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IS THERE EVIDENCE FOR A HUBBLE BUBBLE? THE NATURE OF SN IA COLORS AND DUST IN EXTERNAL GALAXIES

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ABSTRACT

We examine recent evidence from the luminosity-redshift relation of Type Ia Supernovae for the $\sim 3\sigma$ detection of a "Hubble bubble" – a departure of the local value of the Hubble constant from its globally averaged value (Jha et al. 2007). By comparing the MLCS2k2 fits used in that study to the results from other light-curve fitters applied to the same data, we demonstrate that this is related to the interpretation of SN color excesses (after correction for a light-curve shape-color relation) and the presence of a color gradient across the local sample. If the slope of the linear relation (β) between SN color excess and luminosity is fit empirically, then the bubble disappears. If, on the other hand, the color excess arises purely from Milky-Way like dust, then SN data clearly favors a Hubble bubble. We demonstrate that SN data give $\beta \simeq 2$, instead of the $\beta \simeq 4$ one would expect from purely Milky-Way-like dust. This suggests that either SN intrinsic colors are more complicated than can be described with a single light-curve shape parameter, or that dust around SN is unusual. Disentangling these possibilities is both a challenge and an opportunity for large-survey SN Ia cosmology.

Subject headings: cosmology: observations — supernovae: general

1. INTRODUCTION

In an analysis of the luminosity distances of Type Ia supernovae (SNe Ia), Jha et al. (2007) (hereafter J07) presented evidence for an offset between the Hubble constant measured from SNe Ia with $2500 < cz < 7400$ km/sec and from those with $7400 < cz < 45000$ km/sec. Specifically, the more distant SNe are slightly fainter than one would expect, implying that the local value of H_0 is higher. One natural explanation is a "Hubble bubble" – a local monopole in the peculiar velocity field, perhaps caused by a local void in the mass density. The analysis of J07 was carried out using the most recent manifestation of the MLCS light-curve fitter, MLCS2k2, and found a change of $\delta H/H = 6.5\% \pm 1.8\%$. The Δm_{15} method gives similar results (Prieto et al. 2006). In contrast, galaxy-cluster distances give $\delta H/H =\sim 1.5\% \pm 2\%$ (Giovanelli et al. 1999; Hudson et al. 2004), which are marginally inconsistent with the SN result (1.9σ). A Hubble bubble could have serious implications for precision SN Ia cosmology programs.

In this letter we test the evidence for the Hubble bubble using three other light-curve analysis packages: SALT (Guy et al. 2005), SALT2 (Guy et al. 2007), and an unpublished package developed for the 3rd year Supernova Legacy Survey (SNLS, Astier et al. 2006) data (SiFTO). An analysis of the same data set with these tools does not support a bubble if SN data are used to derive the relationship between SN color excess and peak luminosity, but does if this relationship is required to be that of Milky-Way-like dust. Therefore the question of the Hubble bubble is one of the nature of SN colors. A similar result was found independently by Wang (2007, in prep).

2. LIGHT-CURVE FITTERS AND THE MEANING OF SN COLORS

A considerable amount of effort has been devoted to the question of how to best fit SNe Ia light curves. The goal is to measure the relative luminosity distance of different SNe, usually after correcting for the width-luminosity and color-luminosity relationships. These approaches differ considerably in implementation and assumptions, but generally produce very similar results when used to estimate the cosmological density parameters $(\Omega_m, \Omega_\Lambda)$ (Wood-Vasey et al. 2007).

In this analysis we consider four fitting packages: MLCS2k2, as well as three packages developed for use with SNLS: SiFTO, SALT, and SALT2. The latter three are more similar to each other than to MLCS2k2. The details of SiFTO will be presented elsewhere (Sullivan et al., in preparation); it is broadly similar to SALT except that the color excess relation is not imposed during the light-curve fit, but rather when the results of the fit are converted into a distance estimate.

The critical issue for the question of the Hubble bubble relates to how the different fitters handle SN color excesses. All of the models have two parameters: one which describes the light-curve shape, and one the color, both of which affect the peak luminosity. For MLCS2k2 these are Δ and A_V, for SALT they are s and c. These have different technical meanings, but essentially describe the same effects. MLCS2k2 breaks the color relation into two pieces: an time independent piece[6], parameterized by A_V, and a time dependent piece determined by the shape of the light curve, Δ. The time independent piece is assumed to follow the CCM (Cardelli et al. 1989) dust ex-

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[6] Technically, the effective value of R_V depends on the SED, so the effects of this term are weakly time dependent.

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tinction law. In effect, A_V parameterizes the color of the SN after correction for a shape-color relation. SALT follows a similar prescription, with some critical differences. The wavelength behavior of the time-independent piece (parameterized by c) is derived as part of the SALT training process; the results are shown in Guy et al. (2007). This relation is reasonably similar to the CCM law, and is arbitrarily normalized so that c is the $B-V$ color at peak luminosity (plus a small constant) for any s; the same is not true of $U-B$ and $V-R$, which are functions of s. In the following we will refer to the time-independent piece as the color excess relation.

The real difference is how the color excess relation is used to correct the peak luminosities. MLCS2k2 makes the simplest assumption: that it is due to dust. The wavelength behavior of the CCM law is parameterized by the ratio of selective to total extinction (R_V), and this is also used to convert the color excess into the magnitude correction. The other fitters considered here take a different approach. One of the steps in the process of turning their results into a distance estimate is to empirically measure the slope of the relationship between the color c and the luminosity correction (β), as well as between the light-curve shape and luminosity (α) by minimizing the residuals with respect to the Hubble line. Here the model for the predicted peak B magnitude m_B is $m_B = M_B + 5\log_{10} d_L - \alpha(s-1) + \beta c$, where M_B is the absolute peak magnitude, d_L is the luminosity distance, and α and β are determined from SN data; the slopes can be cleanly separated from the intercept without any difficulties. In this formulation, the shape-color relation is absorbed into the α coefficient, and therefore the β correction only applies to the color excess. In this analysis we will generally work with B magnitudes, and therefore if the color excess relation is purely due to dust then we expect $\beta = R_B = R_V + 1 \simeq 4$. Interestingly, the current constraint on β from combined SNLS and low-z data is $\beta \sim 2 \pm 0.2$, which differs from 4 by $> 10\sigma$. A similar value was found by Tripp (1998).

What does $\beta \neq 4$ mean? If β is interpreted as arising from dust, then this would require $R_B = 2$, which is extreme. On the other hand, we know that dust *must* be present at some level. One possible explanation is that the various color parameters are actually measuring some combination of two effects: dust, and some additional intrinsic color variations that are not related to Δ or s. The β for this additional piece is not known, but if it is less than the value for dust, then the effective combined value will be driven down. This additional color parameter could be interpreted as additional scatter in the measured colors of SN Ia; most of the fitters studied here (except SALT) do include terms for such scatter, but assume that it has no effect on the overall luminosity ($\beta = 0$). A worry, then, is that the relative balance of dust and the additional intrinsic color might vary between SN in different environments. Alternatively, it is possible that the dust along the line of sight to some SN Ia is different than standard dust, perhaps due to scattering effects local to the SN (Wang 2005).

3. TESTING THE HUBBLE BUBBLE WITH OTHER FITTERS

The data sample used in the analysis of J07 incorporates a number of SN with sparsely sampled light curves.

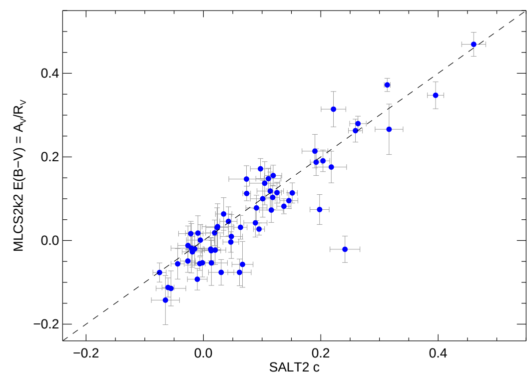

FIG. 1.— The SALT2 c parameter compared with the equivalent MLCS2k2 value, A_V/R_V for our 61 SNe. The A_V prior has been removed from the MLCS2k2 fits to allow easier comparison of the underlying fits. Good agreement is also found in the times of maximum, peak magnitudes, and light-curve shape parameters (although for the latter the relations are non-linear).

We have placed the following additional requirements on our sample: First we require at least one rest frame B observation within -7 to +7 days of the estimated B peak, in order to ensure that m_B is well measured, and at least one U or V observation within -7 to +10 days for the color. We exclude all SN with $s < 0.7$ or $s > 1.3$, since these are outside the model bounds for most of the fitters. Finally, we require that $E(B-V)_{MW} < 0.4$ mag as calculated from the dust maps of Schlegel et al. (1998) and $c < 0.6$ mag, both to avoid regions of anomalous dust. This reduces the sample of 95 SN used by J07 to 61 objects. Since only MLCS2k2 is trained to fit I data, we remove this from all fits. In order to check that this reduction in the sample does not affect the results, we then refit all of these SN using the most recent version of MLCS2k2. We find good agreement with J07, with $\delta H/H = 6.0\% \pm 1.9\%$ for $cz_{\rm void} = 7400$ km/sec and assuming a flat $\Omega_m = 0.3$ ΛCDM universe.

We then fit the same photometry using the other light-curve packages[7]. The different packages show impressive agreement in their basic derived light-curve parameters, as demonstrated in figure 1. In order to measure $\delta H/H$ with SALT/SALT2/SiFTO, we have to determine β. This is calculated from the SN data, but incorporating high-redshift SNLS data as well. SALT, SALT2, and SiFTO give $\beta = 1.82$, 1.75 and 2.31, respectively, with errors of about ± 0.16. The different values are not particularly important for the current analysis; all three can be fixed to the mean value without changing the results qualitatively. After applying the color and light-curve shape corrections, we obtain $\delta H/H = 0.9\% \pm 2.0\%$, $-1.2\% \pm 2.1\%$, and $0.4\% \pm 2.1\%$ – in other words, they do not support a Hubble bubble if β is fit to the data. SALT and MLCS2k2 are compared in figure 2 for various values of $cz_{\rm void}$. The exact values are somewhat sensitive to the cuts applied to the sample. However, it requires considerable hand tuning to find regions of parameter space where any of the fitters besides MLCS2k2 detect a Hubble bubble at greater than 1.4σ, and in all cases MLCS2k2 gives much greater significance.

One might be tempted to interpret this as an er-

[7] The raw light-curve parameters are available from http://qold.astro.utoronto.ca/conley/bubble

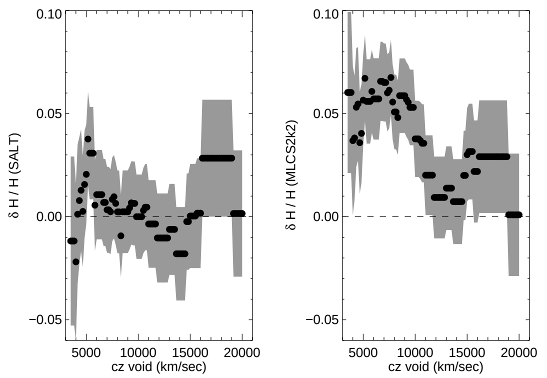

FIG. 2.— The Hubble bubble as a function of the velocity of the step in the Hubble constant, $cz_{\rm void}$. The left panel shows results for SALT (with $\beta = 1.82$), and the right panel for MLCS2k2. The grey band is the error in $\delta H/H$. The constant value for $16000 < cz < 19000$ km/sec simply reflects the lack of any SN in this range.

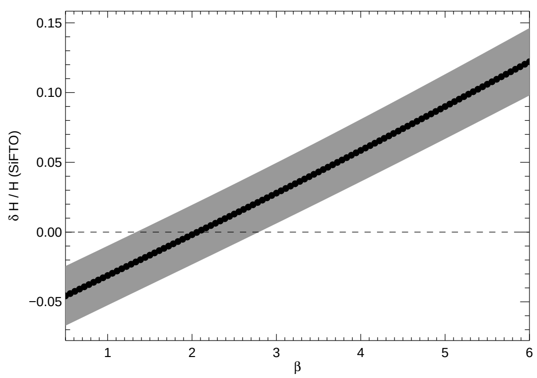

FIG. 3.— $\delta H/H$ vs. the value of β used to convert the measured color parameter into a luminosity correction for SiFTO. The relation is almost, but not quite, linear. Fits to low-z and SNLS data give $\beta = 2.35 \pm 0.16$.

ror in one or more of the packages. However, the actual cause is more interesting: if one sets $\beta = 4.1$ for SALT/SALT2/SiFTO, they *do* find evidence for a Hubble bubble at $> 2.5\sigma$, as shown in figure 3. The color model for the most recent version of Δm_{15}, which also favors the bubble, is similar to that of MLCS2k2. The question of the Hubble bubble therefore boils down to the appropriate value of β – is it the ~ 4 of Milky-Way like dust, or is something more complicated going on?

The value of β is relevant because the nearby portion of the low-z SN sample is redder than the distant portion (figure 4). This is probably due to Malmquist bias (Malmquist et al. 1936) or other selection effects, since redder supernova are fainter and harder to detect. The effects of the color correction are to (relatively) make the blue SNe dimmer and the red SNe brighter. Malmquist bias has little effect as long as the appropriate value of β is applied across the whole sample; however, if the right value is $\beta = 2$ and instead 4 is used, then the distant portion will be made too faint, and the nearby portion too bright, which is exactly the effect observed in J07. MLCS2k2 usually includes a prior on A_V, and the default one does not take into account the redshift dependent effects of Malmquist bias. Adjusting the prior to reflect this increases the value of $\delta H/H$.

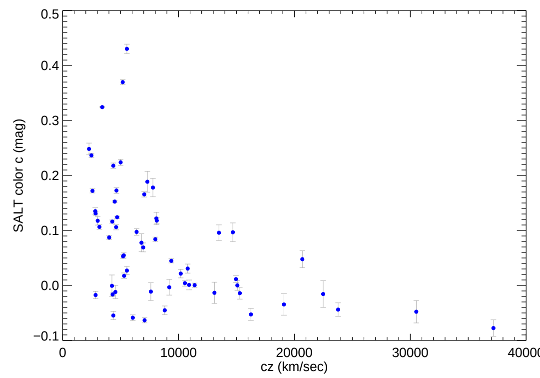

FIG. 4.— The colors of the low-z supernova sample using SALT. The distant portion of the sample is bluer than the nearby portion, which is probably caused by selection effects.

4. THE VALUE OF β

If, in fact, $\beta = R_B$ (i.e., it is purely dust), then we should note that a large range of R_Bs have been observed in different environments. However, a sample mean value of $R_B = 2$ would be quite surprising (Draine 2003), even with selection effects.

The empirical values for β were calculated in a model that assumed a smooth local Hubble flow. It is possible that this could be artificially suppressing $\delta H/H$, so we checked this by refitting β using only high-z SNLS SN, only the low-z SN below $cz_{\rm void}$, and simultaneously with our fits to $\delta H/H$. These give essentially the same result ($\beta \sim 2$), albeit with larger errors than the full sample. Therefore, β is robust against the presence of a Hubble bubble. Monte Carlo studies indicate that the bias in β (b_β) due to errors in the measurement uncertainties and covariances is $|b_\beta| < 0.02$ for fairly extreme cases.

We can also analyze the results of the MLCS2k2 fits using the β framework. This differs from what is meant in J07 by fitting R_V (which enforces a certain relation between the wavelength dependence and scaling of the color excess relation), and is more similar to the analysis carried out in Riess et al. (1996), who found $R_V = 2.5 \pm 0.3$ (corresponding to $\beta = 3.5$) using a smaller sample and an earlier version of MLCS. We first remove the extinction correction from the MLCS2k2 distance estimates, then convert A_V into $E(B-V)$ using R_V, and finally use this to fit for the value of β by minimizing the residuals with respect for the Hubble line via a $\beta E(B-V)$ term. We work in B, and find $\beta = 2.7 \pm 0.3$, which again should be compared with the expected value of 4.1. Restricting the fit to only SN below $cz_{\rm void}$ does not change the results. The fits are shown in figure 5.

Another technique for estimating the amount of extinction is to use late time (~ 45 days after peak) color measurements. The idea is that at late times all SN Ia have a simple relationship between color and epoch, and so any difference between the observed colors and the model at these epochs measures extinction (Phillips et al. 1999, hereafter P99). The evidence for this is based on a handful of SN for which there is independent evidence for low extinction, and the distribution of the measured late-time colors (J07, figure 6). A version of this is used in the training process of MLCS2k2.

This suggests one more test of β. We take the subsample of our 61 SNe that have late-time color measurements

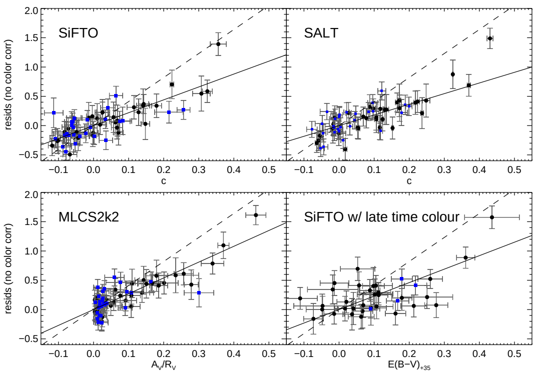

Fig. 5.— Fits to β for SiFTO (top left), SALT (top right), and MLCS2k2 (bottom left). The residuals are compared to the best fitting Hubble line but without correction for the various color parameters, which are shown along the abscissas. The bottom right panel shows the results for SiFTO using the late time colors as described in the text. The solid lines are the best fit to β as given in the text. The dashed lines show $\beta = 4.1$, which is the expected value if the color excess relation is caused by Milky-Way like dust. The black circles are for SN with $cz < 7400$ km/sec, and the blue squares for $cz > 7400$ km/sec. The grouping around $A_V/R_V = 0$ for MLCS2k2 is the result of the A_V prior.

(from J07) and use these values as our color estimate to fit for β. Carrying out this analysis out for all four fitters, we find $\beta \simeq 2.3 \pm 0.3$ for 37 SNe. In order to eliminate any "cross-talk" between the color parameters and the peak magnitudes, we also tested this procedure using only B band data to fit the peak magnitude and light-curve shape, and obtained the same results. Using the late time colors provided by P99 gives $\beta \simeq 1.5$ for 28 SNe. These results again differ considerably from the expectation of 4.1. Note that our findings disagree with those of P99 and Altavilla et al. (2004), who used a combination of the late-time and peak colors.

5. CONCLUSIONS AND DISCUSSION

We have demonstrated that the SN Ia evidence for a Hubble bubble is related to how SN colors are modeled. All of the approaches considered agree that the wavelength dependence of the color excess relation is similar to that of dust, but disagree on whether or not the relation between the measured color excess and the peak luminosity is also dust-like. Our fits give a value of $\beta \sim 2$, which if interpreted via the CCM dust law, requires the extreme value $R_V \sim 1$. Therefore, either a more complicated model of intrinsic supernova colors is required, which goes beyond a single light-curve shape-color relation, or dust in the host galaxies of SNe Ia is quite atypical of Milky-Way dust. If the former, then the late time colors of SNe Ia vary from SN to SN, and therefore do not provide a simple measure of extinction. If one does favor the single-parameter model with Galactic dust, then the evidence for the Hubble bubble from SNe Ia is fairly strong. These results depend on how accurately the light-curve shape-intrinsic color relationship has been modeled, so it is reassuring that the four fitters are in approximate agreement on the value of β.

Requiring an additional intrinsic color relation beyond the shape-color relation raises some challenges for SN research. Unless this relation can be disentangled from dust, we must consider the possibility that the balance of the two effects will change with environment and redshift, perhaps even within the low-z sample, and affect precision SN cosmology. MLCS2k2 might require a more sophisticated prior which takes into account the relation between extinction, light-curve shape, intrinsic color, and would also have to allow for any effects of this intrinsic color on SN luminosity. SALT/SALT2/SiFTO might require different values of β in different environments or for different color thresholds. Using an inappropriate value of β will mostly affect the most distant SN in any survey, where Malmquist bias is important. The potential systematic for a given SN survey can be evaluated by multiplying the uncertainty in β by the change in color excess across the sample. If the two-component color model is correct, then constraining it will not be a trivial task, but it does hold out the possibility of making SNe Ia even better standard candles.

How can we resolve this issue? A deeper nearby supernova sample which has a similar color distribution at all distances out to $cz \sim 25000$ km/sec would provide a good test of the Hubble bubble, since an incorrect value of β would no longer introduce such an effect. Note that SN cosmology analyses which restrict themselves to $z_{\rm min} \gtrsim 0.015$ such as Astier et al. (2006); Riess et al. (2007); Wood-Vasey et al. (2007) are not strongly affected by the existence of the bubble. Determining if a more complicated color model is necessary requires a different approach. A larger sample of SN in low-extinction environments (like elliptical galaxies), or at least in a narrow color range, could be used to search for a non-dust-like color relation. A wider baseline of color measurements could also help this problem; it seems unlikely that the wavelength dependence of the color excess relationship will continue to look like dust at all wavelengths unless it really is dust. The SALT/SALT2 color excess relationship (Guy et al. 2007, figure 3) displays tantalizing hints of departures from the CCM law. If these can be conclusively demonstrated, it would at least prove that there is more going on than Milky-Way like dust, even if it might not elucidate the underlying mechanism.

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