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Reconstructing the ZOA from Galaxy Peculiar Velocities

Saleem Zaroubi

Max-Planck-Institu für Astrophysik, Karl-Schwarzschild Str. 1, D-85741 Garching, Germany

Abstract. Galaxy peculiar velocity data provide important dynamical clues to the structures obscured by the Zone of Avoidance (hereafter, ZOA) with resolution $\gtrsim 500\,\mathrm{km\,s^{-1}}$. This indirect probe complements the very challenging approach of directly mapping of the distribution of galaxies behind the Milky Way. In this work, the Wiener filter method is applied to reconstruct the 3D density and velocity distributions of the universe, within $\lesssim 8000\,\mathrm{km\,s^{-1}}$, using SEcat the largest peculiar velocity catalog yet. This catalog is a combination of the SFI spiral galaxy peculiar velocity catalog and the newly completed nearby early-type galaxy peculiar velocity catalog, ENEAR. The recovered density is smoothed with $900\,\mathrm{km\,s^{-1}}$ Gaussian. The main reconstructed structures are consistent with those extracted from the IRAS 1.2-Jy redshift galaxy catalogs. The revealed structures within the ZOA are identified and their robustness and significance are discussed.

1. Introduction

Extinction due to the galactic plane obscures about 25% of the optically visible universe. In order to account for the Local Group motion relative to the Cosmic Microwave Background (CMB), the flow of galaxies in the Great-Attractor (hereafter, GA) area and other similar phenomena, the full distribution of matter, especially in the local universe, is essential. Direct measurement of the distribution of matter/galaxies requires extensive, tedious and dedicated observational programs in all the available electromagnetic wave-bands (see review by Kraan-Korteweg & Lahav 2000 and references therein).

However, a complementary approach for studying the universe behind the Milky Way is to use the available dynamical data, e.g., galaxy peculiar velocity catalogs, together with statistical reconstruction methods, e.g., Wiener filtering (WF), in order to uncover the mass density distribution, with resolution scale $\gtrsim 500\,\mathrm{km\,s^{-1}}$, hence, singling out the dynamically most significant structures.

Peculiar velocities of galaxies enable a direct and reliable measurement of the *underlying* mass distribution, under the natural assumption that galaxies are unbiased tracers of the large-scale, gravitationally induced, velocity field. Furthermore, since peculiar velocities are non-local and have contributions from different scales and different regions, analysis of the peculiar velocity field provides information on regions not covered by the data, e.g., the ZOA (Kolatt *et al.* 1995; Zaroubi *et al.* 1999), and on scales larger than the sampled regions (Hoffman *et al.* 2000).

Kolatt *et al.* (1995) were the first to attempt to reconstruct the ZOA from galaxy peculiar velocity data, where they used the POTENT method (Bertschinger & Dekel 1989; Dekel 1994) to reconstruct the mass-density distribution, within a sphere of radius $8000\,\mathrm{km\,s^{-1}}$, from the Mark III galaxy peculiar velocity catalog (Willick *et al.* 1997) with $1200\,\mathrm{km\,s^{-1}}$ resolution. Their study has resulted in predicting that the mass distribution of the Great Attractor peaks precisely at the center of the ZOA at a distance of $\approx 4500\,\mathrm{km\,s^{-1}}$. Zaroubi *et al.* (1999) have used the same peculiar velocity catalog to Wiener reconstruct the mass density distribution within $8000\,\mathrm{km\,s^{-1}}$ sphere. Their main conclusions were consistent with those of Kolatt *et al.* (1995).

The common use of WF is for straightforward noise suppression, but it can be easily generalized to achieve two further goals: to reconstruct the density field from the observed radial velocities and to interpolate or extrapolate the reconstruction to regions of poor sampling (for review, see Zaroubi *et al.* 1995 & Hoffman 2000). The later aspect is of special use for the reconstruction of the ZOA. In this work the WF is used to reconstruct the mass density distribution within $8000\,\mathrm{km\,s^{-1}}$ sphere from the largest galaxy peculiar velocity catalog yet. This catalog is a combination of the SFI and the ENEAR peculiar galaxy catalog.

The WF approach has been already applied to the IRAS two and three-dimensional galaxy distribution (Lahav *et al.* 1994), the IRAS three-dimensional redshift distortions (Fisher *et al.* 1995; Webster *et al.* 1997), the COBE/DMR cosmic microwave background mapping (Bunn *et al.* 1994), and to galaxy peculiar velocity catalogs of Mark III and ENEAR (Zaroubi *et al.* 1999; 2000a).

The outline of this paper is as follows. In § 2 we briefly describe the peculiar velocity data used in the present analysis. The method of Wiener reconstruction from peculiar velocity data is introduced in § 3, and the results of its application to the SEcat data set are presented in § 4. The paper concludes with a general discussion (§ 5).

2. The Data Sets

The ENEAR catalog have been extracted from the all-sky ENEAR redshift survey comprising about 1600 galaxies. Individual galaxy distances were estimated from a direct $D_n - \sigma$ template relation derived by combining all the available cluster data, corrected for incompleteness and associated diameter-bias. From the observed scatter of the template relation the estimated fractional error in the inferred distance of a galaxy is $\Delta \sim 0.19$, nearly independent of the velocity dispersion. An objective grouping procedure has been applied to the data in order to lower the inhomogeneous Malmquist bias before correction and to avoid strong non-linear effects (in particular large velocities of galaxies in clusters). The final catalog consists of about 750 objects.

The SFI catalog of peculiar velocities of galaxies (Giovanelli *et al.* 1999), contains about 1300 field spiral galaxies with Tully-Fisher distances. After the grouping procedure the final dataset consists of distances, radial peculiar velocities and errors for ≈ 1250 objects, ranging from individual field galaxies to rich clusters.

The combined catalog, SEcat, consists of ≈ 2000 objects, uniformly covering, apart from the ZOA region, the local universe up to distance of $\approx 6000\,\mathrm{km\,s^{-1}}$. The error in the distance of the objects measured with $D_n - \sigma$, namely objects from the ENEAR catalog, are assumed to have two contributions, the first is the usual $D_n - \sigma$ distance proportional errors. The second is a constant error of $250\,\mathrm{km\,s^{-1}}$ that accounts for the non-linear velocities of galaxies in the high density environment in which early-type galaxies preferentially reside.

The inferred distances are corrected for the homogeneous and inhomogeneous Malmquist bias (for details see Freudling *et al.* 1999; da Costa *et al.* 2000b). The latter was estimated using the PSCz density field (Branchini *et al.* 1999), corrected for the effects of peculiar velocities, using the expressions given by Willick *et al.* (1997). In this calculation, a correction for redshift limit of the sample is included.

Finally the results are compared with the mass-density reconstruction from the Mark III catalog (Willick *et al.* 1997). This catalog, consists of more than 3400 galaxies, has been compiled from several data sets of spirals and elliptical/S0 galaxies with distances inferred by the forward Tully-Fisher and $D_n - \sigma$ distance indicators. These data were re-calibrated and self-consistently put together as a homogeneous catalog for velocity analysis. The catalog provides radial velocities and inferred distances with errors on the order of $17 - 21\%$ of the distance per galaxy. After grouping, the catalog contains ≈ 1200 objects. The sampling covers the whole sky outside the ZOA, but with an anisotropic and non-uniform density that is a strong function of distance. The good sampling typically ranges out to $6000\,\mathrm{km\,s^{-1}}$ but it may be limited to only $4000\,\mathrm{km\,s^{-1}}$ in some directions or extend beyond $8000\,\mathrm{km\,s^{-1}}$ in other directions. The inhomogeniety of the Mark III sampling together with the complicated calibration proceedure employed to obtain the final catalog led many authors to question its reliability (e.g., Davis *et al.* 1996).

3. Wiener Filter

Here we limit the description of the WF to the actual application of the method to the case of radial velocity data. The data for the WF analysis are given as a set of observed radial peculiar velocities u_i^o sampled at positions $\mathbf{r}_i$ with estimated errors ϵ_i that are assumed to be uncorrelated. The peculiar velocities are assumed to be corrected for systematic errors such as Malmquist bias. The observed velocities are thus related to the true underlying velocity field $\mathbf{v}(\mathbf{r})$, or its radial component u_i at $\mathbf{r}_i$, via

$$u_i^o = \mathbf{v}(\mathbf{r}_i) \cdot \hat{\mathbf{r}}_i + \epsilon_i \equiv u_i + \epsilon_i. \tag{1}$$

We assume that the peculiar velocity field $\mathbf{v}(\mathbf{r})$ and the density fluctuation field $\delta(\mathbf{r})$ are related via linear gravitational-instability theory, $\delta = f(\Omega)^{-1}\boldsymbol{\nabla}\cdot\mathbf{v}$, where $f(\Omega) \approx \Omega^{0.6}$ and Ω is the mean universal density parameter. Under the assumption of a specific theoretical prior for the power spectrum $P(k)$ of the underlying density field, we can write the WF minimum-variance estimator of the fields as

$$\mathbf{v}^{\mathrm{WF}}(\mathbf{r}) = \left\langle \mathbf{v}(\mathbf{r}) u_i^o \right\rangle \left\langle u_i^o u_j^o \right\rangle^{-1} u_j^o \tag{2}$$

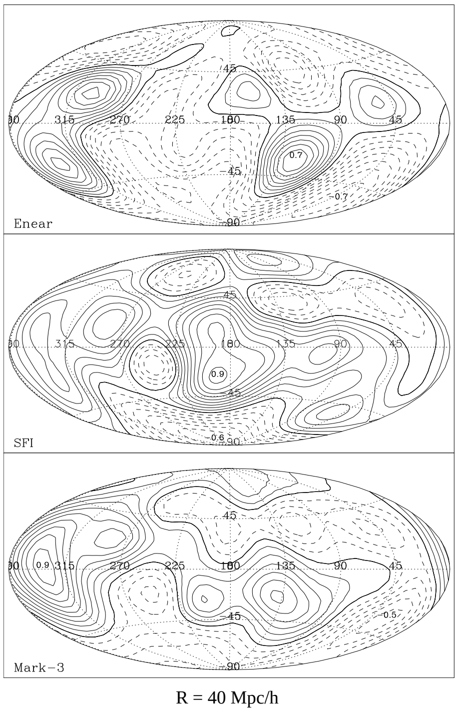

Figure 1. The reconstructed WF density fields from ENEAR (upper panel), SFI (middle panel) and MARK III (lower panel) catalogs shown on spherical shell at $4000\,\mathrm{km\,s^{-1}}$ distance. The Aitoff projection is shown in Galactic coordinates (l, b). Density contour spacing is 0.1, positive contours are solid, negative contours are dashed and $\delta = 0$ is denoted by heavy- sold line

and

$$\delta^{\rm WF}(\mathbf{r}) = \left\langle \delta(\mathbf{r}) u_i^o \right\rangle \left\langle u_i^o u_j^o \right\rangle^{-1} u_j^o. \tag{3}$$

In these equations $\left\langle ... \right\rangle$ denotes an ensemble average. The assumption that linear theory is valid on all scales enables us to estimate, given the power spectrum, the ensemble average quantities appearing in Eqs. (2) & (3) . The reader is referred to Zaroubi *et al.* (1999) for the explicit mathematical formulae used in the calculation. We choose to reconstruct the density field with a finite Gaussian smoothing of radius $900\,\mathrm{km\,s^{-1}}$.

4. Results

First we compare the density reconstruction from the Mark III, SFI and ENEAR catalogs. Figure 1 shows the reconstructed mass-density distribution for each catalog, smoothed with a $900\,\mathrm{km\,s^{-1}}$ Gaussian, on a spherical shell at $4000\,\mathrm{km\,s^{-1}}$ distance. The assumed power spectrum used in the reconstruction from Mark III, SFI & ENEAR has been determined through maximum

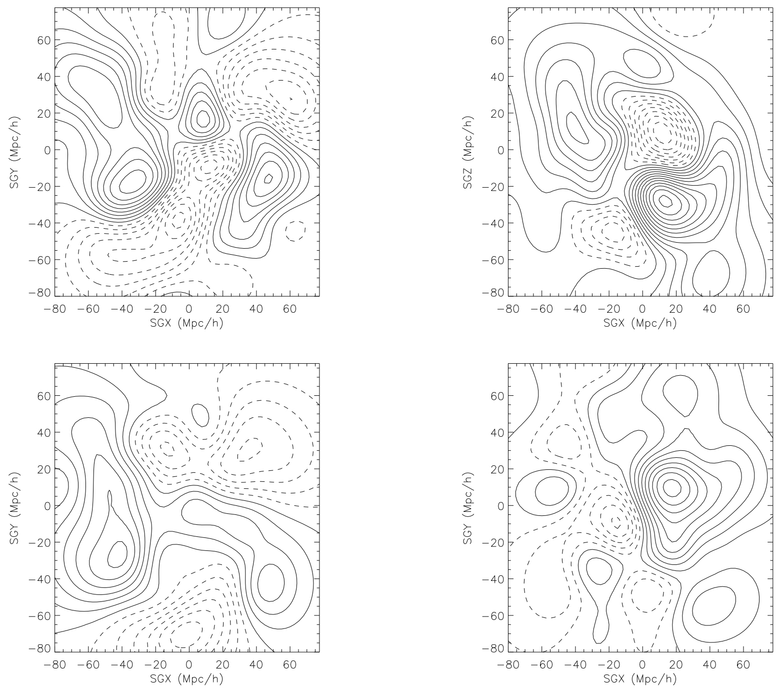

Figure 2. The WF reconstructed density maps from the SEcat catalog. Top left: The density field map in the Supergalactic (SGZ=0) plane, with $900\,\mathrm{km\,s^{-1}}$ Gaussian smoothing. Density contour spacing is 0.1, positive contours are solid, negative contours are dashed and $\delta = 0$ is denoted by heavy-solid line. Top right: the same as the previous panel but for the $SGY = 0$ plane , this plane mostly coincides with the ZOA. Bottom left: The same as before but for the SGZ= $4000\,\mathrm{km\,s^{-1}}$ plane. Bottom right: The same as before but for the SGZ= $-4000\,\mathrm{km\,s^{-1}}$ plane.

likelihood analysis by Zaroubi *et al.* (1997), Freudling *et al.* (1999) and Zaroubi *et al.* (2000a), respectively.

In the three maps the existence of the GA supercluster on the left and the Perseus-Pisces (P-P) supercluster to the right, $(l, b) \approx (135°, -30°)$ is evident. However, the ENEAR map, relative to the two others, shows a more localized GA and P-P. In fact, since the ENEAR catalog measures velocities of early-type galaxies preferentially residing in high density environments, this difference is expected. Conversely, smaller overdensities for the GA and P-P shown in the SFI density reconstruction map is due to the tendency of spiral galaxies to reside in the field. The insufficient sampling of the P-P supercluster in the Mark III catalog renders its recovered density smaller than that of the GA.

The big structure, centered at $(l, b) \approx (200°, -30°)$, appearing in the SFI density reconstruction and in the correspondent SEcat spherical shell (see Figure 3), does not have a counterpart in the ENEAR density map and has much lower density in the Mark III reconstruction. Comparison with the IRAS 1.2-

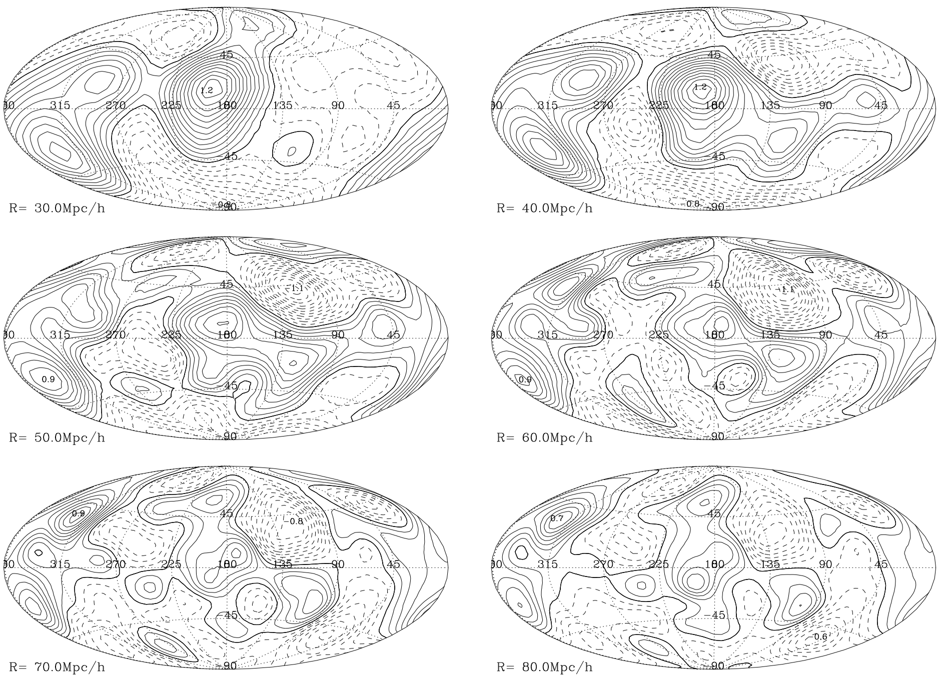

Figure 3. The WF reconstructed density maps from the SEcat catalog evaluated on thin shells at various real space distances, shown in Galactic Aitoff projections.

Jy redshift survey density reconstruction (Webster *et al.* 1997) shows that the peak location of this structure coincides with the position of the massive cluster N1600. The IRAS 1.2-Jy $4000\,\mathrm{km\,s^{-1}}$ shell further shows the existence of several other clusters, i.e., Cancer, Camelopardalis, $\mathbf{C}_\beta$, $\mathbf{C}_\gamma$, $\mathbf{C}_\delta$ and P-P that can account for this huge concentration seen extended from $l \approx 180° - 220°$ and centered around the ZOA.

Obviously, the ENEAR and SFI catalogs complement, therefore we combined them to one catalog, SEcat. Figure 2 shows the maps of the density field, recovered rfom the SEcat catalog, in 4 different slices using a Gaussian smoothing of $900\,\mathrm{km\,s^{-1}}$. In the Supergalactic plane slice (upper left) the main features of our local universe can be easily identified, including the GA and the P-P superclusters at the left and right parts of the map respectively; the Local supercluster appears at the center of the map. The SGY=0 slice (upper right) coincides roughly with the plane obscured by the ZOA. Another two slices are at SGZ= $\pm 4000\,\mathrm{km\,s^{-1}}$ are also shown.

Figure 3 shows the Aitoff projection of the WF SEcat reconstructed density in Galactic coordinates, evaluated across shells at various distances. The structures in these maps match closely those seen in similar reconstruction from the IRAS 1.2-Jy redshift catalog (Webster *et al.* 1997). The $4000\,\mathrm{km\,s^{-1}}$ shell has been discussed earlier, the other shells will be discussed in detail elsewhere (Zaroubi *et al.* 2000b) The velocity field along the Supergalactic plane is pre-

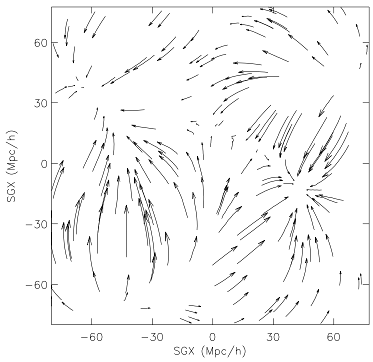

Figure 4. The SEcat reconstructed velocity field, with Gaussian smoothing of $900\,\mathrm{km\,s^{-1}}$ radius, in the Supergalactic plane is displayed as flow lines that start at random points, continue tangent to the local velocity field, and are of length proportional to the magnitude of the velocity at the starting point.

sented in Fig. 4, showing the existence of two convergence regions which roughly coincide with the locations of the GA and PP.

5. Discussion

In spite of the high level of extinction due to the galactic plane, galaxy peculiar velocities together with statistical reconstruction techniques, e.g., WF, present a very useful tool for mapping the ZOA. This approach complements the very challenging task of directly mapping the universe behind the Milky Way.

In this contribution we have showed that the WF method could indeed, within the resolution limit, faithfully reconstruct the nearby universe including regions masked by the Galactic plane. Several issues still need to be addressed as the details of the reconstructed maps can vary from catalog to catalog depending on the distance indicator, i.e., TF *vs.* $D_n - \sigma$ the sampling, noise properties and systematic differences, e.g., calibration.

In attempting to combine the ENEAR and SFI data-sets, one needs to ensure their consistency. Indeed various indications, e.g., calibration, zero point, measured bulk flow (da Costa *et al.* 2000a & 2000b) support the assumed compatibility of ENEAR and SFI, enabling their combination to one new catalog of spiral and elliptical galaxies, SEcat. These issues will be explored in detail in a forthcoming paper (Zaroubi *et al.* 2000b).

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