Density and Velocity Fields from the PSCz Survey

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Abstract.
We present the results for the predicted density and peculiar velocity fields and the dipole from the PSCz survey of 15,000 IRAS galaxies over 84% of the sky. We find a significant component to the dipole arising between 6000 and $15,000\,\mathrm{km\,s^{-1}}$, but no significant component from greater distances. The misalignment with the CMB is 20°. The most remarkable feature of the PSCz model velocity field is a coherent large-scale flow along the baseline connecting Perseus-Pisces, the Local Supercluster, Great Attractor and the Shapley Concentration. We have measured the parameter β using the amplitude of the dipole, bulk flow and point by point comparisons between the individual velocities of galaxies in the MarkIII and SFI datasets, and the large-scale clustering distortion in redshift space. All our results are consistent with $\beta = 0.6 \pm 0.1$.

1. Introduction

One of the motivations for the PSCz survey at its inception in 1992 was the huge effort going into peculiar velocity surveys; neither the QDOT nor the 1.2Jy surveys were deep and dense enough to provide a satisfactory model for the gravity field. Our goals were to (a) maximise sky coverage, and (b) to obtain the best possible completeness and flux uniformity within well-defined area and redshift ranges. The survey consists of 15,000 IRAS galaxies and its sky coverage is 84%. The median depth is just $8100\,\mathrm{km\,s^{-1}}$, although useful information is available out to $30,000\,\mathrm{km\,s^{-1}}$ at high latitudes and $15,000\,\mathrm{km\,s^{-1}}$ everywhere. A more detailed description of the survey specification is given in Saunders *et al.* (1999). The distribution of identified galaxies and the mask are shown in figure 1. The $N(z)$ distribution is shown in figure 2a. The selection function $\psi(r)$ (defined here as the expected density of galaxies seen in the survey as a function of distance in the absence of clustering) is derived using the methods

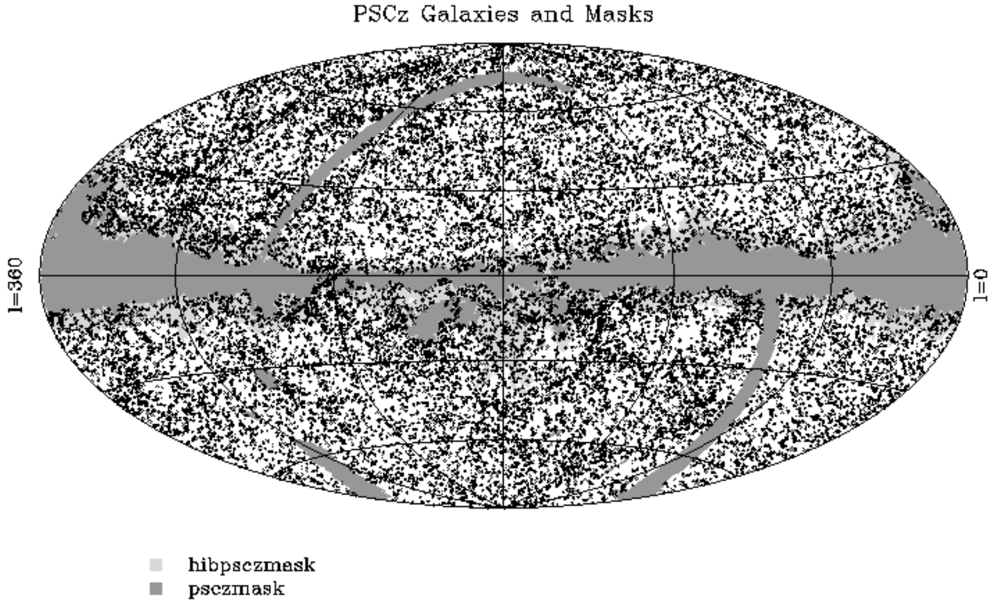


Figure 1. PSCz galaxy catalogue, mask and 'high$|b|$' mask in galactic coordinates.

of Mann *et al.* (1996) and shown in figure 2b. The uncertainties are less than 10% in the range $10 - 300\,h^{-1}$Mpc.

The knowledge of the selection function enables one to weigh galaxy properly and to construct the (redshift-space) density field. A 3D view of this is given in figure 3. Figure 4 shows the PSCz density field in the Supergalactic Plane after removing the effect of redshift space distortions. A variable smoothing length increasing linearly along the radial direction has been used. The continuous line shows the $\delta = 0$ contour (Branchini *et al.* 1999).

2. A New Method for Smoothing and Interpolating Galaxy Surveys

For dynamical tests where we wish to compare the observed distribution of galaxies with observed peculiar velocities, it is necessary to estimate the mass distribution within any masked area. Previous attempts have involved filling the mask with a uniform distribution, or crudely interpolating or cloning the density on either side. A better way was pioneered by Lahav *et al.* (1994), who introduced Wiener filtering to produce a minimum variance interpolation, given a prior estimate of the power spectrum and assuming linear theory.

It is even feasible to perform such studies far into the nonlinear clustering regime by assuming that the field can be reasonably described by lognormal statistics, which is indeed supported by several theoretical assessments. In this case, fitting the log of the density field as a Fourier sum will lead to random phases and Gaussian Fourier amplitudes. The mean field for the interpolation will be the mean density. Our approach is to find the set of harmonics maximis-

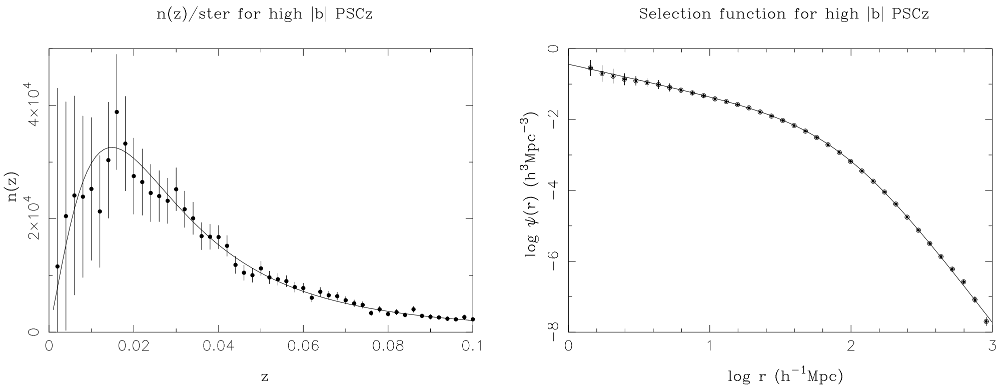


Figure 2a. $N(z)$ distribution for high latitude PSCz survey. Error bars are J_3-weighted. The line is the prediction from the selection function.
Figure 2b. Parametric and non-parametric selection functions for high latitude PSCz survey.

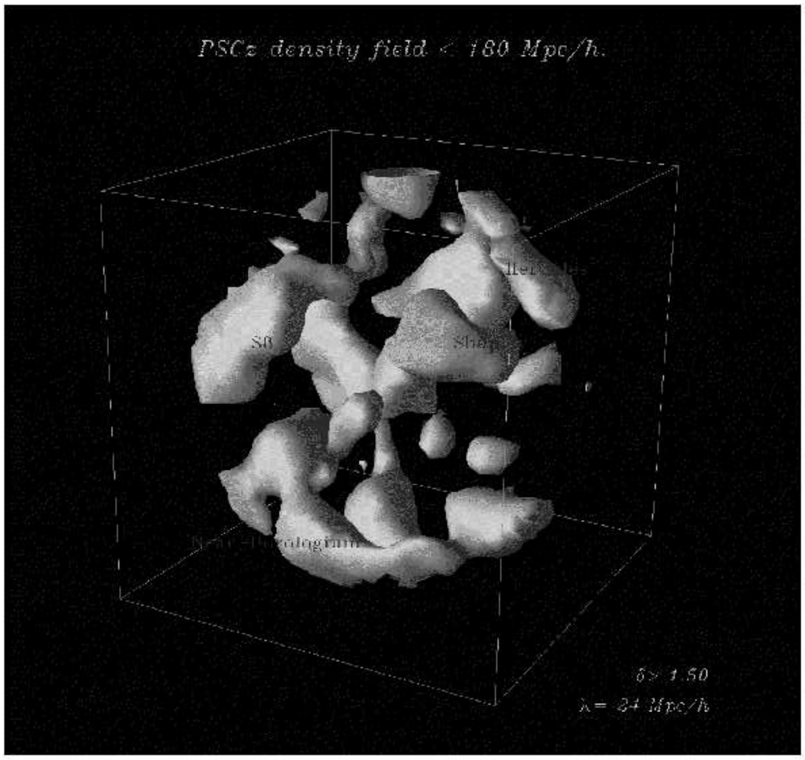


Figure 3. 3D density field of the PSCz in redshift space smoothed with a Gaussian filter of $6\,h^{-1}$Mpc; shown is a single isodensity contour at $\delta = 1.5$.

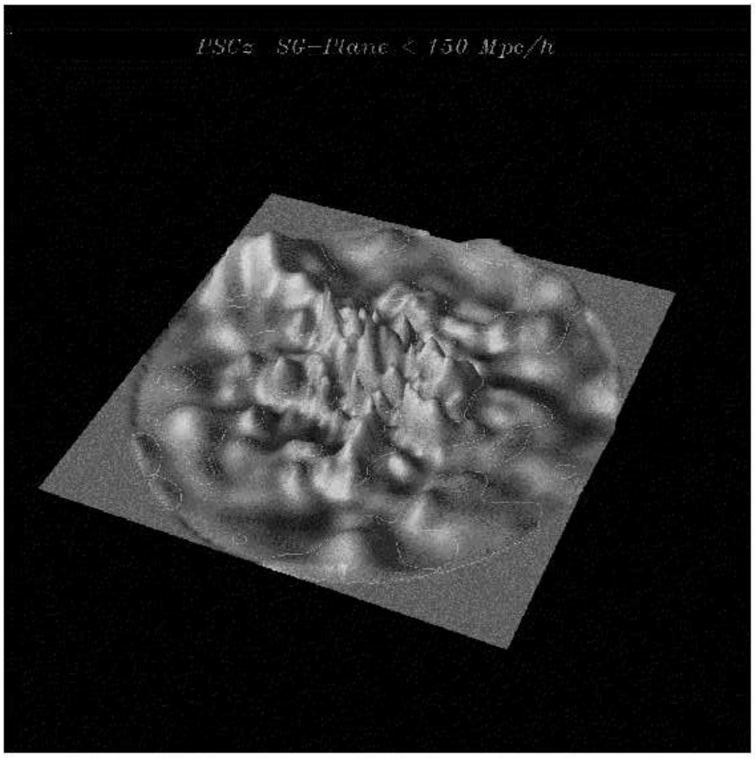


Figure 4. Real space density field of the PSCz in the Supergalactic Plane.

ing the probability that the galaxies, assumed to be Poisson-sampled from the density field, are at the positions actually observed. So we have a set of galaxies at positions $\mathbf{r}_m$, and a set of basis functions f_n, and a set of amplitudes a_n which we wish to determine. The amplitude of the underlying density field at $\mathbf{r}$ is

$$\rho(\mathbf{r}) = \exp \sum_n a_n f_n(\mathbf{r}) \tag{1}$$

and the likelihood for the whole survey as a function of $\{a_n\}$ is given by

$$\ln \mathcal{L}\{a_n\} = \ln \prod_m \rho(\mathbf{r}_m) = \sum_m \sum_n a_n f_n(\mathbf{r}_m). \tag{2}$$

The integral constraint that the total number of galaxies predicted by the density field equals the number actually observed is invoked via a Lagrange multiplier. This yields N equations

$$\sum_m f_n(\mathbf{r}_m) = \int_V f_n \psi(r) \exp[\sum_n a_n f_n(\mathbf{r}_m)], \tag{3}$$

which states that for each harmonic the sum over its value at each of the galaxy positions is equal to the integral over the continuous density field. The equations are non-linear whenever the density field itself is, and we solve them by using the multidimensional Newton-Raphson technique. We have used a spherical harmonic expansion, and we have transformed the radial coordinate of the survey so as to make the selection function unity, rendering the shot noise constant everywhere in the final maps. We have added a simple regularisation term to the likelihood. It is not mandatory for the radial and angular parts to be separable and we have used a 'tapered' mask in which the redshift out

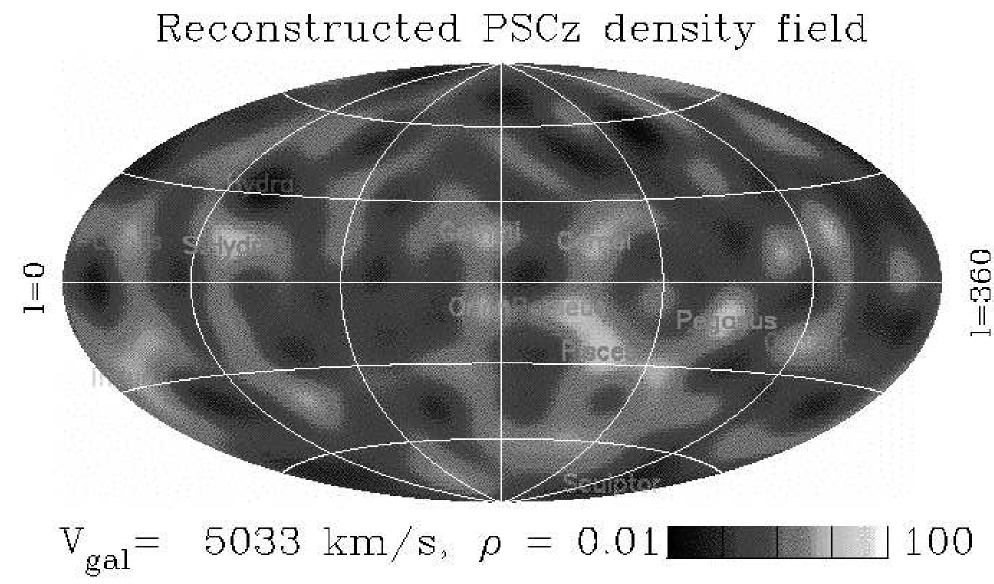


Figure 5. Galaxy density field at a redshift of 5000 km s^{-1} in galactic coordinates.

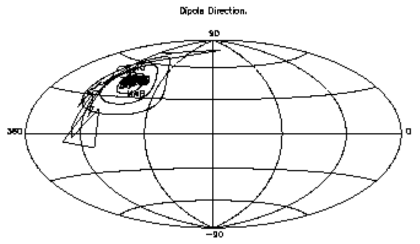
to which completeness is assumed is taken from the Saunders *et al.* (1999). The resulting 3-D density field is shown on the PSCz web page http://www-astro.physics.ox.ac.uk/~wjs/pscz.html. A single shell is shown in figure 5.

3. The PSCz dipole

The PSCz dipole has been investigated and presented by Rowan-Robinson *et al.* 1999 and Schmoldt *et al.* (1999a,b). We here present a somewhat different analysis: we have corrected for redshift space distortions according to Valentine *et al.* (1999) and used the interpolation described above. We have weighted the gravity dipole by $4\pi J_3\psi(r)/(1+4\pi J_3\psi(r))$, as in Strauss *et al.* (1992) (and we have assumed that $4\pi J_3 = 10000h^{-3}\mathrm{Mpc}^3$) to produce a minimum-variance cumulative dipole, given our knowledge of the power spectrum. The results are shown in figures 6a and 6b. The suppression amounts to a factor 1.1 at $100\,h^{-1}$Mpc, 2 at $180\,h^{-1}$Mpc and 10 at $300\,h^{-1}$Mpc. There is no evidence for any significant contribution to the dipole beyond 150 h^{-1}Mpc, and the angular convergence is spectacular. The misalignment with the CMB dipole is 20°.

4. Model Velocity Fields

We have applied several different methods to obtain a self consistent model for the density and velocity fields from the PSCz dataset. All methods assume gravitational instability and linear biasing, some are based on linear theory (Branchini *et al.* 1999 and Schmoldt *et al.* 1999b) some others on the Zel'dovich approximation (Valentine *et al.* and D'Mellow and Taylor, these proceedings), while others use the Least Action Principle (Sharpe *et al.* 1999, Nusser *et al.* 1999). Figure 7 shows the density and velocity fields in a slice along the



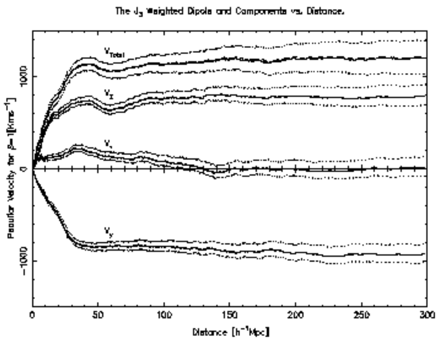


Figure 6a. Angular J_3-weighted cumulative dipole based on PIZA velocity reconstruction.
Figure 6b. The separate components and the combined magnitude. 1 σ shot noise error envelopes are shown.

Supergalactic Plane, reconstructed by Branchini *et al.* (1999). The dominant features in the velocity fields are the infall patterns towards the Great Attractor (-30,20), Perseus Pisces (50,-10), Cetus Wall (20,-50) and Coma (5,70). The most striking property, however, is the large scale coherence of the velocity field, apparent as a long ridge along the Perseus Pisces - Virgo - Great Attractor - Shapley Region baseline. The same general features are found using the other dynamical methods.

5. The Value of β

The comparison between measured peculiar velocities and our PSCz model gravity field allows one to measure the β parameters. Matching the amplitude of the PSCz and CMB dipoles yields a value for $\beta = 0.54 \pm 0.1$, consistent with similar comparisons by Schmoldt *et al.* (1999a,b) and with the likelihood analysis of Branchini *et al.* (1999) which also use the Mark III bulk flow, the PSCz predicted bulk flow and the local shear. Similar values are also found by Sharpe *et al.* (1999) by considering the dynamics of the PSCz galaxies in the Local Group's neighborhood, and by Tadros *et al.* (1999) from considering the large scale statistical distortion of the density field in redshift space.

An estimate of β to within 10% can be achieved by independent comparisons between observed and predicted galaxies' velocities. An analysis along these lines on the basis of the observed velocities of the SFI catalog is in progress.

6. Nonlinear Biasing

The dense sampling of PSCz galaxies and the volume of the sample are large enough to measure the biasing relation. Narayanan *et al.* and Sigad *et al.* (these proceedings) have presented two independent methods for measuring the biasing relation which they apply to the PSCz catalog. In both cases they detect deviations from the simple linear prescriptions which are well described by semi-analytic model for galaxy formation (Kauffman *et al.* 1999, Benson *et al.* 1999).

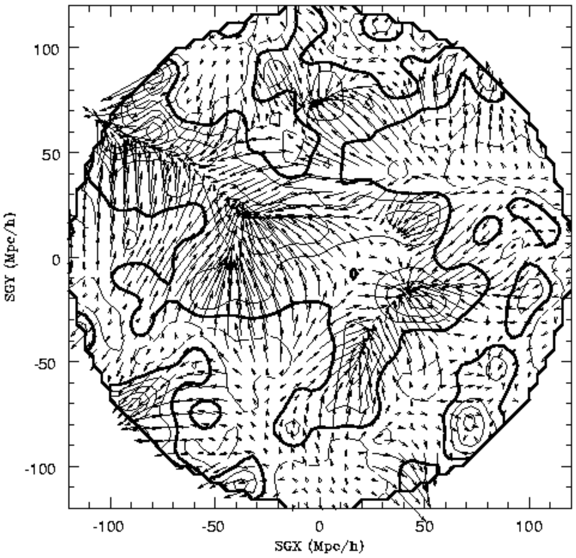


Figure 7 Real space overdensity and velocity field smoothed with a 6 h^{-1}Mpc filter. The thick line shows the $\delta = 0$ contour. Positive (continuous) and negative (dashed) contours are plotted at steps of $\Delta\delta = 0.5$

Figure 8 shows the mean biasing relation for PSCz galaxies obtained by Sigad *et al.* . It is compared with semi-analytic predictions from Kauffman*et al.* (1999) in two different cosmological models.

7. Acknowledgements

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8. Data access

Long and short versions of the catalogue, maskfiles, notes, and an expanded version of this paper, will shortly be available via the PSCz web site (http://www-astro.physics.ox.ac.uk/~wjs/pscz.html).

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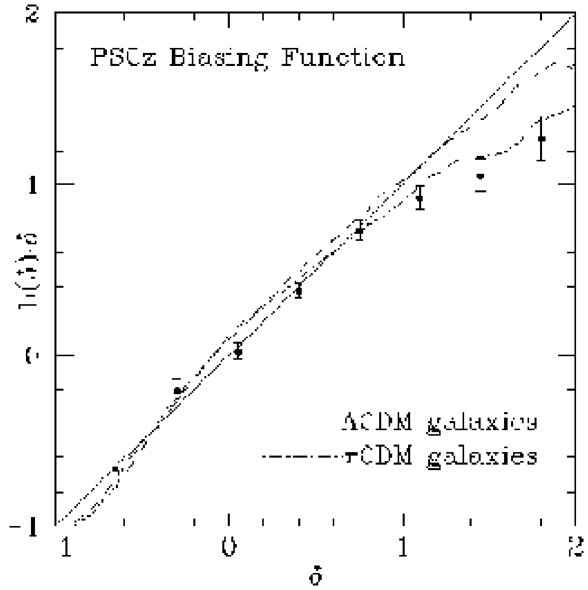

Figure 8. Biasing function for PSCz galaxies (dots). Errorbars represent 1σ bootstrap errors. Predictions from semi-analytic models are displayed for a flat CDM universe with $\Lambda = 0.7$ and (dashed line) and for a τCDM universe (dot-dashed).

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