M 63, i.e., within a radius of \(r_p = 3.0'' (=473\) kpc), four galaxies are known with radial velocities in the range of \(\pm 300\) \(\text{km s}^{-1}\) relative to the velocity of M 63. More detailed information is given in Table 2, whereas their morphological types, apparent magnitudes, radial velocities \((V_{Lg}, \text{km s}^{-1})\), angular \((r_p, ^\circ)\) and linear \((R_p, \text{kpc})\) projected separations are given. Unfortunately, these galaxies do not have individual distance estimates. On projected separations of \(0.5 – 1.0\) Mpc there are 3 more dwarf galaxies with similar radial velocities: CGCG189-050 \((664\) kpc, \(+368\pm5\) \(\text{km s}^{-1}\)), WSRT-CVN51 \((847\) kpc, \(+573\pm3\) \(\text{km s}^{-1}\)) and DDO 182 \((891\) kpc, \(+730\pm1\) \(\text{km s}^{-1}\)). Individual distance estimates for them are also absent. These remote dwarf galaxies are rather associated with other nearby luminous spirals than with M 63.

The distribution of galaxies of the M 63 group in supergalactic coordinates is presented in Figure 3. Five galaxies with measured radial velocities are indicated with solid symbols and dozen galaxies from Table 1 without radial velocities are shown with open circles. The distribution of low surface brightness satellites looks rather asymmetric relative to M 63. The reason for this effect remains unclear.

The system of 4 satellites of M 63 is characterized with the average projected separation \(\langle R_p \rangle = 216\) kpc and the radial velocity dispersion \(\sigma_{\Delta v} = 54\) \(\text{km s}^{-1}\). A noticeable part of the \(\sigma_{\Delta v}\) is caused by velocity measurement errors, \(\langle \sigma^2_{\Delta v} \rangle = (26 \text{ km s}^{-1})^2\). Assuming an arbitrary orientation of the satellite orbits with the mean eccentricity \(\langle e^2 \rangle = 1/2\), the estimate of total (orbital) mass of the central dominated galaxy can be written as
FIGURE 2 Mosaic of direct and inverted images of low surface brightness dwarf galaxies in the vicinity of M 63. Each image fragment is spanning 3.7' across. North is up and East is on the left.

Here, $G$ is the gravitation constant, and $\Delta V$ and $R_p$ are expressed in km s$^{-1}$ and kpc, respectively (Karachentsev & Kudrya, 2014). For 4 satellites, we obtained an estimate of orbital (virial) mass $M_{\text{orb}} = (5.1 \pm 1.8) \times 10^{11} M_{\odot}$ or the mass-to-luminosity ratio $M_{\text{orb}}/L_K = (5.1 \pm 1.8) M_{\odot}/L_{\odot}$. The uncertainty for $M_{\text{orb}}$ is estimated via variations of the product $\Delta V^2 R_p$ from one satellite to another. The derived ratio of $M_{\text{orb}}$ is significantly lower than that of $(27 \pm 9) M_{\odot}/L_{\odot}$ for the Milky Way and $(33 \pm 6) M_{\odot}/L_{\odot}$ for M 31 (Karachentsev & Kudrya, 2014). We are not aware of other examples of large galaxies from the literature with such a low dark-to-stellar mass ratio.

Battaglia et al. (2006) investigated the kinematics of M 63 using observations in the 21-cm line with the Westerbork Synthesis Radio Telescope. Based on the results of these observations they built the rotation curve of the galaxy, $V(R)$, which has a steep rise with the maximum at $\sim 10$ kpc and than a smooth velocity decreasing down to $\sim 175$ km s$^{-1}$ within the last measured point at the distance of 50 kpc (at $D = 9.04$ Mpc). To fit the observed $V(R)$, the authors constructed

$M_{\text{orb}} = (16/\pi G)\langle \Delta V^2 R_p \rangle = 1.18 \times 10^6 \langle \Delta V^2 R_p \rangle$. 

Note, that the average value, $\langle \Delta V^2 R_p \rangle$, gives a statistically biased mass estimate. In the presence of large radial velocity errors, $\epsilon_{\Delta v}$, the product $\langle \Delta V^2 R_p \rangle$ should be replaced by $\langle (\Delta V^2 - \epsilon_{\Delta v}^2) R_p \rangle$, decreasing the orbital mass estimate.
TABLE 1 Probable LSB satellites of M 63 without radial velocities.

| Name    | RA (J2000) | DEC | SGL  | SGB | Type | \(a'\) | B   | \(M_B\) | \(r_p\) | \(R_p\) |
|---------|------------|-----|------|-----|------|--------|-----|--------|--------|--------|
| TBGdw2  | 131447.3+414339 | 76.48 | 14.02 | Tr   | 0.48 | 19.5   | -10.3 | 0.36   | 57     |
| KK 191  | 131339.7+420236 | 76.12 | 13.85 | Tr   | 0.95 | 18.2   | -11.6 | 0.40   | 63     |
| KK 193  | 131529.8+413011 | 76.72 | 14.11 | Tr   | 1.07 | 18.7   | -11.1 | 0.54   | 85     |
| TBGdw5  | 131422.9+413409 | 76.63 | 13.91 | Sph  | 0.42 | 20.9   | -8.9  | 0.55   | 87     |
| TBGdw3  | 131258.0+415117 | 76.29 | 13.70 | Sph  | 0.42 | 21.6   | -8.2  | 0.56   | 88     |
| TBGdw6  | 131834.9+414512 | 76.55 | 14.72 | Irr  | 1.80 | 18.5   | -11.3 | 0.59   | 93     |
| TBGdw7  | 131902.8+420023 | 76.31 | 14.84 | Sph  | 0.45 | 21.7   | -8.1  | 0.60   | 95     |
| TBGdw1  | 131218.5+415833 | 76.15 | 13.59 | Tr   | 0.52 | 19.5   | -10.3 | 0.66   | 102    |
| TBGdw4  | 131208.5+415636 | 76.70 | 13.66 | Tr   | 0.50 | 21.0   | -8.8  | 0.77   | 121    |
| dw1308+40 | 130846.0+405404 | 77.13 | 12.76 | Sph  | 0.37 | 18.4   | -11.4 | 1.76   | 278    |
| dw1305+41 | 130529.0+415324 | 76.02 | 12.32 | Sph  | 0.41 | 17.3   | -12.5 | 1.94   | 306    |
| dw1303+42 | 130314.0+422217 | 75.46 | 12.00 | Irr  | 0.38 | 18.3   | -11.5 | 2.37   | 374    |
| KK 194  | 131719.5+442348 | 73.82 | 14.85 | Irr  | 0.63 | 17.6   | -12.2 | 2.45   | 387    |
| dw1305+38 | 130558.0+380543 | 79.85 | 11.73 | Irr  | 0.32 | 17.9   | -11.9 | 4.44   | 700    |

*) TBGdw2 locates ∼ 1’ NW away from a galaxy WISEAJ131450.79+414247.2 having \(m_g = 15.4\) mag and \(Z = 0.0438\). Also, a faint red galaxy WISEAJ131447.72+414337.4 with \(Z = 0.6799\) is projected into the TBGdw2 body.

*) TBGdw6 may be not a dwarf galaxy but a patch of reflecting nebulae. A galaxy WISEAJ131836.93+414455.4 with \(m_g = 16.9\) mag and \(Z = 0.06277\) is projected into the TBGdw6.

TABLE 2 Assumed members of the M 63 group with known radial velocities.

| Name    | SGL | SGB | Type | \(B_T\) | \(V_{LG}\) | \(r_p\) | \(R_p\) |
|---------|-----|-----|------|--------|----------|--------|--------|
| M 63    | 76.20 | 14.25 | Sbc  | 9.3    | 570 ± 3  | 0      | 0      |
| UGC 8313 | 75.96 | 13.92 | Sm   | 14.7   | 658 ± 8  | 0.41   | 65     |
| KKH 82  | 76.36 | 13.69 | Tr   | 16.4   | 545 ± 26 | 0.58   | 92     |
| CGCG217-018 | 77.62 | 13.47 | BCD  | 14.9   | 608 ± 33 | 1.62   | 256    |
| SDSS132753 | 74.65 | 16.66 | BCD  | 16.2   | 529 ± 39 | 2.87   | 453    |

the galaxy model with contribution of different mass components: a warped gaseous disk, stellar disk and dark matter halo. The best agreement of the model with observed circular velocities was achieved at \(M_{gas} = (0.1 \times 10^{11}) \, M_\odot, M_{star} = (1.0 \times 10^{11}) \, M_\odot\) and \(M_{DM} = (2.4 \times 10^{11}) \, M_\odot\). Thus, the total mass estimate within 50 kpc amounts to \((3.5 \times 10^{11}) \, M_\odot\) that is more than half the total mass we estimated when using the satellite motion at a scale of ~216 kpc. Consequently, the galaxy M 63 has a rather skinny dark matter halo.

Casertano & van Gorkom (1991) noted that among the Local Volume galaxies with distances \(D < 11 \, Mpc\) there are two galaxies, NGC 2683 and NGC 3521, with decreasing rotation curves at their periphery. Recently, Zobnina & Zasov (2020) presented a list of 22 galaxies with decreasing \(V(R)\). Besides the luminous galaxies of the Local Volume, M 63 and NGC 3521, this list contains one more isolated nearby galaxy of high luminosity: NGC 2903. Using the data of Updated Nearby Galaxy Catalog (Karachentsev et al. 2013), we looked for dwarf satellites of these galaxies within \(R_p = 500\) kpc in the velocity range of ±300 km s\(^{-1}\). The results are presented in Table 3. As there are no bright satellites of the Magellanic Clouds type around these galaxies, their number is small. However, it can be stated that the available faint satellites have a low velocity dispersion, \(\sigma_{\Delta v} \approx 47 \, \text{km s}^{-1}\). This leads to the average orbital mass-to-luminosity ratio of \(\langle M_{orb}/L_K \rangle = (4.8 \pm 1.1) \, M_\odot/L_\odot\) on the scale of \(R_p = 165\) kpc.

It is curious to note that the galaxy NGC 3521, like M 63, has a strongly disturbed periphery with an arcuate structure of low surface brightness (Karachentsev et al. 2020).
TABLE 3 Nearby luminous galaxies with declined rotation curves.

| Name        | Type | D  | log($L_K$) | $n_u$ | $\sigma_{\Delta u}$ | $\langle R_p \rangle$ | log($M_{\text{orb}}$) | $M_{\text{orb}}/L_K$ |
|-------------|------|----|------------|-------|--------------------|-----------------------|------------------------|-----------------------|
| NGC2683     | Sb   | 9.82 | 10.81       | 2     | 43                 | 49                    | 11.09                  | 1.9±1.3               |
| NGC2903     | Sbc  | 8.87 | 10.82       | 4     | 45                 | 198                   | 11.68                  | 7.3±6.4               |
| NGC3521     | Sbc  | 10.70 | 11.09       | 2     | 46                 | 198                   | 11.77                  | 4.8±4.0               |
| NGC5055     | Sbc  | 9.04 | 11.00       | 4     | 54                 | 216                   | 11.71                  | 5.1±1.8               |
| Mean        | Sbc  | 9.61 | 10.93       | 3     | 47                 | 165                   | 11.56                  | 4.8±1.1               |

FIGURE 3 Distribution of dwarf galaxies around M 63 in supergalactic coordinates. The galaxies with known radial velocities are shown by solid symbols, the low surface brightness dwarfs from Table 1 without radial velocities are indicated by open circles.

4 | CONCLUDING REMARKS

A deep image of M 63, obtained with an amateur 0.14-m aperture telescope and an exposure time of 50 hours, shows that the system of faint stellar streams at the periphery of this galaxy extends up to 55 kpc from its center. Obviously, these streams are the remnants of the accretion process of one or several satellites of moderate mass. In addition to the already known satellites of M 63, we found 5 more candidates for fainter satellites with a median absolute magnitude of $-8.8$ mag, a median linear diameter of $\sim 1.3$ kpc and the mean surface brightness $\sim 27.8$ mag/sq. arcsec.

From four satellites of M 63 with measured radial velocities, we estimated the orbital mass of the M 63 halo and obtained the ratio of the total mass-to-stellar luminosity of $M_{\text{orb}}/L_K = (5.1 \pm 1.8) M_\odot/L_\odot$. This value is 5 – 6 times lower than the respective ratio for the Milky Way and M 31.

Unlike most spiral galaxies, the M 63 galaxy is distinguished by the presence of decreasing (Keplerian) region on its rotation curve. Several other nearby luminous spiral galaxies (NGC 2683, NGC 2903, and NGC 3521) have the same property. They all show a tendency to have poor, low-mass dark matter haloes with the mean ratio of $M_{\text{orb}}/L_K = (4.8 \pm 1.1) M_\odot/L_\odot$. These galaxies of big stellar mass but with a small number of faint satellites, may form a special population of spiral galaxies characterized by underdeveloped dark halos. The search for new faint satellites around this type galaxy and the measurement of their radial velocities is an urgent observational problem.

ACKNOWLEDGMENTS

We thank the referee for thoroughly reading the manuscript and valuable comments. IDK was supported by RFBR grant 18–02–00005.

References

Battaglia G., Fraternali F., Oosterloo T., Sancisi R., 2006, A & A, 447, 49
Bosma A., 1981, AJ, 86, 1791
Casertano S., van Gorkom J.H., 1991, AJ, 101, 1231
Chonis T.S., Martinez-Delgado D., Gabany R.J., et al, 2011, AJ, 142, 166
Jacobs B.A., Rizzi L., Tully R.B., et al, 2009, AJ, 138, 332
Karachentseva V.E., Karachentsev I.D., 1998, A &AS, 127, 409
Karachentsev I.D., Riepe P., Zilch T., 2020, Ap, 63, 5
Karachentsev I.D., Makarov D.I., Kaisina E.I., 2013, AJ, 145, 101
Karachentsev I.D., Kudrya Y.N., 2014, AJ, 148, 50
Makarov D.I., Prugniel P., Terekhova N., et al, 2014, A & A, 570A, 13
McQuinn K.B.W., Skillman E.D., Dolphin A.E., et al, 2017, AJ, 154, 51
Müller O., Scalera R., Binggeli B., Jerjen H., 2017, A & A, 602A, 119
Staudaher S.M., Dale D.A., van Zee L., et al, 2015, MNRAS, 454, 3613
van der Kruit, P.C. 1979, A&AS, 38, 15
Zobnina D.I., Zasov A.V., 2020, Astronomy Reports, 64, 295

**How cite this article:** Karachentsev I.D., Neyer F., Späni R., and Zilch T. (2020), New dwarfs around the curly spiral galaxy M 63, *Astronomische Nachrichten, 2020*