論文の内容の要旨

The Early-phase Photometric Behavior of Type Ia Supernovae and Its Implications

（Ia 型超新星の早期測光観測とその解釈）

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As one of the most spectacular explosive phenomena in the Universe, the type Ia supernova (SN Ia) has been thought to originate from the thermonuclear explosion of a carbon-oxygen white dwarf in a binary system. Even though SNe Ia have been widely applied as the cosmic distance indicator and helped us to discover the accelerating expansion of the Universe, their progenitor and the physics leading to the explosion are still under debate. Recent theoretical simulations have indicated that SNe Ia discovered within a few days of their explosions (hereafter "early-phase SNe Ia") play an irreplaceable role in tackling the long-standing explosion and progenitor issues of the SN Ia, thus inspiring me to carry out relevant studies with time-domain surveys which are specialized for discovering early-phase SNe Ia.

Despite the great scientific importance of early-phase SNe Ia, relevant studies have not been well conducted because the dimness of early-phase SNe Ia makes them hard to be discovered. Thanks to the excellent survey performance of the Kiso Wide Field Camera (KWFC) mounted on the 1.05-m Kiso Schmidt telescope and the Hyper Suprime-Cam (HSC) on the 8.2-m Subaru telescope, systematical investigations of the early-phase photometric behavior of SNe Ia were carried out by joining the "Kiso Supernova Survey" (**KISS**) project and leading two specific survey projects, the "Survey with KWFC for Young Supernovae" (**SKYS**) and the "MUlti-band Subaru Survey for Early-phase SNe Ia" (**MUSSES**).

In order to test the feasibility of running an early-phase SNe Ia-targeted survey, a series of observations were carried out through two supernova projects with Kiso/KWFC, KISS and SKYS, in 2015. During the seven-months observations, total 13 SN candidates were discovered and four of them were confirmed as early-phase supernovae. Light curves and spectra obtained from KWFC and other follow-up facilities indicate that three of them are early-phase SNe Ia (KISS15m, KISS15n, and SKYS6) and the other one (SKYS9) is an early-phase type IIP supernova. In particular, the three early-phase SNe Ia belong to subluminous, luminous, and normal type, respectively. Early-phase photometry together with follow-up observations of KWFC early-phase SNe Ia enabled us to study the intrinsic connection/difference between different SN Ia subclasses from a unique perspective.

The discovery of three early-phase SNe Ia in our KWFC observations demonstrated the feasibility of conducting early-phase SNe Ia-targeted survey with wide-field imagers and thus inspired us to further investigate early-phase SNe Ia with the best survey facility in the world, the Subaru/HSC. A specialized early-phase SNe Ia survey project with Subaru/HSC, MUSSES, was launched out in April, 2016. The MUSSES project includes survey observations with the 8.2-m Subaru telescope and follow-up observations with 1–10-m ground-based telescopes. In order to carry out such a large project, building a global collaboration is necessary. International collaborations with astronomers from different countries enable us to carry out real-time follow-up observations with more than 10 large aperture telescopes all over the world.

The first MUSSES observing run was carried out in April 2016. We discovered 12 early-phase SN candidates soon after the HSC survey, and especially, a very special early-phase SN Ia, the so-called MUSSES1604D (or SN 2016jhr, Figure 1), attracted our attention. The multiband Subaru/HSC survey and follow-up observations indicated that a prominent but red early flash followed with peculiar spectral features of MUSSES1604D are in conflict with predictions by previously proposed physical mechanisms (e.g. the interaction between the SN ejecta and a companion star or CSM). Further analysis with numerous computational simulations suggested that all peculiarities of MUSSES1604D can be naturally explained by a supernova explosion that is triggered by a detonation of a thin helium shell of its progenitor star (the so-called He-shell detonation scenario). This finding not only indicates the multiple origins of the light-curve excess found in early-phase SNe Ia but provides robust evidence of one kind of explosion mechanism of SNe Ia for the first time.

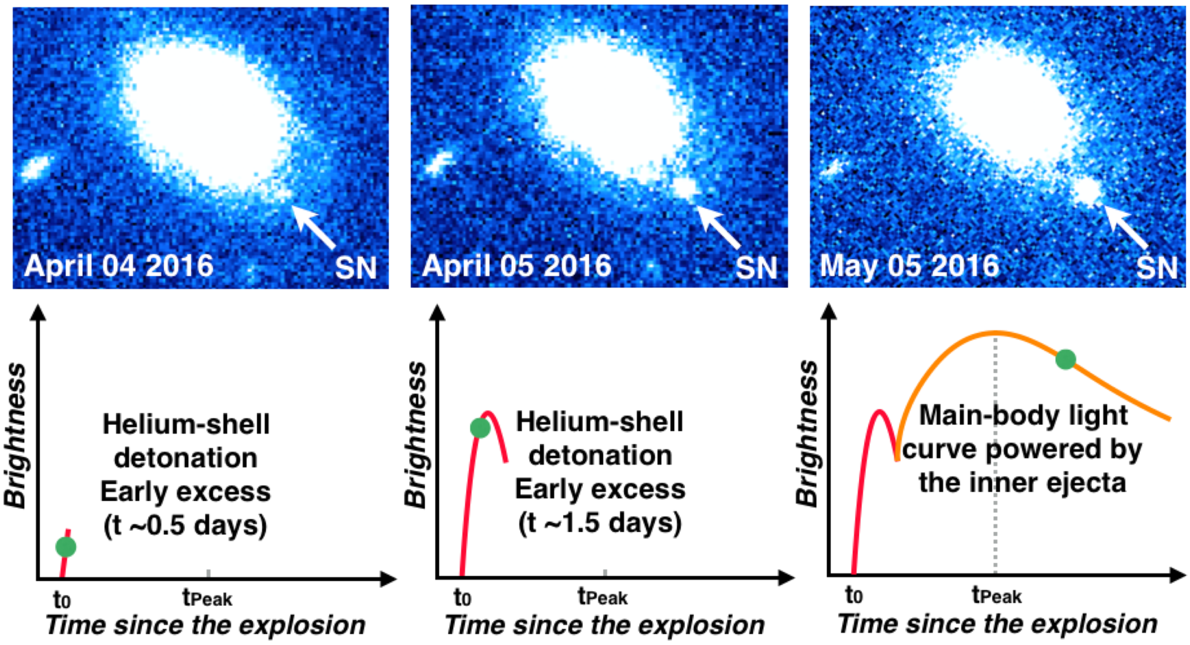

Figure 1: Images (upper panels) and schematic light curves (lower panels) of MUSSES1604D at specific epochs. Solid circles shown in light curves denote stages that the supernova was staying during observations.

Inspired by the discovery of MUSSES1604D, further investigations of early-phase SNe Ia that show additional brightness enhancements (hereafter "early-excess SNe Ia") were carried out. With the most complete early-phase SN Ia sample so far, we carried out a statistical study of early-excess SNe Ia (11 in total, and five of them are newly confirmed) for the first time. The study indicated that previously discovered early-excess SNe Ia show a clear preference for specific SN Ia subclasses. In particular, the early-excess feature shown in all six luminous (91T- and 99aa-like) SNe Ia is in conflict with the viewing angle dependence predicted by the companion-ejecta interaction scenario. Instead, such a high early-excess fraction is likely related to the explosion physics of luminous SNe Ia; i.e., a more efficient detonation happening in the progenitor of luminous SNe Ia may consequently account for the early-excess feature powered by the radiation from a ^{56}Ni-abundant outer layer. The diversity of early-excess features shown in different SN Ia subclasses suggests multiple origins of the discovered early-excess SNe Ia, challenging their applicability as a robust progenitor indicator. Further understanding of the early-excess diversity relies not only on multiband photometry and prompt-response spectroscopy of individual early-excess SNe Ia but also on investigations of the general early-phase light-curve behavior of each SN Ia subclass. A schematic diagram summarizing the possible connections between different early-excess scenarios and their corresponding SN Ia subclasses based on our previous studies is shown in Figure 2.

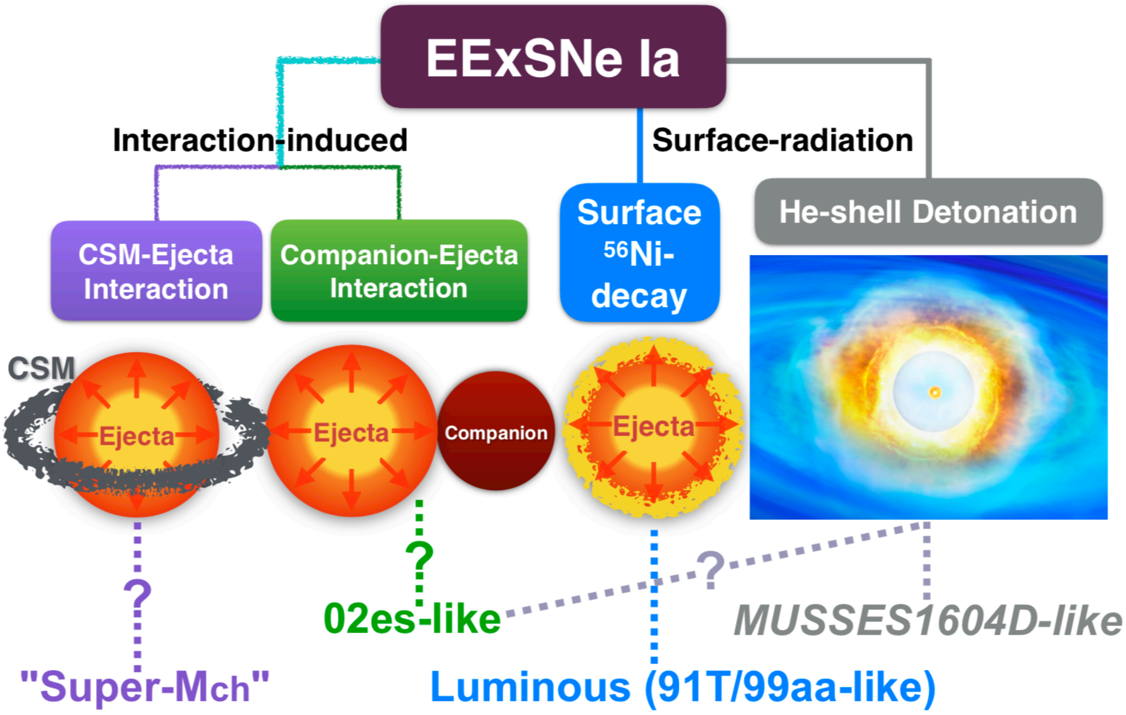

Figure 2. A schematic diagram showing the possible connections between different early-excess scenarios and their corresponding SN Ia subclasses. For luminous 91T/99aa-like SNe Ia, their early-excess features can be well explained by the surface-^{56}Ni-decay scenario. Interaction between extended CSM and ejecta can explain both early excess and ultra-high luminosity of super-M_{Ch} SNe Ia qualitatively. Whether or not the early light-curve excess shown in 02es-like subluminous SNe Ia originates from the companion-ejecta interaction is still under debate. The He-shell detonation scenario is likely related to specific SN Ia subclasses, such as MUSSES1604D-like and possibly, 02es-like SNe Ia.

In the next decade, time-domain astronomy will become one of the most popular branches in astronomy, and pioneering work on early-phase SNe Ia and other kinds of rapid transients can be carried out by using Subaru/HSC and Kiso/Tomo-e Gozen camera. With the forthcoming Tomo-e Gozen transient survey and the MUSSES-FAST, an innovative transient survey that uniquely combines two top-level survey facilities (i.e. HSC and Tomo-e Gozen camera) for the rapid transients study, systematical investigations of dozens of early-phase SNe Ia will be achieved in the next few years. New breakthroughs in not only SNe Ia but also other branches of time-domain astronomy can be expected with the ongoing and forthcoming transient surveys in the near future.