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IMPROVED SUPERNOVA DISTANCES TO TEST THE COSMOLOGICAL PRINCIPLE AND A BIAS IN THE HUBBLE CONSTANT

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ABSTRACT

Type Ia supernovae (SNIa) have become a standard cosmological tool, but there are still improvements needed in this age of precision cosmology. Cosmology is reaching a point where we can now start to test the cosmological principle, that the universe is homogeneous and isotropic on large scales. I have analyzed the currently available dataset of SNIa to search for bulk flows on a variety of scales. We confirmed a velocity asymmetries across the sky of ~ 300 km s^{-1} at low redshift. We cannot rule out a large-scale bulk flow (dark flow) that could be caused by quantum entanglement in the early universe. And we show that a larger SNIa dataset and improved distance precision would provide useful constraints on any dark flow. We plan to simulate future large datasets to determine the optimal observing strategy to constrain the dark flow given the photometric precision, cadence, and sky coverage possible from LSST and other SNIa surveys. Further, we will improve the SNIa distance precision by correlating Hubble residuals with properties of the local environment around the supernova. There appears to be some correlation between the global host properties (e.g. star formation rate, metallicity) and SNIa luminosity residuals. There is a controversy as to whether the local environment is biasing the best estimates of the Hubble constant. We will analyze existing high-resolution Hubble Space Telescope images of SDSS host galaxies to see if the stellar properties at the explosion location correlate with SNIa luminosity.

1. INTRODUCTION

Type Ia supernova (SNIa) have been a standard cosmological tool since they were successfully used to estimate the Hubble constant (Hamuy et al. 1995; Riess et al. 1995), and later see the accelerated expansion of the Universe (Riess et al. 1998; Perlmutter et al. 1999). Cosmology is now focusing on precision and with improved precision we are able to test a fundamental assumption of cosmology: that the universe is homogeneous and isotropic on the largest scales. In order to check the Cosmological Principle, both the statistical and systematic uncertainties in SNIa distances must be reduced. These measurements will give deeper understanding of the evolution of the cosmos and the structure and composition of the universe.

Simple tests can be constructed to see if there is a consistent cosmology in all directions. For these to reach out to distances of gigaparsecs, or of order 0.1 in redshift, SNIa need to have very accurate distance measurements. SNIa distances are already corrected for light curve width and color variations, but further new corrections appear to be improve distance accuracy, such as correlations with host galaxy properties or even the local environment near the explosion. Procuring these tests will advance both supernova cosmology and cosmology as a whole.

2. TESTING THE COSMOLOGICAL PRINCIPLE

The excepted cosmological model, ΛCDM, works under a testable assumption that the universe is isotropic and homogeneous on large scales, scales greater than the size of the present day first acoustic peaks seen in the CMB. We already know that gravity breaks this isotropic condition on small scales and produces peculiar motion of galaxies. Specific theories of inflation (like in Mersini-Houghton & Holman (2009)) produce a preferred direction in our visible universe due to a slight curvature in space-time from pre-inflation interactions. Observationally, if this preferred direction exists, we expect to see a uniform bulk velocity flow that extends outside the local group and into what ΛCDM would predict to be a purely isotropic Hubble expansion. Such a large-scale asymmetry has been called a "dark flow" Mersini-Houghton & Holman (2009). This is a fundamental search to validate our understanding of the mass-energy make-up of the universe and look for entanglement from the era before inflation.

2.1. *Previous Tests*

The universe's isotropic nature has been intensely tested, over the last half a decade, with surveys of nearby galaxies (Ma & Scott 2013; Wiltshire et al. 2013), kinetic Sunyaev- Zeldovich (kSZ) effect on distant clusters (Kashlinsky et al. 2010; Planck Collaboration et al. 2014), and with SNIa data sets (Dai et al. 2011; Rathaus et al. 2013, and others as seen in Table 1). Most searches did not see a bulk flow that was significantly larger then allowed by ΛCDM but some saw a bulk flow of greater then 1000 km s^{-1} out to redshifts of $z = 0.25$, fig. 1. This measurement cannot be explained by ΛCDM alone but needs an inflation theory that predicts this cosmic anisotropy. A summary of the results from past searches can be found in table 1.

My work on initial tests of the Cosmological Principle can be found in Mathews et al. (2016). I worked heavily on developed a new method to search for cosmological

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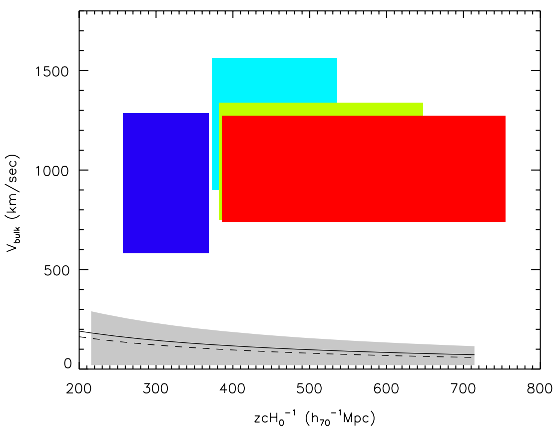

Figure 1. This is the measured bulk flows from kSZ measurements found in Kashlinsky et al. (2010). The blocks are for $z \leq 0.12$, 0.16, 0.2, and 0.25. A 95% confidence of a ΛCDM model is given in the grey-shaded region, with two different priors producing the rms lines. Taken from Kashlinsky et al. (2010).

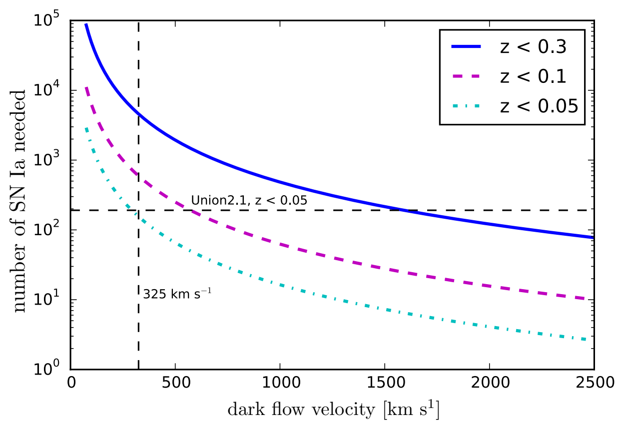

Figure 2. The number of SNIa needed to see a given dark flow velocity, a cosmic scale bulk flow, out to a given redshift. It is seen that Union2.1 can detect flows only out to $z = 0.05$ and nearly 10^4 SNIa would be needed to see a dark flow out to $z = 0.3$. Taken from Mathews et al. (2016)

asymmetries using the angular separation of a SNIa and the direction of the dark flow. We were able to minimize the data fitting both ΛCDM cosmological variables and an bulk flow. If the same bulk flow is visible across all redshifts, then we have found the dark flow signal. This analysis was performed on the Union2.1 (Suzuki et al. 2012) SNIa sample. We found a mild bulk flow of 325 ± 54 km s^{-1} out to $z = 0.05$. This is consistent with most past measurements and does not contradict ΛCDM.

From further analysis, we determined that the loss of signal past $z \sim 0.05$ was not from the lack of a dark flow, but from the increase of the uncertainty in the distance measurements. An order of magnitude reduction of distance modulus error is needed to see out to $z \sim 0.3$. This is unattainable with the current data sets, but we propose two ways to attack this problem. First, further data sets will reduce the statistical error in SNIa distances over large parts of the sky. This relationship is illustrated in fig. 2. This large sample size should be achievable with the Large Synoptic Survey Telescope (LSST) and its uniform photometric reliability of 10 mmag across the visible sky (Ivezic et al. 2008). A large, uniform data set will push the statistical errors at $z \sim 0.3$ to the systematic floor. Second, we propose to lower the systematic floor by including the properties of the local host environment in correcting SNIa distances.

2.2. *Future Tests*

At the end of Mathews et al. (2016), we suggest that LSST will produce a data set that is able to search for the cosmic dark flow. Detailed simulations of LSST- like data sets are critical in understanding the limits of the survey when applied to the dark flow problem. These tests will show if the combination of LSST's sensitivity, cadence, and sky coverage will be sufficient to test for isotropic expansion as predicted by ΛCDM and what limits can be placed on the dark flow. WFIRST may also be able to help in this measurement, however, its sky coverage will be limited compared with LSST. Simulations of the combined LSST and WFIRST data sets will produce useful insights into optimum future surveys.

Since the analysis method is written, getting a good simulated LSST SNIa data set is the hardest part. Telescope uncertainties and project goals have been stated, but these need to be transitioned, and any errors propagated, into positions, redshifts, and distances. The hardest part will be redshift. The community will not be able to get a spectra of the hosts at the rate that LSST will find SNIa, reducing the rate of cosmologically usable SNIa. Though machine learning is ever increasing the photometric redshift measurements, e.g. Carrasco Kind & Brunner (2013). Also with follow up telescopes in different locations then LSST, the footprint of the cosmologically useful SNIa might be different then LSST's footprint. These and others survey complexities will need to be taken into account for any accurate modeling of what can be done with LSST SNIa.

Large surveys are being leveraged to reduce the statistical uncertainties in distance measurements. But we also plan to reduce the systematic error floor by studying the local environments of SNIa.

3. TESTING FOR A BIAS IN THE HUBBLE CONSTANT

The local Hubble constant is simply the slop of the relationship between velocity and distance. Like many aspects of astronomy, measuring distance is the hardest part of this process. The Hubble constant can not be measured locally, because gravitation from the local galaxies and clusters create relatively large bulk motions. The further out one tries to measure distance the less direct the measurement becomes and the more it relies on the "distance ladder." This is where astronomers start with known distances and climb their way out to greater and greater distances by using different measurement techniques alone the way. If an anchoring of two techniques is not consistent with the individual techniques themselves, then a bias can arise. This is likely to appear if two measurements only overlap in a particular subset of objects.

3.1. *New Standardizations*

The SNIa community as a whole is focusing on reducing uncertainty in SNIa distances. Knowing distance more precisely will narrow the range for the Hubble con-

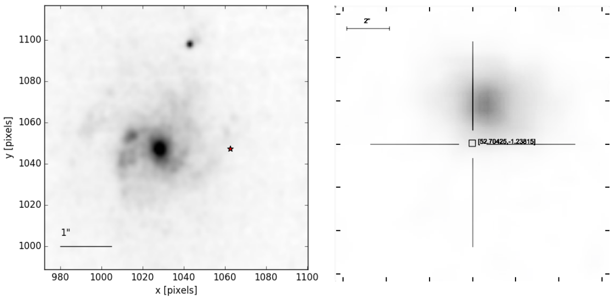

Figure 3. Host galaxy of SDSS SN2635 (2005fw), at a redshift of z=0.143. HST (left) one pixel is 114 pc, and SDSS (right) one pixel is 1,140 pc.

stant, the dark energy equation of state as well as constraining the Cosmological Principle.

SNIa are not standard candles, but rather standardizeable candles. Since Phillips (1993) there has been significant work to improve off this basic correction to the variability in SNIa absolute luminosity. SNIa color is also used to standardize SNIa and this has allowed them to be used for critical cosmological measurements ((Riess et al. 1998; Perlmutter et al. 1999)). Currently well- studied SNIa typically have a 15% error in distance modulus (or 7% in distance). So it takes about 50 SNIa to reduce the statistical error down to a few percent in brightness, which is near the the systematic floor. This floor is partly caused by limits on photometric calibration and partly by intrinsic uncertainties in the supernovae themselves.

A significant amount of research time and energy is spent on trying to reduce the scatter in the absolute magnitude of SNIa. It has been found that a reduction in this can be seen if the properties of the SNIa's host galaxy are accounted for. Host mass (Childress et al. 2013) and host metallicity (Hayden et al. 2013) have been seen to reduce this intrinsic scatter.

The idea that these global properties directly effect the SNIa is a bit of a stretch, so the community has started to look at the local environment around the SNIa. Rigault et al. (2013) looked at SNIa form the Nearby Supernova Factory and looked at H_α within a 1 kpc radius of each SNIa. They found a bias in standardized brightness of the SNIa. Also Rigault et al. (2015); Jones et al. (2015) looked at SNIa in the Constitution sample with host galaxy data from *GALEX* but they disagree on whether there is or is not a bias. Sorting this controversy out is critical in improving the estimate of the Hubble constant.

3.2. *Getting Closer in with HST*

I am currently working with Hubble Space Telescope (HST) images of host galaxies of SNIa found during SDSS-II Supernova Survey (Frieman et al. 2008; Sako et al. 2008). All the SNIa were found in stipe 82, 2.5° wide and about $\sim$ 120° along the Celestial Equator. HST's small angular resolution allows for a much smaller definition of local environment. For a galaxy at $z = 0.1$ HST can get an environment of $\sim$160 pc, verses the 1 kpc that was used with *GALEX* data in Jones et al. (2015); Rigault et al. (2015). This can be seen in the comparison between SDSS (having a simpler angular resolution to *GALEX*) and HST images of the host galaxy of SN 2005fw seen in fig. 3.

This process is not new, but HST's resolution allows us to probe hosts at a higher redshift. These redshifts are needed because the residuals on the Hubble diagram will allow for analysis of systematics rather then bulk motion. The redshift range of SDSS-II Supernovae Survey is $z = 0.05 - 0.4$. The HST observations were taken in two filters, with 360 sec exposures each.

After processing and analysis, the HST images will produce several variables describing the local environments of the SNIa. These variables will be compared to the SNIa's absolute brightness and residual on the Hubble diagram for correlations. The first of these variables being the SNIa's fractional pixel rank (FPR). The FPR is the ranked fraction, by brightness, of the pixel at the SNIa's position relative to the rest of the galaxy. This gives us a proxy for star formation. Another variable would be the color of the SNIa's pixel. Color can give a idea of the type of stars in that region. Further analysis of subsets will be done. We will be able to answer questions like whether there is a bias for SNIa in clumpy regions of elliptical galaxies.

3.3. *Beyond HST*

Difficulties in this analysis will all come from the data itself. The most obvious issue is that there are only 61 host galaxies, compared to around 1000 SNIa were seen with SDSS (Campbell et al. 2013). There is a large number of targets that still could be observed to increase the data set and improve our statistical uncertainties. More HST observations would be optimal, because it is needed for it high angular resolution in the visible. Ground based infrared photometry with adoptive optics would produce an interesting data set, but it would be difficult to add it to our current optical data.

We can get more data in several other ways. SDSS-IV's MaNGA is using integrated field units (IFUs) to get spectra at spacial scales of $\sim$ 2 kpc. IFUs are a common technique and their resolution will only get smaller with time. Alternative IFU's can be used, including Keck OSIRIS that observes in the infrared with a spacial element similar to HST ($0.020'' - 0.100''$) (Larkin et al. 2006), or Gemini GMOS that observes in the optical but has a much larger resolution $0.2''$ (Allington-Smith et al. 2002).

The angular resolution would not be as necessary if we observed host galaxies of local SNIa, but local observations also has issues. First, the number of SNIa is proportional to the volume for which you are looking, and there is more volume at higher redshift. Secondly, there are questions about whether SNIa are the same across cosmic time, so these local environment test should be done for as wide a range of redshifts as possible. For these reasons, SDSS's $z \sim 0.1$ is a good redshift to perform these tests. At this redshift, HST's high angular resolution is the best for observing a true local environment.

4. CONCLUSION

SNIa have been a standard cosmological tool for decades. In this time they have been continually refined to be more exact. Now SNIa detections are numerous enough and precise enough to start testing the Cosmological Principle and looking for a bias in the Hubble constant. The objectives of this research are to continue the

Table 1
Summary of bulk flow searches.

Reference	Obj. Type	No. Obj.	Redshift[a]	Distance[a] h^{-1} Mpc	v_{bf} km s^{-1}	l deg	b deg
Kashlinsky et al. (2010)	kSZ	516	< 0.12	< 345	934 ± 352	282 ± 34	22 ± 20
		547	< 0.16	< 430	1230 ± 331	292 ± 21	27 ± 15
		694	< 0.20	< 540	1042 ± 295	284 ± 24	30 ± 16
		838	< 0.25	< 640	1005 ± 267	296 ± 29	39 ± 15
Dai et al. (2011)	SN Ia	132	< 0.05	< 145	188 ± 120	290 ± 39	20 ± 32
		425	> 0.05	> 145	...	...	...
Ma et al. (2011)	galaxies & SN Ia	4536	< 0.011	< 33	340 ± 130	285 ± 23	9 ± 19
Colin et al. (2011)	SN Ia	142	< 0.06	< 175	260 ± 130	298 ± 40	8 ± 40
Feindt et al. (2013)	SN Ia	128	0.015 - 0.035	45 -108	243 ± 88	298 ± 25	15 ± 20
		36	0.035 - 0.045	108 - 140	452 ± 314	302 ± 48	-12 ± 26
		38	0.045 - 0.060	140 - 188	650 ± 398	359 ± 32	14 ± 27
		77	0.060 - 0.100	188 - 322	105 ± 401	285 ± 234	-23 ± 112
Ma & Scott (2013)	galaxies	2404	< 0.026	< 80	280 ± 8	280 ± 8	5.1 ± 6
Rathaus et al. (2013)	SN Ia	200	< 0.2	< 550	260	295	5
Appleby & Shafieloo (2014)	SN Ia	187	0.015 - 0.045	45 - 130	...	276 ± 29	20 ± 12
Planck Collaboration et al. (2014)	kSZ	95	0.01 - 0.03	30 - 90	< 700	...	...
		1743	< 0.5	< 2000	< 254	...	...
Mathews et al. (2016)	SN Ia	191	< 0.05	< 145	325 ± 54	276 ± 15	37 ± 13
		387	> 0.05	> 145	460 ± 260	180 ± 34	65 ± 340

[a] Distances and redshifts are either the maximum, or a characteristic value if available from the original source. If distance and redshift were not both given in the literature, calculated distances vs. redshift were done with WMAP parameters: $\Omega_M = 0.288$ and $\Omega_\Lambda = 0.712$.

analysis of SNIa calibration and the search of a cosmic-scale bulk flow. The next step in searching for a cosmic-scale bulk flow is to simulate and fully understand what is knowable from future surveys like LSST. The next step for SNIa calibration is to more fully understand the local environment.

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