Cosmicflows-3: Cold Spot Repeller?

Hélène M. Courtois1, R. Brent Tully2, Yehuda Hoffman3, Daniel Pomarède4, Romain Graziani1, and Alexandra Dupuy1

1 University of Lyon, UCB Lyon 1, CNRS/IN2P3, IPN, Lyon, France
2 Institute for Astronomy, University of Hawaii, 2680 Woodlawn Drive, Honolulu, HI 96822, USA
3 Racah Institute of Physics, Hebrew University, Jerusalem, 91904, Israel
4 Institut de Recherche sur les Lois Fondamentales de l’Univers, CEA, Université Paris-Saclay, F-91191 Gif-sur-Yvette, France

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Abstract

The three-dimensional gravitational velocity field within \( z \sim 0.1 \) has been modeled with the Wiener filter methodology applied to the Cosmicflows-3 compilation of galaxy distances. The dominant features are a basin of attraction and two basins of repulsion. The major basin of attraction is an extension of the Shapley concentration of galaxies. One basin of repulsion, the Dipole Repeller, is located near the anti-apex of the cosmic microwave background dipole. The other basin of repulsion is in the proximate direction toward the “Cold Spot” irregularity in the cosmic microwave background. It has been speculated that a vast void might contribute to the amplitude of the Cold Spot from the integrated Sachs–Wolfe effect.

Key words: galaxies: distances and redshifts – large-scale structure of universe

Supporting material: interactive figure

1. Introduction

All-sky maps of the structure in the universe are increasingly extensive. Here, we use the Cosmicflows-3 (CF3) collection of 18,000 galaxy distances (Tully et al. 2016) to study velocities that depart from the Hubble expansion on a scale of 0.1c. The data assembly builds on the 8000 distances of Cosmicflows-2 (Tully et al. 2013) primarily with two new sources. All-sky luminosity–line width measurements with infrared Spitzer satellite photometry provide distances to relatively nearby galaxies, giving improved coverage at low galactic latitudes (Sorce et al. 2012, 2014). Of greatest importance for the present discussion, though, is the contribution from the 6dFGRS program (Magoulas et al. 2012; Campbell et al. 2014; Springob et al. 2014) of fundamental plane distances to galaxies in the southern celestial hemisphere, a zone underrepresented in Cosmicflows-2.

2. Methods

Our derivation of three-dimensional peculiar velocity and mass density fields from observed distances follows the Wiener filter methodology (Zaroubi et al. 1999; Hoffman 2009; Courtois et al. 2012) assuming a power spectrum consistent with the Λ Cold Dark Matter model with the cosmological parameters given by Komatsu et al. (2009). This Bayesian prior is highly constrained by nearby data, where coverage is dense and accurate, but decays to the exigencies of the power spectrum at large distances where data are sparse and have large errors. The amplitudes of the estimated density and velocity fluctuations are suppressed at large distances due to uncertainties. However, power in dipole and quadrupole terms signal the influence of important structures at the farthest extremities of the observational data.

A familiar way to represent the velocity field is with vectors, either located at specified galaxies or seeded on a grid (Zaroubi et al. 1999). Our preference is to use streamlines (Hoffman et al. 2017). A streamline \( \mathbf{v}(s) \) is computed by integrating \( \mathbf{dr}(s) = \mathbf{v}(s)ds \). A streamline can be seeded on a regular grid, or at specified positions such as regions of maxima and minima of the potential. Integrating the streamlines over many integration steps, flows from low-density regions either leave the computational box or converge onto a basin of attraction. Anti-flow streamlines, the negative of the flow field, proceed from high densities either out of the box or to basins of repulsion (Hoffman et al. 2017).

The structures to be discussed are at large distances where the peculiar velocity field can be badly compromised by the Malmquist bias ( Strauss & Willick 1995). Our methodology will be discussed at length by R. Graziani et al. (2017, in preparation). Briefly, distance errors create an artifact of flows toward the peak in the sample distribution because there are more targets scattering away from the peak than into the peak. The peak is set by the convolution of increasing candidates with volume and the loss of candidates at large distances. Except very nearby, the true positions of galaxies are approximately set by their redshifts. A probability distribution can be calculated for the peculiar velocity of each target from a Bayesian analysis based on the assumption of Gaussian errors constrained by the observed distance and error estimate. There is the resolvable complexity that errors that are approximately Gaussian in the distance modulus give lognormally distributed errors in peculiar velocities (Watkins & Feldman 2015).

We evaluate the robustness of our results through comparisons between many constrained realizations (Hoffman & Ribak 1991). The Wiener filter analysis establishes the minimum variance mean fields of velocity and mass density and constrained realizations then sample the scatter around the Wiener filter mean field (Zaroubi et al. 1999).

3. Results

Our Wiener filter analysis, based strictly on peculiar velocities and in ignorance of the distribution of galaxies, produces an intriguing complementary view to structure identified by redshift surveys. Figure 1 and the companion interactive figure 2 provide a visual summary based on

5 The Sketchfab interactive figure can be launched from Figure 2 or from https://skfb.ly/6oXCY. Selecting numbers will take the viewer on a predetermined path. The model can be manipulated freely with mouse controls.
current information. The extreme peaks and valleys of the gravitational potential inferred in linear theory from the filtered velocity field are represented by isopotential surfaces, attractors and repellers distinguished by colors. In the top panel, peculiar velocity flow lines start at seeds within the basins of repulsion and end at the major attractors. In the bottom panel, the flow is inverted and anti-flow streamlines seeded in the basins of attractions converge onto the repellers.

3.1. Repellers

Two repeller sinks are identified in Figure 1. One was already apparent in the Wiener filter study of the precursor Cosmicflows-2 data set and was named the Dipole Repeller (Hoffman et al. 2017). Its location, as computed with the Cosmicflows-3 data set, is at galactic glon = 94°, glat = −16°, distance = 14,000 km s⁻¹, displaced 2°, and 2000 km s⁻¹ (12%) closer than found previously. The cosine of the anti-alignment with the direction of the cosmic microwave dipole (Fixsen et al. 1996) is μ = −0.99; the agreement in direction is 9°. Hoffman et al. (2017) evaluated the uncertainties in the direction and depth of the Dipole Repeller based on constrained realizations and sample cuts with the Cosmicflows-2 data set and found μ = −0.96 ± 0.04 and a distance of 16,000 km s⁻¹. The new results are in even better agreement with the dipole anti-pole. It was inferred by Hoffman et al. that the Dipole Repeller accounts for roughly half of the Milky Way motion reflected in the dipole.

Figure 1. Dominant attractors and repellers in the nearby universe. In the top panel, flow streamlines are seeded in the Dipole and Cold Spot repellers, flows are blue and green, respectively, and converge predominantly onto the Shapley and Perseus–Pisces attractors. In the bottom panel, anti-flow streamlines are seeded in the Shapley attractor, with flows in red and black that travel to the Cold Spot and Dipole repellers, respectively. Our home is indicated by the red, green, and blue arrows of length 10,000 km s⁻¹ directed along the supergalactic SGX, SGY, and SGZ axes. The locations of the attractors and repellers lie at the local extrema of the potential. The surfaces that represent the attractors and voids are at symmetric values of the potential field of ±580. The positions are in supergalactic coordinates and are expressed in units of 100 km s⁻¹.
It is the second repeller sink that draws our current attention. The rough location is $\text{glon} = 168^\circ$, $\text{glat} = -71^\circ$, and velocity $= 23,000 \text{ km s}^{-1}$. It is in the general region of the negative velocity anomaly in Pisces–Cetus noted by Springob et al. (2014). We note in particular that it is in the direction of a feature projected against the so-called cosmic microwave background (CMB) Cold Spot (Szapudi et al. 2015). The Cold Spot is a fluctuation in the CMB at $\text{glon} = 209^\circ$, $\text{glat} = -57^\circ$ with an amplitude that has been argued is difficult to reconcile with the standard $\Lambda$ Cold Dark Matter model (Vielva et al. 2004; Cruz et al. 2008). There were early hints of an underdensity of galaxies in the same direction (Rudnick et al. 2007; Granett et al. 2010) suggesting that the Cold Spot may be a manifestation of the integrated Sachs–Wolfe effect (Sachs & Wolfe 1967), the redshifting of radiation in passing through a void due to the asymmetry of the potential in an accelerating universe. Szapudi et al. (2015) have strengthened the case for an extremely large void in depth, or chance superposition of several less extreme voids, in the Cold Spot direction extending over the redshift range $0.05 < z < 0.3$. Kovács & García-Bellido (2016) argue that the underdense region continues to the relative foreground, and they name the feature the Eridanus supervoid. Several authors (Finelli et al. 2016; Mackenzie et al. 2017; Naidoo et al. 2017) have evaluated the possibility that the negative fluctuation in the CMB is caused by a vast underdensity in the line of sight. The general consensus disfavors the proposition that line-of-sight voids could be important enough to create the Cold Spot from the integrated Sachs–Wolfe effect alone.

Nevertheless, coincidence or not, a dominant repeller is identified in a direction that overlaps with the Cold Spot in projection. We evaluate the angular extent and significance of the repeller revealed by the velocity field through the method of constrained realizations mentioned briefly in Section 2. The density with respect to the mean cosmic density within a sphere of radius $R$ centered at a specified location, $\delta(R) = (\rho(R) - \bar{\rho})/\bar{\rho}$, is derived from the Wiener filter analysis. The uncertainty in density, $\sigma(R)$, is sampled from 54 constrained realizations. The basin of the repeller is identified to lie at $\text{SGX, SGY, SGZ} = [6500, -21300, -6100] \text{ km s}^{-1}$. Figure 3 shows the development of the signal-to-noise $-\delta(R)/\sigma(R)$ with increasing spheres of radius $R$.

There is a complexity associated with Figure 3 that requires explanation. The location of the repeller at $z \sim 0.077$ lies at the extremity of our data zone (a high density of data to $z \sim 0.05$ with sparse supernova sampling to $z \sim 0.1$). The solid curve in Figure 3 illustrates the density signal to rms fluctuations within the intersection of spheres of increasing radius centered on the repeller basin and a sphere of radius $25,000 \text{ km s}^{-1} (z \sim 0.08)$ centered on our position. The choice of the radius of the sphere centered on us is somewhat arbitrary but roughly captures the region where the Wiener filter density construction carries information that departs from the mean. In the case of the dashed curve in the figure, the same signal/uncertainty information is illustrated but now within spheres centered on a location in the direction of the Cold Spot. The specific center is at $\text{SGX, SGY, SGZ} = [3600, -16700, -12900] \text{ km s}^{-1}$, in the direct line of sight of the CMB Cold Spot with a distance that is the same as that of the repeller basin. The curve plots $-\delta(R)/\sigma(R)$ within the intersection of spheres centered on the identified location and the $25,000 \text{ km s}^{-1}$ sphere centered on us.

From the solid curve in Figure 3 it is seen that the significance of the underdensity increases with volume, reaching $\sim 2.3\sigma$ by $R \sim 12,000 \text{ km s}^{-1}$. The peculiar velocity field provides suggestive evidence for an underdensity on this vast scale. We note that the direction to the cosmic Cold Spot lies within this domain. The dashed curve in the figure illustrates the significance of the underdensity if we shift the

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6 The signal in the density field is weak at the extremity of the data where densities from the Wiener filter construction tend to the mean. The potential field is better defined by tidal influences at large distances.
assumed center from our preferred location by a distance equivalent to 8900 km s\(^{-1}\) to a center along the line of sight toward the Cold Spot while keeping the same distance. The significance is reduced but the scale of the implied under-density is similar.

### 3.2. Attractors

The dominant attractor with Cosmicflows-3, as with Cosmicflows-2, is coincident with the Shapley concentration (Raychaudhury 1989; Scaramella et al. 1989). In detail, there is a shift on the sky of \(10^\circ\) (to glon = 306, glat = +22) and distance of +1500 km s\(^{-1}\) (to 15,900 km s\(^{-1}\)). The new 6dFGSv data (Springob et al. 2014) imply that the mass overdensity in this region extends into the galactic plane and to the south of the Milky Way, with a secondary maximum near the south celestial pole. However, aside from the immediate Shapley region, there is a poor correspondence with observed galaxies (Huchra et al. 2012) or X-ray clusters (Kocevski et al. 2007). Again, as with the Cold Spot Repeller, the postulated structure is at the extremity of the data zone. It has to be suspected that the true nature of the attractor in this region will only be revealed by a study to greater depth.

### 4. Discussion

In their discussion of 6dFRSv results, Springob et al. (2014) compared the velocity field implied by their distance and redshift observations with expectations from two independent redshift surveys (Branchini et al. 1999; Erdoğdu et al. 2006). With both comparisons, they noted a large-scale departure from the redshift survey expectations, with observed peculiar velocities systematically negative in the Pisces–Cetus sector (Tully et al. 1992) and positive in the Centaurus sector, the domain of the Shapley concentration (Shapley 1930; Raychaudhury 1989; Scaramella et al. 1989). It is a limitation of the redshift survey approach, though, that there is no account of tidal effects from beyond the range of the survey.

Our approach of inferring mass distribution from velocities accesses information on distant structures from tidal signatures. Sensitivity to their characteristics diminish with distance. The repeller in the direction toward the CMB Cold Spot is the dominant negative density feature of the Wiener filter construction with Cosmicflows-3. The deviation in the direction between the repeller basin and the Cold Spot of 22° is within the uncertainty of our measurement. Our distance to the repeller of \(\sim 23,000\) km s\(^{-1}\) should only be considered a rough lower limit.

We call the underdensity identified by the Wiener filter analysis the Cold Spot Repeller because of its coincidence in direction with the Cold Spot fluctuation in the microwave background. We are providing increased evidence of the existence of a substantial void, or succession of voids, in the Cold Spot direction (Granett et al. 2010; Szapudi et al. 2015; Kovács & García-Bellido 2016). It remains to be determined if the coincidence in this direction has a physical basis. The tentative nature of the association of our repeller and the CMB Cold Spot must be acknowledged. The observational claim that is made here awaits confirmation with redshift and distance measurements to greater distances. However, it is likely that proper resolution will require surveys to twice the current depth, with serious completion to \(z \sim 0.1\), involving an order of magnitude more galaxies or distance estimators with higher accuracy.

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**ORCID iDs**

Hélène M. Courtois [https://orcid.org/0000-0003-0509-1776](https://orcid.org/0000-0003-0509-1776)

R. Brent Tully [https://orcid.org/0000-0002-9291-1981](https://orcid.org/0000-0002-9291-1981)

Daniel Pomarède [https://orcid.org/0000-0003-2038-0488](https://orcid.org/0000-0003-2038-0488)

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