The NGC 1023 Galaxy Group: An Anti-Hubble Flow?

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Abstract

We discuss recently published data indicating that the nearby galaxy group NGC 1023 includes an inner virialized quasi-stationary component and an outer component comprising a flow of dwarf galaxies falling toward the center of the system. The inner component is similar to the Local Group of galaxies, but the Local Group is surrounded by a receding set of dwarf galaxies forming the very local Hubble flow, rather than a system of approaching dwarfs. This clear difference in the structures of these two systems, which are very similar in other respects, may be associated with the dark energy in which they are both imbedded. Self-gravity dominates in the Local Group, while the anti-gravity produced by the cosmic dark-energy background dominates in the surrounding Hubble flow. In contrast, self-gravity likewise dominates throughout the NGC 1023 Group, both in its central component and in the surrounding “anti-Hubble” flow. The NGC 1023 group as a whole is apparently in an ongoing state of formation and virialization. We may expect that there exists a receding flow similar to the local Hubble flow at distances of 1.4–3 Mpc from the center of the group, where anti-gravity should become stronger than the gravity of the system.

1 Introduction

It has been known since the time of Hubble’s observations \cite{1} that the nearby Universe to distances of about 10-15 Mpc is populated by comparatively small groups of galaxies similar to the Local Group. Essentially all major galaxies and most known dwarf galaxies in this volume are collected in such groups \cite{2}. About two dozen dwarf galaxies are observed around the Local Group, which are moving
away from the center of the group. This expanding component of the system represents the nearby local Hubble flow of receding galaxies (see the new study [3] and references therein). For brevity, we will call such a system, with a central, quasi-stationary group surrounded by an expanding flow, a “Hubble cell”. In addition to the local cell [3–9], the Hubble cells around the giant galaxies M81 and Cen A have also been studied [10, 11]. Hubble cells can be considered the main structural unit of the nearby Universe. A theoretical model for a Hubble cell was proposed and developed in [4–9, 12–14]. The main new aspect of this model is that it takes into account the cosmic dark-energy background. In accordance with the standard LambdaCDM cosmology, the model assumes that a group of galaxies together with the surrounding flow of the Hubble recession is imbedded in a uniform dark energy distribution that is constant in time. Dark energy creates anti-gravity. The gravity due to baryonic and dark matter in the group dominates within the volume of the group, while the anti-gravity of the dark energy dominates in the area of the Hubble flow; anti-gravity becomes stronger than the gravity of the group at the distances of 1–3 Mpc from the group center. The boundary between the gravitationally bound, quasi-stationary group and the expanding Hubble flow corresponds to the "zero-gravity surface where the forces of gravity and anti-gravity cancel.

It may be seemed at the first glance that the kinematic structure of the NGC 1023 Group represents a counter-example to this model for a Hubble cell. According to Trentham and Tully [15], there is a gravitationally bound (and virialized) system of dwarf galaxies in the central region of this group, surrounding the giant galaxy NGC 1023, which is the most massive galaxy in the group. A flow of dwarf galaxies is observed outside the central system. This two-component structure is reminiscent of the Local Group, with its flow of receding galaxies. However, Trentham and Tully [15] claim that, in the case of NGC 1023, the flow represents an infall toward the center of the group, rather than an outflow away from it.

In this paper, we discuss the kinematic and dynamical structures of the NGC 1023 Group based on the data [15–19], and evaluate their agreement with our Hubble-cell model. In Section 2, a brief description of a typical Hubble cell, such as the Local Group together with its surrounding local Hubble flow, is given. Section 3 presents data on the NGC 1023 Group and considers the kinematics of its outer component. In Section 4, we consider the dynamical background against which the “anti- Hubble” flow of the group develops. Our results are discussed in Section 5.2.

2 The Local Hubble Cell

The Local Group of galaxies contains two giant galaxies — the Milky Way and M31. The group also includes the Magellanic clouds, M33, and approximately
50 dwarf galaxies. The Local Group is a quasi-stationary, gravitationally bound system immersed in a potential well created primarily by the gravitational force of the dark matter collected in the extended massive halos of the two giant galaxies in the group. The total mass of the group (baryonic and dark matter) is estimated to be $M_{\text{LG}} \simeq (1 - 5) \times 10^{12} M_\odot$ [3, 20, 21, 22]. The diameter of the Local Group is approximately 2 Mpc, while the distance between the centers of the Milky Way and M31 is about 0.7 Mpc. These two galaxies (together with the families of dwarf galaxies populating their individual dark halos) are approaching each other with the velocity that is now near 120 km/s. The onset of the local Hubble flow is just outside the Local Group, at distances of $R > 1.4-1.6$ Mpc from its center [3]. The flow is formed by 22 dwarf galaxies located at distances of up to 3 Mpc. All the dwarf galaxies of this flow are receding from the group, as a rule, with velocities (relative to the group barycenter) that increase with distance from the center of the group.

The local Hubble cell — the Local Group together with the local Hubble flow — serves as a typical example of a Hubble cell. In the velocity–distance diagram presented in [3], 58 galaxies of the cell occupy two well defined regions. The first of these, corresponding to distances to 1.3–1.5 Mpc, is occupied by galaxies of the Local Group. Galaxies in this region have (radial) velocities that are both positive and negative, in the interval from -150 to +170 km/s, with the mean velocity being close to zero. The mean (radial) velocity dispersion of the galaxies in the system is 72 km/s. The second component of the system is the local Hubble flow, where there is no negative velocities, and the velocities of galaxies have values from 60 km/s near the distances of 1.6 Mpc to 250 km/s at the distance of 3 Mpc.

Two other Hubble cells studied in detail are around the M81 galaxy and the Cen A galaxy [10,11]; they are similar to each other and to the Local Cell. Their central groups are similar: in each of them there is a dominant galaxy or pair of massive galaxies. The local Hubble flows around the groups are even more similar. The flows are formed by dwarf galaxies whose total mass in each case is much less than the mass of the central group. The flows display a high degree of regularity, and a nearly linear velocity–distance dependence, with the median local Hubble factor which is in a narrow range: $57 \text{ km/s/Mpc} < H_{\text{med}} < 62 \text{ km/s/Mpc}$.

### 3 The NGC 1023 Group: two components

The NGC 1023 Group, first identified in [23], is sometimes considered a “classic example” [24, 25] of a small system of galaxies. It is located in the direction opposite to the Virgo Cluster, and the group is compact and well isolated in space [16]. Tully [25] identified 14 members of the group, for five of which distances were determined with the use of the Tully–Fisher relation. Distances to 11 galaxy in
the group were derived in [16] based on data obtained on the 6-m telescope of the Special Astrophysical Observatory and the Hubble Space Telescope (nine using the brightest-stars method and two based on the tip of the red-giant branch). In their recent paper “Dwarf Galaxies in the NGC 1023 Group,” Trentham and Tully [15] present data on 70 galaxies in the group, 65 of which were studied using the MegaCam detector on the 3.6-m Canada-France-Hawaii Telescope (CFHT). The main galaxy in the group is the lenticular giant NGC 1023, whose distance is estimated to be from 9.86 Mpc [16] to 11.4 Mpc [25]. Its velocity of recession from the barycenter of the Local Group is 828 km/s [18], and its heliocentric velocity is 637 km/s [15]. Morphological types, Galactic coordinates and angular distances from the main galaxy are given for all the galaxies in [15]; (heliocentric) velocities are available for 25 galaxies, with all velocities lying within 1000 km/s.

We use the data from [15] to construct a heliocentric velocity–angular distance diagram for 27 galaxies in the NGC 1023 Group (Fig.1) which reproduces (in a modified form, see below) Fig.8 of [15]. Note that, as in [15, Fig. 8], our Fig.1 is not a Hubble diagram. A standard Hubble diagram is constructed using radial velocities and radial distances for the galaxies taken relative to the barycenter of the system. In contrast to this, the velocities in Fig.1 are heliocentric; the vertical axis plots the difference between the velocity of each galaxy and the velocity of the main galaxy in the group (637 km/s). A positive velocity in Fig.1 indicates motion toward (or away from) the center of the group, if the given galaxy is located closer to us (or further from us) than the main galaxy in the group. Correspondingly, a negative velocity indicates motion toward (or away from) the center of the given, if the galaxy is located further from us (or closer to us) than the main galaxy. The horizontal axis plots the distance of each galaxy from the main galaxy projected onto the plane of sky. In accordance with [15, 16], the distance of the main galaxy NGC 1023 from the Sun is taken to be 10 Mpc.

The two-component structure of the group is clearly seen in this diagram. The central component is comprised of 20 galaxies, including NGC 1023. Seventeen of these galaxies were taken from [15] and three from the studies [18, 19], which report the discovery of 12 new galaxies of the NGC 1023 group. Heliocentric velocities for three of the galaxies were measured on the 100-m Effelsberg radio telescope. The dwarf galaxies of the central component are concentrated around the main galaxy NGC 1023, and have both positive and negative velocities (or more precisely, velocity differences), from -200 to +300 km/s. The object DDO 22 = UGC 2014, which was considered a member of the central component in [15], is marked by a special symbol in our diagram (a circle with a bar). According to [16], its distance from the Sun is relatively large, 17 ± 2 Mpc, making it unlikely that it is indeed a member of the group. By analogy with the Local Group (see Section 2), we expect that the central component of the NGC 1023 group is gravitationally bound and quasistationary. As was proposed in [15], the dwarfs of the central component move along finite orbits within the massive and extended dark halo of the main galaxy.
With a velocity dispersion for the dwarfs of 140 km/s and a mean harmonic radius of 0.3 Mpc, a standard virial estimate yields for the mass of the central component $M = (6 \pm 3) \times 10^{12} M_\odot$ [15]. The luminosity of all 40 galaxies within a volume with a radius of 0.3 Mpc (not only the 16 included in [15, Fig. 8]) is $2 \times 10^{10} L_\odot$ [15], so that the mass-to-light ratio is approximately 300 in solar units. The dwarfs of the central subsystem considered in [15] are predominantly elliptical galaxies; the three dwarfs from [18, 19] are irregular galaxies.

The outer component in Fig.1 contains 10 galaxies with velocities from -100 to 0 km/s. Their distances from the central galaxy in Fig.1 are 0.4–1.4 Mpc. As was proposed in [15], these galaxies form a flow directed toward the center of the group, and their motion represents a first infall of these objects in the gravitational field of the central component. The mean flow direction is essentially parallel to the horizontal axis, and corresponds to a velocity of roughly -60 km/s. The galaxies in the flow have primarily late morphological types. The galaxy DDO 19 = UGC 1865 in the area of the flow is shown in our diagram by a circle with a bar; according to [16], its distance, 30 ± 3.6 Mpc, is too large to make it likely that it is a member of the group. The negative velocities (velocity differences) of the outer component indicate that these galaxies are falling toward the center of the group—but only if their distances from the Sun are greater than the distance to the main galaxy. This was explicitly assumed in [15], however no radial-distance data are presented in [15].

The question of the radial distances of the galaxies in the flow is of critical importance for our understanding of the real kinematics of the outer component of the NGC 1023 Group. The measurements of [16, 17] provide distances for six galaxies of the flow (including UGC 1865). The distance to DDO 25 = UGC 2023 is 7.7 ± 0.9 Mpc. Three other galaxies — NGC 959, NGC 925, and NGC 891 — have distances of 9.3 ± 1, 8.9 ± 0.25, and 9.82 ± 0.25 Mpc, respectively. If these four galaxies are indeed closer to the Sun than the main galaxy (recall that the distance to NGC 1023 has been estimated to be from 9.86 [16] to 11.4 Mpc [25]), they are not moving toward the center of the group, but instead away from the center. The fifth of the flow galaxies indicated above — NGC 949 — is located at a distance of 14.5 ± 1.7 Mpc, which probably exceeds the distance to NGC 1023. In this case, its negative velocity and relatively large radial distance indicates motion toward the center of the group.

How reliable are these six distances? The distances for two of the galaxies — NGC 891 and NGC 925 — are based on the tips of their red-giant branches [16, 17]; in this case, the accuracy of these measurement are good (appreciably better than 10%), and these distances should be quite reliable. The same method was used to measure the distance to the main galaxy of the group with the same accuracy and reliability (9.86 ± 0.25 Mpc) [16, 17]. The distances to the other galaxies of the flow were measured using the brightest-supergiant method. In this case, there are appreciably systematic uncertainties: the distances to the dwarf galaxies
depend substantially on whether they contain bursts of star formation [27]. This
circumstances remains an essentially unverifiable source of uncertainty. It follows
that there are actually only two reliable distances for the flow component of the
NGC 1023 Group, with both of these (see above) being close enough to the distance
of the main galaxy, so that, even with the high accuracy of these measurements, the
three distances are the same within the errors. Thus, we are not able to elucidate
with certainty where these two galaxies are located closer or further than the main
galaxy of the group. For this reason, the question of the direction of their motion
and the direction of the entire flow remains open.

4 The NGC 1023 Group: dynamical background

In an attempt to clarify the dynamical situation in the group, we will consider a
simple model for the system which enables us to estimate the gravitational and
anti-gravitational forces in the volume of the group. Following the general approach
adopted to study nearby galaxy groups (see Sections 1 and 2), we assume that the
NGC 1023 group (like the Local Group) is imbedded in a distribution of dark
energy, whose density is uniform in space and constant in time. We also assume
that the gravitational force in the group is due mainly to the mass of dark matter
in the spherical halo of its main galaxy, and that the dwarf galaxies of the group
can be treated approximately as test particles. The dynamics of the group can be
described using Newtonian mechanics; the relativistic properties of dark energy
and the anti-gravity it creates can adequately be formulated using the language
of classical forces and potentials. In this model, two forces act on each of the test
particles in the group: the gravity due to the central mass, and the anti-gravity
due to the dark-energy background. In a frame of the barycenter of the mass, the
gravitational force (per unit particle mass) is nearly exactly central, since the dark
halo of the main galaxy can be taken to be approximately spherical; this force is
given by the law of Newtonian gravitation,

\[ F_N = -\frac{GM}{R^2}, \quad (1) \]

where \( G \) is the gravitational constant, \( M \) the central mass, and \( R \) the distance
of the particle from the center of mass. In this frame, the anti-gravitational force
(which is exactly central) is determined by the density of dark-energy \( \rho_V \), and is
given (also per unit mass) by the “law of Einstein anti-gravitation:”

\[ F_E = G2\rho_V(4\pi/3)R^3/R^2 = (8\pi/3)G\rho_V R. \quad (2) \]

As we can see from (1) and (2), the gravitational and anti-gravitational forces
dominate at small and large distances, correspondingly. The forces are equal on
the absolute value at the distance
where the total acceleration of the particles vanishes. Gravity dominates when \( R < R_V \) and anti-gravity when \( R > R_V \). Adapting that the dark-energy density has the value \( \rho_V = 0.72 \times 10^{-29} \text{g/cm}^3 \), as measured in global cosmological observations [28]. The zero-gravity radius then

\[
R_V \simeq 1 \times (M/10^{12}M_\odot)^{1/3} \text{Mpc}. \tag{4}
\]

Substituting the mean virial mass for the central component of the group, \( M = 6 \times 10^{12}M_\odot \), we find that the critical value \( R_V \) for this system is 1.8 Mpc. Given the uncertainties (see above), the estimated mass is probably in the range \((3 - 9) \times 10^{12}M_\odot\), the zero-gravity radius is then \( R_V = 1.4 - 2.1 \text{ Mpc} \).

It follows from these estimates and the data on the distances (angular sizes) of the group components (see Fig.1) that the mean value of the critical radius, \( R_V = 1.6 \) Mpc, exceeds the distance to the galaxy flow; it means that both components of the group prove to be contained within the zero-gravity sphere. This condition is satisfied with a substantial margin for the highest mass estimate for the system. But even for the lowest mass estimate, the observed projected distance to the most distant part of the galaxy flow does not exceed \( R_V \). Thus, the outer component of the system is within the region where gravity dominates. This is the principle difference of the NGC 1023 Group from the Local Hubble Cell: in the NGC 1023 Group, both the central component and the flow are located inside the zero-gravity sphere, while, in the Local Hubble Cell, the central component (Local Group) and the flow are located on different sides of this spherical surface. The fact that gravity dominates in the outer component of the NGC 1023 Group does not mean that anti-gravity plays no role in the dynamics of this component. The dark-energy background reduces the effective gravitating mass, \( M_{\text{eff}} = M - (8\pi/3)\rho_V R^3 \), acting on the particles of the outer component. If, for example, we adopt for the mean virial mass \( M = 6 \times 10^{12}M_\odot \), the effective mass for a galaxy that is most distant (in terms of angular distance) from the center (a projected distance of \( R = 1.4 \text{ Mpc} \)) is roughly half the virial mass \( M \). If the virial mass corresponds to its lowest estimate, \( M = 3 \times 10^{12}M_\odot \) (see above), the effective mass is close to zero at the same distance.

It is most likely that the presence of the outer component in the NGC 1023 Group is a manifestation of ongoing formation of the group. This process proceeds in a non-linear regime, and is developing in the region where gravity dominates over anti-gravity. The anti-gravity is able to slow this process down, but not to stop it.

\[
R = R_V = \left( \frac{3M}{8\pi\rho_V} \right)^{1/3}, \tag{3}
\]
5 Conclusion

In the standard ΛCDM cosmological model, dark energy is described by Einstein cosmological constant. If this is the case, then dark energy should be present everywhere in space, and have a density that is constant in space and time. Applied to the nearby Universe, this means that the Local Hubble Cell and other similar systems of the spatial scales of 1–3 Mpc are imbedded in the uniform cosmological dark-energy background, and should be subject to its anti-gravitational force.

In the dynamics of the galaxy group, the antigravity of the dark energy is able to compete with the gravity due to the baryonic and dark matter of the galaxies. A gravitationally bound system is possible only if gravity is stronger than anti-gravity within its volume. The zero-gravity radius $R_V$ is a critical quantity: the volume of a quasi-stationary gravitationally bound virialized system cannot extend beyond a sphere with this critical radius. As has been elucidated [12–14, 16], the condition $R < R_V$ is satisfied in the Local Group of galaxies, while the surrounding Local Hubble flow is located in the region where antigravity dominates: the distance to the flow from the barycenter of the group exceeds the critical value ($R > R_V$). Where anti-gravity dominates, it tries to make particles recede from the central mass (and from each other) with acceleration. With time, a close to linear dependence of the velocity on distance is established in the flow (in a frame that is fixed to the group barycenter).

The NGC 1023 Group is very similar to the Local Group: its mass and size are close to those of the Local Group. However, details of the internal structure of the groups differ significantly: the Local Group is in a state close to virial equilibrium throughout all its volume, while only the central component of the NGC 1023 Group is close to this state. Virial equilibrium does not extend to the outer component of the NGC 1023 group, where about ten galaxies are contained. As was proposed in [15], the outer component represents a flow of galaxies directed toward the group center. However, we have shown (see Section 3) that this is not supported by all the available (rather sparse) data. However, whatever the direction of the galaxy velocities for this component, it is clearly not an “anti-Hubble” flow, since the outer component is located inside the sphere of the gravity domination (see Section 4). This last circumstance can serve as independent, although indirect, support for the suggestion of [15] that the outer component is falling into the center: since gravity dominates throughout the volume of the group, this direction of motion seems preferred.

Summarizing, we emphasize that the NGC 1023 group is in no way a counter-example to our model of the Hubble cell. The structure and dynamics of the group in does not contradict the model. The two-component NGC 1023 Group most likely represents the central, gravitationally bound region of a more or less standard Hubble cell. If this is the case, we may expect that there should be a flow of receding dwarf galaxies in the vicinity of the group. This receding flow
could be observed at distances (from the center of the group) exceeding the zero-gravity radius \( R > R_V \approx 1.4 - 2 \text{ Mpc} \), in the area where the anti-gravity due to the cosmic dark-energy background dominates. This hypothesis can be verified by searching for further galaxies in the vicinity of the group and accurately measuring their velocities and distances. This would be an interesting observational problem, directly related to the local dynamical effects of dark energy.

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REFERENCES

1. E. P. Hubble, The Realm of Nebulae (New Haven, 1936).
2. I. D. Karachentsev, Astron. J 129, 178 (2005).
3. I. D. Karachentsev, O. G. Kashibadze, D. I. Makarov, and R. B. Tully, Mon. Not. R. Astron. Soc. 393, 1265 (2009).
4. A. D. Chernin, I. D. Karachentsev, M. J. Valtonen, et al., Astron. Astrophys. 415, 19 (2004).
5. P. Teerikorpi, A. D. Chernin, and Yu. V. Baryshev, Astron. Astrophys. 440, 791 (2005).
6. P. Teerikorpi, A. D. Chernin, and Yu. V. Baryshev, Astron. Astrophys. 483, 383 (2006).
7. G. G. Byrd, A. D. Chernin, and M. J. Valtonen, Cosmology: Foundations and Frontiers (URRS, Moscow, 2007).
8. A. D. Chernin, I. D. Karachentsev, M. J. Valtonen, et al., Astron. Astrophys. 467, 933 (2007).
9. A. D. Chernin, P. Teerikorpi, and Yu.V. Baryshev, Adv. Space Res. 31, 459 (2003); arXiv: astro-ph/0012021 (2000).
10. A. D. Chernin, I. D. Karachentsev, D. I. Makarov, et al., Astron. Astrophys. Trans. 26, 275 (2007).
11. A. D. Chernin, I. D. Karachentsev, O. G. Kashibadze, et al., Astrofizika 50, 405 (2007).
12. A. D. Chernin, Usp. Fiz. Nauk 171, 1153 (2001) [Phys. Usp. 44, 1099 (2001)].
13. P. Teerikorpi,A. D. Chernin, I. D. Karachentsev, et al., Astron. Astrophys. 483, 383 (2008).
14. A. D. Chernin, Usp. Fiz. Nauk 178, 267 (2008) [Phys. Usp. 51, 253 (2008)].
15. N. Tretham and R. B. Tully, Mon. Not. R. Astron. Soc. 398, 722 (2009).
16. N. A. Tikhonov and O. A. Galazutdinova, Astrofizika 45, 311 (2002).
17. N. A. Tikhonov and O. A. Galazutdinova, Astrofizika 48, 261 (2005).
18. I. D. Karachentsev, V. E. Karachentseva, and W. K. Huchmeier, Pis’ma Astron. Zh. 33, 577 (2007) [Astron. Lett. 33, 512 (2007)].
19. W. K. Huchmeier, I. D. Karachentsev, and V. E. Karachentseva, Astron. Astrophys. 506, 677 (2009).
20. S. van den Bergh, Astron. J. 124, 782 (2002).
21. S. van den Bergh, Astrophys. J. Lett. 559, L113 (2001).
22. A. D. Chernin, P. Teerikorpi, M. J. Valtonen, et al., Astron. Astrophys. 507, 1271 (2009).
23. M. L. Humason, N. U. Mayall, and A. R. Sandage, Astron. J. 61, 97 (1956).
24. J. Materne, Astron. Astrophys. 33, 451 (1974).
25. R. B. Tully, Astrophys. J. 237, 390 (1980).
26. J. L. Tonry et al., Astrophys. J. 546, 681 (2000).
27. N. A. Tikhonov, private commun. (2010).
28. D. N. Spergel, R. Bean, O. Dore., et al., Astrophys. J. Suppl. Ser. 170, 377 (2007).

Figure caption

Velocity–distance diagram for 30 galaxies of the NGC 1023 Group based on the data of [15-18]. This is not a standard Hubble diagram: the velocities and distances have non-standard meanings. The velocity of each galaxy is the difference between its radial heliocentric velocity and the radial velocity of the main galaxy in the group (637 km/s). The distances shown are the projection of the distance of each galaxy from the main galaxy onto the plane of the sky; the line-of-sight distance from the Sun to the main galaxy is taken to be 10 Mpc. The solid lines show the boundaries of the central quasi-stationary component of the group (distances < 0.4 Mpc) and the outer component (from 0.5 to 1.4 Mpc), which is considered in [15] to be a flow directed toward the center of the group. The open circles denote galaxies from [15] for which CFHT MegaCam data are available, the pluses denote galaxies from [15] for which such data were not obtained, and the filled circles galaxies from [18]. The two galaxies shown as circles with bars most likely lie outside the group.
This figure "1023_fig1.jpg" is available in "jpg" format from:

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