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Local expansion flows of galaxies: quantifying acceleration effect of dark energy

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The nearest expansion flow of galaxies observed around the Local group is studied as an archetypical example of the newly discovered local expansion flows around groups and clusters of galaxies in the nearby Universe. The flow is accelerating due to the antigravity produced by the universal dark energy background. We introduce a new acceleration measure of the flow which is the dimensionless "acceleration parameter" $Q(x) = x - x^{-2}$ depending on the normalized distance x only. The parameter is zero at the zero-gravity distance $x = 1$, and $Q(x) \propto x$, when $x \gg 1$. At the distance $x = 3$, the parameter $Q = 2.9$. Since the expansion flows have a self-similar structure in normalized variables, we expect that the result is valid as well for all the other expansion flows around groups and clusters of galaxies on the spatial scales from ~ 1 to ~ 10 Mpc everywhere in the Universe.

Keywords: Groups of galaxies; Cosmic flows; Dark energy

1 Introduction

Expansion flows of galaxies are observed in a wide range of distances from ~ 1 Mpc to ~ 10 Gpc. On the spatial scales larger than the size (0.3–1 Gpc) of the cosmic cell of uniformity, the flow is considered global or cosmological. The global flow is accelerating, as discovered by Riess et al. (1998) and Perlmutter et al. (1999). The acceleration is produced by dark energy which dominates the global dynamics. The currently standard ΛCDM cosmology is based on these observational grounds and explains successfully the major physical properties of the Universe as a whole. On the other extreme of the spatial scales, an expansion flow of dwarf galaxies is observed (Karachentsev et al. 2009 and references therein) around the Local group at distances of 1–3 Mpc from the group center. This local outflow is accelerating and its dynamics is dominated by dark energy as well (Chernin et al. 2000; Chernin 2001, 2008). In the spatial volume of the flow, the antigravity produced by dark energy is stronger than the gravity produced by the dark and baryonic matter mass of the group. Similar local expansion flows are found around other nearby groups (Karachentsev et al.

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2005–2007; Chernin et al. 2007a,b,c) and also around the Virgo cluster and the Fornax cluster (Karachentsev & Nasonova 2010; Nasonova et al. 2011; Chernin et al. 2010, 2012). The cosmological model is not applicable to the local flows, and one needs a special non-uniform nonlinear model to describe them. A spherical model suggested by Chernin et al. (2000, 2006) reproduces correctly the major features of the observed local flows (see for review Chernin 2001, 2008).

In this note, we discuss the structure, dynamics and evolution of the local expansion flows in terms of the expansion rates and deceleration/acceleration parameters. We also clarify the similarity and difference between the local and global flows.

2 Global parameters

Traditionally, cosmology has been characterized as the "science of two numbers" (Hoyle & Sandage 1956): one of them is the Hubble factor, or the expansion rate $H(t) = \dot{a}/a$, and the other is the dimensionless deceleration parameter:

$$q(t) = -\frac{\ddot{a}a}{\dot{a}^2} = \frac{1}{2}(1 - \frac{3}{1 + \rho_{\rm M}/\rho_{\rm DE}}). \quad (1)$$

Here $a(t)$ is the cosmological scale factor, $\rho_{\rm M}(t) = \rho_{\rm M}(t_0)[a(t_0)/a(t)]^3$ is the density of non-relativistic matter (dark matter and baryons), $\rho_{\rm M}(t_0) = 0.28 \times 10^{-29}$ g/cm^3 is its present ($t_0 = 14.77$ Gyr) value; $\rho_{\rm DE} = 0.72 \times 10^{-29}$ g/cm^3 is the dark energy constant density; recent observational data (Hinshaw et al. 2012) are used here for the cosmic age and the densities. The cosmological acceleration is given by the Friedmann "equation of motion":

$$\ddot{a}(t) = -\frac{4\pi}{3}G[\rho_{\rm M}(t) - 2\rho_{\rm DE}]a(t). \quad (2)$$

The expansion velocity, $V(t) = \dot{a}$, comes from the first integral of Eq. (2):

$$E = \frac{1}{2}V^2 - \frac{4\pi}{3}G[\rho_{\rm M}(t) + \rho_{\rm DE}]a(t)^2, \quad (3)$$

which is the mechanical energy conservation law for the global expansion, and $E = const$ is the total mechanical energy per unit mass. According to recent observational data, energy E is zero to a good accuracy, and the expansion follows the parabolic trajectory (this is already taken into account in Eq. 1 above).

It is seen from Eq. (2) that the epoch of dark energy domination begins when $\rho_{\rm M}(t_0)[a(t_0)/a(t_{\rm ZG})]^3 - 2\rho_{\rm DE} = 0$. In accordance with the data above, the corresponding cosmic age $t_{\rm ZG} = 7$ Gyr, and the zero-gravity redshift

$$(1 + z_{\rm ZG}) = 1.7. \quad (4)$$

Equation (3) shows also that the global expansion evolves towards the de-Sitter regime,

$$\dot{a}(t) = H_{\rm DE}a(t), \quad a(t) \propto \exp(H_{\rm DE}t), \quad (5)$$

which is reached in the limit of infinite expansion, when cosmic time t goes to infinity; here

$$H_{\rm DE} = \left[\frac{8\pi}{3} G\rho_{\rm DE}\right]^{1/2} = 60 \ \ {\rm km/s/Mpc} \tag{6}$$

is a constant asymptotic expansion rate which depends on the dark energy density only.

We may introduce a dimensionless time-dependent expansion rate expressed in terms of cosmic densities and asymptotic rate:

$$h(t) = h_{60}(t) = H(t)/H_{\rm DE} = (1 + \rho_{\rm M}/\rho_{\rm DE})^{1/2}. \tag{7}$$

At present, $H_0 = 69$ km/s/Mpc (Hinshaw et al. 2012) and $h_0 = 1.15$. This indicates that the present cosmological expansion is not too far from the de Sitter asymptotic regime.

As for the deceleration parameter $q(t)$ of Eq. 1, it is positive for redshifts $z > z_{\rm ZG}$, zero at $z = z_{\rm ZG}$ and negative for $z < z_{\rm ZG}$ tending to $q_\infty = -1$ in the limit of infinite expansion. At the present epoch, the deceleration parameter $q_0 = -0.60$.

Together with the traditional deceleration parameter, a dimensionless acceleration parameter may be introduced:

$$Q(t) = \frac{\ddot{a}}{a(z_{\rm ZG} H_{\rm DE}^2)} = \frac{1 + z_{\rm ZG}}{1 + z} - \left(\frac{1 + z}{1 + z_{\rm ZG}}\right)^2. \tag{8}$$

The value is negative at $z > z_{\rm ZG}$ going to $-\infty$ when z goes to infinity and time goes to zero; it is zero at $z = z_{\rm ZG}$ and 1.35 at present ($z_0 = 0$); it goes to $+\infty$ when z goes to -1 and time goes to infinity.

The two dimensionless parameters, $h(t)$ and $Q(t)$, quantify completely the dynamical and evolutionary state of the global expansion flow at any moment of cosmic time.

3 Local acceleration measure

The local expansion flow nearest to us is a receding motion of two dozen dwarf galaxies around the Local group. It was observed by Karachentsev et al. (2009; see also references therein) with the Hubble Space Telescope (HST), 6-m Telescope of SAO RAS and other large instruments. All the galaxies move outwards from the group at distances from 1 to 3 Mpc from its center (Fig. 1). Their velocities increase with distances and follow roughly the linear velocity-distance relation (the Hubble law).

In a spherical model (Chernin et al. 2000, 2006; Chernin 2001, 2008), the observed flow of expansion around the Local Group is described as radial motions of "test particles" in the force field of the gravity produced by the matter mass M of the group and the antigravity produced by the dark energy background in which the group and the outflow are embedded. Following the standard cosmology (see above), we assume that the dark energy density $\rho_{\rm DE}$ is exactly the same in the volume of the flow as near the cosmic horizon where it was first measured.

In terms of General Relativity, the flow area can be described by the Köttler solution which represents a spherically-symmetrical spacetime (known also as the

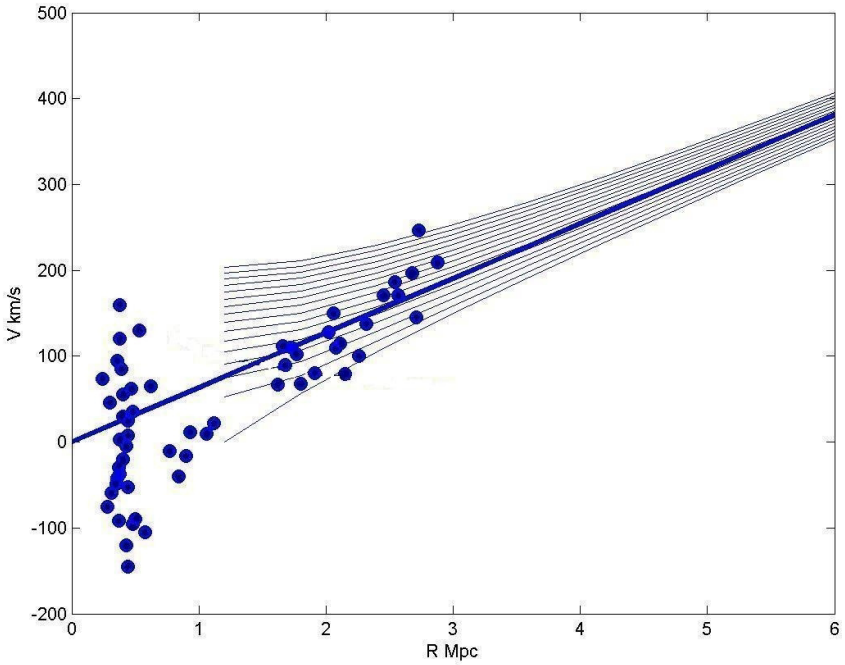


Figure 1 Velocity–distance diagram for the expansion flow around the Local Group (the HST and BTA data: Karachentsev et al. 2009). The zero-gravity distance $R_{\rm ZG}$ is 1.3 Mpc. The gravitationally bound group is at distances $R < R_{\rm ZG}$ where gravity dominates, the flow is at $R > R_{\rm ZG}$ where antigravity dominates. The phase trajectories of the flow are shown according to our model. The phase attractor is given by the bold line $V = H_{\rm DE}R$.

Schwarzschild–de Sitter spacetime) outside a spherical mass M within dark energy of constant density $\rho_{\rm DE}$. The force field may adequately be described in terms of Newtonian mechanics as well when the gravity/antigravity field is weak (in the sense that deviations from the Galilean metric are small). Then the GR solution is reduced (Chernin et al. 2006) to the Newtonian potential $U(R)$:

$$U(R) = -\frac{GM}{R} - \frac{4\pi G}{3}\rho_{\rm DE}R^2. \tag{9}$$

Here R is the radial distance of a given particle from the group center. Then the force (per unit mass) is the sum of the Newtonian gravity and the Einstein antigravity:

$$F(R) = -\frac{dU}{dR} = -\frac{GM}{R^2} + \frac{8\pi G}{3}\rho_{\rm DE}R. \tag{10}$$

At a distance

$$R = R_{\rm ZG} = \left(\frac{M}{\frac{8\pi}{3}\rho_{\rm DE}}\right)^{1/3} \tag{11}$$

the gravity and antigravity balance; it is the local spatial counterpart of the global zero-gravity redshift $z = z_{\rm DE}$. The gravitationally bound Local group is located within the zero-gravity sphere (Chernin 2001) of radius $R = R_{\rm ZG}$ where the gravity dominates. The flow moves in the area where $R > R_{\rm ZG}$ and the antigravity dominates (Chernin et al. 2000, 2006; Teerikorpi et al. 2008; Peirani & de Freitas Pacheco 2008; Teerikorpi & Chernin 2010).

The equation of motion for a test particle in the gravity/antigravity force field is $\ddot{R} = F$, where F is given by Eq. 10. Its first integral is

$$E = \frac{1}{2}V^2 - \frac{GM}{R} - \frac{4\pi G}{3}\rho_{\rm DE}R^2 + E, \tag{12}$$

where $V = \dot{R}$ is the velocity of the particle, $E = const$ is its total mechanical energy (per unit mass).

It is seen from this equation that the motions of the local flow tend asymptotically to the linear velocity–distance regime when $R \to \infty$:

$$V = \dot{R} = H_{\rm DE}R = \left(\frac{8\pi}{3}G\rho_{\rm DE}\right)^{1/2} R. \tag{13}$$

This is exactly the same de-Sitter asymptotic and the constant expansion rate $H_{\rm DE}$ as the global flow has at infinitely large time (Sec. 2).

Among various trajectories in the local flow, the parabolic trajectory with $E = 0$ exists which is a local counterpart to the global parabolic motion of Sec. 2. In the velocity–distance space, the local parabolic trajectory is described as

$$V(R)_{\rm par} = H_{\rm DE}\left[1 + 2\left(\frac{R_{\rm ZG}}{R}\right)^3\right]^{1/2} R. \tag{14}$$

For this trajectory, we may introduce the local deceleration parameter $q(R)$ defined similarly to the global parameter of Eq. (1):

$$q(R) = -\frac{\ddot{R}R}{\dot{R}^2} = \frac{1}{2}\left[1 - \frac{3}{1 + 2\left(\frac{R_{\rm ZG}}{R}\right)^3}\right]. \tag{15}$$

As is seen from here, $q(R) = 0$ at $R = R_{\rm ZG}$ and $q(R) \to -1$ when $R \to \infty$. (Recall that the global deceleration parameter $q(t)$ for the parabolic expansion (Eq. (7)) is zero at the zero-gravity moment and goes to -1 when cosmic time goes to infinity.)

Similar to Eq. (8), we may also introduce the acceleration parameter for the local flow:

$$Q(R) = \frac{\ddot{R}}{R_{\rm ZG}H_{\rm DE}^2} = \frac{R}{R_{\rm ZG}} - \left(\frac{R_{\rm ZG}}{R}\right)^2. \tag{16}$$

The acceleration as given by Eq. (10) does not depend on constant E, and parameter Q does not depend on E either. For each trajectory of the local flow, the parameter depends on the dimensionless distance $x = R/R_{\rm ZG}$ only. For distances

$x = 1, 1.5, 2, 2.5, 3$ we have from Eq. (16) $Q = 0, 1.1, 1.8, 2.3, 2.9$, respectively. For comparison, the global value at present is $Q = 1.35$ which is (predictably) equal to the value of the local parameter at the Einstein–Straus radius (see Teerikorpi et al. 2008) which is $R = R_{\rm ES} = (1 + z_{\rm ZG})R_{\rm ZG}$.

4 Concluding remarks

Expansion flows around groups and clusters of galaxies constitute a new class of cosmic motions accelerated by dark energy. Six objects of this class are well studied, and we expect that there may be many of them on the physical scales of groups ($\sim$1 Mpc) and clusters ($\sim$10 Mpc) everywhere in the Universe.

Three common features due to dark energy are characteristic of the expansion flows:

1. *Self-similarity.* The six expansion flows reveal self-similarity in their phase structure (Chernin et al. 2012) represented most obviously in the normalized variables $x = R/R_{\rm ZG}, y = V/(R_{\rm ZG}H_{\rm DE})$ introduced by Teerikorpi et al. (2008).

2. *Phase attractor.* The asymptotic state of each of the expansion flows is simply $y = x$, in the normalized coordinates. The line $y = x$ is the phase attractor for the

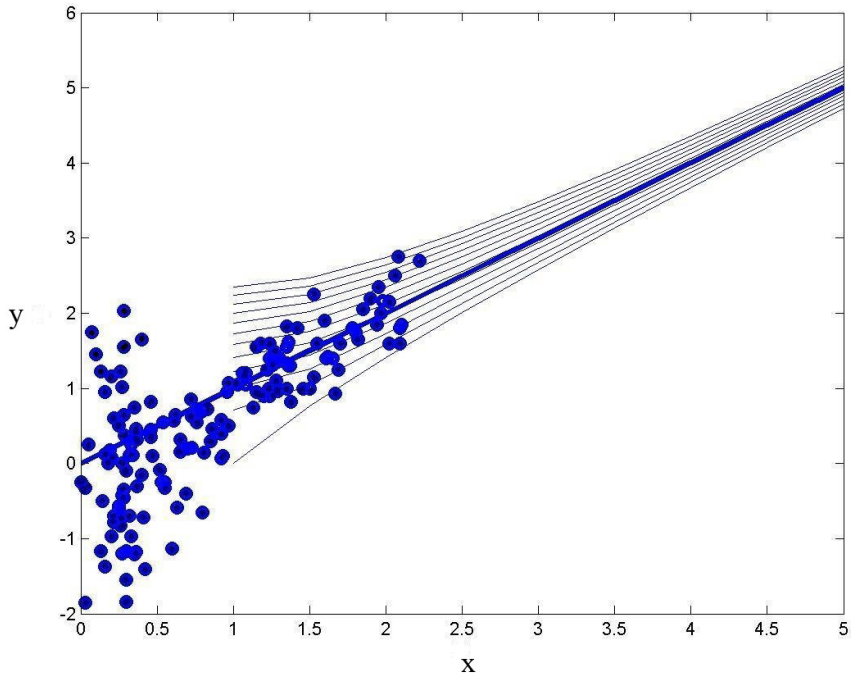


Figure 2 The synthetic velocity-distance diagram for four local flows (the HST and BTA data: Karachentsev 2002–2009). The horizontal axis is the normalized distance $x = R/R_{\rm ZG}$ and the vertical axis is the normalized velocity $y = V/(H_{\rm DE}R_{\rm ZG})$. The group area is at $x < 1$, the flow area is at $x > 1$. The phase attractor is the bold line $y = x$.

local flows (Chernin et al. 2012). It is illustrated by the synthetic phase diagram of Fig. 2 for nearby expansion flows.

3. *Acceleration parameter.* The dimensionless acceleration parameter $Q(x)$ introduced above as a function of the normalized distance x is an exact quantitative measure of the local dynamical effect of dark energy. For every flow, the parameter ranges from zero at the zero-gravity distance ($x = 1$) to 2.9 at $x = 3$ (which is typically the upper limit of the distances in the flows).

Note also that the local expansion flows look like spatial counterparts (depending on the distance x) of the global flow (depending on cosmic time t, or redshift z) considered at the present epoch of dark energy domination. In both cases, the acceleration parameter is zero at $R = R_{\rm ZG}$ and $z = z_{\rm ZG}$, respectively. Also in both cases, the dimensionless expansion rate $h \to 1$ with $t \to \infty$ and $R \to \infty$, correspondingly. The major difference between them is that $dh/dt > 0$ at $R > R_{\rm ZG}$ in the local flows, while $dh/dt < 0$ at $z < z_{\rm ZG}$ in the global flow.

Finally, one can calculate the local accelerations $\ddot{R}$ in usual units in terms of the deceleration parameter, the velocity, and the Hubble factor as follows: $\ddot{R} = QR_{\rm ZG}H_{\rm DE}^2 = -qH\dot{R} = -q\dfrac{H}{(10^{10}\,{\rm yr})^{-1}}\dfrac{\dot{R}}{100\,{\rm km/s}}10^{-3}\,\dfrac{{\rm cm\,s^{-1}}}{\rm yr}$. These expected accelerations in the nearby (a few Mpc) space are of tiny values (~ 0.001 cm/s/yr); it is out of the question to measure directly such variations of the radial velocities of dwarf galaxies. This effect is $\sim 10^3$ times smaller than the expected rate of redshift change for high ~ 1 redshift objects (Sandage 1962; Loeb 1998) which might have some chance of being detected by the future 42 m E-ELT telescope (Liske et al. 2008).

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