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Tidal Stellar Loops and Dark Halo of UGC 7388

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Abstract. We present the dynamic model of the edge-on late-type galaxy UGC 7388. The galaxy has two elongated stellar loops of low surface brightness in a plane inclined to the plane of a stellar disk at a large angle. The loops are thought to be the result of a minor merger. We performed a series of numerical N-body simulations varying parameters of the dark halo of the host galaxy, the distribution of matter in the probable satellite and the orbit parameters. Our dynamical model of a merger reproduces the morphology of loops. We also refined the estimate of the dark halo mass [$M_{\rm halo}(r \leq 4h) = 1.28 M_{\rm disk}$] and determined the age of loops > 2.9 Gyr.

1. Introduction

Deep images of the galaxy outskirts revealed the presence of weak stellar substructures — streams, envelopes, and loops. The first known tidal stream surrounding the Milky Way (the Sagittarius tidal stream) was discovered less than two decade ago (Ibata et al. 1995). Another example is the nearby, edge-on galaxy NGC 5907 with two elliptically-shaped loops in the halo of this galaxy (Shang et al. 1998). More recently, very deep images have clearly revealed large scale, complex structures of arcing loops in the halos of several nearby galaxies, for example, NGC 4013 (Martínez-Delgado et al. 2009) and NGC 5055 (Martínez-Delgado et al. 2010). Another galaxy with prominent stellar loops is the galaxy UGC 7388 (Faúndez-Abans et al. 2009). The galaxy is observed almost edge-on, so the loops are cleary seen on its background.

All these structures are thought to be the result of mergers (Reshetnikov & Sotnikova 2000; Martínez-Delgado et al. 2008). Morphology of loops is determined by orbital parameters, but mainly by the mass distribution of the the central galaxy. Modeling the loop, we can obtain the distribution of mass, including the dark halo mass.

2. Observational Data

Observational data were taken from Faúndez-Abans et al. (2009). They are based on spectroscopic and morphological studies of the galaxy UGC 7388 with the 8.1-m Gemini North telescope.

2.1. Main Galaxy

UGC 7388 is a giant late-type (Sc) spiral galaxy seen almost edge-on. The disk inclination $i \geq 80^\circ$ was roughly estimated from its observed flattening ($b/a \simeq 0.17$) and from the dust lane orientation. According to the NASA/IPAC Extragalactic Database

(NED), the distance to UGC 7388 is 93.8 Mpc. The absolute magnitude of the galaxy is $B = 20.4$. The galaxy has no distinct bulge and the brightness distribution along its major axis can be described by an exponential disk with a radial scale length of 3.0 kpc. The color index of UGC 7388, $(B-V)_0 \simeq 0.5-0.6$ (corrected for the inclination), and the relatively high abundance of neutral hydrogen ($M(\mathrm{H\,I})/L_B \simeq 0.2-0.3$) are also consistent with the fact that it is a late-type galaxy.

The K band photometry gives the ratio of the vertical to radial scales to be $h_z/h \simeq 0.4$. Such a large apparent flattening may suggest that the galactic plane is significantly inclined to the line of sight ($i \leq 70°$ if the true flattening is ≤ 0.15), but a small displacement of the dust lane is in conflict with this assumption. The large ratio h_z/h probably suggests that the stellar disk of UGC 7388 is intrinsically thick.

2.2. Loops

UGC 7388 is surrounded by two faint extended loop-like structures with surface brightness $\mu_B \simeq 24$ mag arcsec^{-2} and $\mu_B \simeq 25$ mag arcsec^{-2}, respectively (see Fig. 1, top panel). The major axis of a smaller and brighter loop is ~ 20 kpc, its apparent flattening is $b/a \simeq 0.6$. The second loop is more extended. Its major axis is 34 kpc and its apparent flattening is $b/a \simeq 0.7$. The brighter and more compact loop rotates relative to the central galaxy. Thus, UGC 7388 could have been classified as a kinematically confirmed polar ring galaxy, but the presence of a second loop-like structure and the non-coincidence of the loop centers with the galactic nucleus speaks in favor of minor merger.

The luminosity of the structures (including a smooth stellar envelope) outside the disk is $(20-30)\%$ of the main galaxy's mass. It gives an upper limit on the mass of the disrupted satellite to be 0.2 ± 0.1 of the main galaxy's mass.

3. Mass Model from the Rotation Curve

Faúndez-Abans et al. (2009) presented the rotation curve of the galaxy UGC 7388. We used these data to find the contributions of a disk and a dark halo into rotation curve.

Disk. We use the following brighness distribution in a stellar disk

$$I(R,z) = I(0,0)\, e^{-r/h}\, \mathrm{sech}^2(z/z_0)\,, \tag{1}$$

where $I(0,0)$ is the central brightness, h is the disc scalelength and z_0 is the scaleheight ($z_0 = 2h_z$). The central brightness $I(0,0)$ defines the total luminosity: $L_{\mathrm{disk}} = 4\pi I(0,0) z_0 h^2$. We adopted the folowing parameters: $h = 3.0$ kpc, $z_0/h = 0.2$ (we consider a thin disk), $M_B = -20.4$ mag. We varied the mass-to-luminosity ratio M_{disk}/L_B in the range $2.4-3.0$.

Dark halo. The halo model is a truncated Navarro-Frank-White (NFW) halo (Navarro et al. 1996). The NFW profile can be characterized by two main parameters: the mass within the sphere of the virial radius M_{200} (or the velocity at the same radius v_{200}) and the concentration parameter $c \equiv r_{200}/r_{\mathrm{s}}$ being simply the ratio of the virial radius to the scale length of the mass distribution.

Rotation curve decomposition. Varying the parameters of the halo and the ratio M_{disk}/L_B we obtained a set of models. We concluded that there is a degeneracy while decomposing the rotation curve. That is why we precised the model during N-body simulations to match the modeled picture and the observed one.

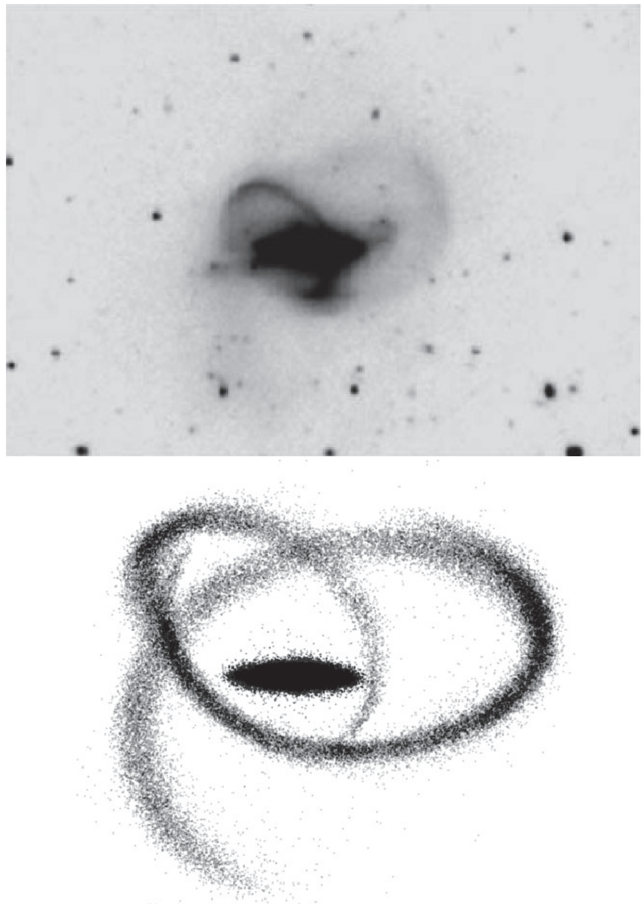

Figure 1. UGC 7388. Top panel: Image for UGC 7388 in the *r*-G0303 filter from Faúndez-Abans et al. (2009). Bottom panel: The model with inclination $i = 60°$, position of the apocenter 45°, mass ratios $M_{200}/M_{\rm disk} = 26.6$ and $M_{\rm disk}/M_{\rm sat} = 7.5$, number of particles $N_{\rm tot} = 1.21 \times 10^6$, and time $t = 2.9$ Gyr.

4. N-Body Simulations

To simulate the evolution of our models, we use the fast *N*-body code GYRFALCON (Dehnen 2000, 2002) and the NEMO package[1] (Teuben 1995).

Main galaxy. To construct a self-consistent model of a main galaxy we used the program MKGALAXY (McMillan & Dehnen 2007) from the package NEMO. The stability of a model was controled by the Toomre parameter $Q > 1$ (Toomre 1964).

Satellite. The satellite was described by Plummer's sphere

$$\rho(r) = \frac{3}{4\pi}\frac{M_{\rm sat}}{a_{\rm sat}^3}\left(1 + \frac{r^2}{a_{\rm sat}^2}\right)^{-5/2} \tag{2}$$

[1] It is available at `http://astro.udm.edu/nemo`.

where M_{sat} is the satellite mass, a_{sat} is the scale length of the mass distribution. We varied a_{sat} in the range $1 - 1.5$ kpc to control the space of satellite disruption and further excluded too concentrated models.

Orbit. The apocenter distance r_a, wich marks an initial position of a satellite, was taken equal to the size of the largest loop $\sim$ 35 kpc. We have assumed that the 'loop' eccentricity $e \simeq 0.7$ roughly corresponds to the orbit eccentricity, so the pericenter distanse is $r_p = r_a(1-e)/(1+e)$. To obtain the initial velocity we calculated the total mass within the sphere of radius r_a: $M(r_a) = M_{disk} + M_{halo}(r_a)$. We varied the inclination i from 30° to 90° and adjusted the argument of the pericenter.

4.1. Results

We used a considerably large number of particles, $N = 5 \times 10^5 - 1.2 \times 10^6$ to reach a high resolution and to trace the evolution of the model on time scales of about $4 - 5$ Gyr. The number of particle for a satellite was $N = 10^4$. We varied v_{200} (or M_{200}) and orbit inclination i. The more massive halo gives a larger angle between loops. The inclination influences the apparent size and ellipticity of loops.

The most plausible model can be characterize by the following parameters: $c = 8$, $v_{200} = 180$ km s^{-1}, $M_{halo} = 26.6\, M_{disk}$, $a_{sat} = 1.5$ kpc. The model image (Fig. 1, bottom panel) resembles the system of loops of the galaxy UGC 7388.

5. Conclusions

In spite of the large degeneracies in the orbital and structural parameters of the loops progenitor, we managed to precise the halo mass [$M_{halo}(r \leq 4h) \simeq 1.28\, M_{disk}$]. The system of loops seems to be older than 2.9 Gyr (it takes more time to destroy the satellite substantially). Nevertheless we can not exclude a major merger because of the large thickness of the disk and presence of an extended faint envelope.

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