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

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

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

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 data set of SNIa to search for bulk flows on a variety of scales. We confirmed a velocity asymmetry 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 data set and improved distance precision would provide useful constraints on any such dark flow. We plan to simulate future large data sets to determine the optimal observing strategy to constrain the dark flow given the photometric precision, cadence, and sky coverage possible from LSST and other future SNIa surveys. Furthermore, 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 influence of the local environment is biasing the best estimates of the Hubble constant (H_0). This bias either corrects or continues the tension between H_0 measured from the CMB or with SNIa. 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 supernovae (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 to see the accelerated expansion of the Universe (Riess et al. 1998; Perlmutter et al. 1999). Cosmology is now focusing on precision and with improved measurements we are able to test its fundamental assumptions. To perform these tests, 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.

The most fundamental assumption is called the Cosmological Principle, that the universe is homogeneous and isotropic on the largest scales. 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. A single SNIa at a redshift of 0.1 is not sufficient to reach the accuracy required to search for a dark flow. But averaging many SNIa measurements in the same direction on the sky can reduce the statistical uncertainty. Because we are looking for differences in the cosmology across the sky, systematic errors are minimized. More SNIa are going to come from the massive survey ongoing and planned for the near future.

As stated above, there is a systematic uncertainty floor in the distance from an individual SNIa. SNIa distances are already corrected for light curve width and color variations, but new corrections appear to improve distance accuracy, such as correlations with host galaxy properties or even the local environment near the explosion. These correlations with the local environment can lead to a bias in the Hubble constant (H_0) because of how SNIa are anchored to object of known distance. Unlike testing if there is a consistent cosmology in all directions, looking for a bias in H_0 is dominated by systematic errors. Finding a bias in H_0 as measured by SNIa will help with the tension between this measurement and the value calculated using the CMB. Performing more analysis of the local environment will advance both supernova cosmology and cosmology as a whole.

brose3@nd.edu

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

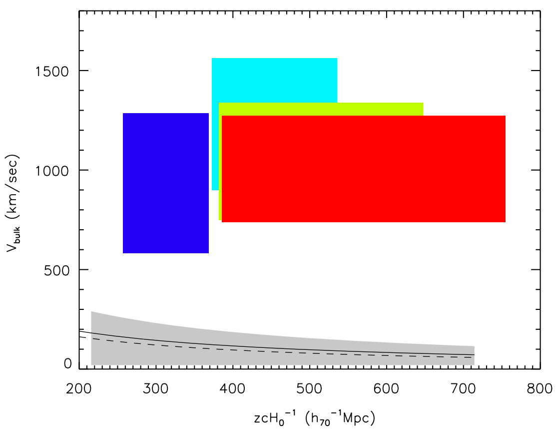

Figure 1. This is the measured bulk flows from the kSZ measurements found in Kashlinsky et al. (2010). The blocks are for $z \leq 0.12$, 0.16, 0.2, and 0.25. A 95% confidence of a ΛCDM model is given in the grey-shaded region, with two different priors producing the rms lines. Taken from Kashlinsky et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

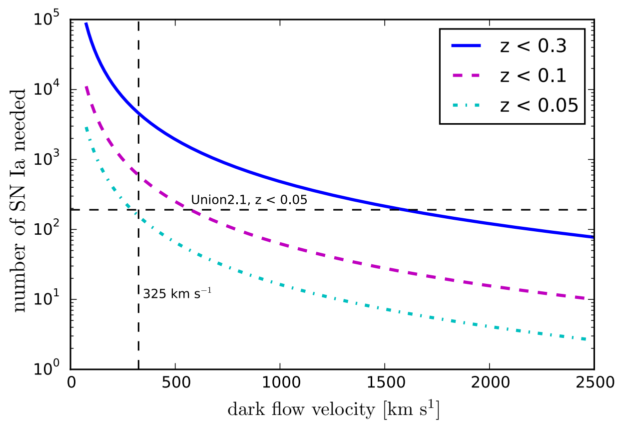

Figure 2. The number of SNIa needed to see a given dark flow velocity, a cosmic scale bulk flow, out to a given redshift. It is seen that Union2.1 can detect flows only out to $z = 0.05$ and nearly 10^4 SNIa would be needed to see a dark flow out to $z = 0.3$. Taken from Mathews et al. (2016)

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), the kinematic Sunyaev- Zeĺdovich (kSZ) effect on distant clusters (Kashlinsky et al. 2010; Planck Collaboration et al. 2014), and with SNIa data sets (Dai et al. 2011; Feindt et al. 2013; Rathaus et al. 2013, and others). Most searches did not see a bulk flow that was significantly larger than allowed by ΛCDM but some saw a bulk flow of greater than 1000 km s^{-1} out to redshifts of $z = 0.25$, Figure 1. This measurement cannot be explained by ΛCDM alone but needs an inflation theory that predicts this cosmic anisotropy.

My work on initial tests of the Cosmological Principle can be found in Mathews et al. (2016). I worked heavily to develop 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 fit the data to a model that contained both a ΛCDM cosmology 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 SNIa sample (Suzuki et al. 2012). We found a mild bulk flow of 326 ± 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 it can soon be achieved. First, larger data sets will reduce the statistical error in SNIa distances over large parts of the sky. Looking for a change of cosmology across the sky means any uniform systematics will be subtracted out and not affect the analysis. A visual account of the needed SNIa to see a given bulk flow can be seen in Figure 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.

2.2. *Future Tests*

At the end of Mathews et al. (2016), we suggest that LSST might produce a data set that is able to search for the 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 measurement precision, cadence, and sky coverage will be able to place limits on the dark flow. The future space telescope WFIRST may also be able to help in this measurement, however, its sky coverage will be limited compared with LSST. It has already been seen that sky coverage produces a bias in the dark flow velocity (Appleby & Shafieloo 2014) if not obscuring measurements completely (Mathews et al. 2016). 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, with 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 accuracy of photometric redshift measurements, e.g. Carrasco Kind & Brunner (2013). With follow up telescopes in different locations than 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 the distance measurement of SNIa. With this decreased uncertainty, we will be able to test the Cosmological Principle and check to see if cosmology is truly constant no matter where you look.

3. TESTING FOR A BIAS IN THE HUBBLE CONSTANT

The Hubble constant is simply the slope of the relationship between velocity and distance. Like many aspects of astronomy, measuring distance is the hardest part of this process. H_0 cannot be measured locally because gravitation from neighboring galaxies and clusters create relatively large bulk motions. To measure distances of the whole of the cosmos one needs to rely 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 along 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 subtype 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 constant, 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 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 scatter can be achieved if the properties of the SNIa's host galaxy are taken into account. 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 affect 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 the host galaxy's H_α within a 1 kpc radius of each SNIa. They found a bias in the SNIa standardized luminosity when they divided their sample in half based on the measured H_α. If there was less H_α then the average corrected luminosity was also lower. 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

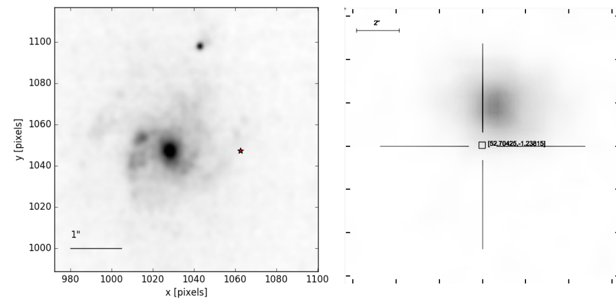

Figure 3. Host galaxy of SDSS SN2635 (SN 2005fw), at a redshift of $z = 0.143$. HST (left) one pixel is 114 pc, and SDSS (right) one pixel is 1,140 pc.

SDSS-II Supernova Survey (Frieman et al. 2008; Sako et al. 2008). All the SNIa were found in Stripe 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 ∼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 Figure 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 than 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 second 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 can also be done and questions like whether there is a bias for SNIa in clumpy regions of elliptical galaxies can be answered.

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 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 of its high angular resolution in the visible. Ground based infrared photometry with adoptive optics would produce a meaningful data set, but it would be difficult to add it to our current optical data.

I 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 ~ 2 kpc and they have a call for ancillary proposals coming out this fall. Even though

MaNGA has large angular resolution, IFU's are a common technique and their resolution will only get smaller with time. Alternative IFU's can be used, including Keck OSIRIS which observes in the infrared with a spacial element similar to HST ($0.020'' - 0.100''$) (Larkin et al. 2006), or Gemini GMOS which observes in the optical but has a much larger resolution $0.2''$ (Allington-Smith et al. 2002).

The angular resolution of HST would not be as necessary if we observed host galaxies of local SNIa, but these observations also have 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, with a concern for a bias in H_0 due to anchoring only a subtype of SNIa these local environment tests 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 their absolute magnitude has been continually refined to be more precise and standardized. Now SNIa detections are numerous enough and their distances are accurate enough to start testing the Cosmological Principle and looking for a bias in the Hubble constant. These two tests are complementary. The next step in searching for a cosmic-scale bulk flow is to lower the statistical uncertainties of SNIa. This will be done by future large scale surveys but their impact needs to be understood through simulations or their usefulness will be limited. The next step for testing for a bias in H_0 is to lower SNIa systematic uncertainties. These uncertainties appear to be correlated with local environments, but the exact variable is still unknown. More high resolution observations need to be done allowing for a thorough analysis of the local environment's effects on SNIa.

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
Carrasco Kind, M., & Brunner, R. J. 2013, MNRAS, 432, 1483
Childress, M., Aldering, G., Antilogus, P., et al. 2013, ApJ, 770, 108
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
Frieman, J. A., Bassett, B., Becker, A., et al. 2008, AJ, 135, 338
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., & 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
Sako, M., Bassett, B., Becker, A., et al. 2008, AJ, 135, 348
Suzuki, N., Rubin, D., Lidman, C., et al. 2012, ApJ, 746, 85
Wiltshire, D. L., Smale, P. R., Mattsson, T., & Watkins, R. 2013, Phys. Rev. D, 88, 083529