RECONSTRUCTING POSITIONS AND PECULIAR VELOCITIES OF GALAXY CLUSTERS WITHIN 25,000 KILOMETERS PER SECOND: THE BULK VELOCITY

ENZO BRANCHINI,1,2 MANOLIS PLIONIS,1,3 AND DENNIS W. SCIAMA1

Received 1995 September 5; accepted 1996 January 31

ABSTRACT

Using a dynamical three-dimensional reconstruction procedure, we estimate the peculiar velocities of \( R \geq 0 \) Abell/ACO galaxy clusters from their measured redshift within 25,000 km s\(^{-1}\). The reconstruction algorithm relies on the linear gravitational instability hypothesis, assumes linear biasing, and requires an input value of the cluster \( \beta \)-parameter (\( \beta = \Omega_0^c/b_\delta \)), which we estimated in Branchini & Plionis to be \( \beta \approx 0.21 \). The resulting cluster velocity field is dominated by a large-scale streaming motion along the Perseus-Pisces/Great Attractor baseline directed toward the Shapley concentration, in qualitative agreement with the galaxy velocity field on smaller scales. Fitting the predicted cluster peculiar velocities to a dipole term, in the Local Group frame and within a distance of \( \sim 18,000 \) km s\(^{-1}\), we recover extremely well both the Local Group velocity and direction, in disagreement with the Lauer & Postman observation. However, we find a \( \sim 5\% \) probability that their observed velocity field could be a realization of our corresponding one, if the latter is convolved with their large distance-dependent errors. Our predicted cluster bulk velocity amplitude agrees well with that deduced by the POTENT and the da Costa et al. analyses of observed galaxy motions at \( \sim 5000–6000 \) km s\(^{-1}\); it decreases thereafter, while, at the Lauer & Postman limiting depth (\( \sim 15,000 \) km s\(^{-1}\)), its amplitude is \( \sim 150 \) km s\(^{-1}\), in comfortable agreement with most cosmological models.

Subject headings: cosmology: theory — galaxies: clusters: general — galaxies: distances and redshifts — large-scale structure of universe

1. INTRODUCTION

There is strong observational evidence for the existence of coherent large-scale galaxy flows in the local universe, extending from the Perseus-Pisces region on the one side to the Hydra-Centaurus/Great Attractor region on the other and pointing within \( \leq 40^\circ \) of the cosmic microwave background (CMB) dipole direction (see reviews and references in Dekel 1994 and Strauss & Willick 1995). These results, together with the large-scale coherence of the cluster gravitational acceleration (Plionis & Valdarnini 1991; Plionis 1995), present a consistent picture in which the Local Group (hereafter LG) participates in a large-scale bulk motion induced by gravity, encompassing a volume of radius \( \sim 15,000 \) km s\(^{-1}\). This picture has recently been challenged by Lauer & Postman (1994, hereafter LP94), who have extended the cosmic flow studies to very large scales using the brightest cluster galaxies as standard candles. They find that the LG motion with respect to the frame defined by the Abell/ACO clusters within 15,000 km s\(^{-1}\) moves in a direction \( \sim 80^\circ \) away from that of the CMB dipole, which then implies that, if the CMB dipole is a Doppler effect, the whole cluster frame is moving with respect to the CMB rest frame with \( \sim 700 \) km s\(^{-1}\). Such a large velocity on such large scales is difficult to reconcile with galaxy bulk velocities on smaller scales, and with the current models of structure formation (cf. Strauss et al. 1995; Feldman & Watkins 1994). Furthermore, it is difficult to understand why the LG peculiar acceleration, estimated from the cluster dipole, is well aligned with the mass (CMB) dipole (see Branchini & Plionis 1996, hereafter BP96, and references therein), while the observed LG peculiar velocity (as estimated by LP94), with respect to the same sample of clusters, is not.

The main aim of this Letter is to predict the Abell/ACO cluster velocity field and bulk flow, within the gravitational instability and linear biasing framework, and compare it with determinations based on the observed peculiar velocities of galaxies and of the LP94 clusters (see also Scaramella 1995 for a complementary approach).

2. METHOD

We use the linear gravitational instability (hereafter GI) framework, linear biasing, and an iterative technique, similar to that of Yahil et al. (1991), to reconstruct the Abell/ACO real cluster positions within 25,000 km s\(^{-1}\), starting from their redshift space distribution, and thus obtain their peculiar velocity field. In the linear approximation, the peculiar velocity \( u \) at position \( r \) is proportional to the gravitational acceleration generated by the cluster distribution \( g \) at the same position, \( u(r) = \beta g(r) \), where \( \beta = \Omega_0^c/b_\delta \), \( \Omega_0 \) is the present value of the cosmological density parameter, and \( b_\delta \) is the usual linear bias parameter that relates the cluster and mass overdensities; \( \delta_c = b_\delta \delta_m \). Note that the large relative separations of galaxy clusters causes them to sparsely trace the underlying density field; it is, however, this fact that makes them ideal probes of the linear cosmic dynamics (cf. Bahcall, Gramman, & Cen 1994), although nonlinear effects could be present in high-density regions, i.e., up to scales of \( \sim 1000 \) km s\(^{-1}\) (cf. Croft & Efstathiou 1994).

Our technique is a two-step procedure whose complete description can be found in BP96; here we just recall the general idea. We first reconstruct the whole-sky redshift-space...
cluster distribution with $cz \leq 25,000$ km s$^{-1}$. This is done by Monte Carlo generating a population of synthetic objects outside the zone of avoidance (i.e., at $|b| > 20^\circ$) and within 20000 km s$^{-1}$, whose spatial distribution accounts for galactic absorption, the radial selection function, and density inhomogeneities between the Abell and ACO catalogs. Furthermore, the synthetic clusters are spatially correlated to the real ones according to the observed spatial cluster--cluster correlation function. The object distribution within the zone of avoidance (hereafter ZoA) is then recovered by randomly cloning the cluster distribution within redshift--Galactic longitude bins in the nearby latitude strips. A similar approach is adopted to reconstruct the whole-sky cluster density field within the (20,000, 25,000) km s$^{-1}$ shell, where, however, synthetic clusters are uncorrelated with the real ones (see BP96 for explanation). The second step consists of iteratively minimizing the redshift-space distortions, allowing for the recovery of the real space cluster positions and peculiar velocities. This procedure redshifts the peculiar cluster velocity fields (using a smoothing radius $R_{\mathrm{sm}}$), which we take to be $R_{\mathrm{sm}} \approx 80(\pm 60)$ km s$^{-1}$, nearly independent of the smoothing adopted. Similarly, the intrinsic uncertainty in the reconstruction procedure, $\sigma_I$, obtained as the scatter of the cluster velocities resulting from different Monte Carlo realizations of the same model), is $\sigma_I \approx 140(\pm 80)$ km s$^{-1}$.

Another source of uncertainty is the approximate nature of the ZoA model and the possible systematic effects related to its increase with distance. In BP96 we implemented various schemes for filling the ZoA and found that the error on the reconstructed cluster positions was smaller than the intrinsic one and, more importantly, the resulting cluster dipole was nearly unaffected, which implies the stability of the bulk velocity measurement.

The parameters that affect mostly the resulting velocity field are the input value of the $\beta_1$ parameter, which, however, does not bias the reconstruction procedure, and, to a lesser extent, the smoothing radius, $R_{\mathrm{sm}}$, which mainly affects the velocities in the high-density regions.

3. THE LOCAL GROUP VELOCITY WITH RESPECT TO THE CLUSTERS

Similar to LP94, we solve for the LG peculiar velocity with respect to the cluster frame, $\vec{u}_{LG}$, by minimizing

$$\chi^2 = \sum_{i=1}^{N} \left( \frac{(cz_i - \vec{d}_i) - \vec{u}_{LG} \cdot r_i}{\sigma_{T,i}} \right)^2,$$

where $d_i$ is the reconstructed three-dimensional cluster distance in the LG frame, $r_i$ the unit position vector, and $\sigma_{T,i}$ is the individual cluster total error computed by adding in quadrature $\sigma_r$, $\sigma_\theta$, and $\sigma_z = 300$ km s$^{-1}$, which represents the average uncertainty in $cz_i$. Note that the $\chi^2$ significance measure of the dipole fit is ill defined since the velocity errors are coupled. We have, however, investigated the stability of our solution to variations of the sample size (with greater than 50% reduction) and error-weighting and found that indeed it is very robust.

In Table 1 we present the solution of equation (1) for the $R_{\odot} = 10^3$ km s$^{-1}$ case and for three limiting radii of the volume used (similar results are obtained for $R_{\odot} = 2 \times 10^3$ km s$^{-1}$). It is important to note that, out to the limiting depth of the LP94 sample ($r_{\ell,p} \sim 15,000$ km s$^{-1}$), we find $\vec{u}_{LG}(r_{\ell,p}) \approx 510 \pm 100$ km s$^{-1}$, with a misalignment angle with respect to the CMB dipole apex of only $\delta \theta_{\odot \odot} = 5^\circ$, while its asymptotic value ($\approx 635 \pm 70$ km s$^{-1}$) is reached at $\approx 18,000$ km s$^{-1}$. This result, which assumes the GI hypothesis and agrees well with the observed CMB dipole, disagrees with the observed LG peculiar velocity, as measured by LP94, which has a similar amplitude but $\delta \theta_{\odot \odot} \approx 80^\circ$. This apparent discrepancy could be, among other things, due to the large distance-dependent uncertainties of the LP94 velocities; in other words, their velocity field could be a realization of an underlying field, represented by our reconstruction once convolved with the large distance-dependent errors ($\sigma \approx 0.16 r$). In fact, using Monte Carlo simulations, in which we replaced each of our cluster three-dimensional distances, $r_i$, with $(1 + \xi_i)r_i$ (where each $\xi_i$ is drawn from a Gaussian with zero mean and variance $\sigma = 0.16$), and then fitting $\vec{u}_{LG}$ (via eq. [1]) for the resulting velocity fields (using a $z^2$ weighting; see LP94), we have found that in ~60% of the cases the derived $\vec{u}_{LG}$ was within 1 $\sigma$ in amplitude and direction, of that of LP94 (more details in Plionis et al. 1996).

Figure 1 shows $|\vec{u}_{LG}|$, the solution of equation (1), computed within spheres of increasing radius, together with the analogous quantity, $|\vec{u}_{\odot\odot}|$, obtained from the gravitational acceleration induced by clusters (cluster dipole; see BP96) acting on the LG, after including a contribution of a ~170 km s$^{-1}$

![Fig. 1.—Comparison between the LG peculiar acceleration, $|\vec{u}_{\odot\odot}|$, as derived by the cluster dipole, and the LG peculiar velocity, $|\vec{u}_{LG}|$, derived from eq. (1) for the $R_{\odot} = 10^3$ km s$^{-1}$ case. Error bars are 1 $\sigma$.](image)
Virgocentric infall and for $\beta = 0.21$. There is a very good matching between the two quantities, while their misalignment with the CMB dipole direction is $\pm 12^\circ$ at the convergence depth. Although $\vec{u}_{\text{ACO}}$ and $\vec{u}_i$ are not independent measures of the dipole, since they derive from the same underlying density field, their good matching constitutes a nontrivial demanding test of our reconstruction procedure, which we pass with success.

4. THE CLUSTER VELOCITY FIELD AND BULK FLOW

In Figure 2 we present our derived cluster peculiar velocity field in a 8000 km s$^{-1}$ wide slice projected onto the supergalactic plane, where most prominent superclusters lie. The open and filled circles refer to inflowing and outflowing objects, respectively, while the length of each vector is equal to 3 times the line-of-sight component of the peculiar velocity in the CMB frame. The circle at the center represents the typical region spanned by dynamical analyses based on galaxy peculiar velocities. The most prominent feature is a large coherent motion in the general direction of the CMB dipole toward the Shapley concentration ($X, Y = (-13,000, +9000)$ km s$^{-1}$), which does not have, however, a constant amplitude; it is small in the Perseus-Pisces region ($X, Y = (+8,000, -4000)$ km s$^{-1}$), then rises in the Great Attractor region ($X, Y = (-4000, +500)$ km s$^{-1}$), while dropping on its backside (cf. Dressler & Faber 1990). Moreover, the bulk velocity rises again near the Shapley concentration, where a strong back infall is apparent.

We have measured the Abell/ACO cluster bulk velocity, which is defined as the center-of-mass velocity of a specified region and is given by the integral of the cluster peculiar velocities $\vec{u}(x)$ over a selected volume specified by a selection function $\psi(x)$,

$$V_{\text{bulk}}^3(r_{\text{max}}) = \int_0^{r_{\text{max}}} \psi(x)\vec{u}(x) \, dx.$$  \hspace{1cm} (2)

We can rewrite equation (2) for our discrete composite cluster sample as $V_{\text{bulk}}^3 = \sum W_i \vec{u}_i / \sum W_i$, where the sums extend over both real and synthetic objects, and $W_i$ is a weight that accounts for cluster masses and Abell/ACO sample differences. The discrete approximation need not be equal to that of equation (2) since it is a sum over the observed clusters that are inhomogeneously distributed. In our case, however, the difference is negligible since we have found consistent estimates of $V_{\text{bulk}}^3$ using the cluster peculiar velocities either at the positions of the clusters or on a regular grid with the grid size of 2000 km s$^{-1}$.

The cluster bulk velocity can be also defined as the residual velocity of the whole cluster frame. Therefore an alternative estimator of the bulk velocity, which utilizes only real clusters and only the line-of-sight component of their peculiar velocities, which was also used by LP94, is

$$V_{\text{bulk}}^3(r_{\text{max}}) = C - \vec{u}_{\text{ACO}}(r_{\text{max}}),$$  \hspace{1cm} (3)

where $C$ is the CMB dipole vector and $\vec{u}_{\text{ACO}}(r_{\text{max}})$ is given by equation (1). Note that our reconstruction procedure assumes that the mass fluctuations responsible for the cluster peculiar motions are contained within the sample considered, imposing the bulk flow to vanish beyond 25,000 km s$^{-1}$. Varying the limiting sample depth, we have verified that this constraint does not appreciably affect the bulk flow amplitude within 20,000 km s$^{-1}$.

In Table 2 we present the results of equation (3) as a function of sample limiting depth for the $R_{\text{max}} = 10^5$ km s$^{-1}$ case (these results do not appreciably depend on the smoothing adopted). Note that the bulk flow at $r_{\text{eff}}$ has an amplitude of $\sim 150$ km s$^{-1}$, in comfortable agreement with currently accepted cosmological models. In Figure 3 we plot both estimators $V_{\text{bulk}}^3$ and $V_{\text{bulk}}^3$ as filled circles and starred symbols, respectively, but now as a function of the effective depth ($r_{\text{eff}} \approx \frac{1}{2} r_{\text{max}}$). Note that for the $V_{\text{ID}}^3$ estimator we have used $r_{\text{max}} \approx 10,000$ km s$^{-1}$ in order to have sufficient data for the $\chi^2$ minimization to be stable. Although the two estimators are not independent, they are, however, based on a different set of clusters and velocities, and they provide a consistent estimate of the bulk velocity. We also plot as open circles the bulk velocity obtained by the POTENT reconstruction of the Mk III velocity field (Dekel 1994) and as starred symbols the recent da Costa et al. (1995) bulk velocity. At the region where both the galaxy and cluster bulk velocity estimates overlap (at $r_{\text{eff}} \sim 4000–6000$ km s$^{-1}$), the different bulk flow amplitudes appear to be in very good agreement with each other. Note that our bulk flow determination is mostly unaffected by the window “shrinkage” effect (Kaiser 1988), since the cluster

\begin{table}[h]
\centering
\caption{Residual Bulk Motion of Cluster Frame within Distance $r_{\text{max}}$}
\begin{tabular}{cccc}
\hline
$r_{\text{max}}/r_{\text{eff}}$ & $V_{\text{bulk}}^3$ (km s$^{-1}$) & $l$ & $b$ & $\delta \theta_{\text{max}}$ \\
\hline
100/75 & 305 & 297 & 31 & 18 \\
150/113 & 115 & 284 & 45 & 17 \\
\hline
\end{tabular}
\end{table}
selection function has a value \( \approx 1 \) up to \( \sim 20,000 \) km s\(^{-1}\) and does not suffer from the use of only line-of-sight peculiar velocities (Regös & Szalay 1989), since the \( V_{\text{3D}} \) estimator is based on the full three-dimensional velocity field.

5. CONCLUSIONS

An iterative reconstruction procedure, based on linear GI theory and linear biasing, has been used to derive the velocity field traced by Abell/ACO clusters within 25,000 km s\(^{-1}\). Our main results are as follows:

1. The predicted cluster velocity field, in the LG frame, is such that it reflects the whole LG motion with respect to the CMB, in apparent disagreement with the LP94 velocity data. Our derived LG velocity is well aligned with the CMB dipole, and it reaches its asymptotic value at \( \sim 18,000 \) km s\(^{-1}\), in agreement with the locally derived cluster dipole. We have found a small but nonnegligible probability (\( \sim 6\% \)) that the LP94 observed velocity field could be consistent with our predicted one, their apparent disagreement being possibly due to the convolution of the underlying velocity field with their large distance-dependent errors.

2. The main features of the observed velocity field probed by galaxies (cf. Strauss & Willick 1995) are also reproduced by our predicted cluster velocity field. There is an extension of our cluster bulk flow out to \( \sim 15,000 \) km s\(^{-1}\), where a back infall to the Shapley concentration is evident. The derived bulk flow velocity has an amplitude in very good agreement with that of POTENT and da Costa et al. (1995) at \( \sim 5000 \) km s\(^{-1}\); it decreases thereafter while pointing toward the CMB dipole direction. Our predicted bulk velocity at \( r_{\text{max}} \sim 10,000 \) and \( 15,000 \) km s\(^{-1}\) is \( \sim 300 \) and \( \sim 150 \) km s\(^{-1}\), respectively, consistent with most theories of structure formation.

We thank the referee, M. Strauss, for many useful comments and criticisms. We also thank F. Mardirossian and M. Mezzetti for discussions. M. P. acknowledges receipt of an EEC Human Capital and Mobility Fellowship. E. B. and D. W. S. are grateful to Ministero dell’Università e della Ricerca Scientifica e Tecnologica for financial support.

REFERENCES

Bahcall, N. A., Gramann, M., & Cen, R. 1994, ApJ, 436, 23
Branchini, E., & Plionis, M. 1996, ApJ, 460, 569 (BP96)
Croft, R. A. C., & Efstathiou, G. 1994, MNRAS, 268L, 23C
da Costa, L. N., et al. 1995, Proc. 25th Moriond Astrophysics Meeting on Clustering in the Universe, ed. C. Balkowski, S. Maurogordato, C. Tao, J. Ván Than Trán (Gif-sur-Yvette: Editions Frontières), in press
Dekel, A. 1994, ARA&A, 32, 99
Dressler, A., & Faber, S. M. 1990, ApJ, 354, 13
Feldman, H. A., & Watkins, R. 1994, ApJ, 430, L17
Kaiser, N. 1988, MNRAS, 239, 149
Lauer, T. R., & Postman, M. 1994, ApJ, 425, 418 (LP94)
Plionis, M. 1995, Proc. 25th Moriond Astrophysics Meeting on Clustering in the Universe, ed. C. Balkowski, S. Maurogordato, C. Tao, J. Ván Than Trán (Gif-sur-Yvette: Editions Frontières), in press
Plionis, M., et al. 1996, in preparation
Plionis, M., & Valdarnini, R. 1991, MNRAS, 249, 46
Regös, E., & Szalay, A. S. 1989, ApJ, 345, 627
Scaramella, R. 1995, Proc. 25th Moriond Astrophysics Meeting on Clustering in the Universe, ed. C. Balkowski, S. Maurogordato, C. Tao, J. Ván Than Trán (Gif-sur-Yvette: Editions Frontières), in press
Strauss, M. A., Cen, R., Ostriker, J. P., Lauer, T. R., & Postman, M. 1995, ApJ, 444, 507
Strauss, M. A., & Willick, J. A. 1995, Phys. Rep., 261, 271
Yahil, A., Strauss, M. A., Davis, M., & Huchra, J. P. 1991, ApJ, 372, 380

FIG. 3.—The cluster bulk velocity as estimated by the two methods described in the text (for \( R_{\text{sm}} = 10 \) h\(^{-1}\) Mpc), together with the galaxy-based POTENT and the da Costa et al. (1995) values; 1 \( \sigma \) error bars are plotted.