Young Type Ia Supernova Science In ZTF

Last Update: January 26, 2017

1 Scientific Motivation

Despite the facts that thousands of Type Ia supernovae (SNe Ia) have been discovered and that a large number of high-quality light curves and spectra have been obtained, The origin of SNe Ia and their explosion mechanism remain mysterious. Recent developments in theory and observation, has shown that systematical observations of extraordinarily young SNe Ia is a promising avenue to make big progresses in this field.

Specifically, ZTF with its huge field of view, has great potentials in investigating the following three issues of SNe Ia: (1) estimating the fraction of SNe Ia born in the single degenerate channel with the SN-companion collision signatures; (2) investigating the initial rise behavior and its connection to ^{56}Ni mixing in the ejecta; (3) characterizing SN-CSM interaction to probe the mass loss history of the progenitor system.

1.1 SN-Companion Collision

The single degenerate (SD) and double degenerate (DD) channels are two main scenarios for progenitors of SNe Ia. SN-companion collision are only expected from the SD channel and thus the emission from SN-companion collision serve as a "smoking gun" for the SD channel.

According to the model in Kasen (2010), the collision emits an X-ray flash on timescales of $\sim 10\,$mins and then heats up surrounding ejecta material into high temperatures. Then the hot ejecta material produces thermal emission with a spectrum that peaks in the UV. Using the analytical equations in Kasen (2010) and the approximation of angular dependence in Brown et al. (2012), and assuming a typical binary separation $a = 10^{13}\,$cm, an ejecta mass $M = 1.4M_{\odot}$, and a constant opacity $\kappa = 0.2\,\mathrm{cm}^2\,\mathrm{g}^{-1}$, we calculate the expected thermal emission from the SN-companion collision as viewed in different angles and in the UV and optical bands (Figure 1).

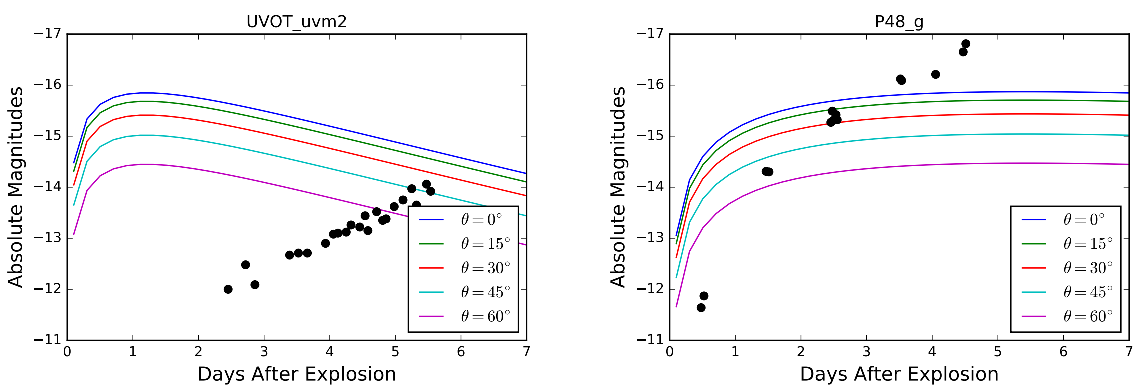

Figure 1: Theoretical light curves of SN-companion collision in a binary separated by $10^{13}\,$cm in the UVOT *uvm2* (left panel) and PTF g (right panel) bands. The ejecta mass is assumed to be $1.4M_{\odot}$, and the opacity of the ejecta is $0.2\,\mathrm{cm}^2\,\mathrm{g}^{-1}$. Colors are used to represent different viewing angles. In comparison, the observed light curve of SN2011fe is shown in black circles.

Figure 1 clearly shows that the UV wavelengths are much more preferred for three reasons than the optical in searches for SN-companion collision signatures. First, due to the high temperatures ($\gtrsim 10^4\,$K) of the emitting region, the SN-companion collision is brighter in the UV. Second, the contrast between the SN-companion collision signature and the SN emission is much larger in the UV than in the optical. Third, since the SN-companion collision produces a peak in the UV, it is easier to decouple different light curve components. Therefore, given the currently available instruments in the optical and UV, the best strategy to search for the SN-companion collision signature is to discover SNe in a wide-field experiment of one-day cadence and trigger space-based UV follow-up observations (e.g., *Swift*/UVOT) within a day of discovery.

1.2 Diversity Of Radioactively Powered Light Curves

Thanks to the almost constant mass of ejecta and synthesized ^{56}Ni, the light curves of SNe Ia around peak are quite uniform. However, their early-phase light curves may show great diversity. Since different mechanisms or stochastic procedures in the SN explosion may lead to distinct degrees of mixing in the ejecta, the moment when the first photons from the radioactive decay escape the SN ejecta is characterized by the photon diffusive timescale from the shallowest layer with deposited ^{56}Ni to the photosphere of the ejecta. For the same reason, the initial rise rate also depends on the shallowest distribution of ^{56}Ni.

Piro & Morozova (2016) calculated the early light curve of SNe Ia with weak and strong mixing (left panel of Figure 2) and found that (1) a SN with deeply deposited ^{56}Ni has a dark period of up to $\simeq$ two days before the rise of its radioactively powered light curve, while a SN with strong mixing has a negligible dark period; (2) the initial rise rate of a SN with weak mixing is less than that of a SN with strong mixing. Hence, characterizing the initial rise rates of SNe Ia will allows us to probe the mixing degrees of ^{56}Ni in the ejecta, which in turn constrains the explosion mechanism. According to the left panel of Figure 2, a one-day cadence survey in the optical is sufficient to carry out this study.

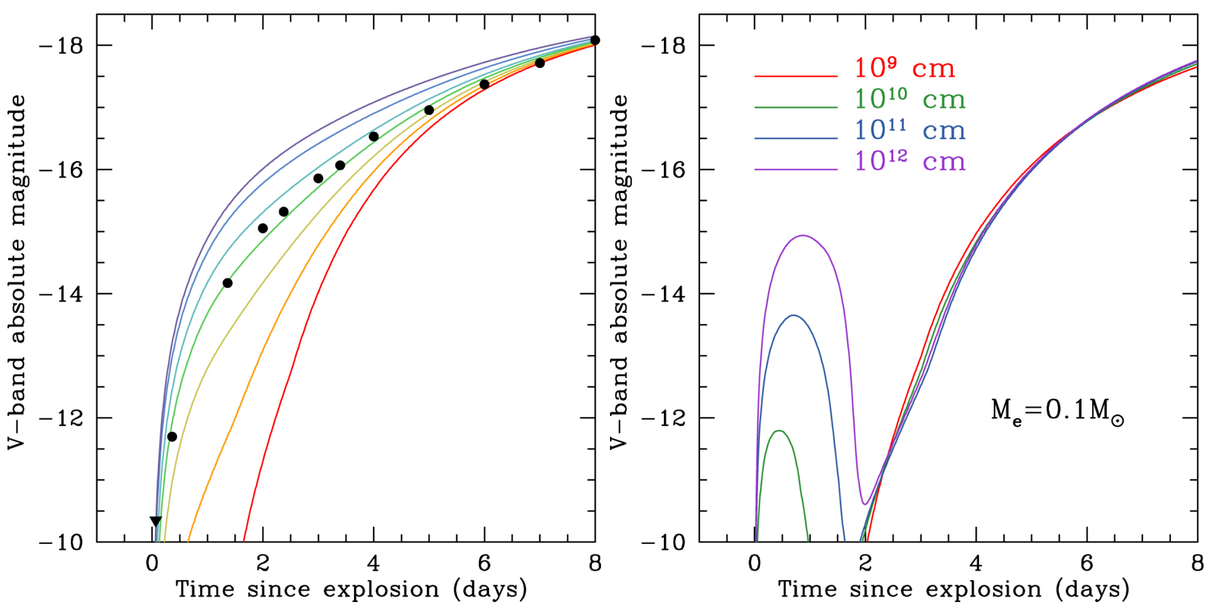

Figure 2: *Left panel:* The radioactively powered light curves of SNe with weak (red) and strong (blue) mixing. The circles and triangle are the observed light curve of SN2011fe. [Figure 7 in Piro & Morozova (2016)] *Right panel:* The early light curve peak produced by an extended material of $0.1 M_\odot$ at different distances from the explosion center. The SN ejecta is assumed to have weak mixing of ^{56}Ni . [Figure 10 in Piro & Morozova (2016)]

1.3 SN-CSM Interaction

Most progenitor scenarios of SNe Ia involve some sort of mass transfer process, which in principle should leave excess material around the progenitor system. Should this circumstellar medium (CSM) exists at the time of SN explosion, the ejected material will interact with the CSM, imprinting observable signatures in the early emission of the SN.

Piro & Morozova (2016) discussed the possible signature from the SN-CSM interaction. After being heated up by the SN shock, the CSM will emit thermal radiation as it cools down. According to calculations, the SN-CSM collision will produce a light curve peak at early phases (right panel of Figure 2). Should SN-CSM interaction exists, this extra peak in the early-phase SN Ia light curve can be captured by a one-day cadence survey.

2 Proposed experiments

To meet the scientific goals listed above, we request the following experiment:

- Pointings: Given the simulated light curves and the sensitivity of ZTF, the early-phase light curve is only detectable for SNe within 100 Mpc. Hence the pointings should be focused on local structures within this distance.

- Cadence: According to the simulated light curves, a one-day cadence is needed. In order to remove moving objects, every pointings should be visited twice each night.

- Filter: Given the fact that the expected light curves of SN-companion collision are brighter in the g band and the fact that the sky is darker in the g band, this experiment should use the g-band filter only.

- Scanning Query: This experiment requires a realtime query that looks for candidates that (a) have two observations separated by at least half an hour in the discovery night, (b) have non-detection on the night before discovery, and (c) are spatially associated with galaxies within 100 Mpc.

Assuming that each night is 6hr-long, ZTF will be able to survey 10^4 square degrees with the proposed cadence. Given a SN Ia rate of $3 \times 10^{-5}\,\mathrm{SNe\,Mpc^{-3}\,yr^{-1}}$, ZTF is expected to find $\simeq 30$ young SNe within 100 Mpc every year. Hence, undertaking this experiment for two year will provide a sample of $\simeq 60$ SNe Ia. This sample will be sufficient to address the scientific goals:

- Provided that the SN-companion collision signature is visible in $\sim 10\%$ of the SNe in the SD channel, and the SD channel makes up no less than one sixth of the whole SNe Ia population, then our sample will detect ~ 1 SN-companion event in the UV light curves.

- The optical light curve will be sufficient to address the initial rise rate distribution of SNe Ia and make inference to the distribution of ^{56}Ni in the ejecta.

- Such a large sample is sufficient to address existence of CSM through SN-CSM interaction signature.

3 Supporting Observations

3.1 Photometric Follow-Up

The key to detecting SN-companion collision signatures is to fast-response follow-up UV observations (in practice, it means *Swift*). In the iPTF era, the turnaround time between our discovery and *Swift* observations is 24 hours or less. Given the expected large number of SNe Ia, we may want to discuss an automated triggering mechanism with the *Swift* team.

If *Swift* is not available for follow-up observations, then LCOGT u-band follow-up observations can serve as a substitute, although the signature may not be as strong as in the UV.

Combining the one-day cadence survey data in the g band and the UV or u-band data also provides photospheric color evolution.

3.2 Spectroscopic Follow-Up

This project does not require fast-cadence spectroscopic follow-up. However, a classification spectrum around the peak of the SN is needed to type the SN. Given the distance range and the peak magnitude of $g \sim -19.3\,\mathrm{mag}$, the SED Machine is sufficient to carry out this task.

4 Expertise To Undertake This Project

5 Manpower And Timeline

References

Brown, P. J., Dawson, K. S., Harris, D. W., et al. 2012, ApJ, 749, 18

Kasen, D. 2010, ApJ, 708, 1025

Piro, A. L., & Morozova, V. S. 2016, ApJ, 826, 96