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AN ESTIMATE OF Ω_m WITHOUT CONVENTIONAL PRIORS

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ABSTRACT

Using mean relative peculiar velocity measurements for pairs of galaxies, we estimate the cosmological density parameter Ω_m and the amplitude of density fluctuations σ_8. Our results suggest that our statistic is a robust and reproducible measure of the mean pairwise velocity and thereby the Ω_m parameter. We get $\Omega_m = 0.30^{+0.17}_{-0.07}$ and $\sigma_8 = 1.13^{+0.22}_{-0.23}$. These estimates do not depend on prior assumptions on the adiabaticity of the initial density fluctuations, the ionization history, or the values of other cosmological parameters.

Subject headings: cosmological parameters — cosmology: observations — cosmology: theory — distance scale — galaxies: distances and redshifts — large-scale structure of universe

1. INTRODUCTION

In this Letter, we report the culmination of a program to study cosmic flows. In a series of recent papers, we introduced a new dynamical estimator of the Ω_m parameter, the dimensionless density of the nonrelativistic matter in the universe. We use the so-called streaming velocity, or the mean relative peculiar velocity for galaxy pairs, $v_{12}(r)$, where r is the pair separation (Peebles 1980, p. 170). It is measured directly from peculiar velocity surveys, without the noise-generating spatial differentiation, used in reconstruction schemes such as POTENT (see Courteau et al. 2000 and references therein). In the first paper of the series (Juszkiewicz, Springel, & Durrer 1999), we derived an equation relating $v_{12}(r)$ to Ω_m and the two-point correlation function of mass density fluctuations, $\xi(r)$. Then, we showed that v_{12} and Ω_m can be estimated from mock velocity surveys (Ferreira et al. 1999) and finally, from real data: the Mark III survey (Juszkiewicz et al. 2000). Whenever a new statistic is introduced, it is of particular importance that it passes the test of reproducibility. Our Mark III results pass these tests: the $v_{12}(r)$ measurements are independent of the galaxy morphology and the distance indicator.

In this Letter, we extend our analysis to three new surveys, with the aim of testing reproducibility on a larger sample and, in case of a positive outcome, improving on the accuracy of our earlier measurements of Ω_m and σ_8, the rms mass density contrast in a sphere of radius of 8 h^{-1} Mpc, where h is the usual Hubble parameter, H_0, expressed in units of 100 km s^{-1} Mpc^{-1}. In our notation, the symbol σ_8 always refers to matter density, while $\sigma_8^{\rm PSCz}$ refers to the number density of Point-Source Catalog Redshift (PSCz) survey galaxies.

Unlike our analysis, other estimators of cosmological parameters are often degenerate, hence σ_8 and Ω_m cannot be extracted without making additional Bayesian prior assumptions, which we call conventional priors: a particular choice of values for h, the baryon and vacuum densities, Ω_b and Ω_Λ, the character of the primeval inhomogeneities (adiabaticity, spectral slope, t/s ratio), the ionization history, etc. (Bridle et al. 2003). The estimates of Ω_m and σ_8 presented here *do not* depend on conventional priors. The only prior assumption that we make is that up to σ_8, the PSCz estimate of $\xi(r)$ describes the mass correlation function. We test this assumption by comparing the predicted $v_{12}(r)$ to direct observations. We also check how robust our approach is by replacing the PSCz estimate of $\xi(r)$ with an automatic plate measuring (APM) estimate and two other pure power-law toy models.

2. THE PAIRWISE MOTIONS AND GALAXY CLUSTERING

The approximate solution of the pair conservation equation derived by Juszkiewicz et al. (1999) is given by

$$v_{12}(r) = -\tfrac{2}{3}H_0 r\Omega_m^{0.6}\bar{\xi}(r)[1+\alpha\bar{\xi}(r)], \tag{1}$$

$$\bar{\xi}(r) = \frac{3\int_0^r \xi(x)x^2\,dx}{r^3[1+\xi(r)]}, \tag{2}$$

where $\alpha = 1.2 - 0.65\gamma$ and $\gamma = -(d\ln\xi/d\ln r)|_{\xi=1}$. As a model for $\xi(r)$, we use the Fourier transform of the PSCz power spectrum (Hamilton & Tegmark 2002, eq. [39]), which can be expressed as

$$\xi(r) = (\sigma_8/0.83)^2[(r/r_1)^{-\gamma_1} + (r/r_2)^{-\gamma_2}], \tag{3}$$

where $r_1 = 2.33\ h^{-1}$ Mpc, $r_2 = 3.51\ h^{-1}$ Mpc, $\gamma_1 = 1.72$, $\gamma_2 = 1.28$, and σ_8 is a free parameter. If the PSCz galaxies follow the mass distribution, then $\sigma_8 = \sigma_8^{\rm PSCz} = 0.83$. The quantities σ_8 and $\xi(r)$ describe nonlinear matter density fluctuations at redshift zero. The PSCz fit with $\sigma_8 = 0.83$ in equa-

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tion (3) is plotted in Figure 1, together with the APM correlation function measurements for comparison. For $r < 15\ h^{-1}$ Mpc, the APM correlation function is well approximated by equation (3) with $r_1 = 3.0\ h^{-1}$ Mpc, $r_2 = 2.5\ h^{-1}$ Mpc, $\gamma_1 = 1.9$, and $\gamma_2 = 1.1$. For $2\ h^{-1}$ Mpc $< r < 15\ h^{-1}$ Mpc, which is the range of separations of interest here, the PSCz and APM correlation functions in Figure 1 are almost indistinguishable. This provides an added reason to believe that choosing PSCz as a template for $\xi(r)$ was a good idea. To test the stability of our conclusions with respect to uncertainties regarding the small-r behavior of $\xi(r)$, we compare predictions for $v_{12}(r)$ based on PSCz parameters for equation (3) with those based on the APM survey. To study the sensitivity of $v_{12}(r)$ and inferred cosmological parameters to the assumed slope of $\xi(r)$, we also consider two simplified pure power-law toy models, given by

$$\xi(r) = (\sigma_8/0.83)^2 (r/r_0)^{-\gamma}, \tag{4}$$

where $\gamma = 1.3$ and 1.8, while $r_0 = 4.76$ and $4.6\ h^{-1}$ Mpc, respectively.

3. PECULIAR VELOCITY SURVEYS

We now describe our measurements. Each redshift distance survey provides galaxy positions, $\boldsymbol{r}_A$, and their radial peculiar velocities, $s_A = \boldsymbol{r}_A \cdot \boldsymbol{v}_A / r_A \equiv \hat{\boldsymbol{r}}_A \cdot \boldsymbol{v}_A$, rather than three-dimensional velocities $\boldsymbol{v}_A$. We use hats to denote unit vectors, while indices $A, B = 1, 2, \ldots$ count galaxies in the catalog. Consider a set of pairs (A, B) at fixed separation $r = |\boldsymbol{r}_{AB}|$, where $\boldsymbol{r}_{AB} \equiv \boldsymbol{r}_A - \boldsymbol{r}_B$. To relate the mean radial velocity difference of a given pair to $v_{12}(r)$, we have to take into account a trigonometric weighting factor,

$$\langle s_A - s_B \rangle = v_{12}(r) q_{AB,}$$
$$q_{AB} \equiv \hat{\boldsymbol{r}}_{AB} \cdot (\hat{\boldsymbol{r}}_A + \hat{\boldsymbol{r}}_B)/2 = -q_{BA.} \tag{5}$$

To estimate v_{12}, we minimize the quantity $\chi^2(v_{12}) = \sum_{A,B} [(s_A - s_B) - q_{AB} v_{12}(r)]^2$. The condition $\partial\chi^2/\partial v_{12} = 0$ implies

$$v_{12}(r) = \sum_{A,B} (s_A - s_B) q_{AB} \Big/ \sum_{A,B} q_{AB}^2. \tag{6}$$

In this study we use the following independent proper distance catalogs:

1. *Mark III*.—This survey (Willick et al. 1995, 1996, 1997) contains five different types of data files: Basic Observational and Catalog Data, Individual Galaxy Tully-Fisher (TF) and D_n-σ Distances, Grouped Spiral Galaxy TF Distances, and Elliptical Galaxy Distances as in the Mark II (for TF and D_n-σ methods, see Binney & Merrifield 1998, p. 394). The subset that we use here contains 2437 spiral galaxies with TF distance estimates. The total survey depth is over $120\ h^{-1}$ Mpc, with homogeneous sky coverage up to $30\ h^{-1}$ Mpc.

2. *Spiral Field I-Band (SFI)*.—This is an all-sky survey (da Costa et al. 1996; Giovanelli et al. 1998; Haynes et al. 1999a, 1999b), containing 1300 late-type spiral galaxies with *I*-band TF distance estimates. The SFI catalog, although sparser than Mark III in certain places, covers more uniformly the volume out to $70\ h^{-1}$ Mpc.

3. *Nearby Early-type Galaxies Survey (ENEAR)*.—This sample (da Costa et al. 2000) contains 1359 early-type elliptical galaxies brighter than $m_B = 14.5$ with D_n-σ measured distances. ENEAR is a uniform all-sky survey, probing a volume comparable to the SFI survey.

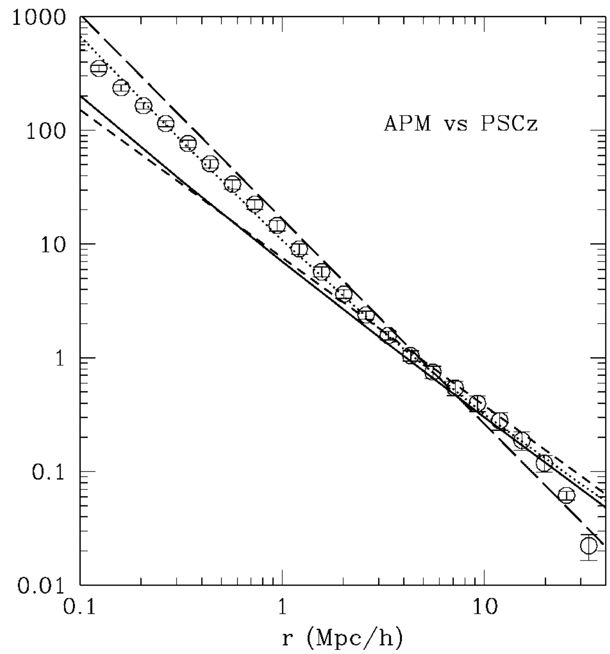

FIG. 1.—APM correlation function measurements (*circles with error bars*) compared to four closed-form expressions for $\xi(r)$: two power-law toy models with slopes $\gamma = 1.3$ (*short-dashed line*) and 1.8 (*long-dashed line*) and two more realistic, broken power-law empirical fits, given by eq. (3). The latter two represent the PSCz survey (*solid line*) and the APM survey (*dotted line*). All four expressions for $\xi(r)$ assume $\sigma_8 = 0.83$.

4. *Revised Flat Galaxy Catalog (RFGC)*.—This catalog (Karachentsev et al. 2000) provides a list of radial velocities, H I line widths, TF distances, and peculiar velocities of 1327 spiral galaxies that was compiled from observations of flat galaxies from FGC (Karachentsev, Karachentseva, & Parnovsky 1993) performed with the 305 m telescope at Arecibo (Giovanelli, Avera, & Karachentsev 1997). The observations are confined within the zone $0° < \delta \leq +38°$ accessible to the radio telescope.

4. RESULTS

Figure 2 shows our estimates of $v_{12}(r)$. Although the catalogs that we used are independent and distinct and survey very different galaxy and morphology types, as well as different volumes and geometries, our results are robust and consistent with each other. The error bars are the estimated 1 σ uncertainties in the measurement due to lognormal distance errors (around 15%), sparse sampling (shot noise), and finite volume of the sample (cosmic variance). For more details on error estimates used here, see Landy & Szalay (1992), Haynes et al. (1999a, 1999b), and Ferreira et al. (1999).

The agreement among the $v_{12}(r)$ estimates from different surveys, plotted in Figure 2, becomes even more impressive when compared to discrepancies between different estimates of a close cousin of our statistic, the pairwise velocity dispersion $\sigma_{12}(r)$. The velocity dispersion appears to be less sensitive to the value of Ω_m than to the presence of rare rich clusters in the catalog and to galaxy morphology, with estimates of σ_{12} at separations from 1 to a few megaparsecs varying from 300 to 800 km s^{-1} from one survey to another (Davis & Peebles 1983; Żurek et al.

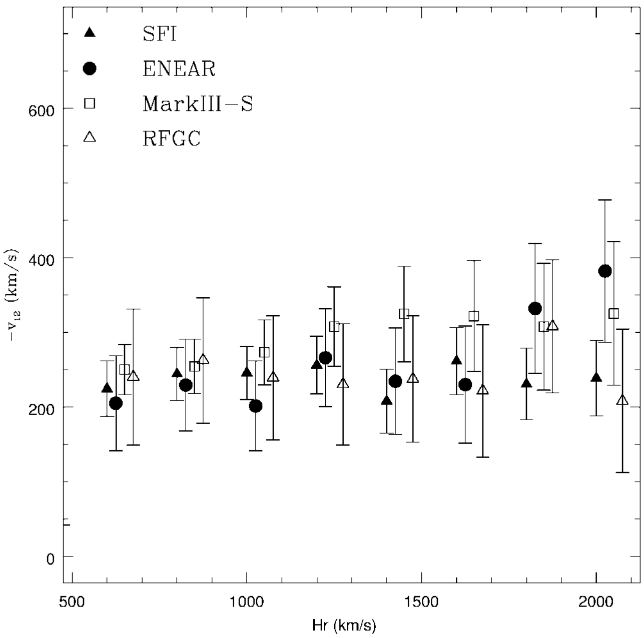

FIG. 2.—Pairwise velocities $v_{12}(r)$ for the four surveys. The Mark III-S $v_{12}(r)$ measurements come from our earlier work (Juszkiewicz et al. 2000). Clearly, the results from all surveys agree well with each other.

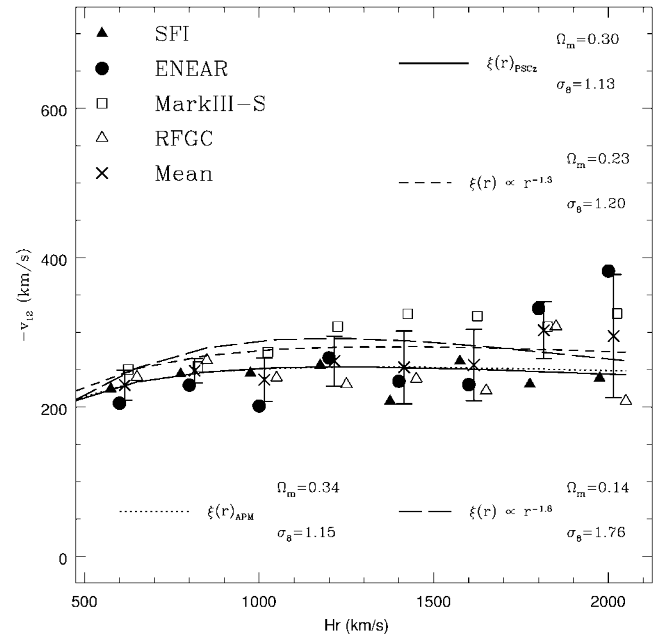

FIG. 3.—Crosses and the associated error bars show the weighted mean pairwise velocity, obtained by averaging over four surveys. Individual survey data points are also shown; we have suppressed their error bars for clarity. These direct measurements of v_{12} are compared to four $v_{12}(r)$ curves, derived by assuming four different models of $\xi(r)$, plotted in Fig. 1. The labels identify best-fit Ω_m and σ_8 parameters.

1994; Marzke et al. 1995; Zhao, Jing, & Börner 2002). The lack of systematic differences between $v_{12}(r)$ estimates in Figure 2 is incompatible with the linear biasing theory unless the relative elliptical-to-spiral bias, b_E/b_S, is close to unity at separations $r > 5\ h^{-1}$ Mpc, in agreement with our earlier studies (Juszkiewicz et al. 2000); for the same reason our results strongly disagree with recent semianalytic simulations (Sheth et al. 2001; Yoshikawa, Jing, & Börner 2003).

In Figure 3, we show the results for each of the catalogs that we investigated, as in Figure 2, but now we overlay the weighted mean of the individual catalogs. Since the results are robust, combining the catalogs reduces the errors and gives us a strong prediction for the parameter values. Figure 3 shows the results of our theoretical best fits: the solid (dotted) line follows the double power-law correlation function using the PSCz (APM) correlation function (eq. [3]). Clearly, the slope differences in $\xi(r)$ at small separations do not affect $v_{12}(r)$ in the range of separations that we consider. Moreover, given the error bars on v_{12}, the $\gamma = 1.3$ power-law toy model prediction for $v_{12}(r)$, as well as the resulting best-fit values of σ_8 and Ω_m, are similar to those based on the APM and PSCz correlation functions. For $\sigma_8 \approx 1$ and $\xi(r) \propto r^{-\gamma}$ at $r > 10\ h^{-1}$ Mpc, linear theory applies and $v_{12} \propto r^{1-\gamma}$. Therefore all three of the models considered above give $v_{12} \propto r^{-0.3}$, in good agreement with the observed nearly flat $v_{12}(r)$ curve. All of the above does not apply to our $\gamma = 1.8$ toy model, which is significantly steeper than the APM and PSCz $\xi(r)$ at large r, and for $\sigma_8 \approx 1$, the $v_{12}(r)$ is expected to drop almost by half between 10 and 20 h^{-1} Mpc. It is possible to flatten the $v_{12}(r)$ curve only by increasing σ_8 and extending the nonlinear regime to larger separations. The example considered here gives $\sigma_8 = 1.76$, in conflict with all other estimates of this parameter (see the discussion below). Correlation functions, steeper than APM or PSCz, often appear in semianalytic simulations, and this example shows how $v_{12}(r)$ measurements can be used to constrain those models.

In Figure 4, we plot the resulting 1, 2, 3, and 4 σ likelihood contours in the (Ω_m, σ_8)-plane. The quoted errors define the 1 σ or 68% statistical significance ranges in each of the two parameters and correspond to the innermost contour in Figure 4. The low χ^2 per degree of freedom is indicative of the correlations between $v_{12}(r)$ measurements at different separa-

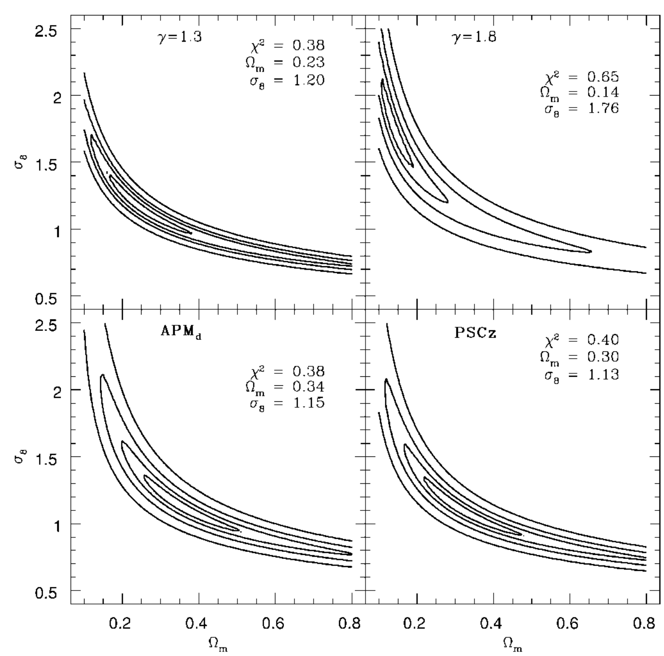

FIG. 4.—Results of the maximum likelihood analysis. The top panels show results for power-law toy models, while the bottom panels are based on realistic representations of observations: the APM and PSCz data, respectively. Likelihood peak coordinates and the values of χ^2 for each model are also indicated. The innermost contours define the 68% or 1 σ areas around the peaks. The remaining nested contours show the 2 σ, 3 σ, and 4 σ boundaries.

tions r. One of the sources of correlations is the finite depth of our surveys. Note also that since we are dealing with pairs of galaxies, the same galaxy can, in principle, influence all separation bins. The contours derived using the PSCz correlation function (eq. [3]) are shown in the bottom right panel. The best-fit values are

$$\Omega_m = 0.30^{+0.17}_{-0.07} \quad \text{and} \quad \sigma_8 = 1.13^{+0.22}_{-0.23}. \qquad (7)$$

The likelihood contours based on the APM correlation function (with best-fit values $\Omega_m = 0.34^{+0.16}_{-0.14}$ and $\sigma_8 = 1.15^{+0.15}_{-0.20}$) and the $\gamma = 1.3$ power-law model ($\Omega_m = 0.23^{+0.15}_{-0.06}$ and $\sigma_8 = 1.20^{+0.20}_{-0.25}$) are similar. Our estimate of σ_8 agrees with the results of studies of clustering of galaxy triplets in real and Fourier space in three different surveys: the APM (Gaztañaga 1995; Frieman & Gaztañaga 1999), the PSCz (Feldman et al. 2001), and the Two-Degree Field (Verde et al. 2002). A similar value of σ_8 was recently inferred from the observed position of the inflection point in the APM $\xi(r)$ (Gaztañaga & Juszkiewicz 2001). All of the above measurements are consistent with a σ_8 within 20% of unity. A σ_8 close to unity follows from maximum likelihood analysis of weak gravitational lensing (Van Waerbeke et al. 2002) after assuming $\Omega_\Lambda = 0.7$, $\Omega_m = 0.3$, and $h = 0.7$. Measurements of the abundance of clusters (Bahcall et al. 2003) tend to give σ_8 closer to the lower end of our 68% interval if $\Omega_m = 0.3$. The good agreement between these results, obtained with different methods, riddled with systematic errors of different nature, suggests that our estimates of statistical errors are reasonable and that the systematic errors are subdominant (unless there is an evil cosmic conspiracy of errors). The parameters in equation (7) also agree with those inferred from the power spectrum of the anisotropy of the cosmic microwave background (CMB) temperature distribution on the sky: $\sigma_8 = 0.9 \pm 0.1$ and $\Omega_m = 0.29 \pm 0.07$ (see Table 2 in Spergel et al. 2003). It is important to bear in mind, however, that unlike the CMB results, our estimates were obtained from the velocity and PSCz data alone, without the conventional priors. Therefore, the $v_{12}(r)$ measurements combined with the CMB or the supernova data can be used to break the cosmological parameter degeneracy. Choosing $\gamma = 1.8$, which is significantly steeper than the observed $\xi(r)$, gives $\Omega_m = 0.14^{+0.06}_{-0.04}$ and $\sigma_8 = 1.76^{+0.34}_{-0.26}$ (Fig. 4, *top right*), in conflict with all of the independent estimates of σ_8 discussed above. This suggests that the observed slope of the APM and PSCz correlation functions is close to the slope of the dark matter correlation function.

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