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Galaxy peculiar motions under a diffusive-stochastic regime

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ABSTRACT

Context. To investigate peculiar large scale motions under a diffusive-stochastic fluid description.
Aims. Our basic aims are to find the profile of the pairwise galaxy velocity distribution using the dynamical fluid equation and to constrain the profile with current observational data.
Methods. We rewrite the fluid equation for the galaxy fluid using a coarse-grained approach. Then, we solve the equation to find the theoretical velocity probability distribution. Next, we study the mode correlations in the Fourier space and find the profile to be compared with current observational data.
Results. The theoretical profile for the mode correlations is a Lorentzian, which is in good agreement with data. Also, our model allowed us to constrain, for the first time, the viscosity parameter of the cosmic fluid as $\sim$3.35 Mpc^2 Gyr^{-1}.
Conclusions. We find evidence that galaxy peculiar motions can be described as a fluid under a linear diffusive-stochastic regime at scales larger than $\sim 5\ h^{-1}$ Mpc.

Key words. cosmology: large-scale structure of Universe – hydrodynamics

1. Introduction

The galaxy motion has two components: the velocity due to the Hubble flow plus the velocity that describes the motion with respect to the background. This second component is known as peculiar velocity and corresponds to the difference between the predicted expansion velocity of a galaxy and its observed velocity: $\boldsymbol{v} = \boldsymbol{u} - \mathrm{H}\boldsymbol{r}$ (where H is the Hubble constant). Using comoving coordinates, $\boldsymbol{x} = \boldsymbol{r}/a$, and the conformal time, τ, we have the hydrodynamical equation for the cosmic fluid

$$\frac{\partial \boldsymbol{v}}{\partial \tau} + (\boldsymbol{v}\cdot\nabla)\boldsymbol{v} + \frac{\dot{a}}{a}\boldsymbol{v} + \frac{\nabla p}{\rho} + \nabla\phi = 0 \quad (1)$$

where ϕ is gravitational potential and a is the scale factor (see, for instance, Coles & Lucchin 1995).

On scales of $\sim 1\ h^{-1}$ Mpc, galaxy clustering is highly nonlinear and the peculiar field should be taken as an incoherent and random field. On the other hand, on scales larger than $\sim 5\ h^{-1}$ Mpc, the velocity field is irrotational and one can expect the linear perturbation theory to be a good guide to study the peculiar velocity field through a systematic comparison with observational data (e.g. Davis 1998). But most of information now available on peculiar velocities is indirectly obtained from extensive galaxy redshift surveys: LCRS (Las Campanas Redshift Survey), SDSS (Sloan Digital Sky Survey) and 2dF (2 degree Field). These surveys just probe the positions of galaxies in the redshift space, which are not necessarily the same in the physical space, since mass concentrations distort the structures in the redshift space (e.g. Kaiser 1986). As a result, measurements of the galaxy two-point correlation function are contaminated by such distortions and what we really measure is the redshift-space correlation function (Juszkiewicz et al. 2000).

Alternatively, one can study the anisotropies created by the peculiar velocities in the redshift-space correlation function (Peebles 1980). To do that, one should split the redshift-space correlation function in two dimensions, where the axes correspond to the directions parallel and perpendicular to the line-of-sight separation of a galaxy pair. The resultant correlation function is anisotropic since the peculiar velocities distort the correlation function along the line-of-sight. These anisotropies can be used to estimate the peculiar velocity dispersion of galaxies at different scales. Using this method, several works based on numerical data and survey analysis find that the paiwise galaxy peculiar velocity distribution has an approximated exponential with the pairwise velocity dispersion probably in the range $300 \lesssim \sigma_{12} \lesssim 500$ km s^{-1} (Davis & Peebles 1983; Marzke et al. 1995; Guzzo et al. 1997; Ratcliffe et al. 1998; Peacock 2001). Note that this approach only gets the second moment of the distribution and the exponential is just a fitting function. A more robust method extracts the Fourier transform of the velocity distribution from the Fourier transform of galaxy-galaxy correlation function in the redshift space using a deconvolution procedure. In this case, the method returns the entire distribution function, not only its dispersion (Landy et al. 1998). Applying this method to large surveys (LCRS, SDSS and 2dF), it was found that, in all cases, the velocity distribution is well characterized by an exponential or, equivalently, a Lorentzian in the Fourier space with width given by the pairwise velocity dispersion around 300 km s^{-1} (Landy 2002). Although the present knowledge indicates a Lorentzian for the pairwise velocity distribution function of galaxies, it is not simple to relate hydrodynamics to this result, through Eq. (1). In the next section, we show that such a profile is expected in hydrodynamical scenarios under a diffusive-stochastic regime.

2. The diffusive-stochastic regime

Structure formation in the universe can be described in the context of fluid dynamics. The usual approach is to perturb and linearize the hydrodynamics equations to follow the evolution of perturbations until the modes enter into the nonlinear regime. In this approach, let us to change the time variable from τ to b (the growing mode of the linear theory) and rescaling the peculiar velocity and the potential gravitational as

$$\boldsymbol{v} = \frac{\boldsymbol{u}}{a\dot{b}} = \frac{\mathrm{d}\boldsymbol{x}}{\mathrm{d}b} \quad \text{and} \quad \varphi = \left(\frac{3}{2}\Omega_0 \dot{a}^2 b\right)^{-1} \phi \tag{2}$$

so we can rewrite Eq. (1) as

$$\frac{\partial \boldsymbol{v}}{\partial b} + (\boldsymbol{v}\cdot\nabla)\boldsymbol{v} = \frac{3}{2}\frac{\Omega_0}{bf^2}\nabla(\theta-\varphi) + \nu\nabla^2\boldsymbol{v}. \tag{3}$$

where $f(t) = \mathrm{d}\ln b/\mathrm{d}\ln a$, $\Omega_0 = 8\pi G\rho_0/3H_0^2$ and we have neglected the thermal pressure, added an ad hoc diffusion term and taken the velocity field as the gradient of a velocity potential ($\boldsymbol{v} \equiv \nabla\theta$) as long as the motion is linear and streams of particles do not cross. Assuming that over the mildly nonlinear regime the gravitational potential is approximately equal to the velocity potential, we finally get

$$\frac{\partial \boldsymbol{v}}{\partial b} + (\boldsymbol{v}\cdot\nabla)\boldsymbol{v} = \nu\nabla^2\boldsymbol{v} \tag{4}$$

which is known as the adhesion approximation, that corresponds to a fluid under a nonlinear diffusion regime (Gurbatov et al. 1989). In the context of coarse-grained hydrodynamics, where galaxy clustering is taken into account as mesoscopic structures, it was recently shown how to physically introduce the diffusion term in the fluid equation (Ribeiro & Peixoto de Faria 2005). In this case, due to the granular kinetics, the dynamics is also driven by a noise term

$$\frac{\partial \boldsymbol{v}}{\partial b} + (\boldsymbol{v}\cdot\nabla)\boldsymbol{v} = \nu\nabla^2\boldsymbol{v} + \nabla\eta. \tag{5}$$

Now, let us rewrite the fluid equation as

$$\frac{\partial \boldsymbol{v}}{\partial b} = \lambda(\boldsymbol{v}\cdot\nabla)\boldsymbol{v} + \nu\nabla^2\boldsymbol{v} + \nabla\eta \tag{6}$$

where we have introduced the parameter λ to control the level of nonlinearity in the problem. In the case of very small λ (i.e. taking the fluid on scales larger than ~5 h^{-1} Mpc), we have the Edwards-Wilkinson (EW) equation

$$\frac{\partial \boldsymbol{v}}{\partial b} \approx \nu\nabla^2\boldsymbol{v} + \nabla\eta \tag{7}$$

which describes the diffusive-stochastic regime of the fluid, i.e., a linear diffusion driven by a noise term (Edwards & Wilkinson 1982).

3. Correlation function for the diffusive mode in the EW case

The EW equation (or the associated Fokker-Planck equation) has probability distribution for the wavenumber modes v_k given by

$$P(v_k, b) \propto \prod_k \exp\left[-\frac{\nu}{\Delta^G}\frac{1}{L}\frac{|v_k - v_k^0 \mathrm{e}^{-\nu k^2 b}|^2}{1-\mathrm{e}^{-2\nu k^2 b}}\right] \tag{8}$$

(see Edwards Wilkinson 1982), where v_k^0 is the initial value for $b = 0$, L is the length scale and we have assumed a Gaussian amplitude distribution for the noise term η

$$P(\eta) = \exp\left[-\frac{1}{2\Delta^G}\int \eta(xb)^2 \,\mathrm{d}x\,\mathrm{d}b\right] \tag{9}$$

with short-range correlations according to

$$\langle \eta, \eta' \rangle = \Delta^G \delta(x - x')\delta(t - t') \tag{10}$$

where Δ^G is the noise strength parameter (Fogedby 2005). Note that, for $b \to \infty$, $P(v_k, b)$ approaches the stationary Gaussian distribution

$$P_{\rm st}(v) \propto \exp\left[-\frac{\nu}{\Delta^G}\int v(x)^2 \,\mathrm{d}x\right]. \tag{11}$$

At the same time, mode correlations in the k-space have Lorentzian line shape characteristic of a conserved diffusive mode

$$\langle v, v' \rangle = \frac{\Delta^G}{\nu}\frac{\nu k^2}{\omega^2 + (\nu k^2)^2} \tag{12}$$

with hydrodynamical linewidth νk^2 vanishing in the long wave length limit. In terms of physical quantities, we can get the linewidth by making $\nu k^2 \to \sigma_{12}/L$. The slope of the correlation function for the diffusive mode should be compared to the Fourier transform of the galaxy pairwise velocity distribution function. Taking values of σ_{12} from several works (see Table 1), we obtain the mean value: $\bar{\sigma}_{12} = 359 \pm 10$ km s^{-1} (with $\chi^2 = 0.2492$); and a typical scale L of ~300 Mpc. Using these values in Eq. (12) we plot the behaviour of $\langle v, v' \rangle$ in Fig. 1. This figure should be compared with Fig. 1 of Landy (2002), which allows us to identify a good agreement between the correlations of the diffusive-stochastic regime with the galaxy pairwise velocity distribution in SDSS data. In addition, our model allow us to constrain the viscosity parameter for the cosmic fluid: $\nu = \bar{\sigma}_{12}h^{-1}L/4\pi^2 \approx 3.35$ Mpc^2 Gyr^{-1} (where we have assumed $k = 2\pi/L$ and $h = 0.7$).

Table 1. Pairwise peculiar velocity dispersion (km s^{-1}).

Survey	σ_{12}	$\Delta\sigma_{12}$	Reference
CfA1	340	40	Davis & Peebles (1983)
IRAS 1.2Jy	317	40	Fisher et al. (1994)
CfA2+SSRS	540	180	Marzke et al. (1995)
LCRS	452	60	Lin et al. (1995)
PPRS	345	95	Guzzo et al. (1997)
TNRS	326	67	Small et al. (1999)
Duhram/UKST GRS	416	36	Ratcliffe et al. (1998)
CfA2+SSRS	295	99	Marzke et al. (1995)
LCRS	363	44	Landy et al. (1998)
LCRS	570	80	Jing et al. (1998)
LCRS	510	70	Jing & Borner (2001)
2dF	331	19	Landy (2002)
SDSS	357	17	Landy (2002)

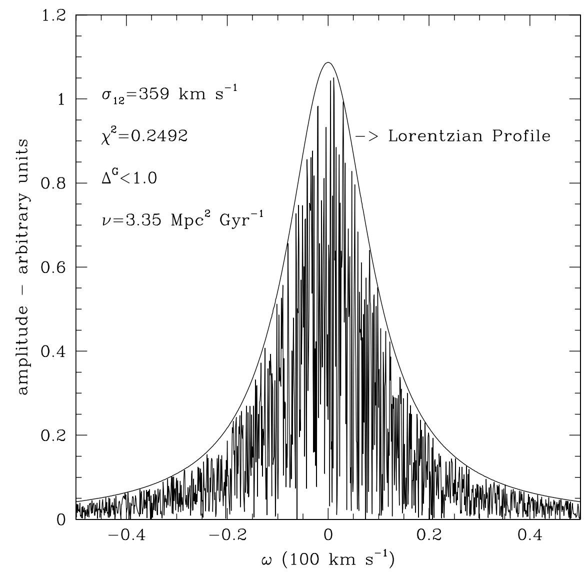

Fig. 1. Lorentzian envelope for the $\langle v, v' \rangle$ correlation with Gaussian strengh parameter $\Delta^G < 1$.

4. Discussion

In continuity of the work of Ribeiro & Peixoto de Faria (2005), we explore the possibility of describing the galaxy motions in the Universe as a cosmic fluid under a diffusive-stochastic regime. The idea is to assume the viscosity and noise terms as natural developments in the coarse-grained large scale description. The good correspondence between the diffusive-stochastic modes and galaxy pairwise velocity distribution functions (based on several redshift surveys) reinforces the idea of this regime as a good approximation to the cosmic fluid up to large scales. At the same time, an important missing point in the model is about neglecting the nonlinear term in Eq. (7). Although we should not expect intense nonlinear effects on scales larger than ~8 h^{-1} Mpc, it is important to verify this assumption according to the relative importance of the terms in the fluid equation. As an example, we write the observational expression for the peculiar velocity, $v = cz - H_0 d$, and define the large scale Reynolds number as $R_e = vd/\nu$, where d means the distance or the scale L. Using these definitions, we ran 500 Monte Carlo simulations of R_e for $300 < v < 600$ km s^{-1}. This range of peculiar velocity is representative of local galaxy motions. For instance, the Milk Way is infalling towards the Virgo cluster at ~300 km s^{-1}, while Virgo is infalling towards Hydra-Centaurus cluster at ~300 km s^{-1}, producing a resultant peculiar velocity of the local galaxy distribution of ~600 km s^{-1} towards Hydra-Centaurus. In Fig. 2, we show the behaviour of R_e for different values of ν. The Reynolds number is a measure of the relative importance between the nonlinear and the difusive terms. For the value of ν we found based on observational data, only at very small scales we have $R_e \gg 1$, giving support to our approximation on scales $\gtrsim 5$ h^{-1} Mpc. As an illustration, we also plot in this figure simulations for smaller values of ν. These points indicate that nonlinear effects could be expected on larger scales only for observationally unjustified small values of the viscosity term. Our conclusion is that, for the current available data, the diffusive-stochastic regime seems to be a good approximation and should drive the cosmic fluid at most scales of astrophysical interest. At smaller scales, nonlinearity gets importance and the fluid is probably driven by a noisy Burgers equation (Buchert et al. 1999). All this suggests a scenario where at different scales we have different dynamical descriptions for the cosmic fluid. A detailed analysis of specific solutions for the Edwards-Wilkinson to noisy-Burgers regime transition with appropriate boundary conditions will be presented in a forthcoming paper.

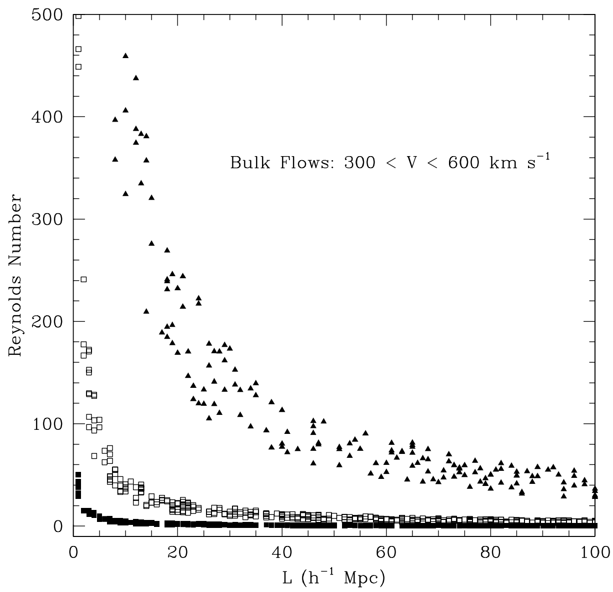

Fig. 2. Reynolds Number for 500 Monte Carlo realizations of Bulk Flows with $300 < v < 600$ km s^{-1}. Filled squares means $\nu = 3.35$; open squares means $\nu = 0.335$; and filled triangles means $\nu = 0.0335$ Mpc^2 Gyr^{-1}.

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