The RMS Peculiar Velocity of Clusters

Richard Watkins
Department of Physics and Astronomy, Dartmouth College, Hanover NH 03755, USA
rwatkins@dartmouth.edu

21 March 2022

1 INTRODUCTION

Several recent papers have shown that the peculiar velocities of clusters of galaxies can be used to put strong constraints on cosmological parameters (Croft and Efstathiou 1994; Bahcall, Gramann, and Cen 1994; Bahcall and Oh 1996; Moscardini et al. 1996; Borgani et al. 1997; Shi 1997). Much of their utility in this regard derives from the fact that the motions of clusters probe the peculiar velocity field predominantly on scales where it is still linear, making the comparison to theoretical models relatively straightforward. In addition, peculiar velocities of clusters can in principle be measured to much higher accuracy than those of galaxies, since many galaxies can be measured per cluster. Thus the motions of clusters should provide a valuable tool in the study of large scale structure.

However, results obtained thus far using different catalogs of cluster peculiar velocities have been contradictory (see, e.g., Moscardini et al. 1996). In order to have confidence in the use of cluster peculiar velocities as a probe of large scale structure it is important to understand why this is so. In this Letter we study this issue, focusing on the estimation of the rms peculiar velocity of clusters. This statistic gives us a convenient way to compare different samples of cluster peculiar velocities and can be compared directly to predictions of cosmological models obtained from either $N$-body simulations or linear theory. Indeed, as we show below, the rms peculiar velocity of clusters can be directly related to the combination of parameters $\Omega_0^{0.6} \sigma_8$, where $\sigma_8$ is the rms mass fluctuation on a scale of 8 h$^{-1}$Mpc, $H_0 = 100 h$ km s$^{-1}$ Mpc$^{-1}$).

We use a likelihood analysis to estimate the rms peculiar velocity of clusters from line-of-sight velocities and their estimated errors. This analysis allows us to assess the consistency of two samples in a model independent way. We apply our method to two well-studied catalogs of cluster peculiar velocities; a new sample based on measurements of 782 spiral galaxies in the fields of 24 clusters described in Giovanelli et al. (1997) (hereafter the SCI sample) and a subset of the cluster peculiar velocities contained in the Mark III catalog (Willick et al. 1995, 1996, 1997a) based on measurements of 346 galaxies in the fields of 31 clusters described in Mould et al. (1991), Han (1992), and Mould et al. (1993) (hereafter the HM sample). The HM sample was used to set the zero-point of the Tully-Fisher relation for the Mark III catalog. These samples cover the sky uniformly, have comparable depths, and are based on Tully-Fisher distance determinations. As we shall show below, these two samples yield results which are inconsistent at a high level.

We argue that the inconsistency between the two sam-
The normalization $B_k$ can be expressed in terms of the rms linear mass fluctuation on scales of $8 \, h^{-1}$Mpc, $\sigma_s$, which is defined by

$$\sigma_s^2 \equiv \frac{1}{(2\pi)^3} \int_0^\infty P(k) W_s^2(k) \, dk, \quad (3)$$

where $W_s(k) = 3j_1(k R_s)/k R_s$ with $R_s = 8 \, h^{-1}$Mpc and $j_1$ is a spherical Bessel function. Following Colberg et al. 1997, we can express $\sigma_v$ as

$$\sigma_v = \frac{100 \, \text{km s}^{-1}}{\sqrt{3} \, \Omega_0^{0.6} \sigma_s \sqrt{f(\Gamma)}}, \quad (4)$$

where the function $f(\Gamma)$ is defined as

$$f(\Gamma) \equiv 4\pi h^2 \frac{\int P(k) W^2(k) \, dk}{\int P(k) W^2_2(k) \, dk}.$$
Figure 1. The normalized likelihood functions for $\sigma_v$ obtained from the SCI and HM samples.

Figure 2. Peculiar velocities and 1σ errors of the 12 objects common to the SCI and HM samples.

$\sigma_v = 489$ km s$^{-1}$ predicted by an $\Omega_0 = 1$ CDM model normalized to microwave background fluctuations (Bahcall et al. 1994). (Note that these papers quote the 3-D rms velocity, which must be divided by $\sqrt{3}$ for comparison to $\sigma_v$, the 1-D rms velocity.) The larger value favored by the HM sample is quite consistent with $\Omega_0 = 1$ CDM normalized to COBE fluctuations.

We can quantify the disagreement between the two samples using their normalized likelihood functions. The probability of the two samples having values of $\sigma_v$ which differ by $\Delta$ is given by $P(\Delta) \propto \int_0^\infty L_{HM}(\Delta + \sigma_v) L_{SCI}(\sigma_v) \, d\sigma_v$. A measure of the probability that the two data sets are drawn from distributions with the same $\sigma_v$ is given by the relative area under the curve satisfying $P(\Delta) < P(\Delta = 0)$. Using this measure we find that the SCI and HM samples disagree on the value of $\sigma_v$ at the 99.8% confidence level.

Insight into the nature of the discrepancy between the two samples can be gained by examining the 12 objects that they have in common. In Fig. 2, we show the velocity and error estimates for these 12 clusters as given in the SCI ($x$-axis) and HM ($y$-axis) catalogs. The measurements are in good agreement except for the Cancer cluster, corresponding to the point in the lower middle of the plot. This cluster has been studied by Bothun et al. (1983), who concluded that it consisted of several discrete groups spread in velocity over 2800 km s$^{-1}$. Furthermore, their results suggest that the groups are not gravitationally bound, but rather are separating with the Hubble flow. Giovanelli et al. (1997) selected all of their Cancer cluster galaxies from the largest mass group, whereas the Cancer cluster galaxies in the HM sample are drawn from several of the groups. The good agreement of the reported velocities for the less complex clusters suggests that the inconsistency regarding the Cancer cluster is due to the difference in membership criteria. Indeed, it seems likely that the velocity from the HM sample does not reflect that of a single gravitationally bound object.

In order to explore the possibility that the discrepancy between the SCI and the HM samples is due to effects that are not properly accounted for in the error estimation, we construct subsamples SCI$^\star$ and HM$^\star$ of the cluster samples from which we remove clusters that we consider suspect. These mostly consist of clusters which the observers noted as having ambiguities in their associated galaxy samples or particularly poor data. We also remove clusters for which other observers have noted evidence for multiple mass concentrations or overlap with other clusters. From the SCI sample, we excise six paired clusters (A2197/A2199, Pavo/Pavo II, and A2634/A2666) which have possible cluster membership ambiguities. A2634 and Pavo II are also in the HM sample, and we remove them from this sample as well. The following additional clusters are removed from the HM sample: Cancer (see above), Pisces (Sakai et al. 1994), MKW1S, and A779 (Mould et al. 1993), due to their having multiple mass concentrations; 3C 296, due to its distribution of galaxies on the sky not being well defined (Mould et al. 1993); 1559+19, due to it being sparsely sampled and composed of rather inhomogenous data (Mould et al. 1991); N5419, due to poor sampling and possible substructure (Mould et al. 1991); and OCA 3560 (Mould et al. 1991), due to possible contamination by foreground or background galaxies. This leaves us with reduced samples of 18 SCI$^\star$ clusters and 18 HM$^\star$ clusters.

In Fig. 3 we show normalized likelihood functions for $\sigma_v$ obtained from the SCI$^\star$ and HM$^\star$ subsamples. While the results for the SCI sample are essentially unchanged, we see a marked reduction in the maximum likelihood value of $\sigma_v$ for
the HM$_*$ clusters. We have determined that the probability of selecting a subset of 18 clusters at random from the HM sample that results in a maximum likelihood value of $\sigma_v$ as small or smaller than that of the HM$_*$ sample is only 0.002. This strongly suggests that the suspect clusters in the HM sample have systematically higher measured velocities relative to their reported errors than the other clusters in the sample. Given that the excised clusters were chosen due to ambiguities in their galaxy samples, it seems likely that these ambiguities have contributed to their measured velocities from unaccounted-for errors. The fact that the SCI results are not changed significantly by the removal of the suspect clusters is probably due to the strict membership criteria employed by Giovanelli et al. (1997) in the selection of their cluster galaxy samples. The use of these strict criteria lowers the probability of incorrect membership assignment and helps to ensure that each galaxy sample describes a single collapsed object, thus reducing the possible errors in the velocities measured for the 6 suspect clusters.

With the suspect clusters removed, the two subsamples are in good agreement, both favoring a relatively low value of $\sigma_v$. The SCI$_*$ subsample, which has smaller errors than the HM$_*$ subsample, yields $\sigma_v = 247_{-80}^{+123}$ km s$^{-1}$ (here and below errors are quoted at the 90% confidence level). Making the assumptions about the power spectrum outlined above, this gives $\Omega_0 \sigma_8 = 0.42_{-0.21}^{+0.24}$ in good agreement with a previous analysis of the SCI data by Borgani et al. (1997). We get only a slight improvement in the accuracy of our result by combining the SCI$_*$ and HM$_*$ samples; keeping the measurement with the smaller error for clusters present in both results in a combined sample of 28 clusters yielding $\sigma_v = 257_{-76}^{+108}$ km s$^{-1}$ and $\Omega_0 \sigma_8 = 0.44_{-0.10}^{+0.19}$. Using the likelihood function we find that the combined sample is consistent with the value of 489 km s$^{-1}$ predicted for standard $\Omega_0 = 1$ CDM normalized to COBE at the 99.7% confidence level.

4 DISCUSSION

We have shown that when suspect clusters are removed, the SCI and the HM samples show excellent agreement, both favoring relatively low values for the rms peculiar velocity of clusters; using a combined sample we find $\sigma_v = 257_{-76}^{+108}$ km s$^{-1}$. If one makes some reasonable assumptions about the shape of the power spectrum, this converts to $\Omega_0 \sigma_8 = 0.44_{-0.10}^{+0.19}$. These results are in good agreement with the results of cluster abundance studies, but are inconsistent with $\Omega_0 = 1$ CDM normalized to COBE at the 99.7% confidence level.

Our results suggest that peculiar velocities calculated for galaxy samples that are not representative of a single mass concentration are susceptible to large unaccounted-for errors. This is perhaps not too surprising, since velocities are calculated assuming that all of the sample galaxies have a common distance. While this assumption is always violated to some extent due to the non-zero thickness of a cluster, the presence of multiple mass concentrations or contamination by foreground or background galaxies makes it much more likely that the galaxy sample will by distributed anisotropically about the cluster center, leading to a bias in the measured velocity. This problem is especially severe for spiral galaxy samples, since they tend to inhabit the outer regions of clusters. The fact that the central cores of clusters consist primarily of ellipticals makes it likely that as the fundamental-plane distance measure continues to improve it will become the preferred method for measuring the peculiar velocity of clusters.

It is unclear what implications, if any, these results have for the Mark III catalog of galaxy peculiar velocities. Although the HM cluster data set was used in the calibration of this catalog, Willick et al. (1995) recognized that not all of the galaxy samples were well modeled as belonging to a single cluster and accounted for this in their calibration procedure.

More cluster peculiar velocities are needed in order to improve the robustness of our results. In particular, a larger sample will allow us to study the dependence on cluster selection and the validity of our approximation that cluster peculiar velocities are gaussian distributed. However, our results underscore the importance of careful galaxy sample selection when measuring cluster peculiar velocities.

ACKNOWLEDGMENTS

The author wishes to thank J. Mohr, H. Feldman, G. Wegner, and W. Freudling for useful discussions. This work was supported in part by NSF grant PHY-9453431 and NASA grant NAGW-4720.

REFERENCES

Aaronson M., Bothun G. D., Cornell M. E., Dawe J. A., Dickens R. J., Hall P. J., Han M. S., Huchra J. P., Lucey J. R., Mould...
The RMS Peculiar Velocity of Clusters

J. R., Murray J. D., Schommer R. A., and Wright A. E., 1989, ApJ, 338, 654
Bahcall N. A. and Oh S. P., 1996, ApJ, 462, L49
Bahcall N. A., Cen R, and Gramann M., 1994, ApJ, 430, L13
Borgani S., da Costa L. N., Freudling W., Giovanelli R., Haynes M. P., Salzer J., and Wegner G., 1997, astro-ph/9703144
Bothun G. D., Geller M. J., Beers T. C., and Huchra J. P., 1983, ApJ, 268, 47
Colberg J. M., White S. D. M., Jenkins A., Pearce F. R., Frenk C. S., Thomas P. A., Hutchings R., Couchman H. M. P., Peacock J. A., Efstathiou G., Nelson, A. H., 1997, astro-ph/9703148
Croft R. A. C. and Efstathiou G., 1994, ApJ, 430, L13
Efstathiou G., Bond J. R., and White S. D. M., 1992, MNRAS, 258, L23
Giovanelli R., Haynes M. P., Herter R., Vogt N. P., Wegner G., Salzer J. J., da Costa L. N., and Freudling W., 1997, AJ, 113, 22
Han M., 1992, ApJS, 81, 35
Moscadini L., Branchini E., Brunozzi P. T., Borgani S., Plionis M., and Coles P., 1996, MNRAS, 282, 384
Mould J. R., Staveley-Smith L., Schommer R. A., Bothun G. D., Hall P. J., Han M. S., Huchra J. P., Roth J., Walsh W., and Wright A. E., 1991, ApJ, 383, 467
Mould J., Akeson R. L., Bothun G. D., Han M., Huchra J. P., Roth J., and Schommer R. A., 1993, ApJ, 409, 14
Peacock J. A. and Dodds S. J., 1994, MNRAS, 267, 1020
Sakai S., Giovanelli R., and Wegner G., 1994, AJ, 108, 33
Shi X., 1997, astro-ph/9705022
Willick J. A., Courteau S., Faber S. M., Burstein D., Dekel A., 1995, ApJ, 446, 12
Willick J. A., Courteau S., Faber S. M., Burstein D., Dekel A., and Kolatt T., 1996, ApJ, 457, 460
Willick J. A., Courteau S., Faber S. M., Burstein D., Dekel A., and Strauss M. A., 1997a, ApJS, 109, 333
Willick J. A., Strauss M. A., Dekel A., and Kolatt T., 1997b, ApJ, 486, 629

© 0000 RAS, MNRAS 000, 000–000