

(1) Basic Information

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“Discovering the Nature of Dark Energy: Towards Better Distances from Type Ia Supernovae”

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(2) Authorized Distribution Limitation Notices

None.

(3) Executive Summary

Type Ia supernovae (SNe Ia; exploding white-dwarf stars) were the key to the Nobel-worthy 1998 discovery and subsequent verification that the expansion of the Universe is accelerating, driven by the effects of dark energy. Understanding the nature of this mysterious, yet dominant, component of the Universe is at the forefront of research in cosmology and fundamental physics. SNe Ia will continue to play a leading role in this enterprise, providing precise cosmological distances that improve constraints on the nature of dark energy. However, for this effort to succeed, we need to more thoroughly understand relatively *nearby* SNe Ia, because our conclusions come only from comparisons between them and distant (high-redshift) SNe Ia. Thus, detailed studies of relatively nearby SNe Ia are the focus of this research program.

Many interesting results were obtained during the course of this project; these were published in 32 refereed research papers that acknowledged the grant. A major accomplishment was the publication of supernova (SN) rates derived from about a decade of operation of the Lick Observatory Supernova Search (LOSS) with the 0.76-meter Katzman Automatic Imaging Telescope (KAIT). We have determined the most accurate rates for SNe of different types in large, nearby galaxies in the present-day Universe, and these can be compared with SN rates far away (and hence long ago in the past) to set constraints on the types of stars that explode. Another major accomplishment was the publication of the light curves (brightness vs. time) of 165 SNe Ia, along with optical spectroscopy of many of these SNe as well as other SNe Ia, providing an extensive, homogeneous database for detailed studies. We have conducted intensive investigations of a number of individual SNe Ia, including quite unusual examples that allow us to probe the entire range of SN explosions and provide unique insights into these objects and the stars before they explode. My team’s studies have also led to the identification of subsamples of SNe Ia that can be used to provide the most reliable cosmological distances, and we developed ways to deal with the dust that makes SNe Ia appear fainter than they really are. Using the KAIT/LOSS sample, we produced an excellent Hubble diagram (galaxy recession speed vs. distance), accurately showing the expansion of the Universe. Even smaller scatter was achieved when spectroscopic characteristics were taken into account. Another high-quality Hubble diagram was constructed with SNe Ia from the Sloan Digital Sky Survey (SDSS). These Hubble diagrams provide useful new constraints on the nature of the dark energy that is accelerating the expansion of the Universe. As an added bonus of our research, we also studied core-collapse SNe, which differ fundamentally from SNe Ia.

The results of my team’s work have been disseminated to a broad audience, in my complementary missions of cutting-edge research and effective public outreach and teaching. I have given many dozens of public lectures each year, generally focusing on exciting current topics in astronomy, with the results of my group’s research included when appropriate. Television, radio, newspaper, and magazine reporters frequently contact me for interviews about my work, and I have played a prominent role in many TV astronomy documentaries. I receive and reply to hundreds of questions per year from the general public. At the University level, I discuss our findings when teaching my very popular (700-800 students) introductory astronomy course. I have taken selected students from this class on trips to Lick Observatory, where they see the research process up close. I involved a large number of undergraduate students (some of whom are not even science majors, and many of whom are women) in my research, as well as graduate students and postdocs. Undergraduates sometimes made sufficiently significant contributions to earn them coauthorship on refereed papers. The students and postdoctoral researchers were trained in the latest techniques of observations, data calibration and analysis, and interpretation, including sophisticated statistical methods. The skills they learned will be useful for a variety of careers outside astronomy as well, and they will pass their enthusiasm and technical knowledge onto others.

(4) Actual Accomplishments vs. Goals and Objectives

In the abstract of our original proposal, we stated that to make progress in the field, “... the high-redshift SN Ia Hubble diagram needs to be anchored by a large sample of *nearby* objects. We propose a coordinated program to strengthen the results of all future SN Ia projects through detailed analysis of the quickly growing nearby sample, with particular attention to the results of LOSS and the SDSS-II SN Survey. We will focus on the dominant systematic effects: (1) understanding the combined effects of host-galaxy dust, variation of the dust extinction law, and scatter in the intrinsic colors of SNe Ia; (2) identifying subsamples of SNe Ia that give more precise and accurate luminosity distances, with lower systematic error floors; and (3) using spectroscopy to quantify luminosity evolution in SNe Ia and constrain progenitors and explosion models. The results of these studies will make SNe Ia more precise and more accurate distance indicators, and increase the power of SN Ia projects to elucidate the nature of dark energy.”

The actual accomplishments of our research matched and even exceeded the above goals. Specifically, major results from LOSS were indeed published (Papers 19–21), as were the derived light curves for 165 SNe Ia (Paper 17). Results from the SDSS-II SN Survey were published in Papers 4 and 12. Goal (1) was addressed in the above studies, as well as in Papers 2 and 24. Much progress on goal (2) was made in Papers 1, 2, 3, 9, 10, 11, 25, 26, and 32. Goal (3) was tackled in Papers 3, 8, 13, 15, 18, 22, and 27–31. The goals were exceeded through the work published in Papers 5, 6, 7, 14, 16, and 23.

(5) Project Activities

Many interesting results were obtained during the course of this project. Refereed papers that explicitly acknowledge funding from this grant are given in the next section. The main results are summarized here.

Paper 1 (Wang *et al.* 2009a) presents detailed ultraviolet (UV), optical, and near-infrared light curves, as well as densely sampled optical spectra, of a normal (“golden standard”) Type Ia SN. This object will serve as a means to fill in observational gaps (either in wavelength or time) in future SNe Ia that presumably are not as well studied.

Paper 2 (Wang *et al.* 2009b) shows that improved distances to SNe Ia can be obtained by recognizing and isolating two spectroscopic subclasses. This is very important for decreasing the scatter in the Hubble diagram.

Paper 3 (Simon *et al.* 2009) sets constraints on the amount of circumstellar matter around a SN Ia that had very little extinction due to dust, providing insights into the progenitor systems of SNe Ia.

Paper 4 (Kessler *et al.* 2009) provides the Hubble diagram and cosmological parameters derived from the first-year data of the SDSS-II Supernova Survey, to which we contributed with Keck follow-up spectroscopy of SN candidates; see also Paper 12.

Papers 5 (Rau *et al.* 2009) and 6 (Law *et al.* 2009): We are informal collaborators in the Palomar Transient Factory (PTF), which is being conducted with the 1.2-m Oschin Schmidt telescope at Palomar Observatory. Part of the focal plane is tiled with CCDs, giving a field of view of 7.2 square degrees. The science goals of PTF are outlined in Paper 5, while the system overview, performance, and first results are described in Paper 6. This survey led to the discovery and classification of a very large number of SNe, some of which were studied in detail, leading to improvements in our understanding of SNe.

Paper 7 (Gal-Yam *et al.* 2009): Pair-instability SNe, in which gravitational contraction results from the loss of pressure support as high-energy gamma-ray photons spontaneously produce electron-positron pairs, were thought to result only from the most massive stars in the very early Universe. Here we present observations of a nearby object (SN 2007bi) that appears to have synthesized so much radioactive nickel that it could only be produced via the pair-instability process. (See the press release at <http://newscenter.lbl.gov/news-releases/2009/12/02/superbright-supernova/> .)

Paper 8 (Poznanski *et al.* 2009) suggests that SN 2002bj, which had a peculiar spectrum and an extremely rapid light curve, may have been the first identified example of the theoretically suggested “.Ia supernova” — the explosion of an outer helium layer of a white dwarf in an AM CVn system.

Paper 9 (Zhang *et al.* 2009) provides an analysis of SN 2007gi, a SN Ia that is in the luminous, high-velocity-gradient subgroup of SNe Ia. The other main subgroup has low luminosities and low velocity gradients. Recognizing two such subgroups helps improve the utility of SNe Ia as cosmological distance indicators.

Papers 10 (Contreras *et al.* 2009) and 11 (Folatelli *et al.* 2009): We are informal collaborators in the Carnegie Supernova Program, which published its first sets of results on about three dozen nearby SNe Ia. The photometry is exquisite, and this sample has become an important component of the Hubble diagram of SNe Ia.

Paper 12 (Dilday *et al.* 2009) provides measurements of the rate of SNe Ia at redshift < 0.3 from the SDSS-II Supernova Survey described in Paper 4.

Paper 13 (Perets *et al.* 2010): Until now, two progenitor systems were thought to account for the observed properties of known SNe: core collapse of a massive star or thermonuclear runaway of an accreting white dwarf. The observed properties of SN 2005E defy both paradigms; it may represent a new kind of explosion, and we explore some possibilities. (See the press release at <http://newscenter.berkeley.edu/2010/05/19/super-nova2005e/> .)

Paper 14 (Sharon *et al.* 2010) derives a low SN Ia rate in clusters of galaxies at redshifts $z = 0.5\text{--}0.9$, implying that most of the iron production in clusters must have occurred early in the history of the Universe, at $z > 1$.

Paper 15 (McLelland *et al.* 2010) show that the subluminous SN 2007qd may be a “missing link” between normal SNe Ia that explode via delayed detonation and peculiar, low-luminosity SNe Ia such as SN 2002cx that might undergo a thermonuclear deflagration.

Paper 16 (Milne *et al.* 2010; see also the companion paper by Brown *et al.* 2010, *ApJ*, **721**, 1608) use *Swift* satellite data to determine the UV absolute magnitudes and other

near-UV properties of a large number of SNe Ia. These will be useful in comparisons with high-redshift SNe Ia.

Paper 17 (Ganeshalingam *et al.* 2010): We developed and perfected a pipeline to automatically measure both the filtered and unfiltered light curves of SNe. Here we present *BVRI* light curves of 165 SNe Ia from our KAIT robotic telescope and LOSS. This is a major new contribution to the existing set of filtered light curves of SNe Ia.

Paper 18 (Silverman *et al.* 2011) provides extensive observations and analysis of SN 2009dc, a very luminous and slowly evolving SN Ia that may have had a super-Chandrasekhar progenitor. This is an important new subclass of SNe Ia from two perspectives: (a) it may indicate another channel for producing SNe Ia, and (b) such objects need to be taken into account when using SNe Ia for cosmological distance determinations, as they could significantly bias the results.

Papers 19 (Leaman *et al.* 2011), 20 (Li *et al.* 2011a), and 21 (Li *et al.* 2011b): We have also used our KAIT/LOSS sample of SNe (nearly 1000 objects) to determine the observed rates of different kinds of SNe in the local Universe. This was the PhD thesis work of quadriplegic graduate student Jesse Leaman, done under my guidance and that of Weidong Li. Ours is the largest and most homogeneous set of nearby SNe ever assembled for this purpose, and we have the first local SN rate analysis based on CCD imaging and modern image-subtraction techniques. Specifically, in these three papers, a complete SN sample is constructed, and the observed (uncorrected for host-galaxy extinction) luminosity functions of SNe are derived. A comparison between our SN rates and the published measurements shows that they are consistent with each other to within the uncertainties when the calculations are done in the same manner. Nevertheless, our data demonstrate that the SN rates cannot be adequately described by a single parameter using either galaxy Hubble types or $B - K$ colors. A secondary parameter in galaxy “size,” expressed by luminosity or stellar mass, is necessary as part of a rate-size relation: the galaxies of smaller sizes have higher SN rates per unit mass or per unit luminosity. Physically, the rate-size relation for core-collapse SNe is probably linked to the correlation between the specific star-formation rate and the galaxy size, but it is not clear whether the same link can be established for SNe Ia. We discuss the two-component (“tardy” and “prompt”) model for SN Ia rates, and find that the SN Ia rates in young stellar populations might have a strong correlation with the core-collapse SN rates.

Paper 22 (Maoz *et al.* 2011): Recovery of the SN delay-time distribution (DTD) – the SN rate versus time that would follow a brief burst of star formation – can shed light on SN progenitors and physics, as well as on the timescales of chemical enrichment. Here we present an approach to recover the SN DTD that avoids the averaging and loss of information that plagues other schemes, comparing the star-formation histories of individual galaxies to the numbers of SNe discovered by LOSS in each galaxy. We find a SN Ia DTD signal (99% confidence level) in our shortest-delay, “prompt” bin at < 420 Myr. We further find a strong indication of SNe Ia that are “delayed” by > 2.4 Gyr. Thus, the data support the existence of both prompt and delayed SNe Ia. We also find that most or all stars more massive than 8 solar masses lead to visible SN explosions.

Paper 23 (Smith *et al.* 2011a) analyzes the observed fractions of core-collapse SN types from LOSS and discusses the corresponding implications for massive-star evolution. For a standard initial mass function, observed fractions of SN types cannot be reconciled with the expectations of single-star evolution. The mass range of Wolf-Rayet (WR) stars that shed their hydrogen envelopes via their own mass loss accounts for less than half of the observed fraction of SNe Ibc. The true progenitors of SNe Ibc must extend to a much lower range of initial masses than classical WR stars, and we argue that most SN Ibc and SN IIb progenitors must arise from binary Roche-lobe overflow. We consider the possibility of direct collapse to

black holes without visible SNe, but find this hypothesis difficult to accommodate in most scenarios.

Paper 24 (Poznanski *et al.* 2011) uses our extensive atlas of SN Ia spectra and photometry to show that low-resolution Na D absorption is a bad proxy for extinction. This study demonstrates that one of the standard techniques for determining the extinction of SNe Ia is seriously flawed – an unfortunate situation, but definitely best to not be ignorant of it.

Paper 25 (Ganeshalingam *et al.* 2011) uses the data in Paper 17 to determine the rise-time distribution of nearby SNe Ia. We find that low-luminosity SNe Ia have faster rise times than normal or overluminous SNe Ia, contrary to some previous conclusions by others. These results are important when using the light-curve shape to standardize the luminosity of high-redshift SNe Ia.

Paper 26 (Ganeshalingam *et al.* 2012) shows that SN 2002es is a peculiar SN Ia, with low expansion velocities and a rapidly fading light curve. Oddballs such as this must be removed from samples of SNe Ia when conducting cosmological studies.

Paper 27 (Silverman *et al.* 2012a): In this first paper in a series we present 1298 low-redshift optical spectra of 582 SNe Ia observed from 1989 through 2008 as part of the Berkeley SN Ia Program (BSNIP). We describe the resulting SN Database (SNDB), which is an online, public, searchable database containing all of our fully reduced spectra and companion photometry.

Paper 28 (Silverman *et al.* 2012b): In this second paper in the BSNIP series, we present measurements of spectral features of 432 low-redshift optical spectra of 261 SNe Ia within 20 days of maximum brightness. We investigate how expansion velocity and pseudo-equivalent width evolve with time and how they correlate with each other.

Paper 29 (Silverman *et al.* 2012c): In this third paper in the BSNIP series, we compare spectral feature measurements to photometric properties of 108 low-redshift SNe Ia with optical spectra within 5 days of maximum brightness. We obtain a Hubble diagram having one of the smallest scatters ever published and at the highest significance ever seen in such a study.

Paper 30 (Silverman *et al.* 2012d): In this fourth paper in the BSNIP series, we search for carbon absorption features in 188 optical spectra of 144 young, low-redshift SNe Ia. At early times, there is a $> 30\%$ chance of detecting C II absorption. Carbon represents the most direct way of investigating primordial white dwarf material and its relation to SN Ia explosion scenarios and mechanisms.

Paper 31 (Silverman *et al.* 2013): In this fifth paper in the BSNIP series, we analyze late-time optical spectra of low-redshift SNe Ia. Nearly all high-velocity-gradient objects have redshifted nebular lines, while most low-velocity-gradient objects have blueshifted nebular lines. With asymmetric explosions, the viewing angle may be quite important.

Paper 32 (Ganeshalingam, Li, & Filippenko 2013) presents a cosmological analysis of the LOSS SN Ia photometry. We show a Hubble diagram of 586 SNe at $z = 0.01\text{--}1.4$ with a residual scatter of 0.176 mag. Assuming a flat Universe, we find that the best fit for the dark energy equation-of-state parameter $w = 0.86$ ($+0.13, 0.16$; statistical) ± 0.11 (systematic) from SNe alone, consistent with a cosmological constant.

(6) Products Developed

(a) Refereed Publications

- 1) X. Wang, *et al.* (2009). *Astrophys. Jour.*, **697**, 380–408. “The Golden Standard Type Ia Supernova 2005cf: Observations from the Ultraviolet to the Near-Infrared Wavebands.”
- 2) X. Wang, A. V. Filippenko, M. Ganeshalingam, W. Li, J. M. Silverman, L. Wang, R. Chornock, R. J. Foley, E. L. Gates, B. Macomber, F. J. D. Serduke, T. N. Steele, and D. S. Wong (2009). *Astrophys. Jour. (Letters)*, **699**, L139–L143. “Improved Distances to Type Ia Supernovae with Two Spectroscopic Subclasses.”
- 3) J. D. Simon, *et al.* (2009). *Astrophys. Jour.*, **702**, 1157–1170. “Variable Sodium Absorption in a Low-Extinction Type Ia Supernova.”
- 4) R. Kessler, *et al.* (2009). *Astrophys. Jour. Supp. Ser.*, **185**, 32–84. “First-Year Sloan Digital Sky Survey-II Supernova Results: Hubble Diagram and Cosmological Parameters.”
- 5) A. Rau, *et al.* (2009). *Pub. Astron. Soc. Pacific*, **121**, 1334–1351. “Exploring the Optical Transient Sky with the Palomar Transient Factory.”
- 6) N. Law, *et al.* (2009). *Pub. Astron. Soc. Pacific*, **121**, 1395–1408. “The Palomar Transient Factory: System Overview, Performance, and First Results.”
- 7) A. Gal-Yam, *et al.* (2009). *Nature*, **462**, 624–627. “Supernova 2007bi as a Pair-Instability Explosion.”
- 8) D. Poznanski, *et al.* (2010). *Science*, **327**, 58–60. “An Unusually Fast-Evolving Supernova.”
- 9) T. Zhang, *et al.* (2010). *Publ. Astron. Soc. Pacific*, **122**, 1–11. “Optical Observations of the Rapidly Expanding Type Ia Supernova 2007gi.”
- 10) C. Contreras, *et al.* (2010). *Astron. Jour.*, **139**, 519–539. “The Carnegie Supernova Project: First Photometry Data Release of Type Ia Supernovae.”
- 11) G. Folatelli, *et al.* (2010). *Astron. Jour.*, **139**, 120–144. “The Carnegie Supernova Project: Analysis of the First Sample of Low-Redshift Type-Ia Supernovae.”
- 12) B. Dilday, *et al.* (2010). *Astrophys. Jour.*, **713**, 1026–1036. “Measurements of the Rate of Type Ia Supernovae at Redshift $\lesssim 0.3$ from the Sloan Digital Sky Survey II Supernova Survey.”
- 13) H. B. Perets, *et al.* (2010). *Nature*, **465**, 322–325. “A Faint Type of Supernova from a White Dwarf with a Helium-Rich Companion.”
- 14) K. Sharon, *et al.* (2010). *Astrophys. Jour.*, **718**, 876–893. “The Type Ia Supernova Rate in Redshift 0.5–0.9 Galaxy Clusters.”
- 15) C. M. McClelland, *et al.* (2010). *Astrophys. Jour.*, **720**, 704–716. “The Subluminous Supernova 2007qd: A Missing Link in Thermonuclear Deflagration?”
- 16) P. A. Milne, *et al.* (2010). *Astrophys. Jour.*, **721**, 1627–1655. “Near-Ultraviolet Properties of a Large Sample of Type Ia Supernovae as Observed with the Swift UVOT.”

- 17) M. Ganeshalingam, *et al.* (2010). *Astrophys. Jour. Supplement Ser.*, **190**, 418–448. “Results of the Lick Observatory Supernova Search Photometry Program: *BVRI* Light Curves of 165 Type Ia Supernovae.”
- 18) J. M. Silverman, M. Ganeshalingam, W. Li, A. V. Filippenko, A. A. Miller, and D. Poznanski (2011). *Mon. Not. Royal Astron. Soc.*, **410**, 585–611. “Fourteen Months of Observations of the Possible Super-Chandrasekhar Mass Type Ia Supernova 2009dc.”
- 19) J. Leaman, W. Li, R. Chornock, and A. V. Filippenko (2011). *Mon. Not. Royal Astron. Soc.*, **412**, 1419–1440. “Nearby Supernova Rates from the Lick Observatory Supernova Search. I. The Methods and Database.”
- 20) W. Li, J. Leaman, R. Chornock, A. V. Filippenko, D. Poznanski, M. Ganeshalingam, X. Wang, M. Modjaz, S. Jha, R. J. Foley, and N. Smith (2011). *Mon. Not. Royal Astron. Soc.*, **412**, 1441–1472. “Nearby Supernova Rates from the Lick Observatory Supernova Search. II. The Observed Luminosity Functions and Fractions of Supernovae in a Complete Sample.”
- 21) W. Li, R. Chornock, J. Leaman, A. V. Filippenko, D. Poznanski, X. Wang, M. Ganeshalingam, and F. Mannucci (2011). *Mon. Not. Royal Astron. Soc.*, **412**, 1473–1507. “Nearby Supernova Rates from the Lick Observatory Supernova Search. III. The Rate-Size Relation, and the Rates as a Function of Galaxy Hubble Type and Colour.”
- 22) D. Maoz, *et al.* (2011). *Mon. Not. Royal Astron. Soc.*, **412**, 1508–1521. “The Supernova Delay Function: Recovery Method and Application to the Lick Observatory Supernova Search.”
- 23) N. Smith, W. Li, A. V. Filippenko, and R. Chornock (2011). *Mon. Not. Royal Astron. Soc.*, **412**, 1522–1538. “Observed Fractions of Core-Collapse Supernova Types and Initial Masses of their Single and Binary Progenitor Stars.”
- 24) D. Poznanski, M. Ganeshalingam, J. M. Silverman, and A. V. Filippenko (2011). *Mon. Not. Royal Astron. Soc.*, **415**, L81–L84. “Low-Resolution Sodium D Absorption is a Bad Proxy for Extinction.”
- 25) M. Ganeshalingam, W. Li, and A. V. Filippenko (2011). *Mon. Not. Royal Astron. Soc.*, **416**, 2607–2622. “The Rise-Time Distribution of Nearby Type Ia Supernovae.”
- 26) M. Ganeshalingam, *et al.* (2012). *Astrophys. Jour.*, **751**, ID 142. “The Low-Velocity, Rapidly Fading Type Ia Supernova 2002es.”
- 27) J. M. Silverman, *et al.* (2012). *Mon. Not. Royal Astron. Soc.*, **425**, 1789–1818. “Berkeley Supernova Ia Program – I: Observations, Data Reduction, and Spectroscopic Sample of 582 Low-Redshift Type Ia Supernovae.”
- 28) J. M. Silverman, J. J. Kong, and A. V. Filippenko (2012). *Mon. Not. Royal Astron. Soc.*, **425**, 1819–1888. “Berkeley Supernova Ia Program – II: Initial Analysis of Spectra Obtained Near Maximum Brightness.”
- 29) J. M. Silverman, M. Ganeshalingam, W. Li, and A. V. Filippenko (2012). *Mon. Not. Royal Astron. Soc.*, **425**, 1889–1916. “Berkeley Supernova Ia Program – III: Spectra Near Maximum Brightness Improve the Accuracy of Derived Distances to Type Ia Supernovae.”
- 30) J. M. Silverman and A. V. Filippenko (2012). *Mon. Not. Royal Astron. Soc.*, **425**, 1917–1933. “Berkeley Supernova Ia Program – IV: Carbon Detection in Early-Time Optical Spectra of Type Ia Supernovae.”

- 31) J. M. Silverman, M. Ganeshalingam, and A. V. Filippenko (2013). *Mon. Not. Royal Astron. Soc.*, **430**, 1030–1041. “Berkeley Supernova Ia Program – V: Late-Time Spectra of Type Ia Supernovae.”
- 32) M. Ganeshalingam, W. Li, and A. V. Filippenko (2013). *Mon. Not. Royal Astron. Soc.*, **433**, 2240–2258. “Constraints on Dark Energy with the LOSS SN Ia Sample.”

(b) Websites

- (i) http://astro.berkeley.edu/bait/public_html/kait.html

Supernovae discovered during LOSS with KAIT are listed on this website. Also, there are some photographs that the public can view and use. In addition, we post the press releases that have resulted from our research.

- (ii) http://hercules.berkeley.edu/database/index_public.html

This website contains our database of *BVRI* light curves of 165 SNe Ia (Ganeshalingam *et al.* 2010), as well as our vast library of SN Ia spectra (Silverman *et al.* 2012a). The spectra cover the entire optical window (3200–10,000 Å), observed and reduced in a consistent manner, representing the largest homogeneous set of SN Ia spectra published thus far. By making our database available to the community, the amount of science to be obtained from it certainly grows.

(c) Collaborations Fostered

We had a large number of collaborators on the various subsets of this project. Many of these are likely to continue in the future.