ABSTRACT

We calculate the large-scale bulk flow from the Cosmicflows-2 peculiar velocity catalog (Tully et al. 2013) using the minimum variance method introduced in Watkins et al. (2009). We find a bulk flow of $262 \pm 60$ km/sec on a scale of $100 h^{-1}$ Mpc, a result somewhat smaller than that found from the COMPOSITE catalog introduced in Watkins et al. (2009), a compendium of peculiar velocity data that has many objects in common with the Cosmicflows-2 sample. We find that distances are systematically larger in the Cosmicflows-2 catalog for objects in common due to a different approach to bias correction, and that this explains the difference in the bulk flows derived from the two catalogs. The bulk flow result from the Cosmicflows-2 survey is consistent with expectations from $\Lambda$CDM, and thus this catalog potentially resolves an important challenge to the standard cosmological model.

1 INTRODUCTION

The large-scale bulk flow is an important cosmological probe of large scale structure. Being the average of the peculiar velocities of the objects in a large volume, it is in principle only dependent on motions on scales which are still in the linear regime and thus can be directly related to the power spectrum of matter perturbations using linear theory. However, in practice, the interpretation of bulk flow measurements is complicated by the large uncertainties inherent in peculiar velocity measurements, the difficulties of understanding and correcting for biases, and by the nonuniform distributions of sample objects in peculiar velocity surveys. Understanding and accounting for these complexities is crucial in order for the bulk flow to be useful as a cosmological probe.

One of the main challenges in interpreting bulk flows estimated by using large-scale peculiar velocity surveys is that it is often unclear which velocity field scales they are probing. Even the best estimations of the bulk flow were shown (Kaiser 1988; Watkins & Feldman 1995; Juszkiewicz et al. 2000; Nusser et al. 2001; Hudson 2003; Feldman et al. 2003a; Sarkar et al. 2007; Watkins & Feldman 2009; Feldman & Watkins 2008) to be affected by internal motions and other small scale affects. The scales from which the bulk flow motions arose were both large (scales larger than the sampled volume) and those of the order of, or smaller than, the volume in question. It has become clear that these effects are non-negligible and should be accounted for by the formalism (Watkins et al. 2002; Hudson 2003; Feldman et al. 2003b; Sarkar et al. 2007).

While we tend to think of the bulk flow of a survey as being the motion of the volume containing the survey objects, in practice it may reflect velocities on much smaller scales. Thus, in thinking about the meaning of the bulk flow, we want to approximate the volume itself as a solid moving in tandem, while the velocities that arise from the forces originating inside the volume are removed by some scheme. For example, a bulk flow calculated as the average of the velocities of a set of survey objects weighted by their peculiar velocity uncertainties has a dominant contribution from objects at smaller distances, both because they are more numerous and because their measurement uncertainties are typically much smaller. One consequence of this confusion is that bulk flows measured using different surveys or different methods are generally not comparable, a fact that greatly complicates their use and utility as probes of large-scale structure.

In order to standardize the study of bulk flows, we introduced the minimum variance (MV) method for obtaining estimates of bulk flows on specific scales that are comparable between surveys (Watkins, Feldman, & Hudson 2009, hereafter WFH); (Feldman, Watkins, & Hudson 2010, hereafter FWH). The MV method of calculating the bulk flow utilizes the velocity information in a survey to estimate the flow of an idealized, uni-
formly distributed set of objects with properties that can be set independent of the properties of the survey.

The bulk flow components are in general weighted averages of measured radial peculiar velocities from a survey. The estimated bulk flow components can be seen as convolutions of the power spectrum of the cosmic mass fluctuations with the window functions, which depend on both the spatial distribution of the sample objects as well as the weights. The window functions thus define the scales the survey probes and tells us which scale motions contribute to the bulk flow. In the MV method, weights are chosen so that the resulting bulk flow estimates are as close as possible to what we would have calculated for an idealized survey. Thus as long as the actual survey has reasonable coverage of the volume of the idealized survey, the bulk flow estimate will probe the power spectrum in a standard way, making MV bulk flow estimates comparable between different surveys. Specifically, the MV convolution prevents small scale power leakage (aliasing) by having very little contribution from small scales where nonlinear contributions become significant, resulting in unbiased large-scale linear information. When the window functions pick up small scale noise that leaks into the power spectrum convolution it masquerades as large scale signal.

WFH used the MV method to analyze a compendium of available peculiar velocity data which was dubbed the COMPOSITE catalog. This analysis found bulk flows on scales of 100h$^{-1}$ Mpc that were incompatible with the standard cosmological model at the 98-99% confidence level. Some subsequent analyses using different catalogs and/or different analysis methods have agreed with the WFH results (Ma et al. 2011 Macaulay et al. 2011 2012), while others failed to confirm the existence of these flows; however, given the difficulties of comparing bulk flows neither have they definitely ruled them out. In particular, Ma & Scott (2013); Davis et al. (2011); Nusser et al. (2011); Nusser & Davis (2011) used analysis methods where it was not clear that they were probing as large a scale as WFH. In the case of Turnbull et al. (2012), the small size of the supernova sample they used was such that even though the MV method was used, the results were consistent with both the WFB results and the standard cosmological model. Thus the existence of large flows on the scale of 100h$^{-1}$ Mpc is still an open question.

In this paper we apply the MV formalism to the recently released Cosmicflows-2 catalog (Tully et al. 2013). This catalog contains most of the data used in the COMPOSITE catalog of WFH, along with a significant amount of more recent data. The catalog contains distances computed using several methods including the Tully-Fisher Relation (TFR), SNIa light curves, Surface Brightness fluctuations, Fundamental Plane, Cepheid variables, and the Tip of the Red Giant Branch. The large number of objects in the catalog that have distances measured with more than one method makes it possible to calibrate the methods for maximum consistency. The Cosmicflows-2 catalog is notable for its size and its depth. The group catalog has 5,223 objects, with good coverage beyond cz > 10,000 km s$^{-1}$, making it well suited for measuring the bulk flow on scales of 100h$^{-1}$ Mpc.

In Section 2 we describe the peculiar velocity samples we analyze. In Section 3 we review the formalism we utilize for the analysis. We discuss our results in Section 4 and conclude in Section 5.

## 2 DATA

The Cosmicflows-2 catalog (Tully et al. 2013) is a compendium of distances and peculiar velocities of over 8000 galaxies, some from the literature and some from new measurements. The majority of the galaxy distances are determined via the TRF and the Fundamental Plane relation, both of which give uncertainties of around 20% of the distance, with a smaller portion of the distances coming from more accurate distance measures including Type Ia Supernovae, Surface Brightness Fluctuation, Cepheids, and Tip of the Red Giant Branch. The catalog extends out to redshifts of 30,000 km s$^{-1}$, although it has densest coverage for the volume within 3,000 km s$^{-1}$.

The COMPOSITE sample consists of various peculiar velocity catalogs. The SFI++ peculiar velocity survey of spirals in the field and in groups (Masters et al. 2006 Springob et al. 2007 2009) which consists of 2720 TF galaxies and 736 groups to make 3456 data points with characteristic depth of 35 h$^{-1}$Mpc. The surface brightness fluctuation survey of Tonry et al. (2001) with 69 field and 23 groups, with a characteristic depth of 17 h$^{-1}$Mpc. The ENEAR survey of Fundamental Plane (FP) distances to nearby early-type galaxies (da Costa et al. 2000 Bernardi et al. 2002 Wegner et al. 2003) with characteristic depth of the sample is 29 h$^{-1}$Mpc. Also included in the compilation are 103 Type Ia supernovae distances from the compilation of Tonry et al. (2003), limited to a distance of 150 h$^{-1}$Mpc. The SC (Giovanelli et al. 1998 Dale et al. 1999) is a TF-based survey of spiral galaxies in 70 clusters within 200 h$^{-1}$Mpc. The characteristic depth of the combined sample is 57 h$^{-1}$Mpc. The SMAC (Hudson et al. 1999 2004) is an all-sky Fundamental Plane (FP) survey of 56 clusters. The characteristic depth of the survey is 65 h$^{-1}$Mpc. The EFAR (Colless et al. 2001) is a survey of 85 clusters and groups, based on the FG distance indicator with characteristic depth is 93 h$^{-1}$Mpc. Willick (1999) is a Tully-Fisher based survey of 15 clusters with a characteristic depth of 111 h$^{-1}$Mpc. The COMPOSITE sample is described in detail in WFB.
of groups and galaxies in common with the COM-
POSITION compilation. An important feature of the
Cosmicflows-2 catalog is that the authors have util-
ized the large number of objects with multiple dis-
tance measurements using different methods to apply
corrections to ensure consistency between data from
difference sources. While in most cases these correc-
tions were simply shifts in zero points, for some sets
of objects more complicated adjustments were made.
Two general corrections were made to account for the
deviation from the linear Hubble relation at large red-
shift and to correct for error bias, which is the skew-
ness in distance errors due to the fact that it is distance
moduli and not distances that have a Gaussian error
distribution.

The fact that Tully et al. have adjusted published
values for distances and peculiar velocities suggests
that even though the COMPPOSITE and Cosmicflows-2
catalogs have many of their objects in common, what
they tell us about large scale flows could potentially
be very different. However, since the catalogs do have
a different spatial distribution, particularly on small
scales where Cosmicflows-2 has many more objects,
direct comparisons of the bulk flows in these catalogs
are best done with methods such as the MV formal-
ism which estimates flows that are independent of the
distribution of objects.

There are two catalogs in the Cosmicflows-2 pa-
per. One consists of every galaxy that have a distance
which we call CF2galaxy, which has 8315 entries (Tully
et al. 2013 Table 1). They also compiled another cat-
alog where they condensed the individual entries into
groups with 5223 entries which we call CF2group (Tully
et al. 2013 Table 2). Both catalogs are presented with
peculiar velocities with and without a correction for the
nonlinear Hubble relation at large $z$. In each ta-
ble, they also give adjusted peculiar velocities to ac-
count for a bias that arises because it is the distance
moduli that have Gaussian error distributions, not the
distances themselves. In our analysis below we have in-
vestigated both galaxy and group compilations in thei-
rown adjusted and unadjusted incarnations.

3 THEORY

Intuitively, we think of the bulk flow of a sample of
objects as being the motion of the volume containing
the sample. However, in practice measured bulk flows
can be much more difficult to interpret. For example,
in the maximum likelihood estimation (MLE) method
(e.g. Kaiser 1988, 1991, Sarkar et al. 2007, Watkins
& Feldman 2007), the components of the bulk flow $U_i$
are calculated as a weighted average over the measured
radial velocities $S_q$ of the objects at positions $\vec{r}_q$ in the
survey

$$U_i = \sum_q w_{i,q} S_q$$

where the MLE weights, $w_{i,q}$ are given by

$$w_{i,q} = A_{ij} \frac{\hat{r}_{q,j}}{\sigma^2_q + \sigma^2_z},$$

$\hat{r}_q$ is a unit vector in the direction of the $q^{th}$ object and

$$A_{ij} = \frac{\hat{r}_{q,i} \hat{r}_{q,j}}{\sigma^2_q + \sigma^2_z}.$$
the idealized survey to be a dense set of objects with a gaussian radial distribution function with radius $R_G$.

To optimize the weights for the surveys, we begin by considering a hypothetical ideal survey whose moment components $U_i$ have the desired window function that probes a desired scale. In practice we use an ideal survey that consists of a very large number of objects isotropically distributed with a gaussian falloff in density, $n(r) \propto \exp(-r^2/2R_G^2)$, where $R_G$ is the scale over which the flow is analyzed. Now, suppose that we have a galaxy or cluster survey consisting of positions $r_i$ and measured line-of-sight velocities $v_i$ with associated measurement errors $\sigma_i$. We can calculate the weights $w_{i,q}$ that specify the moments $U_q = \sum_i w_{i,q} v_i$ that minimize the average variance, $\langle (U_q - U) \rangle^2$. We call these the MV weights. The MV moments $U_q$ calculated from these weights are the best estimates of the moments of the ideal survey, if it were to exist, that can be obtained from the available data. We also expect that, within limits that will be described more fully below, the window functions of $u_i$ will match those of the ideal survey.

The MLE formalism averages peculiar velocities using weights calculated to minimize the error of the flow moments. It does that by ignoring other essential features of the dataset. In particular, it does not take into account the spatial distribution of the galaxies. The window functions of the resulting bulk flow moments will thus reflect the scales of maximum information, which will vary from survey to survey. The MV formalism; however, calculates weights by minimizing the theoretical variance between the estimate of the bulk flow from the actual survey and that of an ideal survey that is very dense, covers the whole sky, and has a Gaussian fall off of a particular and adjustable depth. Thus the MV scheme provides a way to find velocity moments as a function of a controllable scale ($R_G$). Further, because the MV bulk flow estimate is of a standardized quantity independent of the survey characteristics, it can be compared between different surveys. In contrast, since the MLE formalism samples the power spectrum in a different way for each survey, direct comparison between catalogs is not possible.

As an illustration of how the MV method works, consider analyzing a typical peculiar velocity catalog with measurement uncertainties that increase linearly with distance. A typical survey also tends to be more dense at small distances, where measurements are easier to make. The maximum likelihood method applied to this survey will give higher weight to nearby galaxies, where there is more information, so that the bulk flow will reflect scales somewhat smaller than that of the survey. If one applied the MV method to the same survey, the parameter $R_G$ could be varied to examine how the bulk flow changes with depth. As $R_G$ is increased, more weight is put on the more distant galaxies in the bulk flow estimate. In principle, the downside of changing the weights is that it increases the uncertainty in the resulting estimate; however, we have found that in reasonable applications of the MV method this increase in uncertainty has not been significant. Specifically, the MV method works well when the volume of the idealized survey is well populated objects from the peculiar velocity sample.

### 4 RESULTS

In Fig. 1 we show the window functions for the MV estimates of the three components of the bulk flow for the two surveys for $R_G = 20$ (left panels) and $50$ h$^{-1}$ Mpc (right panels) for the Cosmicflows-2 catalog (upper panels) and the COMPOSITE (lower panels). The thin lines are the window functions for the MV for each of the bulk flow Galactic Cartesian components ($x$ - red, $y$ - green, $z$ - blue) respectively. The thick black line is the ideal window function (since the ideal survey is isotropic, all component are the same). It is clear that the window functions for the two samples agree with each other very well.

![Figure 1](image_url)

**Figure 1.** The normalized window functions of the bulk flow component for $R_G = 20$ h$^{-1}$Mpc (left panels) and $R_G = 50$ h$^{-1}$Mpc (right panels) for the Cosmicflows-2 catalog (upper panels) and the COMPOSITE (lower panels). The thin lines are the window functions for the MV for each of the bulk flow Galactic Cartesian components ($x$ - red, $y$ - green, $z$ - blue) respectively. The thick black line is the ideal window function (since the ideal survey is isotropic, all component are the same). It is clear that the window functions for the two samples agree with each other very well.
Figure 2. The estimates of the MV BF of the Cosmicflows-2 (solid lines) and COMPOSITE (dashed lines) catalogs as a function of $R_G$ in galactic coordinates. cally lower on larger scales. Given that the two surveys probe the power spectrum in the same way, it is likely that the disagreement shown in Fig. 2 is due to systematic differences in distance measurements between the two catalogs.

In order to investigate the differences between the COMPOSITE and the Cosmicflows-2 surveys, we examined the radial dependence of the bulk flows in more detail. In Fig. 3 (left panel) we show the maximum likelihood bulk flow component $-u_y$ for $20h^{-1}$Mpc thick shells for both surveys. Maximum likelihood estimates work well for shells since the objects in a shell are all at similar distances, so there is no issue with having a radius dependent weighting as there is in the case of spherical volumes. In the figure we see that for the COMPOSITE survey, the shell $-u_y$ initially drops with radius, but then at about $50h^{-1}$Mpc, $-u_y$ turns around and begins to increase. This is difficult to understand physically, as it suggests that the outer shells, and hence the volume, are moving in a coherent flow in which the inner shells somehow do not participate. It seems unlikely that the inner part of the volume would have a compensating relative motion to the outer part that would make it appear at rest. Again, we see that the Cosmicflows-2 does not exhibit the anomalously large flow in the outer shells.

Given that we are working with the radial components of peculiar velocities, contributions to the bulk flow component $u_y$ primarily come from objects near the $\pm y$ directions. It is interesting to separate the contributions to the bulk flow coming from these two regions. In the right panel of Fig. 3 we show the same information as in left panel except that we have given the contribution to the bulk flow in the (Cosmicflows-2, COMPOSITE) surveys from galaxies with $y > 0$ (solid, long-dash) and $y < 0$ (short-dashed, dash-dot) separately.

Figure 3. In the left panel we show the maximum likelihood bulk flow component $-u_y$ for $20h^{-1}$Mpc thick shells for the COMPOSITE (long-dash line) and the Cosmicflows-2 (solid line) surveys. In the right panel we show the same information as in left panel except that we have given the contribution to the bulk flow in the (Cosmicflows-2, COMPOSITE) surveys from galaxies with $y > 0$ (solid, long-dash) and $y < 0$ (short-dashed, dash-dot) separately.

Figure 4. The distances for the COMPOSITE and Cosmicflows-2 for 2425 common objects. It is clearly seen that the CF2 distances are systematically larger than those of the COMPOSITE survey. This leads to a smaller magnitude for $u_y$ as discussed in the text.

Given that we are working with the radial components of peculiar velocities, contributions to the bulk flow component $u_y$ primarily come from objects near the $\pm y$ directions. It is interesting to separate the contributions to the bulk flow coming from these two regions. In the right panel of Fig. 3 we show the same information as in left panel except that we have shown the contribution to the bulk flow from galaxies with $y > 0$ and $y < 0$ separately. For the COMPOSITE sur-

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are less susceptible to selection Malmquist bias since SFI++ distances. Distances calculated by Tully et al. SFI++ survey, which is an acknowledged issue with the ascribe this trend to selection Malmquist bias in the with redshift compared to the SFI++ distances. They compared to those given in the SFI++ catalog (Masters et al. 2071 common galaxies calculated using their method. For example, Tully et al. (2013) compare distances to different methodologies used in calculating distances. contributed from peculiar velocities in the Cosmicflows-2 survey the contribution from magnitude of u above, systematically increasing distances reduces the magnitude of y > 0 is increased, systematic distances increasing reduces the magnitude of u. We see in Fig. 3 right panel that in the Cosmicflows-2 survey the contribution from y < 0 is reduced while the contribution from y > 0 is increased, although, as expected, the increase is much smaller in magnitude. The fact that distant galaxies have systematically larger distances in the Cosmicflows-2 survey as compared to the COMPOSITE survey is due to the different methodologies used in calculating distances. For example, Tully et al. (2013) compare distances to 2071 common galaxies calculated using their method to those given in the SFI++ catalog (Masters et al. 2006, Springob et al. 2007), which were used to compile the COMPOSITE sample. Their Fig. 9 shows a trend, their distances are systematically larger and increasing with redshift compared to the SFI++ distances. They ascribe this trend to selection Malmquist bias in the SFI++ survey, which is an acknowledged issue with the SFI++ distances. Distances calculated by Tully et al. are less susceptible to selection Malmquist bias since they use the inverse TFR (Willick 1994). However, this only explains the difference in distance measurements for about 2000 TFR galaxies common to the two catalogs; for a full accounting of the methodology differences in the distance calculations used we direct the reader to Tully et al. (2013).

In Table 1 we show estimates of the MV bulk flow components for $R_G = 50 h^{-1}$ Mpc for the COMPOSITE sample and for several different versions of the Cosmicflows-2 compilation. First, we show the COMPOSITE results for comparison. Then we show the Cosmicflows-2 group catalog, for both the adjusted and direct distance estimates, consisting of 5223 galaxies and groups (Tully et al. 2013 Table 2) and the galaxy sample with 8315 individual galaxies that have not been put into groups (Tully et al. 2013 Table 1). We also show the probability of finding flows as large or larger [$P(> \chi^2)$] for both WMAP9 (Bennett et al. 2013) and and Planck (Planck Collaboration et al. 2013) central parameters.

In the results shown in Fig. 2 and Table 1 we have included an adjustment made by Tully et al. to account for the fact that distance moduli have Gaussian error distributions, so that uncertainties in distances are not symmetric about the central values. This effect enhances negative peculiar velocities relative to positive peculiar velocities. Here we also show the results when this adjustment is not made. Tully et al. (2013) also make a small correction for deviations from a linear Hubble relation. Here we show the results if this correction is not made. Finally, in Table 2 we show results for the case where redshifts are used instead of distances.

| Survey       | $u_x$ (km s$^{-1}$) | $u_y$ (km s$^{-1}$) | $u_z$ (km s$^{-1}$) | $|v|$ (km s$^{-1}$) | $P_{WMAP}$ | $P_{Planck}$ |
|--------------|---------------------|---------------------|---------------------|-------------------|------------|-------------|
| COMPOSITE    | 101.0 ± 38.3        | -362.0 ± 39.2       | 39.3 ± 30.6         | 377.9 ± 62.7      | 1.9        | 1.6         |
| CF2 adjusted | 88.4 ± 36.9         | -240.4 ± 37.6       | 55.0 ± 29.6         | 262.0 ± 60.5      | 17.1       | 15.7        |
| CF2 group    | 98.0 ± 36.9         | -273.0 ± 37.6       | 57.3 ± 29.6         | 295.6 ± 60.5      | 9.5        | 8.5         |
| CF2 adjusted | 116.0 ± 36.4        | -267.8 ± 37.1       | 46.2 ± 29.2         | 295.4 ± 59.6      | 9.6        | 8.6         |
| CF2 galaxy   | 108.2 ± 36.4        | -258.3 ± 37.1       | 39.9 ± 29.2         | 282.9 ± 59.6      | 12.1       | 10.9        |

| Survey       | $u_x$ (km s$^{-1}$) | $u_y$ (km s$^{-1}$) | $u_z$ (km s$^{-1}$) | $|v|$ (km s$^{-1}$) | $P_{WMAP}$ | $P_{Planck}$ |
|--------------|---------------------|---------------------|---------------------|-------------------|------------|-------------|
| COMPOSITE    | 25.7 ± 36.9         | -367.7 ± 37.8       | 38.2 ± 29.8         | 370.6 ± 60.6      | 5.9        | 5.6         |
| CF2 adjusted | 39.7 ± 36.1         | -208.0 ± 37.2       | 55.1 ± 29.5         | 218.8 ± 59.7      | 26.9       | 27.1        |
| CF2 group    | 44.1 ± 36.6         | -229.3 ± 37.6       | 58.1 ± 30.0         | 240.6 ± 60.5      | 15.8       | 15.9        |
| CF2 adjusted | 34.1 ± 35.5         | -284.5 ± 36.6       | 77.6 ± 28.9         | 296.8 ± 58.7      | 39.6       | 38.5        |
| CF2 galaxy   | 31.6 ± 36.0         | -280.4 ± 37.1       | 72.6 ± 29.4         | 291.3 ± 59.4      | 20.6       | 20.0        |

Table 1. Bulk flow vectors for the surveys (in Galactic Cartesian coordinates) for MV weights for $R_G = 50 h^{-1}$ Mpc. The quoted errors includes both noise and the difference from the idealized survey geometry. The last two columns are total observed probability $P(> \chi^2)$ of finding flows as large or larger, in percent, for the central parameters ($h, \Omega_m, \sigma_8$) from WMAP9 (Bennett et al. 2013 (0.700, 0.279, 0.821)) and Planck (Planck Collaboration et al. 2013 (0.671, 0.318, 0.834)).

Table 2. The same as Table 1 using redshifts for distances.
of distances to specify the positions of objects in the samples.

5 DISCUSSION

WFH and FWH reported a larger than expected bulk flow on scales of 100 $h^{-1}$Mpc based on a compilation of distance and peculiar velocity data dubbed the COMPOSITE survey. [Tully et al. 2013] presented a new compilation of peculiar velocity data, Cosmicflows-2, which both adds new data and adjusts published distances and peculiar velocities to achieve consistency between the constituent datasets, which use a variety of different distance measurement techniques. In this paper we have analyzed the large scale motions in the Cosmicflows-2 samples and found that they are significantly smaller than those in the COMPOSITE catalog. While WFH found that bulk flows on scales of $100 h^{-1}$ Mpc were inconsistent with the standard ΛCDM model at the 98% confidence level, the probability of finding flows as large or larger as those shown in Table 1 is of $O(10\%)$, showing consistency between theory and observations. Thus the Cosmicflows-2 sample potentially resolves an important challenge for ΛCDM cosmology.

Using the MV method it is possible to estimate the bulk flow on different scales using a given set of peculiar velocity measurements. A puzzling feature of the measurement and analysis of large scale peculiar velocities is the same in all regions of space, an assumption that has been questioned in several recent papers. [Giovanelli et al. 1999, Conley et al. 2007, Sinclair et al. 2010, Wiltshire et al. 2013]. Furthermore, a bulk flow can itself cause an apparent spatial variation in the Hubble constant. By adjusting all of the subsets of the Cosmicflows-2 catalog to have the same Hubble constant, [Tully et al. 2013] may have inadvertently suppressed a real bulk flow.

A related issue is that [Tully et al. 2013] say that their catalog is consistent with a value for the Hubble parameter of 74.4 $±$ 3.0 km s$^{-1}$Mpc$^{-1}$, a value that is in conflict with the recent Planck measurement of 67.4 $±$ 1.4 km s$^{-1}$Mpc$^{-1}$ [Planck Collaboration et al. 2013], which is lower than other local measurements as well. Since peculiar velocity determinations depend crucially on understanding the characteristics of cosmological redshift, until the discrepancy between local and global measurements of the Hubble parameter is resolved, we cannot be confident that we truly understand motions on scales of $\gtrsim (100 h^{-1}$Mpc).

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