Draft version March 22, 2016
Preprint typeset using LaTeX style emulateapj v. 12/16/11

PRECISION COSMOLOGY: TESTING THE COSMOLOGICAL PRINCIPLE WITH IMPROVED SUPERNOVA DISTANCES

Benjamin Rose, *advised by* P. M. Garnavich
University of Notre Dame, Center for Astrophysics, Notre Dame, IN 46556
Draft version March 22, 2016

ABSTRACT

I am looking for at improving cosmology with SNIa

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 important distance accuracy, such as correlations with host galaxy properties or even the local environment near the explosion. Procuring these tests will **finish my thesis statement.**

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. **go into theory detail?** 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'. **by whom, Kashlinsky's first paper or his "review" paper?**

2.1. *Previous Tests*

The universe's isotropic nature has been tested, over the last decade, with surveys of nearby galaxies (Ma & Scott 2013), kinetic Sunyaev-Zeldóvich (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 $z = 0.25$. 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. **remove both table references here.**

kaslinskly plot of measurements and what LCDM can allow.

other plot from aps presentation

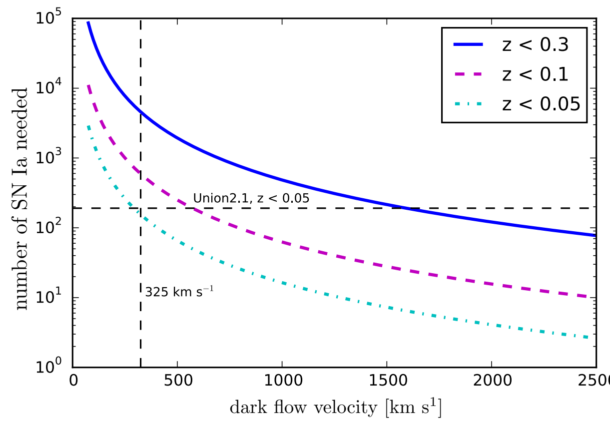

Figure 1. The number of SNIa needed to see a given dark flow velocity, a cosmic scale bulk flow, out to a given redshift. It is seen that Union2.1 can detect flows only out to $z = 0.05$ and nearly 10^4 SNIa would be needed to see a dark flow out to $z = 0.3$. Taken from Mathews et al. (2016)

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 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,

brose3@nd.edu

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 Figure 1. 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*

Testing the Cosmological Principle can and should be continued. In search for a cosmic anisotropy, studies have used galactic surveys, the kinetic Sunyaev- Zeldovich effect, and SNIa, but another possibility is using baryon acoustic oscillations (BAO). This distance measure is complementary to SNIa estimates and subject to smaller systematic uncertainties. The BAO analysis will follow a similar procedure as developed in Mathews et al. (2016) for SNIa. The test requires a data set with significant sky coverage, and this is possible with SDSS's eBOSS and eventually DESI.

Mathews et al. (2016) shows 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.

These 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.

talk about difficulties and solutions

3. STANDARDIZING TYPE IA SUPERNOVA

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 constant and 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.

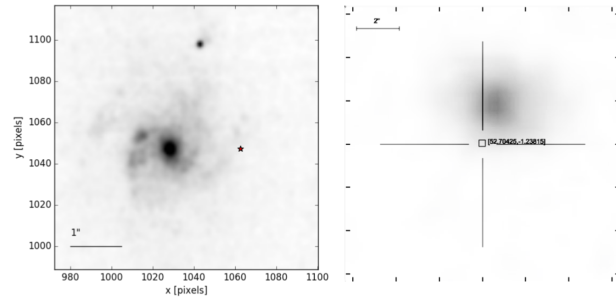

Figure 2. Host galaxy of SDSS SN2635 (2005fw), at a redshift of z=0.143. HST (left) one pixel is 114 pc, and SDSS (right) one pixel is 1,140 pc.

3.1. *New Standardizations*

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. *Using HST*

combine HST and future work sections

I am currently working with Hubble Space Telescope (HST) images of host galaxies of SNIa found during SDSS-II Supernova Survey. 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 ∼160 pc, verses the 1 kpc that was used with *GALEX* data in Jones et al. (2015); Rigault et al. (2015).

This set of HST images will give us a few variables for the local environment that we might be able to use for Corrections to the SNIa's absolute brightness. The first 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. These two variables will be compared to the residuals on the Hubble diagram to look for a bias. 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.

Understanding the local environment can be done with SNIa in the local universe, but that has some 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 this 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 range to perform these tests. At this redshift, HST's high angular resolution is the best for observing a true local environment.

3.3. *Future Work*

We plan several ways to study the local environment of SNIa. SDSS-IV's MaNGA is using integrated field units (IFUs) to get spectra at spacial scales of ~ 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). Proposals have been submitted to get IFU spectra on sub-sets of the host galaxies using MaGNA..

More photometry will also be useful. There are more hosts that HST can observe. Around 1000 SNIa were seen with SDSS (Campbell et al. 2013) but there are only around 60 in HST's archive. There is a large number of targets that still could be observed to increase the data set and improve our statistical uncertainties. Infrared photometry could also take advantage of ground based adaptive optic telescopes.

talk about difficulties and solutions
conclusion

REFERENCES

Allington-Smith, J., Murray, G., Content, R., et al. 2002, PASP, 114, 892
Appleby, S., & Shafieloo, A. 2014, J. Cosmology Astropart. Phys., 3, 007
Campbell, H., D'Andrea, C. B., Nichol, R. C., et al. 2013, ApJ, 763, 88
Childress, M., Aldering, G., Antilogus, P., et al. 2013, ApJ, 770, 108
Colin, J., Mohayaee, R., Sarkar, S., & Shafieloo, A. 2011, MNRAS, 414, 264
Dai, D.-C., Kinney, W. H., & Stojkovic, D. 2011, J. Cosmology Astropart. Phys., 2011, 015
Feindt, U., Kerschhaggl, M., Kowalski, M., et al. 2013, A&A, 560, 90
Hamuy, M., Phillips, M. M., Maza, J., et al. 1995, AJ, 109, 1
Hayden, B. T., Gupta, R. R., Garnavich, P. M., et al. 2013, ApJ, 764, 191
Ivezic, Z., Tyson, J. A., Abel, B., et al. 2008, arXiv.org, 0805.2366v4
Jones, D. O., Riess, A. G., & Scolnic, D. M. 2015, ApJ, 812, 31
Kashlinsky, A., Atrio-Barandela, F., Ebeling, H., Edge, A., & Kocevski, D. 2010, ApJ, 712, L81
Larkin, J., Barczys, M., Krabbe, A., et al. 2006, in Proc. SPIE, Vol. 6269, Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, 62691A
Ma, Y.-Z., Gordon, C., & Feldman, H. A. 2011, Phys. Rev. D, 83
Ma, Y. Z., & Scott, D. 2013, MNRAS, 428, 2017
Mathews, G. J., Rose, B., Garnavich, P., Yamazaki, D., & Kajino, T. 2016, ApJ *submitted*, arXiv:1412.1529
Mersini-Houghton, L., & Holman, R. 2009, J. Cosmology Astropart. Phys., 006
Perlmutter, S., Aldering, G., Goldhaber, G., et al. 1999, ApJ, 517, 565
Phillips, M. M. 1993, ApJ, 413, L105
Planck Collaboration, Ade, P. A. R., Aghanim, N., et al. 2014, A&A, 561, A97
Rathaus, B., Kovetz, E. D., & Itzhaki, N. 2013, MNRAS, 431, 3678
Riess, A. G., Press, W. H., & Kirshner, R. P. 1995, ApJ, 445, L91
Riess, A. G., Filippenko, A. V., Challis, P., et al. 1998, AJ, 116, 1009
Rigault, M., Copin, Y., Aldering, G., et al. 2013, A&A, 560, A66
Rigault, M., Aldering, G., Kowalski, M., et al. 2015, ApJ, 802, 20
Suzuki, N., Rubin, D., Lidman, C., et al. 2012, ApJ, 746, 85
Turnbull, S. J., Hudson, M. J., Feldman, H. A., et al. 2012, MNRAS, 420, 447
Weyant, A., Wood-Vasey, M., Wasserman, L., & Freeman, P. 2011, ApJ, 732, 65

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	$\cdots$	$\cdots$	$\cdots$
Weyant et al. (2011)	SN Ia	112	< 0.028	< 85	538 ± 86	250 ± 100	36 ± 11
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
Turnbull et al. (2012)	SN Ia	245	< 0.05	< 145	245 ± 76	319 ± 18	7 ± 14
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	$\cdots$	276 ± 29	20 ± 12
Planck Collaboration et al. (2014)	kSZ	95	0.01 - 0.03	30 - 90	< 700	$\cdots$	$\cdots$
		1743	< 0.5	< 2000	< 254	$\cdots$	$\cdots$
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 $\Omega_\Lambda = 0.712$.