The dipole repeller

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Our Local Group of galaxies is moving with respect to the cosmic microwave background (CMB) with a velocity of \( V_{\text{CMB}} = 631 \pm 20 \text{ km s}^{-1} \) and participates in a bulk flow that extends out to distances of \(-20,000 \text{ km s}^{-1}\) or more. There has been an implicit assumption that overdensities of galaxies induce the Local Group motion5–7. Yet underdense regions push as much as overdensities attract3, but they are deficient in light and consequently difficult to chart. It was suggested a decade ago that an underdensity in the northern hemisphere extends out to beyond 100 megaparsecs and down to a resolution of \( 15,000 \text{ km s}^{-1} \) away contributes significantly to the observed flow7. We show here that repulsion from an underdensity is important and that the dominant influences causing the observed flow are a single attractor — associated with the Shapley concentration — and a single previously unidentified repeller, which contribute roughly equally to the CMB dipole. The bulk flow is closely anti-aligned with the repeller out to \( 16,000 \pm 4,500 \text{ km s}^{-1} \). This ‘dipole repeller’ is predicted to be associated with a void in the distribution of galaxies.

The large-scale structure of the Universe is encoded in the flow field of galaxies. A detailed analysis of the flow uncovers the rich structure manifested by the distribution of galaxies, such as the prominent nearby clusters10–13, the Laniakea supercluster14 and the Arrowhead mini-supercluster15. A close correspondence between the observed density field, derived from redshift surveys, and the reconstructed three-dimensional (3D) flow field has been established out to beyond 100 megaparsecs and down to a resolution of a few megaparsecs16. Yet the flow contains more information on distant structures, as found from tides and from continuity across the zone obscured by the Galactic disk, the ‘zone of avoidance’17. The Cosmicflows-2 dataset of galaxy distances18 provides reasonably dense coverage to \( R \approx 10,000 \text{ km s}^{-1} \) (distances are expressed in terms of their equivalent Hubble velocity).

The linear 3D velocity field is reconstructed here from the Cosmicflows-2 data by the Bayesian methodology of the Wiener filter and constrained realizations (see Methods). The Wiener filter is a Bayesian estimator that assumes a prior model: here it is the \( \Lambda \) CDM model. It is a conservative estimator which balances between the data and its errors and the assumed prior model. Where the data are weak, the Wiener-filter estimation tends to the null hypothesis of a homogenous universe: that is, a vanishing peculiar velocity. Yet it uncovers structures out to \( \approx 16,000 \text{ km s}^{-1} \) at the extremity of the Cosmicflows-2 coverage. The variance around the mean Wiener-filter estimator is sampled by the constrained realizations.

The Wiener-filter flow field is used to construct the cosmic web, defined here by means of the velocity field17 (V-web; see Methods) This is done by evaluating the velocity shear tensor on a grid and counting the number of its eigenvalues above a threshold value: 3 corresponds to a knot, 2 to a filament, 1 to a sheet and 0 to a void. In the linear regime, the flow is proportional to the negative of the gravitational field; hence it constitutes a gradient of a scalar potential. Figure 1 shows the large-scale structure out to a distance of 16,000 km s\(^{-1}\) in a plane that contains the Local Group, the Shapley attractor and the dipole repeller. Three different aspects of the flow are depicted: streamlines, the V-web and the velocity potential.

When describing the gravitational dynamics in co-moving coordinates, by which the expansion of the Universe is factored out, underdensities repel and overdensities attract. The velocity field is represented here by means of streamlines (see Methods), the sources and sinks of which are the attractors and repellers of the large-scale structure (see Fig. 1 and the Supplementary Video). The telltale signature of a single dominant attractor or repeller is the close alignment of the dipole with the expansion eigenvector of the shear tensor and a degeneracy of the other two eigenvalues/eigenvectors. The observed flow is clearly not dominated by either a single attractor or repeller. In the following, we emphasize the directional aspects of the dipole and shear eigenvectors, which are robustly recovered by the Wiener filter. Figure 3 presents an Aitoff projection of the following directions: (1) the dipole repeller; (2) the Shapley attractor; (3) the CMB dipole and its anti-apex; (4) the bulk velocity of top-hat spheres of \( R = (2,000, 3,000, ..., 15,000) \text{ km s}^{-1} \), \( V_{\text{bulk}}(R) \), of the Wiener-filter reconstructed flow field; (5) the three eigenvectors of the shear tensor \( \langle \hat{e}_i \rangle, i = 1, 2, 3 \rangle \) of the Wiener filter field. The figure shows the strong anti-alignment of the bulk flow out to 15,000 km s\(^{-1}\) with the dipole repeller. Beyond that radius, the bulk flow loses its coherence, as the scatter in direction steadily increases. The eigenvector of the shear tensor that reflects the direction of maximal expansion \( \langle \hat{e}_3 \rangle \) is aligned with the direction of the Shapley attractor out to \( R = 7,000 \text{ km s}^{-1} \). Supplementary Fig. 2 further presents the mean and the scatter around the cosine of the angles formed between the bulk velocity and the dipole repeller, \( \mu_e(R) = \cos(V_{\text{bulk}} \cdot R_{\text{Gil}}) \), and between \( e_i \) and the Shapley attractor, \( \mu_e(R) = \cos(\hat{e}_3(R) \cdot R_{\text{Shapley}}) \).
Two aspects of the bulk velocity — the anti-alignment itself ($\mu_{\text{bulk}}(R) = -0.96 \pm 0.04$) and its distance scale ($R = 16,000 \, \text{km s}^{-1}$) — strongly corroborate the Wiener-filter finding of the dipole repeller and its dominant role in dictating the observed flow. The direction and distance coincide with the position of the dipole repeller — a non-trivial occurrence. It is interesting to study the shear tensor. The expansion eigenvector is closely aligned with the direction to the Shapley attractor out to $R \approx 7,000 \, \text{km s}^{-1}$, the distance of the foreground (Norma–Centaurus–Hydra) Great Attractor, located at the bottom of the Laniakea basin of attraction at supergalactic coordinates ($\approx 4,700, 1,300, 500$) $\, \text{km s}^{-1}$. It is the combined mass distribution within the Laniakea and Shapley superclusters that dominates the tidal field, with the inverse cubic distance dependence of the tidal interaction tipping the balance at our location towards the Laniakea/Great Attractor.

Our main findings are tested against statistical and systematic uncertainties. There is no doubt about the existence of the Shapley concentration, and therefore we focus our attention mostly on the dipole repeller. The strong support for the existence of the dipole repeller comes not only from its close alignment of the bulk velocity but also from the small scatter around the mean Wiener-filter value, $\mu_{\text{bulk}}(R) = -0.96 \pm 0.04$ for $R \approx 16,000 \, \text{km s}^{-1}$ (Supplementary Fig. 2). Assuming that the dipole repeller is the dominant structure that determines the direction of the bulk flow, the scatter in $\mu_{\text{bulk}}(R)$ can be translated to uncertainty in the position of the repeller, $\Delta R_{\text{Dip}} \approx 4,500 \, \text{km s}^{-1}$ (see Methods). The basins of repulsion and attraction around the dipole repeller and Shapley attractor, out to a distance of $\approx 8,000 \, \text{km s}^{-1}$, contribute fairly evenly to the velocity of the Local Group. At $8,000 \, \text{km s}^{-1}$, the repeller and the attractor contribute $59 \pm 26$ and $67 \pm 27 \, \text{km s}^{-1}$, respectively, to the CMB dipole (see Methods). Next, the robustness of the dipole repeller is tested against subsampling of the data. These consist of cuts either by distance ($6,000, 8,000$ and $10,000 \, \text{km s}^{-1}$), or by galaxy and data type (see Methods), corresponding to a degradation in the quality of the data by volume coverage, number of data points and magnitude of errors (see Methods). All subsamples considered here locate the dipole repeller in an underdense region and recover a basin of repulsion that pushes the Local Group in the direction of the CMB dipole.

The general picture that emerges here is of a complex flow that cannot be explained by a simple toy model, yet the main structures that shape the observed flow can be identified. The Wiener filter recovers a flow dominated by a single attractor and a single repeller, which roughly equally contribute to the CMB dipole. The role played by the Shapley attractor is not surprising; the earlier findings on influences beyond the Great Attractor suggested it. The existence of the dipole repeller was only vaguely hinted at before. A study of the all-sky distribution of X-ray-selected clusters uncovered a significant underdensity of clusters in the northern hemisphere roughly $15,000 \, \text{km s}^{-1}$ away. It suggested that this underdensity may be as significant as the overdensity of clusters in the southern hemisphere in inducing the local flow. Earlier examinations of galaxy peculiar velocities found a north–south anisotropy in (galactic) $y$-component of the velocities and found that the sources responsible for the bulk flow are at an effective distance $>30,000 \, \text{km s}^{-1}$. Here, the source of the repulsion is identified for the first time. The dual dominance of the dipole repeller and the Shapley attractor is the main new finding of this study. The strong anti-alignment of the CMB dipole with the dipole repeller out to a distance of $16,000 \, \text{km s}^{-1}$ suggests the possible dominance of the repeller over the attractor. The predicted position of the dipole repeller is in a region that is as yet poorly covered by existing

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**Figure 1** | A face-on view of a slice $6,000 \, \text{km s}^{-1}$ thick, normal to the direction of the pointing vector $\hat{r} = (0.604, 0.720, -0.342)$. Three different elements of the flow are presented: mapping of the velocity field is shown by means of streamlines (seeded randomly in the slice); red and grey surfaces present the knots and filaments of the V-web, respectively; and equi-gravitational potential surfaces are shown in green and yellow. The potential surfaces enclose the dipole repeller (in yellow) and the Shapley attractor (in green) that dominate the flow. The yellow arrow originates at our position and indicates the direction of the CMB dipole (galactic longitude $l = 276^\circ$, galactic latitude $b = 30^\circ$). The distance scale is given in units of $\text{km s}^{-1}$. © 2017 Macmillan Publishers Limited, part of Springer Nature. All rights reserved.
redshift surveys. We predict the dipole repeller to be associated with a void in the distribution of galaxies.

In the linear regime of gravitational instability, repellers are as abundant and dominant as attractors. Yet, observationally, repellers are much harder to identify than attractors. The association of repellers with underdensities renders them strongly deficient in galaxies, in general, and clusters of galaxies, in particular, and thereby makes their direct detection challenging. Our use of peculiar velocities as tracers of the large-scale structure overcomes that observational hindrance and unveils the existence of the new extended structure located at $\alpha = 22^\circ 25^\prime$ min, $\delta = +37^\circ$ (galactic longitude $l = 93^\circ$, galactic latitude $b = -17^\circ$; supergalactic latitude and longitude SGL = 332°, SGB = 39°) that we call the ‘dipole repeller’.

**Methods**

**Cosmicflows-2 dataset.** The present study is based on the second release catalogue of galaxy distances and peculiar velocities, Cosmicflows-2, which extends sparsely to recession velocities of 30,000 km s$^{-1}$ (redshift $z \approx 0.1$). It consists of 8,161 entries with high density of coverage inside 10,000 km s$^{-1}$. Here we used a grouped version of the Cosmicflows-2 data, in which all galaxies forming a group (of two or more) are merged to one data entry. The grouped Cosmicflows-2 data consists of 4,885 entries. Six methodologies are used for distance estimation: Cepheid star pulsations; the luminosity terminus of stars at the tip of the red giant branch; surface brightness fluctuations of the ensemble of stars in elliptical galaxies; type Ia supernovae; the fundamental plane in luminosity, radius and velocity dispersion of elliptical galaxies; and the Tully–Fisher (TF) correlation between the luminosities and rotation rates of spiral galaxies.

**Wiener filter and constrained realizations.** In the standard model of cosmology, the linear velocity field constitutes a Gaussian random vector field. The Wiener-filter/constrained-realizations reconstruction is based on an assumed prior cosmological model — the $\Lambda$CDM model with cosmological parameters inferred from the Wilkinson Microwave Anisotropy Probe (WMAP).

The current Wiener-filter and constrained-realization fields are the ones reported in our bulk velocity article. The results presented here are insensitive to the exact values of the $\Lambda$CDM parameters, in particular to the differences between the WMAP and Planck parameters.

**Cosmic V-web.** The cosmic web is defined here by the means of the V-web model. The normalized velocity shear tensor at a given grid cell is defined by:

$$\Sigma_{\alpha\beta} = -{1 \over 2H_0} (\partial_\alpha u_\beta + \partial_\beta u_\alpha)$$

(1)

The standard definition of the velocity shear tensor is modified here by the Hubble constant ($H_0$) normalization, which makes it dimensionless. The minus sign is introduced so that a positive eigenvalue corresponds to a contraction. Eigenvalues are ordered by decreasing value, hence $\lambda_1$ points in the direction of maximum collapse and $\lambda_2$ points toward maximum expansion.

The V-web model starts with the continuous velocity field and its associated velocity shear tensor (Equation (1)). Consider a given point in space at which the shear tensor is evaluated, and thereby its eigenvalues and eigenvectors. The V-web is defined by a threshold value ($\lambda_\Sigma$) — a free parameter that defines the web. The number of eigenvalues above $\lambda_\Sigma$ defines the web classification at that point: 0, 1, 2 or 3 corresponds to the point being a void, sheet, filament or knot.

The V-web is defined by the effective resolution of the velocity field and by the value of the threshold. Here a Gaussian smoothing of $R = 250$ km s$^{-1}$ and $\lambda_\Sigma = 0.04$ are assumed.

The sources and sinks of the velocity field, namely the repellers and attractors, are closely associated with the voids and knots of the V-web. The voids (knots) are regions of diverging (converging) flow, namely regions where the Hessian of the velocity potential is negative (positive) definite, yet these regions are in general moving with respect to the CMB frame of reference. The repellers and attractors are defined here as stationary voids and knots respectively, and hence correspond to local extrema of the gravitational potential. Note that the Great Attractor, which moves towards the Shapley attractor, is not an attractor as defined here.

**Multipole expansion of the flow.** A first-order expansion of a potential (that is, irrotational) velocity field, $v(r)$, around a point labeled by 0 yields:

$$v_0(r) \approx v_{00} + (\partial_\alpha v_{0\beta} r_\beta = v_{00} - H_0 \Sigma_{0\alpha} r_\alpha$$

(2)

where $v_{0\alpha}$ and $\Sigma_{0\alpha}$ are evaluated at the point $0$. This expansion is equivalent to a dipole and quadrupole expansion of the (velocity) potential. The flow in a sphere

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**Figure 2 | A 3D view of the velocity field.** It is shown here by means of the flow streamlines (in black-blue, left panel) and of the anti-flow (in yellow-red, right panel). Anti-flow is defined here by the negative (namely, the reverse) of the velocity field. The same streamlines are seeded on a regular grid and are coloured according to the magnitude of the velocity. The flow streamlines diverge from the repeller and converge on the attractor. For the anti-flow, the divergence and convergence switch roles: they diverge from the attractor and converge on the repeller. The knots and filaments of the V-web are shown for reference. Cartesian supergalactic coordinates (SGX, SGY, SGZ) are assumed here. (For a 3D view, look at the accompanying Supplementary Video, at time 00:56–01:28.)
In the linear regime the peculiar velocity \(\Omega\Omega\ g\) of objects. Mass elements and galaxies move only a few megaparsecs in a lifetime. The parameter \(\Omega\) is calculated by integrating the line of a streamline, the line equation of a streamline, \(lv l=\sum (R)\), and a shear term, \(\Sigma (R)\), in the manner of electrostatics. The parameters of the model (that is, the bulk velocity vector and the symmetric tensor) are found by minimizing the quadratic residual between the model and the actual velocity field, with a spherical top-hat window function weighting.

**Streamlines.** In the linear regime the flow field is irrotational —that is, it is a potential flow—and hence the velocity field can be written as a gradient of a scalar (velocity) potential, \(v = \nabla \phi\). In the linear regime the peculiar velocity \(v_0\) and gravitational field \(g\) are simply related by \(v = \frac{\Omega v_0}{\nabla \phi}\), where \(\Omega\), \(\Omega\), and \(H\) are, respectively, the time-dependent cosmological density parameters for matter and for dark energy, and Hubble’s constant. The velocity and gravitational potential are similarly related. Inspired by the similarity between the gravitational potential in linear theory, hence also the velocity potential, to the electrical potential in electrostatics, we present the flow field by field lines which we call streamlines. The parameters of the model (that is, the bulk velocity vector and the symmetric tensor) are found by minimizing the quadratic residual between the model and the actual velocity field, with a spherical top-hat window function weighting.

**Quantitative comparison of repeller versus attractor.** The contribution \(\Delta \Omega\) of the dipole repeller and the Shapley attractor to the motion of the Local Group is compared by means of setting spheres of radius \(R\) around both objects, and calculating the velocity induced by the density inside these spheres at the Local Group. The linear-theory density-velocity relation is used in such a calculation. A word of caution is needed before proceeding to the comparison. The attractor region is much better sampled by the Cosmicflows-2 data than that of the dipole repeller; hence the Wiener-filter suppression of the signal is stronger at the dipole repeller, and the constrained variance of the residual around the mean is larger there (Supplementary Fig. 1). The figure presents the contribution \(\Delta \Omega\) to the Local Group velocity projected onto the direction of the CMB dipole. Out to \(R = 8,000\) km s\(^{-1}\), the contributions of the attractor and repeller are almost identical. At \(R = 8,000\) km s\(^{-1}\), the repeller and the attractor contribute \(52 \pm 26\) and \(67 \pm 27\) km s\(^{-1}\), respectively, to the CMB dipole. The slight deficiency of the dipole repeller is fully consistent with the enhanced suppression of the Wiener filter. The Perseus–Pisces supercluster, at a distance of \(R > 8,000\) km s\(^{-1}\) away from the repeller, leads to the decrease in the velocity contribution by the dipole-repeller-centric spheres. The dip is the reflection of the tug-of-war between the Perseus–Pisces supercluster and the Great Attractor. Very similar results are obtained when considering the contribution to the amplitude of the full 3D velocity of the Local Group. The conclusion that follows is that out to \(R \approx 8,000\) km s\(^{-1}\), the Shapley attractor’s basin of attraction and the dipole repeller’s basin of repulsion contribute equally to the Local Group motion.

**Uncertainties assessment.** The probability distribution of the alignment of the bulk velocity and the eigenvectors of the shear tensor is sampled by means of an ensemble of 20 constrained realizations, constrained by the Cosmicflows-2 data and evaluated within the WMAP parameters of the ΛCDM model. The constrained realizations are evaluated on a grid of size 256 × 256 × 256, spanning a box of 256,000 km s\(^{-1}\). The bulk velocity and the velocity shear tensor are obtained by a convolution of the velocity field with a spherical top-hat window of radius \(R\) and are evaluated at the centre of the box, in other words the location of the Local Group. Supplementary Fig. 2 presents the alignment of the bulk velocity and the third eigenvector of the shear tensor with the dipole repeller and the Shapley attractor, respectively, over a range of radii of \(R = (20, 30, ... 300) \times 1000\) km s\(^{-1}\). This again translates to an uncertainty in the radial position of roughly 4,500 km s\(^{-1}\).

The robustness of the dipole repeller against subsampling of the data is considered. First, the Cosmicflows-2 data is subsampled by type: the ‘singles’ subsample consists of 4,264 data entries based on a single galaxy only, and the ‘pairs’ subsample is made of 3,943 single data with TF–only distances. The ungrouped Cosmicflows-2 data consists of 8,399 galaxies. The relative fractional distance error of the TF distances is 0.088 ± 0.007. In assessing the constraining power of the various subsamples, one should consider both the number of data points and the magnitude of the errors. For comparison, the relative error for the grouped entries (that is, data entries based on more than one galaxy) is 0.186 ± 0.046. The majority of the non–TF-singles’ are data with supernova type-Ia distances for which the relative distance errors are 0.088 ± 0.007. In assessing the constraining power of the various subsamples, one should consider both the number of data points and the magnitude of the errors. For comparison, the relative error for the grouped entries (that is, data entries based on more than one galaxy) is 0.186 ± 0.046. The majority of the non–TF-singles’ are data with supernova type-Ia distances for which the relative distance errors are 0.088 ± 0.007. In assessing the constraining power of the various subsamples, one should consider both the number of data points and the magnitude of the errors. For comparison, the relative error for the grouped entries (that is, data entries based on more than one galaxy) is 0.186 ± 0.046. The majority of the non–TF-singles’ are data with supernova type-Ia distances for which the relative distance errors are 0.088 ± 0.007. In assessing the constraining power of the various subsamples, one should consider both the number of data points and the magnitude of the errors. For comparison, the relative error for the grouped entries (that is, data entries based on more than one galaxy) is 0.186 ± 0.046. The majority of the non–TF-singles’ are data with supernova type-Ia distances for which the relative distance errors are 0.088 ± 0.007. In assessing the constraining power of the various subsamples, one should consider both the number of data points and the magnitude of the errors. For comparison, the relative error for the grouped entries (that is, data entries based on more than one galaxy) is 0.186 ± 0.046. The majority of the non–TF-singles’ are data with supernova type-Ia distances for which the relative distance errors are 0.088 ± 0.007. In assessing the constraining power of the various subsamples, one should consider both the number of data points and the magnitude of the errors. For comparison, the relative error for the grouped entries (that is, data entries based on more than one galaxy) is 0.186 ± 0.046. The majority of the non–TF-singles’ are data with supernova type-Ia distances for which the relative distance errors are 0.088 ± 0.007. In assessing the constraining power of the various subsamples, one should consider both the number of data points and the magnitude of the errors. For comparison, the relative error for the grouped entries (that is, data entries based on more than one galaxy) is 0.186 ± 0.046. The majority of the non–TF-singles’ are data with supernova type-Ia distances for which the relative distance errors are 0.088 ± 0.007. In assessing the constraining power of the various subsamples, one should consider both the number of data points and the magnitude of the errors. For comparison, the relative error for the grouped entries (that is, data entries based on more than one galaxy) is 0.186 ± 0.046. The majority of the non–TF-singles’ are data with supernova type-Ia distances for which the relative distance errors are 0.088 ± 0.007. In assessing the constraining power of the various subsamples, one should consider both the number of data points and the magnitude of the errors. For comparison, the relative error for the grouped entries (that is, data entries based on more than one galaxy) is 0.186 ± 0.046. The majority of the non–TF-singles’ are data with supernova type-Ia distances for which the relative distance errors are 0.088 ± 0.007. In assessing the constraining power of the various subsamples, one should consider both the number of data points and the magnitude of the errors. For comparison, the relative error for the grouped entries (that is, data entries based on more than one galaxy) is 0.186 ± 0.046. The majority of the non–TF-singles’ are data with supernova type-Ia distances for which the relative distance errors are 0.088 ± 0.007. In assessing the constraining power of the various subsamples, one should consider both the number of data points and the magnitude of the errors. For comparison, the relative error for the grouped entries (that is, data entries based on more than one galaxy) is 0.186 ± 0.046. The majority of the non–TF-singles’ are data with supernova type-Ia distances for which the relative distance errors are 0.088 ± 0.007.
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R.B.T. and H.M.C. carried out the observations and data analysis; D.P. contributed graphics and visualization; Y.H. carried out the numerical and theoretical analysis. All co-authors contributed to the writing of the paper, led by Y.H.

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Competing interests
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