OBSERVING REQUEST
University of Arizona Observatories

Year: 2015 **Term:** Jan–Jun **Proposal type:** short-term⋆

Late Optical and NIR Imaging of Type Ia Supernovae

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CoI(s): Peter Garnavich (Notre Dame University), Ginger Bryngelson (Francis Marion University), Jessica Lair (Eastern Kentucky University)

Abstract of Scientific Justification

We propose to use the 90Prime, PISCES and WFCAM/UFTI cameras at the 2.3m Bok and UKIRT telescopes to observe the type Ia supernovae, SNe 2014J, 2013dy and 2013ct at late epochs (450–610 days post-explosion) in the optical and NIR, and obtain subtraction images for SN 2012ht. The deposition of kinetic energy during the slowing of non-thermal positrons dominates the late light curves of SNe Ia. Late observations of SNe Ia probe the magnetic field strength and alignment, by detecting the degree to which positrons escape the ejecta. The slope of the BVR-band light curves of normally- and super-luminous SNe Ia follow the slope predicted if positrons escape in quantity. However, NIR light curves of seven SNe Ia display completely flat light curves, which has been interpreted as being evidence of positron trapping in the SN ejecta. Observations made of four additional SNe Ia, obtained during previous trimesters, support the existence of a NIR plateau, with a hint of a bi-modal distribution. We propose U,B,V,R,I,J,H,K filter observations of 3 normal SNe Ia to support optical and NIR observations of these SNe with the Kuiper, Bok, Mayall, LBT, and *Swift* telescopes. Observations of young SNe Ia will also be performed during these nights to support a collaboration seeking UV-optical-NIR light curves for a collection of SNe Ia.

Summary of observing runs requested for this project

Run	Telescope	Cage	Instrument	PI	AO	Nights	Moon	Scheduling Optimal	Scheduling Acceptable	Sharing Poss.	Sharing Adv.
1	UKIRT	PF	WFCAM			4	grey	Jan–June	Jan–June	yes	yes
2	UKIRT		UFTI			4	grey	Jan–June	Jan–June	yes	yes
3	Bok	PF	90P			6	grey	Jan,Apr-June	Jan,Apr-June	yes	yes
4	Bok	f9	PISCES			6	grey	Jan,Apr-June	Jan,Apr-June	yes	yes

Scheduling constraints and unusable dates *(up to 4 lines)*: None

no text past this line

A ⋆ appended to the proposal type indicates a continuation proposal; a ⋆ appended to the name of a proposer indicates the proposer is a (graduate) student; a proposer whose name is underlined is certified on the proposed telescope/instrument combination; if a ∗ appears within the PI or AO box in the observations summary table, the instrument is a PI instrument and/or Adaptive Optics are requested – signatures are required on the next page.

Target list (attach list if longer than 26 objects)

#	Object	RA	Dec	mag / color / type / redshift / comment / etc.
1	SN2012ht	10:53:22	+16:46:35	subtraction images
2	SN2014J	09:55:42	+69:40:26	18.5–19.7 optical, 18.5–20.0 NIR
3	SN2013dy	22:18:18	+40:34:10	23.0 optical, 20.9 NIR
4	SN2013ct	01:12:55	+00:58:46	23.5 optical, 20.8–21.5 NIR

Approval for Instrument Use from PI: yes

Graduate students *(provide the following information for **each** student named as PI or CoI on the cover page. Have the advisor's signature(s) appear on **all** submitted copies)*

Student's Name	Advisor's Name	Advisor's Signature	2nd-yr	Thesis

Scientific Justification

The light curves of type Ia supernovae (SNe Ia) are powered by energy deposition from the products of the ^{56}Ni $\rightarrow$ ^{56}Co $\rightarrow$ ^{56}Fe decay chain when a carbon-oxygen white dwarf suffers a thermonuclear runaway. At early epochs, the gamma-ray photons from the ^{56}Ni $\rightarrow$ ^{56}Co decays ($\tau \sim 9^d$) power the steep rise to maximum luminosity followed by the nearly as steep decline from peak. The gamma-ray photons from the ^{56}Co $\rightarrow$ ^{56}Fe decays ($\tau \sim 111^d$) then dominate the energy deposition, and the light curve flattens relative to the initial decline rate (see Pinto & Eastman 2000). At yet later epochs, photons begin to freely escape the ejecta and the slowing of energetic positrons (created in 19% of the ^{56}Co $\rightarrow$ ^{56}Fe decays) dominates the energy deposition. The transition from gamma-ray photon to positron dominance is governed by the column depth of material that these products must encounter to escape the ejecta.

Positrons are charged particles and thus their transport is influenced by the strength and alignment of the ejecta's magnetic field. As detailed in Chan & Lingenfelter (1993)[1] (see also Milne et al. 1999[9], Ruiz-Lapuente & Spruit 1998[14], Colgate et al.[2]), a weak and/or radially aligned magnetic field (scenario R) would permit the escape of $\sim$ 5% of decay positrons from the SN Ia ejecta, but almost no escape from SN Ib/Ic ejecta. By contrast, a strong, turbulent field that traps positrons in-situ (scenario T) would permit some non-thermal survival, but no escape for either SN type. Escaping positrons (scenario R) remove energy from the ejecta, resulting in a light curve which is fainter than that produced by instantaneous positron energy deposition (i.e. at the time when the positron is created). Trapped, non-thermal positrons (scenario T) store energy, and eventually deposit the energy, leading to brighter light curves than those expected from instantaneous positron energy deposition.

Milne, The & Leising (1999,2001)[9, 10] simulated energy deposition rates for SN Ia models and compared these to the observed light curves. Although the available data was modest, the indication was that positrons *do escape* the SN Ia ejecta if the V band traces the bolometric luminosity. The V-band observations from the second data set were normalized at 60^d to produce Figure 1a (see Milne, The & Leising (2001)[10] for photometry references). The SNe Ia have been categorized as normally-, sub- and super-luminous based on the value of their B-band decline from peak to 15 days after peak (parameterized as Δm_{15}(B)). At late times, the R & T curves diverge, with the separation reaching one magnitude by $\sim$$700^d$. This divergence favors very late-time observations in distinguishing between the positron transport scenarios.

Since October 2000, we have obtained BVRI light curves of SNe Ia with Steward Observatory telescopes. The slopes of the BVRI light curves of the seven best 2000-2001 SNe from our normally- and super-luminous SN Ia study are shown in Figure 1b (Lair et al. 2006). It is clear from the figure that the I band follows a shallower slope than the BVR band light curves. The flatness of the I band confirms the findings reported by Sollerman et al. 2004 for SN 2000cx, but for many SNe Ia rather than just one. Late optical observations of normal SNe Ia from this campaign have contributed to the recognition that some normal SNe Ia deviate to a flatter decline after 300+ days (Garnavich, in preparation). This late flattening is not something predicted by positron transport, and poses interesting new questions, Figure 2a. Late optical observations of subluminous SNe Ia from this campaign have contributed to the recognition that the color evolution of subluminous events differ from that of normal SNe Ia (2003gs: Krisciunas et al. 2009).

Sollerman et al. (2004) also reported J & H band light curves that did not fade *at all* from 350 days to 480 days after the maximum (21.8 mag and 21.1 mag respectively). Based upon the NIR light curves, combined with the optical light curves, they reported a bolometric light curve flatter than predicted by positron escape, indeed the slope matched that predicted by positron trapping. Simulations presented in that work roughly fit the B,V,R and J,H light curves with positron trapping. Spyromilio et al. (2005) report a similar flattening in the H-band for SN 1998bu. More recently, Elias-Rosa et al. (2006) report bright NIR emission from SN 2003cg, Stritzinger et al. (2004) report bright NIR emission from SN 2001el, and Leloudas et al. (2009) report bright NIR emission from the transitionally-subluminous SN 2003hv. Photometry obtained from this program have detected a NIR plateau for 8 SNe Ia so far.

Analysis of data collected by this program to date supports the existence of a NIR plateau for all SNe Ia studied. However, the NIR plateau does not last beyond 400 days, at which time the NIR light curves begin to fade. Since positron trapping and positron escape models only begin to diverge at 400+ days, while 250 -

400 day NIR photometry has confirmed the NIR plateau, it does not distinguish between positron trapping and escape. Indeed, since Sollerman et al. 2004 did not show comparable light curves for positron escape, their work did not quantify whether positron escape could provide an equally acceptable fit. The current goal is to utilize larger aperture NIR telescopes to extend the NIR photometry to 600+ days post-peak to truly manage to distinguish between positron trapping and escape.

SNe 2013ct & 2013dy are two normal SNe Ia that are well-separated from their host galaxies and are excellent candidates for late study, regardless of seeing conditions. In January 2015, they will be 600^d+ and 525^d+ past-peak, affording an excellent test of positron escape. Both SNe will be science targets only in January. SN 2014J was a very nearby high-velocity SN Ia that peaked brighter than 10.0 mag. It is heavily extincted, but has been well-studied to date. late epoch observations can be combined with published early-epoch observations to produce a complete study of this SN. The SN is too far north for the Kuiper, Minn-60 and UKIRT telescopes and 2014J is proposed only for the Bok.

References

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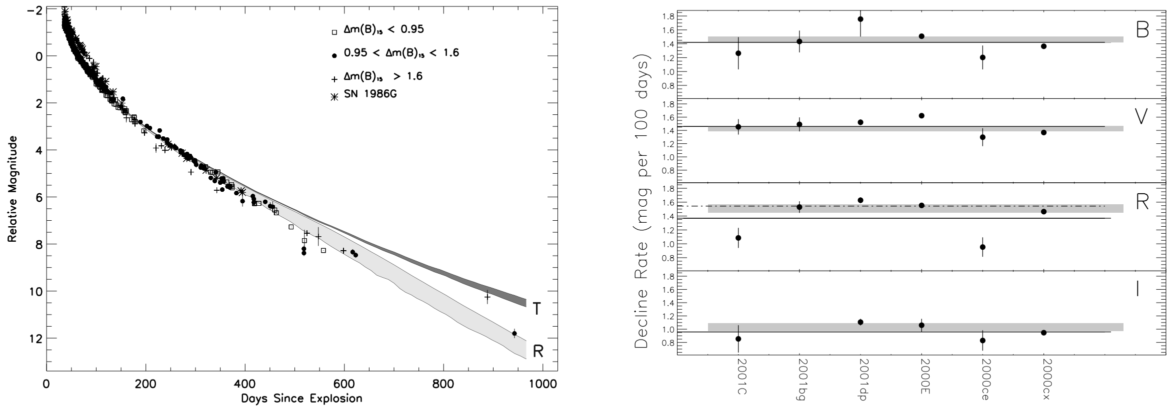

Figure 1: Left: V-band observations of SNe Ia including SN 2000cx, a Steward Observatory and VLT-studied SN. The fits are model-generated bolometric light curves for the Chandrasekhar-mass model, DD23C [4]. Normally-, super-, and sub-luminous SNe Ia are represented by circles, squares, and crosses respectively. All SNe have been normalized at 60^d, and fit to the model at 200^d. The sub-luminous data have been shifted by -0.5 magnitudes to fit the models at 200^d. The radial magnetic field line models are shaded light grey and labeled (R), and the turbulent trapping magnetic field line models are shaded dark grey and labeled (T). Right: The slopes of the BVRI light curves of SNe 2000E, 2000ce, 2000cx, 2001C, 2001bg and 2001dp between 200-500 days. The solid line is the average of the six SNe and the shaded bar is the average slope of the 12 N/SP SNe Ia from MTL01 (shown with 1σ error bars). The dash-dot line (R-band) is a re-calculation of the average, leaving out SNe 2000ce and 2001C.

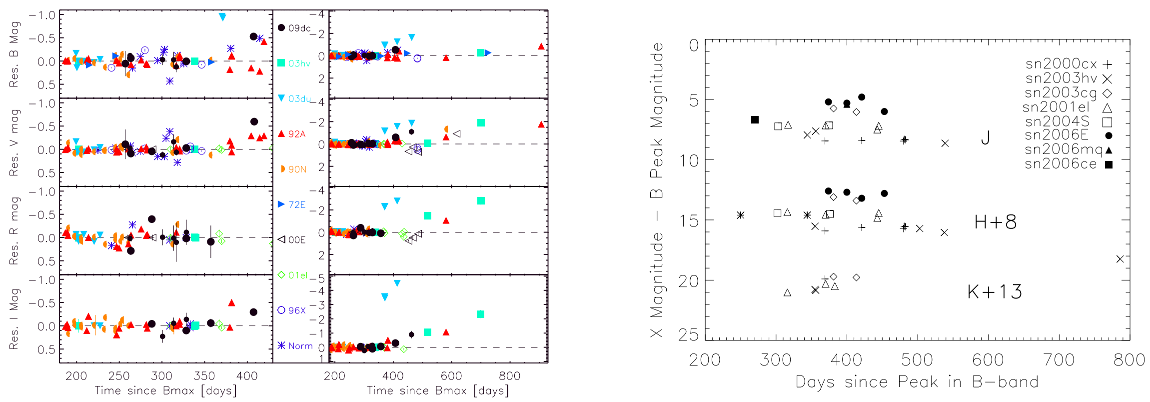

Figure 2: Left panel: BVRI observations of the 10 SNe best-observed beyond +300 days, changing the plotted range from 200-400 days and 200-900 days, respectively. Photometry of 2000E, 2003hv and 2009dc has been obtained as part of this program. Right panel: NIR photometry of 8 SNe Ia, including photometry of 2006E which was obtained as part of this program. From the PhD thesis of G. Bryngelson (Clemson University).

Experimental Design & Technical Description *Describe your overall observational program. How will these observations contribute toward the accomplishment of the goals outlined in the science justification? If you've requested long-term status, justify why this is necessary for successful completion of the science.* ***(up to one page)***

We request 12 hours of UKIRT time to perform the following observations. 4 hours are requested to obtain subtraction images of SN 2012ht in JHK. 4 hours are requested to obtain JHK detections of SN 2013dy in early 2015. 4 hours are requested to obtain JHK detections of SN 2013ct in early 2015. WFCAM or UFTI are both acceptable options for these observations, and the observations do not require disruptive scheduling.

Three 2-night runs are requested utilizing the PISCES camera on the 2.3m Bok telescope. The runs are requested to be in January, April and June to avoid conflicts with PI Milne's commitments to be at the UKIRT telescope in February and March.

Summary of Time Requested and Awarded *The TAC needs to understand the scope of this project — (1) tell us how many UAO nights you've already had for this project, how many you request this time, and (a good guess of) how many you need to complete the project; (2) if a substantial amount of observing for this project comes from non-UAO telescopes, tell us about that observing, and how the UAO part fits in; (3) if you are collaborating with people who have telescopes, especially if you are part of a large collaboration, tell us who is leading the project, and how UAO time and your participation fit in. (**up to one page**)*

These observations are part of a larger project that has been on-going since late 2000. Roughly four nights per month on each the 1.5m Kuiper and 2.3m Bok telescopes have been devoted to observing SNe at late times. Drs. Jessica Lair and Ginger Bryngelson have presented studies of SNe Ia based upon these observations as significant portions of their PhD theses.

Jessica Lair is preparing a study of SN 2005hk, 2008A, 2008ae, 2011at, 2011dn, 2012Z and 2013dh, seven peculiar SNe Iax that have been well-studied in this campaign. All this work is being performed under the leadership of Peter Milne. Peter Garnavich has utilized the LBT and Spitzer to obtain NIR and MIR observations of a collection of 2008-2011 SNe Ia. Garnavich and Milne are working jointly to interpret the findings and publish the results.

Two of the SNe observed in this program have been determined by HST imaging to feature light echoes, SN 2007af and 2009ig. Through regular monitoring of both SNe, we are in the position to study the transition from intrinsic emission to light echo emission, probing the geometry of the echo creation. Dina Drozdov at Clemson University has studied the light echo of SN 2007af as the topic of her Master's degree thesis, SN 2009ig and all SN Ia light echoes will be studied for her PhD thesis.

Previous Use of Steward Facilities *List **all** allocations of telescope time for the present project and allocations for other projects on facilities available through UAO during the past 2 years, together with the current status of the data (cite publications where appropriate). Mark those allocations related to the present proposal (i.e, precede text with* `\related` *command). (**up to one page**)*

The Super-LOTIS, Kuiper and Bok telescopes have all been used to observe the SNe that are the proposed targets of this proposal. Observations of seven normally- and super-luminous SNe Ia comprised the data presented in Lair et al. 2007.

Lair, J.C., Leising, M.D., Milne, P.A., & Williams, G.G., *AJ* **132**, 2024 (2006).

Observations of SNe 2003gs, 2003hv, 2007ax, 2008D, 2006bp, 2006ce, 2008Q, 2011fe, GRB070115, GRB070419A have all been obtained as part of this program and published as a portion of a larger effort.

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