EFAR peculiar velocities and bulk motions

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Abstract. The EFAR project has measured peculiar motions in two distant volumes of the universe using Fundamental Plane (FP) distances for 85 clusters with $6000\,\mathrm{km\,s^{-1}}<cz<15000\,\mathrm{km\,s^{-1}}$. The scatter in distance about the FP is observed to be 20% per galaxy for EFAR sample, resulting in peculiar velocities with a median precision of $1075\,\mathrm{km\,s^{-1}}$ for the 50 clusters with 3 or more galaxies. We find that there is no evidence for a large bulk flow within either of the two volumes sampled by the EFAR clusters. The measured bulk motion in both regions is small and consistent with zero. The Lauer & Postman (1994) bulk motion is ruled out at the 4σ level. There is no evidence supporting the SMAC (Hudson et al. 1999) or LP10K (Willick 1999) bulk motions, but the directionality of the EFAR sample would only allow a weak (2σ) detection at best.

1. Introduction

The main goal of the EFAR project is to use the Fundamental Plane (FP) for early-type galaxies to measure cluster distances and peculiar velocities, and

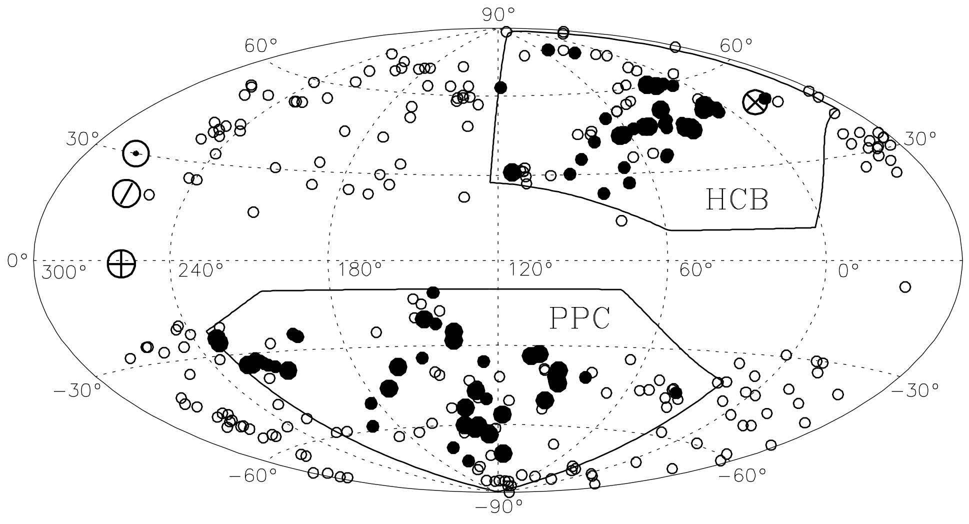

Figure 1. The EFAR cluster sample. The plot shows Abell clusters in the EFAR sample (●), non-Abell clusters in the EFAR sample (•), and Abell clusters not in the EFAR sample (○). Also marked are the directions with respect to the CMB frame of the Local Group dipole (⊙), the Lauer & Postman (1994) dipole (⊗), the SMAC (Hudson et al. 1999) dipole (⊕) and the LP10K (Willick 1998) dipole (⊘).

so determine the large-scale motions in two relatively distant volumes. The secondary goals are: (i) to test for environmental effects on the cluster FP and evaluate their implications for FP distance estimates; (ii) to develop improved distance estimators; and (iii) to study the properties of early-type galaxies in clusters with a large, homogeneous database.

In this paper we describe the methodology used to fit the Fundamental Plane and derive peculiar velocities for the clusters in the EFAR sample. We test the peculiar velocities for systematic errors of various types, and then examine the velocity field for evidence of bulk motions. Particular attention is given to testing the claims of large dipoles on these scales made by Lauer & Postman (1994), Hudson et al. (1999) and Willick (1998).

2. EFAR Observations

The clusters of galaxies in the EFAR sample are selected in two large, distant (i.e. non-local) volumes: Hercules-Corona Borealis (HCB, 40 clusters) and Perseus-Pisces-Cetus (PPC, 45 clusters). The clusters come from the ACO catalog (Abell et al. 1989), the list of Jackson (1982) and from scans of Sky Survey prints by the authors (Wegner et al. 1996). The nominal redshift range spanned by the clusters is $6000\,\mathrm{km\,s^{-1}} < cz < 15000\,\mathrm{km\,s^{-1}}$. The distribution of the EFAR clusters on the sky, and with respect to the directions of various large-scale dipoles, is shown in Figure 1.

Galaxy selection in each cluster is by elliptical morphology on Sky Survey prints, and by apparent diameter. The total sample includes 736 early-type galaxies in the 85 clusters. Apparent diameters are measured visually for all early-type galaxies in the cluster fields. The range in apparent visual diameter is from 10 arcsec to over 60 arcsec. The sample selection function is defined in terms of these visual diameters (D_W). In total, 2185 D_W diameters were measured for early-type galaxies in the cluster fields. Selection functions are determined separately for each cluster, and are approximated by fitted error functions in $\log D_W$. The mean value of the visual diameter is $\langle\log D_W\rangle$=1.3 (i.e. 20 arcsec), and the dispersion in $\log D_W$ is 0.3 dex.

Spectroscopic data (redshifts, velocity dispersions and Lick Mgb/Mg$_2$ line indices) were measured for 714 early-type galaxies from this sample (Wegner et al. 1999). A total of 1319 spectra were obtained on a variety of telescopes, providing repeat measurements for 45% of the sample. The spectra yielded median errors of 9% in the dispersions, 7% in Mgb and 0.015 mag in Mg$_2$. Comparisons with literature measurements show good agreement.

Photometry (Saglia et al. 1997a) was obtained in the R band with a zero-point uncertainty of 0.03 mag. Circularised galaxy light profiles were fitted with models having both an $R^{1/4}$ bulge and an exponential disk. Only 14% of the sample were adequately fit by a pure $R^{1/4}$ bulge profile. The uncertainties in the fitted parameters were estimated from both internal comparisons and simulations (Saglia et al. 1997b): 90% of the galaxies have errors in M_{tot} of less than 0.15 mag, in R_e of less than 0.11 dex, and in the FP parameter $\log R_e - 0.3\langle SB_e\rangle$ of less than 0.03 dex.

Membership in the sample clusters (or fore/background clusters) is determined from redshift distributions using both EFAR redshifts and redshifts from the ZCAT compilation.

3. The Fundamental Plane

The FP is defined from clusters having 6 or more galaxies with reliable velocity dispersions (σ), effective radius (R_e) and mean effective surface brightness ($\langle SB_e\rangle$). Simulations show that including clusters with fewer galaxies increases the variance on the fitted FP parameters.

To be included in the FP fit, galaxies must have good quality photometric and spectroscopic data. This means: (i) high-quality (Q=1,2) photometric fits, so $\delta(\log R_e - 0.3\langle SB_e\rangle)\leq 0.01$; (ii) large and precisely-determined dispersions, $\sigma > 100\,\mathrm{km\,s^{-1}}$ and $\delta\log\sigma\leq 0.5$ dex; (iii) selection diameters $D_W \geq 12.6\,\mathrm{h^{-1}}$ kpc and selection probabilities $P_{sel}\geq 0.1$. There was *no* morphological selection criterion. After 3σ-clipping about the FP fit to remove outliers and interlopers, the final sample comprises 255 galaxies in 29 clusters.

The galaxy distribution in ($\log R_e, \log\sigma, \langle SB_e\rangle$) space is assumed to be a 3D Gaussian. We perform a simultaneous maximum likelihood (ML) fit to a global FP and individual peculiar velocity offsets for each cluster. The parameters of the fit are the FP coefficients (in the form $\log R_e = a\log\sigma + b\langle SB_e\rangle + c$), the means and dispersions of the 3D Gaussian galaxy distribution, and the cluster peculiar velocities (V_{pec}). The peculiar velocities are fitted as offsets $\delta\log R_e$ in the FP, with $\langle\delta\log R_e\rangle$=0. Residual biases in the peculiar velocities are removed

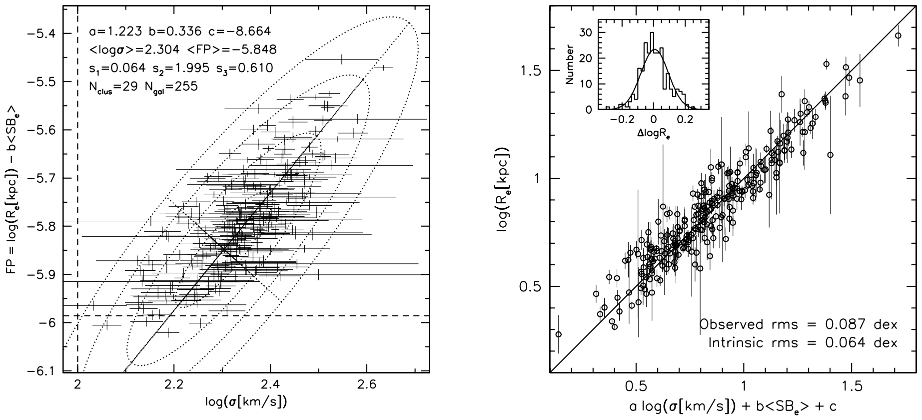

Figure 2. The EFAR Fundamental Plane, as fit to the 20 clusters with $\geq$6 galaxies. The left panel shows the FP projected in the $(\log\sigma, \log R_e - 0.3\langle SB_e\rangle)$ plane and gives the best-fit parameters; the dotted ellipses are the projected 1σ-4σ contours of the 3D Gaussian fit to the galaxy distribution. The right panel shows the edge-wise projection of the FP in the $(\log R_e, a\log\sigma + b\langle SB_e\rangle + c)$ plane and the distribution of residuals about the fit.

via simulations. Coma ends up with virtually zero motion in the CMB frame (V_{pec}=$-29\,\mathrm{km\,s^{-1}}$).

The ML Gaussian method has a number of advantages over conventional approaches to fitting the FP. It accounts for the intrinsic distribution within the FP (to the extent that this is approximated by a 3D Gaussian), the errors in all three measured quantities (especially the relatively large errors in σ), the *a priori* D_W diameter selection effects (through selection probability weighting), and the *a posteriori* selection on σ, R_e and P_{sel} (by integrating probabilities over the allowed volume). The method also minimises the bias in the fitted parameters compared to alternative regression methods. In detailed simulations comparing the ML Gaussian method with regression fits, only the ML method gave fitted parameters with systematic biases smaller than the random errors. It also yielded the smallest errors in the recovered peculiar velocities, both in terms of systematic biases and in the scatter in V_{pec} for single clusters.

Figure 2 shows two views of the best-fit FP for the 20 clusters with $\geq$6 galaxies. The left panel shows the FP projected in the $(\log\sigma, \log R_e - 0.3\langle SB_e\rangle)$ plane, illustrating the dominance of the spectroscopic uncertainties over the photometric uncertainties and giving the parameters of the fit. The right panel shows the edge-wise projection of the FP in the $(\log R_e, a\log\sigma + b\langle SB_e\rangle + c)$ plane and the distribution of residuals about the fit. The best-fit FP is

$$\begin{aligned} \log R_e \quad = \quad & 1.223\log\sigma + 0.336\langle SB_e\rangle - 8.664. \qquad (1) \\ & \pm 0.089 \qquad\quad \pm 0.013 \qquad\quad \pm 0.354 \end{aligned}$$

The observed rms scatter about the FP is found to be 0.087 dex (implying that distance estimates have an uncertainty of 20% per galaxy), while the intrinsic

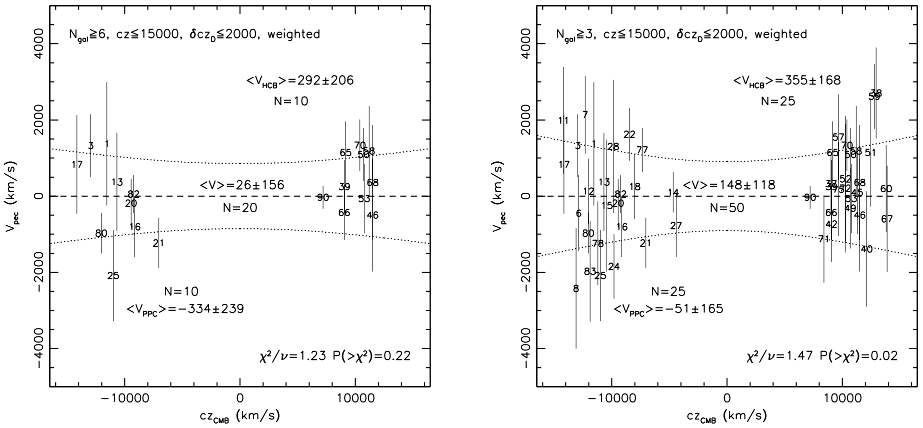

Figure 3. Peculiar velocities as a function of redshift. The left panel shows the 20 clusters with $\geq$6 galaxies; the right panel shows the 50 clusters with $\geq$3 galaxies.

scatter (obtained directly from the ML fit of the intrinsic dispersion about the FP) is 0.064 dex, or 15%.

The uncertainties in the fitted FP parameters are estimated using 1000 detailed simulations of the fitting process applied to the EFAR dataset. For all parameters, systematic biases are found to be less than (or at most comparable to) the random errors. The robustness of the FP fit was tested by examining 35 variations to the choice of selection and fitting parameters. Only the most extreme choices (such as applying severe limits on the galaxies' likelihoods or selection probabilities) gave significantly different fits. The fit was *not* significantly perturbed by varying the morphological types included, or by the choice of Burstein & Heiles (1984) or Schlegel et al. (1998) absorption corrections.

4. Peculiar Velocities and Bulk Motions

Once the global FP was determined from the best 20 clusters, peculiar velocities for *all* clusters were obtained by fixing the FP parameters and applying the ML Gaussian method to determine each cluster's FP offset, $\delta \log R_e$. In order to minimise the effects of the uncertainties in the cluster peculiar velocities, we limit the sample in all subsequent analysis to clusters having at least 3 galaxies, and with $cz{<}15000\,\mathrm{km\,s^{-1}}$ and $\delta cz_D{<}2000\,\mathrm{km\,s^{-1}}$.

We first look to see whether there is any evidence that differences in the stellar population between clusters are producing systematic errors in the measured peculiar velocities. We find no correlation between each cluster's V_{pec} and its offset from the mean cluster Mg–σ relation. However, as shown by Colless et al. (1999), this is only a weak test of stellar population effects on FP distance estimates. We also look to see whether large peculiar velocities could simply be due to poor FP fits (whether from intrinsic FP variations, observational errors or cluster interlopers), as has been suggested by Gibbons et al. (1999). We find

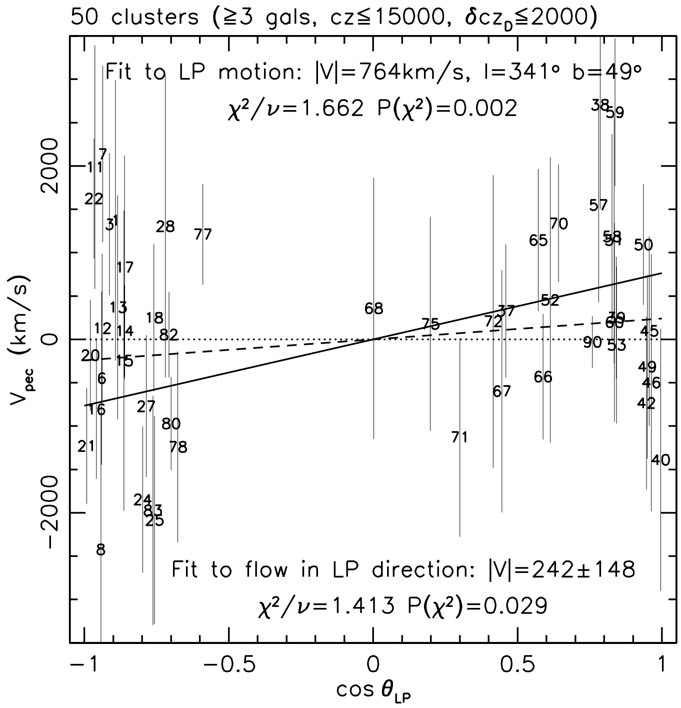

Figure 4. Cluster peculiar velocities plotted against the cosine of their angle with respect to the Lauer & Postman (1994) dipole (as revised by Colless 1995). The solid line is the Lauer & Postman dipole prediction, which is rejected at the 0.2% level by a χ^2 test; the dashed line is a χ^2 fit to a pure bulk motion in this direction, rejected at the 2.9% level.

no general trend of increasing V_{pec} amplitude with the reduced χ^2 of the FP fits, although we do exclude from further analysis the 3 clusters with $\chi^2/\nu{>}3$, which do have relatively large $|V_{pec}|$. Finally, we check for radial variations of the mean peculiar velocity in redshift shells (which might result from a residual Malmquist bias, for example). We find no evidence for non-zero $\langle V_{pec}\rangle$ in any direction in any cz shell in either of the two regions.

With no indication of any systematic biases in our peculiar velocities, we turn to look for evidence of bulk motions. Figure 3 shows the peculiar velocities of the clusters as a function of redshift in the CMB frame, with clusters in the HCB region given positive redshifts and those in the PPC region given negative redshifts. The left panel shows the sample of 20 clusters (10 in each of the two regions) with 6 or more galaxies. There is no evidence for any bulk motion across the sample. Each region's mean velocity is only non-zero at the 1.5σ level, and a χ^2-test can only reject a model with zero bulk motions at the 22% level. If we expand the sample to include all 50 clusters with 3 or more galaxies (again with half in each region), we again find that the overall motion and the motion in the PPC region are insignificant. The mean motion of the HCB region, however, is significant at the 2.1σ level, and a model with zero bulk motions is rejected by a

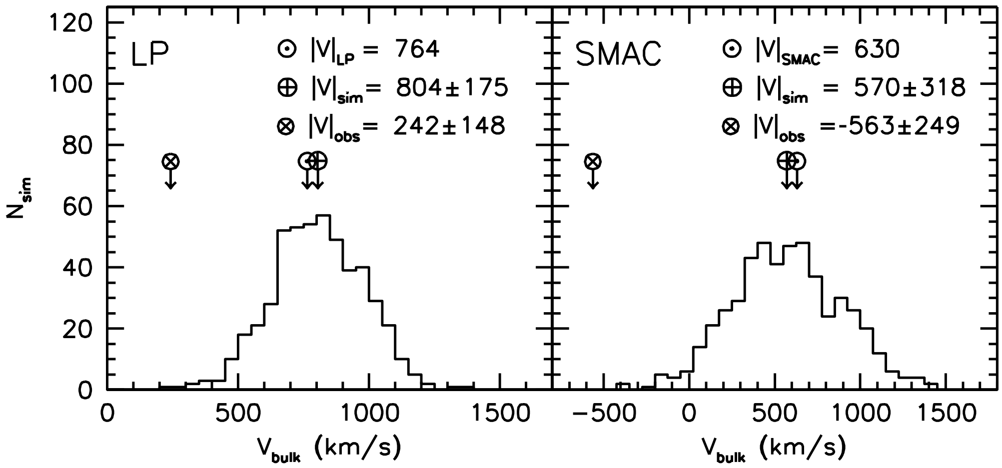

Figure 5. Simulation of the bulk motions recovered from the EFAR dataset assuming the underlying velocity field is described by the Lauer & Postman (left) and SMAC (right) bulk motions with no additional 'thermal' peculiar velocities.

χ^2-test at the 2% level. This apparent motion, however, is entirely due to just 2 clusters with large V_{pec} (J12, J19), and disappears if they are omitted from the sample.

As well as searching for a bulk flow in our sample, we can also test whether the bulk flows obtained by other authors are consistent with our observed peculiar velocities. Figure 4 shows the peculiar velocities of the EFAR clusters plotted against the cosine of their angle with respect to the direction of the bulk flow of 764 km s^{-1} in the direction (l,b)=(341°, 49°) found by Lauer & Postman (1994; as revised by Colless 1995). This direction is close to the HCB–PPC axis of the EFAR sample, so our data provide a good test of this claimed bulk motion. In fact, we find that a χ^2 test rejects the nominal Lauer & Postman bulk flow as a representation of the EFAR data at the 0.2% level, in accord with the results of Giovanelli et al. (1998) and Müller et al. (1998). We can perform a similar test to check the validity of the bulk motion of 630 km s^{-1} in the direction (l,b)=(260°, −1°) claimed by Hudson et al. (1999) for the SMAC cluster sample. However we obtain only a weak constraint because the SMAC dipole direction is almost orthogonal to the axis of the EFAR sample, as shown in Figure 1. The same result applies to the LP10K dipole (Willick 1998), since its direction is close to that of the SMAC dipole.

Figure 5 shows simulations of the bulk motions recovered from the EFAR dataset under the assumption that the underlying velocity field is described by the Lauer & Postman (left) or SMAC (right) bulk flow (with no additional 'thermal' peculiar velocities). The simulations reveal that EFAR should be able to detect the Lauer & Postman flow at better than 4σ, but that the SMAC flow would not be detectable at better than 2σ. These detections would be weaker if there was a significant thermal component to the peculiar velocity field.

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