THE PECULIAR VELOCITIES OF LOCAL TYPE Ia SUPERNOVAE AND THEIR IMPACT ON COSMOLOGY

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Received 2007 March 5; accepted 2007 April 12; published 2007 May 11

ABSTRACT

We quantify the effect of Type Ia supernova (SN Ia) peculiar velocities on the derivation of cosmological parameters. The published distant and local SNe Ia used for the Supernova Legacy Survey first-year cosmology report form the sample for this study. While previous work has assumed that the local SNe are at rest in the CMB frame (the no-flow assumption), we test this assumption by applying peculiar velocity corrections to the local SNe using three different flow models. The models are based on the IRAS PSCz galaxy redshift survey, have varying β = Ω_m/b, and reproduce the Local Group motion in the CMB frame. These data sets are then fit for w, Ω_m, and Ω_Λ using flatness or ΛCDM and a BAO prior, and the χ² statistic is used to examine the effect of the velocity corrections on the quality of the fits. The most favored model is the β = 0.5 model, which produces a fit significantly better than the no-flow assumption, consistent with previous peculiar velocity studies. By comparing the no-flow assumption with the favored models, we derive the largest potential systematic error in w caused by ignoring peculiar velocities, Δw = +0.04. For Ω_m the potential error is ΔΩ_m = −0.04, and for Ω_Λ, the potential error is ΔΩ_Λ < +0.01. The favored flow model (β = 0.5) produces the following cosmological parameters: w = −1.08 ± 0.09, Ω_m = 0.27 ± 0.02 assuming a flat cosmology, and Ω_Λ = 0.80 ± 0.13 and Ω_m = 0.27 ± 0.02 for a w = −1 (ΛCDM) cosmology.

Subject headings: galaxies: distances and redshifts — large-scale structure of universe — supernovae: general

1. INTRODUCTION

Dark energy has challenged our knowledge of fundamental physics since the direct evidence for its existence was discovered using Type Ia supernovae (SNe Ia; Riess et al. 1998; Perlmutter et al. 1999). Because there are currently no compelling theoretical explanations for dark energy, the correct refinement of the velocity corrections on the quality of the fits. The most favored model is the β = 0.5 model, which produces a fit significantly better than the no-flow assumption, consistent with previous peculiar velocity studies. By comparing the no-flow assumption with the favored models, we derive the largest potential systematic error in w caused by ignoring peculiar velocities, Δw = +0.04. For Ω_m the potential error is ΔΩ_m = −0.04, and for Ω_Λ, the potential error is ΔΩ_Λ < +0.01. The favored flow model (β = 0.5) produces the following cosmological parameters: w = −1.08 ± 0.09, Ω_m = 0.27 ± 0.02 assuming a flat cosmology, and Ω_Λ = 0.80 ± 0.13 and Ω_m = 0.27 ± 0.02 for a w = −1 (ΛCDM) cosmology.

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the mass density. The peculiar velocity in the cosmic microwave background (CMB) frame is then given by linear perturbation theory (Peebles 1980) applied to the density field (see, e.g., Yahil et al. 1991; Hudson 1993):

\[ v = \frac{\beta}{4\pi} \int_{r_{\text{max}}} \frac{\delta(r') (r' - r)}{|r' - r|} d^3r' + V. \]  

In this Letter, we use the density field of the IRAS PSCz galaxies (Branchini et al. 1999), which extends to a depth \( R_{\text{max}} = 20,000 \text{ km s}^{-1} \). Contributions to the peculiar velocity arising from masses on scales larger than \( R_{\text{max}} \) are modeled by a simple residual dipole, \( V \). Thus, given a density field, the parameters \( \beta \) and \( V \) describe the velocity field within \( R_{\text{max}} \). For galaxies with distances greater than \( R_{\text{max}} \), the first term above is set to zero.

The predicted peculiar velocities from the PSCz density field are subject to two sources of uncertainty: (1) the noisiness of the predictions due to the sparsely sampled density field and (2) the inapplicability of linear perturbation theory on small scales. Typically these uncertainties are accounted for by adding an additional “thermal” dispersion, which is assumed to be Gaussian. From a careful analysis of predicted and observed peculiar velocities, Willick & Strauss (1998) estimated these uncertainties to be \( \approx 100 \text{ km s}^{-1} \), albeit with a dependence on density. Radburn-Smith et al. (2004) found reasonable \( \chi^2 \) values if \( 150 \text{ km s}^{-1} \) was assumed in the field, with an extra contribution to the small-scale dispersion added in quadrature for SNe in clusters. Here we adopt a thermal dispersion of \( 150 \text{ km s}^{-1} \).

For this study, we explore the results of three different models of large-scale flows and compare them to a case where no flow model is used. These models have been chosen to span the range of flow models permitted by peculiar velocity data, and all of these models reproduce the observed \( \sim 600 \text{ km s}^{-1} \) motion of the Local Group with respect to the CMB. The first model assumes a pure bulk flow (model PBF; hence \( \beta = 0 \)), with \( V \) having vector components \( (57, -540, 314) \text{ km s}^{-1} \) in Galactic Cartesian coordinates. The second model assumes \( \beta = 0.5 \) (model B05), with a dipole vector of \( (70, -194, 0) \) km s\(^{-1}\). The third model adopts \( \beta = 0.7 \) (model B07), which requires no residual dipole. We compare these models to the no-correction scenario adopted by A06 and others with \( \beta = 0 \) and \( V = 0 \), which we call the “no-flow” or NF scenario. Note that a recent comparison (Pike & Hudson 2005) of results from IRAS predictions versus peculiar velocity data yields a mean value fit with \( \beta = 0.50 \pm 0.02 \) (stat), so the B05 model is strongly favored over the NF scenario by independent peculiar velocity analyses.

### 3. Cosmological Fits

Prior to the fitting procedure, the peculiar velocities for each model are used to correct the local SNe (using a variation of eqs. [11] and [13] in Hui & Greene 2006). We then fit our corrected SN data in two ways using a \( \chi^2 \)-gridding cosmology fitter\(^1\) (also used by Wood-Vasey et al. 2007). The first fit uses a flat cosmology \( (\Omega = 1) \) with the equation of state parameter \( w \) and \( \Omega_\Lambda \) as free parameters. The second fit assumes a \( \Lambda \text{CDM} \) \( (w = -1) \) cosmology with \( \Omega_\Lambda \) and \( \Omega_m \) as free parameters. We used the same intrinsic SN photometric scatter \( (\sigma_{\text{int}} = 0.13 \text{ mag}; \text{A06}) \) for every fit. The resulting \( \chi^2 \) probability surfaces for both fits are then further constrained using the baryon acoustic oscillation (BAO) result from Eisenstein et al. (2005). The final derived cosmological parameters are then used to calculate the \( \chi^2 \) for each fit (see A06, § 5.4).

The fitting procedure employed here differs in implementation from that used in A06. Three additional parameters, often called nuisance parameters, must be fit along with the two cosmological parameters. These parameters are the constant of proportionality for the SN light-curve shape, \( \alpha \), the correction for the SN observed color, \( \beta_c \), and a SN brightness normalization, \( M \). We distinguish \( \beta_c \) from the \( \beta \) used to describe the flow models above. A06 used analytic marginalization of the nuisance parameters \( \alpha \) and \( \beta_c \) in their fits. Here these parameters are fully gridded like the cosmological parameters. This avoids a bias in the nuisance parameters that results because, in the analytic method, their values must be held fixed to compute the errors. The result is that our fits using the NF scenario produce slightly different cosmological parameters than quoted in A06.

### 4. Results

The results of the cosmological fits for each model are listed in Table 1 and plotted in Figures 1 and 2. They demonstrate two effects of the peculiar velocity corrections: a change in the values of the cosmological parameters and a change in the quality of the fits as measured by the \( \chi^2 \) statistic. We expect, if a given model is correct, to improve the fitting since our corrected data should more closely resemble the homogeneous universe described by a few cosmological parameters. The \( \chi^2 \) of the fits for each flow model can be compared to the \( \chi^2 \) for the NF scenario (shown by the dashed lines in the figures) as a test of this hypothesis. Using \( \Delta \chi^2 = -2 \ln (L/L_{\text{NP}}) \), where \( L \) is the likelihood, we find that the pure bulk flow is over \( 10^3 \) times less likely than the NF scenario, while the B05 and B07 models are 13.5 and 8.6 times more likely, respectively.

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\(^1\) See [http://qold.astro.utoronto.ca/conley/simple_cosfitter/](http://qold.astro.utoronto.ca/conley/simple_cosfitter/).
The peculiar velocities of SN host galaxies arise from large-scale structures over a range of scales. The component arising from small-scale, local structure is the least important: it is essentially a random variable that is reduced by $\sqrt{N}$. More problematic is the large-scale coherent component. Such a large-scale component can take several forms: an overdensity or underdensity; a large-scale dipole; or “bulk” flow.

The existence of a large-scale but local ($<7400$ km s$^{-1}$) underdensity, or “Hubble bubble,” was first discussed by Zehavi et al. (1998). Recently, Jha et al. (2007) have reinforced this claim with a larger SN data set; they find that the difference in the Hubble constant inside the bubble and outside is $\Delta H/H = 6.5\% \pm 1.8\%$. If correct, this could have a dramatic effect on the derived cosmological parameters (Jha et al. 2007, Fig. 17), especially for those studies that extend their local sample down below $z < 0.015$. However, the “Hubble bubble” was not confirmed by Giovanelli et al. (1999), who found $\Delta H/H = 1.0\% \pm 2.2\%$ using the Tully-Fisher (TF) peculiar velocities, or by Hudson et al. (2004), who found $\Delta H/H = 2.3\% \pm 1.9\%$ using the fundamental plane (FP) distances.

According to equation (1), a mean underdensity of IRAS galaxies of order $\sim 40\%$ within 7400 km s$^{-1}$ would be needed to generate the “Hubble bubble” quoted by Jha et al. (2007). However, we find that the IRAS PSCz density field of Branchini et al. (1999) is not underdense in this distance range; instead, it is mildly overdense (by a few percent) within 7400 km s$^{-1}$ (see also Branchini et al. 1999, Fig. 2). As a further cross-check, when we refit the Jha et al. (2007) data after having subtracted the predictions of the B05 flow model, the “bubble” remains in the Jha et al. (2007) data. Thus, the Jha et al. “bubble” cannot be explained by local structure, unless that structure is not traced by IRAS galaxies. Moreover, when we analyze the 99 SNe within 15,000 km s$^{-1}$ from Tonry et al. (2003) in the same way, we find no evidence of a significant “Hubble bubble” ($\Delta H/H = 1.5\% \pm 2.0\%$), in agreement with the results from TF and FP surveys. The Tonry et al. (2003) sample and that of Jha et al. (2007) have 67 SNe in common. The high degree of overlap suggests that the difference lies in the different methods for converting the photometry into SN distance moduli.

A local large-scale flow can also introduce systematic errors if the low-z sample is biased in its sky coverage; in this case, an uncorrected dipole term can corrupt the monopole term, which then biases the cosmological parameters. For the large-scale flow directions considered here, this does not appear to affect the A06 sample; we note that the PBF-corrected case has similar cosmological parameters to the “no-flow” case. However, if coherent flows exist on large scales, this may affect...
surveys with unbalanced sky coverage, such as the SN Factory (Aldering et al. 2002) or the SDSS SN survey.²

The most promising approach to treating the effect of large-scale flows is a more sophisticated version of the analysis presented here: combine low-redshift SNe with other low-redshift peculiar velocity tracers, such as Tully-Fisher SFI++ survey (Masters et al. 2006) and the NOAO Fundamental Plane Survey (Smith et al. 2004), and use these data to constrain the parameters of the flow model ($\beta$ and the residual large-scale flow $V$) directly. One can then marginalize over the parameters of the flow model while fitting the cosmological parameters to the low- and high-$z$ SNe.

² See http://sdssdp47.fnal.gov/sdsssn/sdsssn.html.

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