CHAPTER 5.

Megaparsec Velocity Flows

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Birdeye's view of the IAU Symposium 308 Banquet.

The White Hall in the 16th century
House of the Brotherhood of the Black Heads.

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The Zeldovich Universe:
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Cosmicflows-2

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Abstract. A compendium of over 8000 galaxy distances has been accumulated. Distance measurements permit the separation of observed velocities into cosmic expansion and peculiar velocity components. Only the radial component of peculiar velocities can be measured and individual errors are large, but a Wiener Filter procedure permits the reconstruction of three-dimensional motions and the density field that is responsible for these motions. A coherent flow pervades the entire domain of $\pm 15,000$ km/s. Techniques are discussed for the separation of local and tidal components of the flow. Laniakea supercluster is identified as a region of contiguous infalling flows.

Keywords. Galaxies: distances and redshifts; peculiar velocities; dark matter; large scale structure of galaxies.

1. Distances

The overarching goal of the Cosmic Flows program is to map the distribution of matter in the local region of the universe from the departures from cosmic expansion engendered by the matter. The overall program has many elements that have been discussed in detail in other publications. The intent of this brief article is to provide a roadmap through the labyrinth of activities.

A primary product of the program is distances to individual galaxies. If the interest is in maps of peculiar velocities, the radial component of deviations from Hubble expansion, then only relative distances are needed. One needs to cancel the overall expansion with a value of the Hubble Constant appropriate to the distance measurements. A zero-point scale error factors out.

Of course, it makes sense to match as well as possible to the best information available on all scales. The expectation has been raised that the Hubble Constant can be determined with an accuracy of a few percent (Riess *et al.* 2011; Freedman *et al.* 2012). It does not take too great a memory to recall a time when the value of H_0 was very contentious. Figure 1 is offered in the spirit of a warning. The plot shows a recent version of the correlation between galaxy luminosity and rotation rate at H band. Four galaxies are identified by name. Prior to circa 1990, the absolute calibration depended on just these galaxies. All four of these galaxies lie within 1σ of the mean relation defined by current much larger samples. Yet they all happen to lie fainter than the mean correlation at their observed linewidths. But 1σ amounts to a 10% offset, the difference between H_0 in the mid 80's (Pierce & Tully 1988) and H_0 in the mid 70's. The most recent calibration of the luminosity $-$ linewidth correlation combines luminosity information obtained in the satellite infrared with optical photometry, uses 36 absolute calibrators, and is linked to

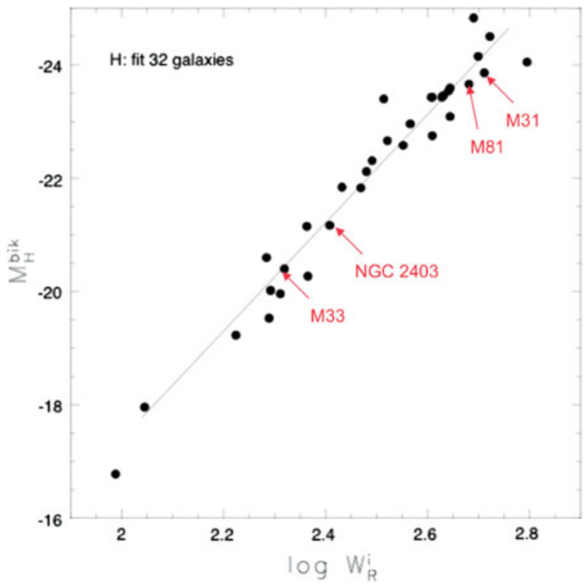

Figure 1. Luminosity-linewidth correlation for galaxies with either Cepheid or tip of the red giant branch distances. Prior to early 1990's, only the 4 identified galaxies had known Cepheid distances.

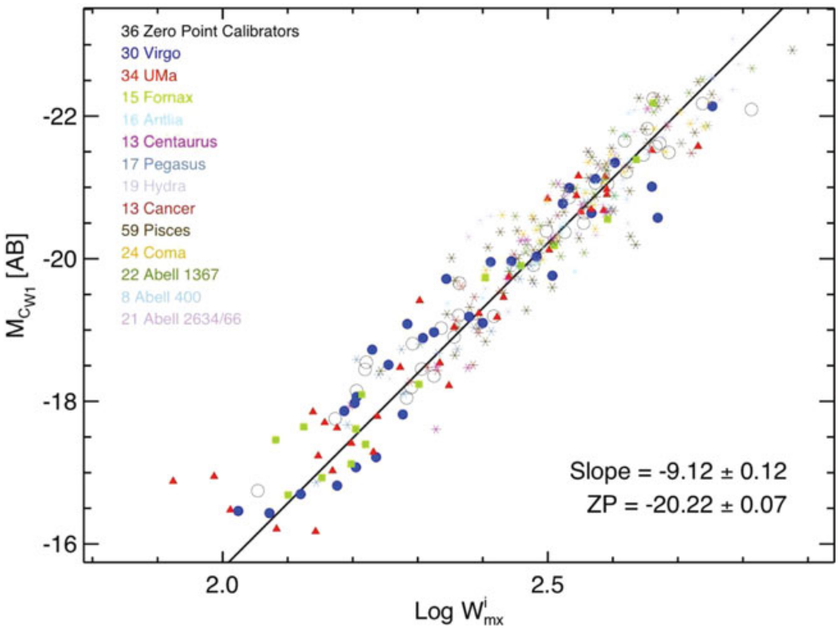

Figure 2. Luminosity−linewidth relation using WISE photometry at 3.4 μm including an adjustment for a color term. A slope template is created from a sample of galaxies in 13 clusters and the zero point is established by 36 nearby galaxies with Cepheid or TRGB distances.

the SNI*a* methodology which allows H_0 to be determined at distances well beyond the domain affected by deviant motions. This procedure leads to the measurement $H_0 = 74.4$ km/s/Mpc with a 68% probability uncertainty of 4% (Neill *et al.* 2014).

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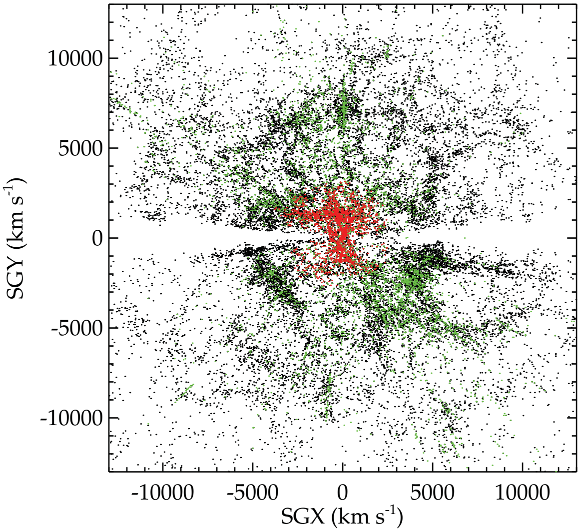

Figure 3. Projection of the distribution of galaxies on the supergalactic equator. All galaxies from the 2MASS $K < 11.75$ redshift survey with SGZ $< \pm 4000$ km/s in black, galaxies with distance measures in Cosmicflows-1 in red, and galaxies with distance measures in Cosmicflows-2 in green. The plane of our Galaxy lies at SGY=0 and causes the wedges of evident incompletion.

The initial release from the program, renamed Cosmicflows-1 (Tully *et al.* 2008), has been superceded by Cosmicflows-2 (Tully *et al.* 2013). Six primary methodologies have been combined for the measurement of distances: one based on the Cepheid period−luminosity relation, a second on the luminosity of the tip of the red giant branch, the third on the properties of surface brightness fluctuations in systems dominated by old populations, a forth on the elliptical galaxy fundamental plane correlation, a fifth on the spiral galaxy luminosity−linewidth relation, and finally on the standard candle nature of type Ia supernovae. Members of our collaboration have made major contributions with two of the methodologies. Cosmicflows-2 contains almost 300 tip of the red giant branch distance measurements based on imaging using Hubble Space Telescope (Jacobs *et al.* 2009); subsequent observations have increased the number to almost 400. Meanwhile roughly 4000 distances in Cosmicflows-2 are contributed by the luminosity−linewidth correlation, combining optical photometry (Courtois *et al.* 2011a) and neutral Hydrogen global profile linewidths (Courtois *et al.* 2011b). Infrared photometry at 3.6 μm obtained with Spitzer Space Telescope provided an alternative calibration (Sorce *et al.* 2013). In the next release of Cosmic Flows the infrared photometry will make a much larger contribution (Sorce *et al.* 2014; Neill *et al.* 2014). Figure 2 shows the most recent version of the luminosity−linewidth relation based on 3.4 μm photometry with WISE, the Wide-field Infrared Survey Explorer.

In all, Cosmicflows-2 provides distances for over 8000 galaxies, with roughly 6000 contributed by the luminosity−linewidth method, 1500 coming from the fundamental plane, and 1200 given by methods that afford individual distances with accuracies of 10% or better. The projection of these galaxies in supergalactic coordinates is shown in Figure 3.

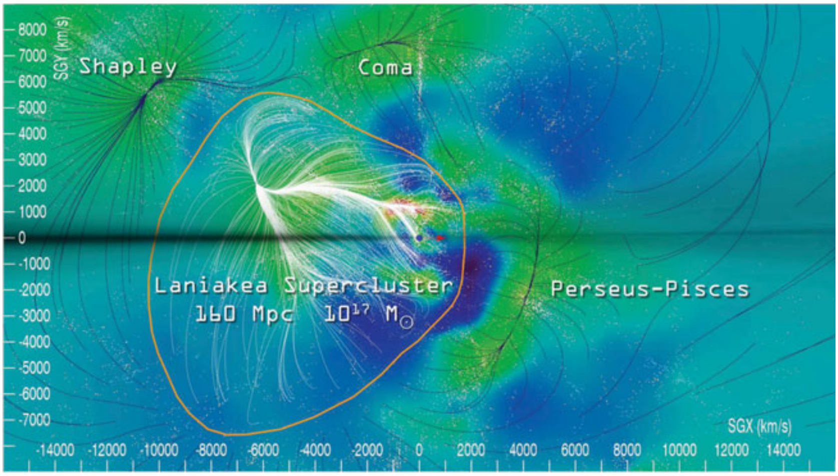

Figure 4. Laniakea supercluster of galaxies. The color palette indicates densities running from low at blue to high at red. Local flows in white lie within the region bounded by the orange outline. External flows to other attractors are in black. Important features are labeled. The horizontal dark wedge identifies the zone of obscuration.

2. Velocities and Densities

The Cosmicflows-2 data set is characterized by high density and accuracy nearby degrading to sparse sampling and large uncertainties at greater distances. The procedure of Wiener Filtering provides a Bayesian probability that the data fits a prior model consistent with a WMAP or Planck power spectrum assuming initial Gaussian fluctuations. Constrained realizations sample the statistical scatter about the mean Wiener Filter field. The reconstruction is only valid in the linear regime but this approximation holds down to scales of a few Mpc in the velocity field. At large scales, coherence in velocity flows carry information on tidal influences significantly beyond the range of distance measurements.

An initial analysis with Cosmicflows-1 data (Courtois *et al.* 2012, 2013) has been followed with a Cosmicflows-2 study (Tully *et al.* 2014). A coherent flow is evident across the entire domain of observations extending $\pm 15,000$ km/s, with the Shapley Concentration at the evident terminus. The extensive nature of the flow results in the unsatisfactory situation that there is still no resolution of the extent of the influences responsible for our motion with respect to the cosmic microwave background. In the study reported in Nature the emphasis was on intermediate scale structures. By giving consideration to the reconstructed densities in a restricted region, local flows due to that distribution of matter can be determined. Tidal components from regions external to the restricted region are given by the vector subtraction of the local velocities from the global velocities. This procedure permits the isolation of individual basins of attraction. It is of great interest that the current velocity field information permits a definition of the full extent of the basin of attraction that includes our galaxy. A view in Figure 4 of a slice in the supergalactic equatorial plane illustrates the structure that is identified.

Our galaxy is found to lie in a basin of attraction that extends across roughly 160 Mpc diameter in all three orthogonal directions, a volume enclosing $10^{17}\ M_\odot$ and including 100,000 large galaxies. The densest part is in the vicinity of the Norma and Centaurus clusters at roughly the location of what has been called the Great Attractor region. The outer reaches tend to lie in voids but there are interesting locations where apparent filaments run between adjacent basins of attraction. The filaments are shearing at the

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juncture between the entities. The name Laniakea supercluster has been given to our home large scale structure (in Hawaiian: 'lani' = heaven; 'aiea' = extremely large). Our Milky Way galaxy lies at the periphery of Laniakea, near the boundary with the adjacent Perseus−Pisces structure.

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