RESEARCH PROPOSAL: PHYSICS OF SUPERNOVAE AND INTERSTELLAR MATTER: A DISENTANGLING EFFORT

Yi Yang, Texas A&M University Department of Physics and Astronomy
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Studying cosmic dust has important consequence on understanding a wide range of astronomical process, i.e., ranging from star formation to galaxy evolution. Probably the most direct effect of dust is the extinction. Incomprehensive knowledge on dust is hindering our study of the universe. For example, the Type Ia supernova (SN) cosmology requires better estimation of interstellar extinction to reduce systematic uncertainties. The extinction properties measured towards Type Ia SNe suggest the properties of extragalactic dust may be incompatible with the Galactic dust, resulting in a systematic uncertainty in the intrinsic luminosity and distances to the Type Ia SNe. Additionally, the exact progenitor systems of Type Ia SNe and explosions remain unknown.

Comprehensive understanding of **(1) the extinction and optical properties of the extragalactic dust grains**, and **(2) the mechanism and the progenitor for Type Ia SN explosions**, are both essential. The scattering properties of dust will be imprinted on the light scattered by the interstellar medium (ISM), and the mass-loss history of the progenitor before the final explosion can be revealed by the scattered light from ejecta close to the SN. These principles motivate me to take advantage of the interstellar light echoes to probe the optical properties of the ISM and the circumstellar light echoes to constrain the circumstellar matter (CSM) and hence the progenitor system of the Type Ia SNe. The major task of this proposal is to investigate the light echoes in nearby galaxies to probe the optical properties of the echoing material. Additionally, the circumstellar environment of Type Ia SNe will be examined through the search and study of the echoing dust and our ongoing *HST* imaging polarimetry campaign.

Peculiar extinction laws towards Type Ia SNe: how well do we know the interstellar dust? The characterization of dust in the diffuse ISM relies heavily on the observed wavelength dependencies of extinction and polarization (Patat et al., 2015; Voshchinnikov et al., 2012). The observed wavelength dependence of interstellar extinction R_V contains information on both the size and composition of the grains. The value of $R_V = 3.1$ (Cardelli et al., 1989) has been often considered the Galactic standard, but with a range from 2.2 to 5.8 (Fitzpatrick, 1999) for different lines of sight. There is increasing evidence that extinction curves towards Type Ia SNe systematically favor a steeper law (R_V<3, see Cikota et al., 2016 for a summary of R_V results of earlier studies). This discrepancy has remained unexplained. Scattering by the CSM tends to reduce R_V in the optical (Goobar, 2008; Patat et al., 2006; Wang, 2005). The effect on R_V and the light curve shape, however, also depends on the geometrical configuration and dust grain properties (Amanullah & Goobar, 2011; Brown et al., 2015). It is of critical importance to understand whether the systematically low R_V values towards Type Ia SNe are caused by (1) systematic differences from the optical properties of extragalactic dust grains, or (2) inhomogeneities in the vicinity of the SN-Earth line of sight, or (3) modifications by CSM scattering.

I propose to study the optical properties of dust grains in the Milky Way and nearby galaxies through the resolved light echoes around SNe. I will use the new method I developed to focus on **(1) the spatial variation**, and **(2) the scattering wavelength dependence** of the light echoes. This has been triggered by our recent discovery that different components of the ISM can exhibit different R_V towards the Type Ia SN 2014J within only a few parsecs on the plane of the sky in the nearby starburst galaxy M82. I have found a small R_V comparable to the value measured along the SN-Earth line of sight for a thin, dense dust slab, and a moderate R_V similar to Milky Way-like dust for an inhomogeneous interstellar dust cloud ranging ∼500 pc in the foreground of the SN (see Figure 1 and Yang et al., 2016). Specifically, when studying the extragalactic dust with a Type Ia SN, a question should be asked: Does the deduced R_V represent the average properties of the dust? Mandel et al. (2011) have found that for SNe with low extinction, $A_V \lesssim 0.4$, $R_V \approx 2.5-2.9$ is favored, while at high extinction, $A_V \gtrsim 1$, low values of $R_V<2$ are favored. Exploiting the high spatial resolution of *HST* and employing our method to calculate the optical properties and scattering wavelength dependence of the spatially resolved dust components, I will conduct a more universal test to the optical properties of the ISM in the local group and the nearby extragalactic environments.

Previous light echo modeling employed a method to integrate the echo signals inside a single aperture and fit the total echo flux with certain dust models (i.e., see the references in Table 1). Moreover, the wavelength dependence does not depend on the column density and geometrical configuration of the dust, and can be directly measured by comparing the optical properties obtained in different colors. **The multi-color, multi-epoch, and high-resolution *HST* images establish the feasibility of this study** (see Table 1 of Yang et al., 2016 for a summary of resolved extragalactic light echoes). I propose to use the *HST* archival data of nearby SNe with both **(1) multi-color information**, and **(2) well-resolved spatial profiles**. Table 1 summarizes the information of the SNe and associated archival datasets I propose to study. Figure 3 presents the snapshots of proposed echoes, obtained from *HST* MAST data archive. Difference imaging will be performed to better reveal the faint and time-variant echo signals thanks to the frequent visits of these nearby galaxies by *HST*. Additionally, studying the light echo evolution in multiple epochs will measure the optical properties and wavelength dependence of extragalactic ISM in a three-dimensional space.

Light echoes in the Milky Way and the LMC are also important to improve our understanding of the ISM in the local group. Sparks et al. (2008) demonstrated the polarization properties of the light echoes around a galactic variable V838 Monocerotis and provided an independent distance measurement by examining the radial profile of the echo polarization (Sparks, 1994). A study of the echoing medium conducted by Tylenda & Kamiński (2012) suggests the peculiarity extinction of the foreground dust. I will revisit the echoing medium around V838 Mon using the *HST* archival data with our method, and also examine the polarization wavelength dependency to better characterize the different dust components in our Milky Way. Moreover, light echoes in the LMC have been found and used to probe the progenitor properties of historical transients (Davidson & Humphreys, 2012; Rest et al., 2008, 2012). I will analyze the currently available datasets to study the dust properties. New data from Hubble Legacy Surveys will also be analyzed if possible. We will also propose to *HST* to observe new light echoes of future SNe in nearby galaxies.

I also propose a two-pronged observational approach to constrain the Type Ia progenitor system through inner echo detection and polarimetric follow-up at extremely late and early phases, respectively. Our ongoing *HST* imaging polarimetry campaign will monitor the SN 2014J to at least 3.3 years past the maximum light. We will map out any significant CSM at $\leqslant$3.3 light years perpendicular to the plane of the sky. At a distance of 3.5 Mpc to M82, this corresponds to 1.2 pixels in the ACS/WFC field. The detection of a resolved echo close to the SN at very late times will be an unambiguous signature of the CSM, while a non-detection will yield an unprecedented constraint. The polarimetric properties of a Type Ia SNe at late nebular phase will also be examined for the first time. I have detected the flattening of the light curves at 649 and 796 days past the maximum light and found no circumstellar light echoes beyond 1 light year of the SN. The flattening can be due to the reprocessing of electrons and X-rays emitted by the decay of ^{57}Co (see also Seitenzahl et al., 2009 and Graur et al., 2016 for the case of SN 2012cg), or a faint light echo caused by CSM within 1 light year of the SN. Figure 4 presents these two possible mechanisms explaining the late time flattening light curves of SN 2014J. For Type Ia SNe, I assume our observation in *HST* broad V band is proportional to the bolometric light curve of the SN at the late time (Milne et al., 2001). Our future data will place further constraints on distinguishing these two possible scenarios. These study will be naturally related to the progenitor system of Type Ia SNe.

For the early epochs, I will continue our efforts on the spectropolarimetric follow-up of Type Ia SNe at extremely early phases to catch the pre-explosion configuration before it is wiped out by the ejecta. A few pieces of evidence suggest a nondegenerate companion scenario (SN 2006X: Patat et al., 2007; PTF 11kx: Dilday et al., 2012; and iPTF14atg: Cao et al., 2015), i.e., a compact white dwarf accretes matters from a subgiant or even a main sequence star. However, other evidence favors a double degenerate scenario: the merger of two white dwarfs (see, for example, SN 2011fe Bloom et al., 2012). Traces of interactions between ejecta and a separate companion may be detected at $\lesssim$5 days past explosion (Kasen, 2010). A significantly higher degree of polarization around this epoch would be a strong indication of the highly asymmetric process between two white dwarfs. However, spectropolarimetry keeps finding very low degree of continuum polarization (Maund et al., 2013; Wang & Wheeler, 2008), incompatible with the double-degenerate scenario. I will pay close attention to early Type Ia SNe discoveries and trigger our VLT spectrophotometry campaign to expand the sample of early SNe and understanding better the progenitor mechanisms of Type Ia SNe.

To summarize, the expected scientific results of this proposal include (1) A systematic and more universal characterization of the optical properties and associated size distributions and compositions of the interstellar dust in the Milky Way, the LMC, and nearby extragalactic environments; (2) Strong constraints on the circumstellar environment around a few nearby Type Ia SNe. I will compile our new understanding of the dust into the current method of extinction correction for SN cosmology. The constraints on the CSM will further help to explore the mysterious explosion physics of Type Ia SNe.

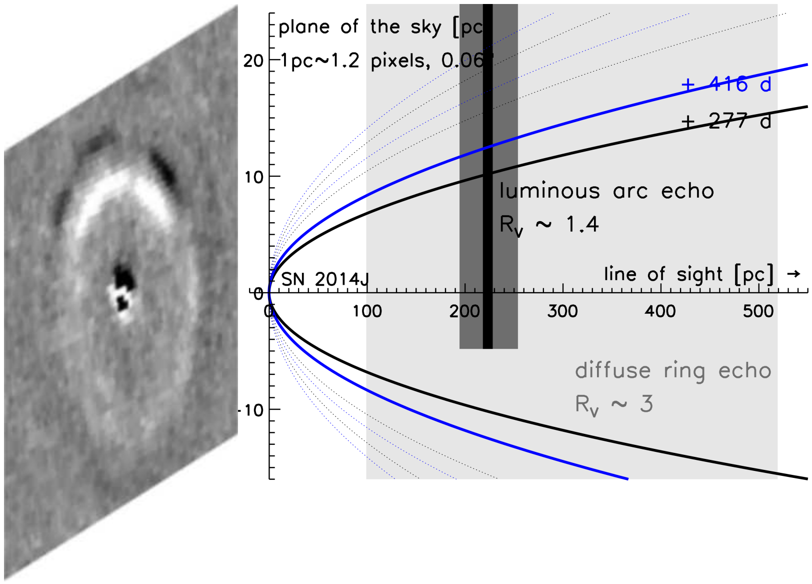

Fig 1. **Resolved Interstellar light echoes:** Schematic diagram of SN 2014J and light echoes showing the **thin dense dust slab** resulting in the luminous arc (R_V ~1.4) and the **diffuse dust cloud** rising the diffuse ring (R_V ~3) which are found to have different dust grain properties. Paraboloids represent the iso-delay light surfaces at different epochs. Dashed paraboloids indicate our future constraints on 649, 796, 985, and 1170 days, from inner to outer, respectively.

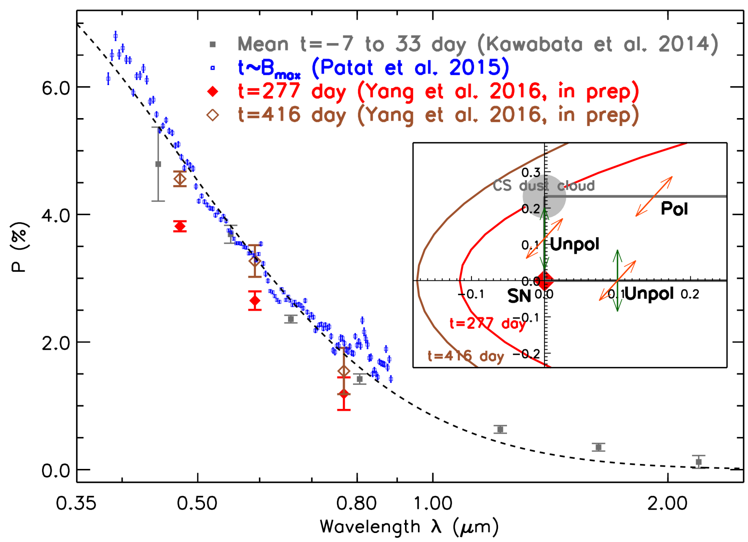

Fig 2. **Unresolved Circumstellar light echo:** Polarimetry of SN 2014J measured at different epochs. Conspicuous deviations of polarization at day 277 can be due to the presence of CSM. The inset diagram shares the coordinates with Fig 1 and explains photons can be polarized by a circumstellar dust cloud at a large scattering angle. Contribution from the polarized flux will cause the time-variant polarization measured from the SN.

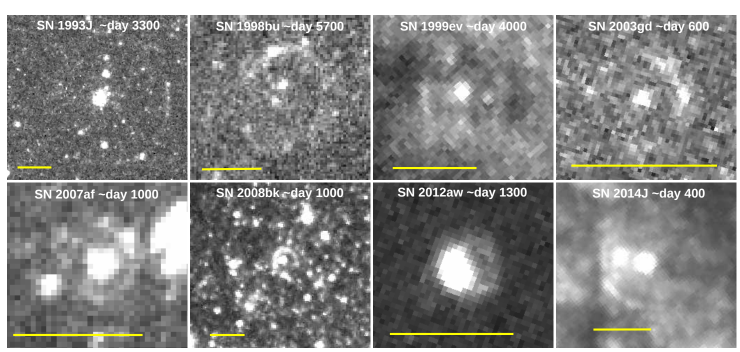

Fig 3. Snapshots of the light echoes around extragalactic SNe I proposed to study with archival data. The line segment in each panel represents 1″ in the field.

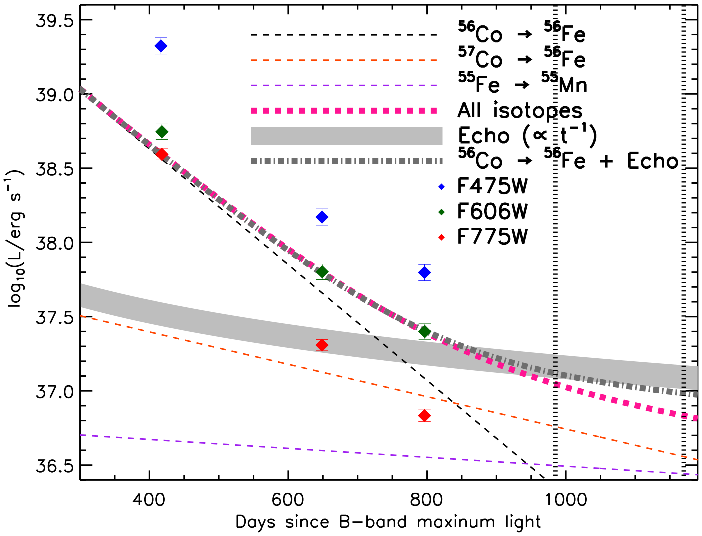

Fig 4. Possible mechanisms explaining the late time flattening light curves of SN 2014J (Yang et al. 2016, in prep). Isotope models from Graur et al. (2016) are used. F606W data $\gtrsim 500$ days have been assumed to be proportional to the bolometric light curves (Milne et al., 2001) and free from possible positron leakage. Only F606W observations after 500 days have been fitted with models counting in multiple isotopes and ^{56}Co plus a faint unresolved light echo. Isotope fitting requires a $\sim$3.5 times the solar ^{57}Co/^{56}Co ratio. Two more epochs will be obtained (the scheduled date of observations are marked by vertical dotted lines) to distinguish the two possible scenarios.

Table 1. Spatially Resolved Extragalactic Echoes to Study

SN	Type	Host Galaxy	Distance (Mpc)	References	Dataset proposed to use Proposal ID$^{[PI]}$
1993J	IIb	M81	3.6	Liu et al. (2003); Sugerman & Crotts (2002)	5480[1], 9073[2], 10584[3], 12531[4]
1998bu	Ia	M96	9.9	Cappellaro et al. (2001)	9299[5], 10607[6], 11646[7], 13364[8]
1999ev	II-P	NGC 4274	9.9	Maund & Smartt (2005)	9353[9], 11675[10]
2003gd	II-P	M74	9.5	Sugerman (2005); Van Dyk et al. (2006)	9733[9], 9796[11], 10272[4]
2007af	Ia	NGC 5584	22.5	Drozdov et al. (2015)	11570[12]
2008bk	II-P	NGC 7793	3.7	Van Dyk (2013)	12262[10], 12285[13], 12163[14], 13364[8], 12196[15]
2012aw	II-P	M95	10.0	Van Dyk (2013)	13364[8], 13825[10], 14149[4]
2014J	Ia	M82	3.5	Crotts (2015)	13717[16], 14663[16], 13626[7]

^{PI} (1) Kirshner (2) Bregman (3) Zezas (4) Filippenko (5) Ford (6) Sugerman (7) Crotts (8) Calzetti (9) Smartt (10) Maund (11) Miller (12) Riess (13) Soria (14) Barth (15) Radburn-Smith (16) Wang

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