Subaru Telescope
National Astronomical Observatory of Japan

Semester S18A
Proposal ID S18A0113N
Received 09/07/2017

Application Form for Telescope Time (Normal+Intensive Programs)

1. Title of Proposal

Probing Circumstellar and Interstellar Media using Supernovae

2. Principal Investigator

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3. Scientific Category

☐ Solar System	☐ Normal Stars	☐ Extrasolar Planets	☐ Star and Planet Formation
☐ Metal-Poor Stars	⋆ Compact Objects and SNe	☐ Milky Way	☐ Local Group
☐ ISM	☐ Nearby Galaxies	☐ AGN and QSO Activity	☐ QSO Abs. Lines and IGM
☐ Cosmology	☐ Gravitational Lenses	☐ Proto-Clusters and Galaxy Environment	
☐ Clusters of Galaxies	☐ High-z Galaxies(LAEs, LBGs)	☐ High-z Galaxies(others)	☐ Miscellaneous

4. Abstract *(approximately 200 words)*

Early high-resolution spectroscopy is essential for our understanding of supernovae (SNe), their progenitors and the medium they explode in. Thermonuclear SNe (SNe Ia) have an unknown origin, but it could involve mass transfer from a companion star onto the progenitor white dwarf. Clear detection of circumstellar (CS) material in such a binary system would test the nature of these systems, which in turn provides invaluable information for precision cosmology. For core-collapse SNe (SNCC), CS signatures can be used to map the final stages of the progenitor star through its mass loss history. Both types of supernova can also excite interstellar (IS) gas in their neighborhood, and they provide excellent torches to study IS absorption lines and Diffuse Interstellar Bands (DIBs) along the line of sight in non-local regions of the host galaxies and in our Galaxy. As the expected line widths could be considerably less than 100 km/s, high-resolution spectra are needed. In this ToO proposal we suggest to observe 4 nearby SNe, ideally 2 SNe Ia and 2 stripped-envelope SNCC, to make a detailed study of their environments and the IS medium towards them.

5. Co-Investigators

Name	Institute
Keiichi Maeda	Kyoto Univ.
Akito Tajitsu	NAOJ
Maximillian Stritzinger	Aarhus University

6. Thesis Work

☐ This proposal is linked to the thesis preparation of ____________________

7. Subaru Open Use Intensive Programs

☐ This is a proposal for Intensive Programs.

8. List of Applicants' Related Publications *(last 5 years)*

Kundu, E., Lundqvist, P., Perez-Torres, M. A.,et al. 2017, ApJ, 842, 17
Lundqvist, P.,, Mattila, S., Sollerman, J., et al. 2013, MNRAS, 435, 329
Lundqvist, P.. Nyholm, A., Taddia, F., et al. 2015, A&A, 577, 39
Maeda, K. 2012, ApJ, 758, 81
Maeda, K. 2013, ApJ, 762, 14
Maeda, K. Katsuda, S., Bamba, A., Terada, Y., & Fukazawa, Y. 2014, APJ, 785, 95
Maeda, K., Kutsuna, M., & Shigeyama, T. 2014, ApJ, 794, 37
Maeda, K., Nozawa, T., Nagao, T., & Motohara, K. 2016, MNRAS, 452, 3281
Maeda, K., Nozawa, T., Sahu, D. K., et al. 2013, ApJ, 776, 5
Maeda, K., Hattori, T., Milisavljevic, D., et al. 2015, 807, 35
Maeda, K., Tajitsu, A., Kawabata, K. S., et al. 2016, ApJ, 816, 57
Maeda, K., Nozawa, T., Nagao, T., & Motohara, K. 2016, MNRAS, 452, 3281
Perez-Torres, M. A., Lundqvist, P., Beswick, R. J., et al. 2014, ApJ, 792, 38
Stritzinger, M. D., Hsiao, E., Valenti, S., et al. 2014, A&A, 561, 146
Stritzinger, M., Taddia, F., Fransson, Claes, et al. 2012, ApJ, 756, 173,
Stritzinger, M. D., Valenti, S., Hoeflich, P., et al. 2015, A&A, 573, 2
Stritzinger, M. D., Anderson, J. P., Contreras, C., et al. 2017, arXiv:1707.07615

9. Condition of Closely-Related Past and Scheduled Observations

Please fill in here, if this proposal is a continuation of (or inextricably related with) the previously accepted proposals. This is to describe what kind of relevant/similar proposals have existed in the past. If your scheduled observation exists, please describe it.

Proposal ID	Title (may be abbreviated)	Observational condition	Achievement (%)

10. Post-Observation Status and Publications

Please report the status or outcome of your main Subaru observations carried out in the past. All observations relevant to this proposal should be included here. Similarly, all those within last 3 years with which you were involved as P.I. must be reported.

Year/Month	Proposal ID	PI name	Status: completion/reduction/analysis	Status: publication
2004	S04A-040	Lundqvist	ToO. No data were taken.	
2004	S04B-035	Lundqvist	ToO. No data were taken.	
2005 7/8	S05A-104	Lundqvist	ToO. Data reduced and analyzed. Low signal-to-noise.	

11. Experience

Our team includes Japanese scientists who are very experienced with Subaru observations with various instruments including HDS, and also scientists who are experts of the high spectral resolution observations. We need only normal assistance by the support astronomer and the telescope operator.

 Proposal ID S18A0113N

Title of Proposal

Probing Circumstellar and Interstellar Media using Supernovae

12. Observing Run

Instrument	#Nights	Moon	Preferred Dates	Acceptable Dates	Observing Modes
HDS	2	dark/gray	Any	Any	Spec, Echelle

2nd choice:

comments:

Total Requested Number of Nights: 2 — Minimum Acceptable Number of Nights: 2

13. Scheduling Requirements

[⋆] ToO [ ] Time Critical — *Remote Observation* [ ] at Hilo [ ] at Mitaka

This is a target-of-opportunity proposal for young supernovae. No fixed month can be provided.

14. List of Targets

Target Name	RA	Dec	Magnitude (Band)
SN2017XX			V <17 (V <16 at the peak)

Our targets are yet to be discovered. See the scientific justification for details.

15. Observing Method and Technical Details

Please describe in detail about instrument configuration, exposure time, required sensitivity, and so on.

Our typical setup is the following: Collimator & Cross = Red, Cross scan = 4.07 degree, no filters. This allows the wavelength coverage between 3726 A and 6379 A, covering many features of interest in our study (e.g., Ca II H&K, Ca I 4226 A, CH+ 4232 A, CH 4300 A, Na I D, DIBs 4428, 5780, 6196 and 6283). We have checked the EFS on the HDS web page, confirming that these lines do not fall on the bad columns. We will use ADC so that we can observe targets far from zenith. Using a slit width of 0.4 arcsec, we will obtain the spectral resolution of 90,000, i.e., 3.3 km/s. We will bin the data into 2x2 to improve the efficiency. The slit length will be set so as to avoid the overlap with the next-order spectrum, i.., typically roughly 5 arcsec.
According to the HDS ETC, under a seeing of 0.5 arcsec, our setup will allow S/N per pix for an exposure of one hour as follows: S/N = 30 in all the wavelength for a target with V =16-17, S/N = 50 for V = 15-16, S/N = 80 for V = 14-15. For very bright targets brighter than V = 14-15 we will reach S/N >100. This is adequate to study strong components in the Na I D and Ca II H&K absorbing systems (>100 mA) and their variability, and also weaker features (i.e., molecules and DIBs with 10-100 mA). For the bright ones, we can address the temporal variability of the weak lines. For especially bright and highly reddened targets, we will perform two separate exposures in the blue and red, to cover Na I UV 3302,3303 A in the blue and K I 7665,7699 A in the red. This is to provide a precise measurement of the Na I column density and extinction for the system where the Na I D is highly saturated.
As described in the Science Justification, we are aiming for 4 SNe. Each SN will be observed at three epochs, i.e., a maximum of 12 observations will be spread over the period. Adding the standard star observation, calibration, and overhead, we expect the that total amount of time is 2 nights. The above setup is our standard, but we may refine the setup (e.g., wavelength coverage) depending on the information obtained through different follow-up resources (i.e., light curves and low/medium-dispersion spectra) to achieve the highest impact in scientific outcome. Lundqvist and Stritzinger are members of the NOT Unbiased Transient Survey which receives triggers from unbiased sky surveys (the Gaia satellite and ASAS-SN) so we quickly have first-hand information about the SN type.

16. Instrument Requirements *Specify the number of masks (MOIRCS/MOS) or the set of filters to use (HSC).*

17. Backup Proposal in Poor Conditions *(specify object names)*

This is a ToO proposal. No backup needed.

18. Public Data Archive of Subaru

⋆ *Yes, I have checked SMOKA.*

If your targets have already been observed by Subaru in the past, please describe why you need to observe them again.

19. Justify Duplications with the HSC SSP *(for HSC proposers)*

Probing Circumstellar and Interstellar Media using Supernovae.

P. Lundqvist, K. Maeda, M. Stritzinger et al.

1. Summary: Early high-resolution spectroscopy is essential for our understanding of supernovae (SNe), their progenitors and the medium they explode in. Thermonuclear SNe (SNe Ia) have an unknown origin, but it could involve mass transfer from a companion star onto the progenitor white dwarf. Clear detection of circumstellar (CS) material in such a binary system would test the nature of these systems, which in turn provides invaluable information for precision cosmology. For core-collapse SNe (SNCC), CS signatures can be used to map the final stages of the progenitor star through its mass loss history. Both types of supernova can also excite interstellar (IS) gas in their neighborhood, and they provide excellent torches to study IS absorption lines and Diffuse Interstellar Bands (DIBs) along the line of sight in non-local regions of the host galaxies and in our Galaxy. As the expected line widths could be considerably less than 100 km s^{-1}, high-resolution spectra are needed. Here we propose to observe 4 nearby SNe, ideally 2 SNe Ia and 2 stripped-envelope SNCC, to make a detailed study of their environments and the IS medium towards them.

2. Circumstellar gas in Type Ia Supernovae: For supernova progenitors with a zero-age main sequence mass < 8-10 $M_{\odot}$ in tight binary systems, a thermonuclear explosion can occur when the progenitor has become a white dwarf (WD) and has accreted enough matter from its companion to explode (single-degenerate scenario, SD), or if it merges with another WD companion (i.e., double-degenerate scenario, DD). Colliding WDs may also be a possibility. Whatever their origin, SNe Ia are heavily used as distance indicators, but we are still ignorant when it comes to the nature of the binary companion, which hampers their use to do precision cosmology. If CS gas is detected, this would point to a SD scenario.

The CS medium can manifest itself as a common wind from the progenitor system, or as discrete shells. So far no narrow *emission* lines have been seen in early spectra of *normal* SNe Ia. The deepest such searches, coupled with theoretical predictions, were done by Mattila et al. (2005) and Lundqvist et al. (2013), and models were made to estimate upper limits on the progenitor wind densities. It turns out that narrow *absorption* lines are better probes, and the most promising method to detect CS gas around SNe Ia is to search for time variations in Ca II λλ3934,3968, Na I λλ5890,5896 and K I λλ7665,7699. SNe Ia are notoriously weak emitters in the ultraviolet and can therefore only weakly ionize gas at some distance from their explosion location.

There are now a few cases showing time-varying Na I line profiles. Patat et al. (2007) use this to argue that the normal SN Ia 2006X was surrounded by a CS shell. SN 2007le (Simon et al. 2009) and SN 2006dd (Stritzinger et al. 2010) could provide further support for this scenario. In the paper by Sternberg et al. (2011), it is argued that a large number of SNe Ia in their sample tend to have blueshifted narrow absorption lines, which could signal the presence of CS shells. In some cases, like SN 2013gh (Ferretti et al. 2016) and SN 2014J (Maeda et al. 2016) the time-varying absorption is, however, probably caused by IS clouds in the supernova neighborhood rather than by CS gas.

CS gas can also be probed through radio and X-ray studies. Here the very nearby SNe 2011fe and 2014J are the most well-studied (Chomiuk et al. 2016; Margutti et al. 2014; Pérez-Torres et al. 2014; Kundu et al. 2017), and the upper limits on CS gas argues for very clean environments, which could point to a DD origin in these two cases (cf. Fig.1). However, one must bear in mind that radio and X-ray emission only probes the current position of the supernova blast wave. CS gas can either already have been overtaken, or it could lie further away from the supernova. Time-varying absorption lines provide important additional constraints since they probe gas between the supernova shock and the observer. The PI has been granted time on Australian Telescope Compact Array (ATCA) to study SNe Ia in radio, and participates in similar campaigns in the north using eMERLIN and the European VLBI Network (EVN) (PI: M. Pérez-Torres). The PI and Co-I:s Maeda and Stritzinger are also members of the NOT Unbiased Transient Survey (Mattila et al. 2016)[1], to quickly type young nearby SNe of any kind which assures suitable candidates to further study in greater detail with powerful telescopes like Subaru.

3. Circumstellar gas in Core-Collapse Supernovae: High spectral resolution observations are still very rare for SNCC, and in particular this is the case for stripped-envelope supernovae, i.e., those of Types Ib (no hydrogen in the ejecta) and Ic (no hydrogen or helium). Even for Type IIb, i.e., those with almost no hydrogen, data are scarce. This is unfortunate since several of these supernovae show radio and X-ray emission due to circumstellar interaction, and in recent work Type Ic SNe show a preference to explode in dusty environments (Galbany et al. 2017; Stritzinger et al. 2017), which means IS absorption lines could be expected. Figure 1 shows both CS and IS lines for the Type IIb SN 1993J.

Increasing the SNCC sample is essential to investigate a statistic difference in the blueshifted and redshifted absorptions in SNe Ia (§ 2), since the SNCC serve as a reference. In this pilot study, we will concentrate on high-resolution spectroscopy of stripped-envelope SNe. There is strong motivation for time-sequence observations. For example, Milisavljevic et al. (2014) used low-resolution spectra of the highly reddened Type Ic SN 2012ap to argue for variability in DIBs, with different behavior for different DIBs, indicating that at least part of the DIBs could be related to the environment around a massive star, challenging previous ideas. We want to push this further, by obtaining high-resolution observations to monitor weaker DIB features or DIBs in less reddened stripped-envelope SNe, and to study

[1] http://csp2.lco.cl/not/

the evolution of narrow emission lines to investigate the time-dependent photoionization of the CS medium, as was done for SN 1987A in Lundqvist & Fransson (1996). Spectra taken as early as possible are particularly useful, followed by spectra after maximum to constrain CS and IS media.

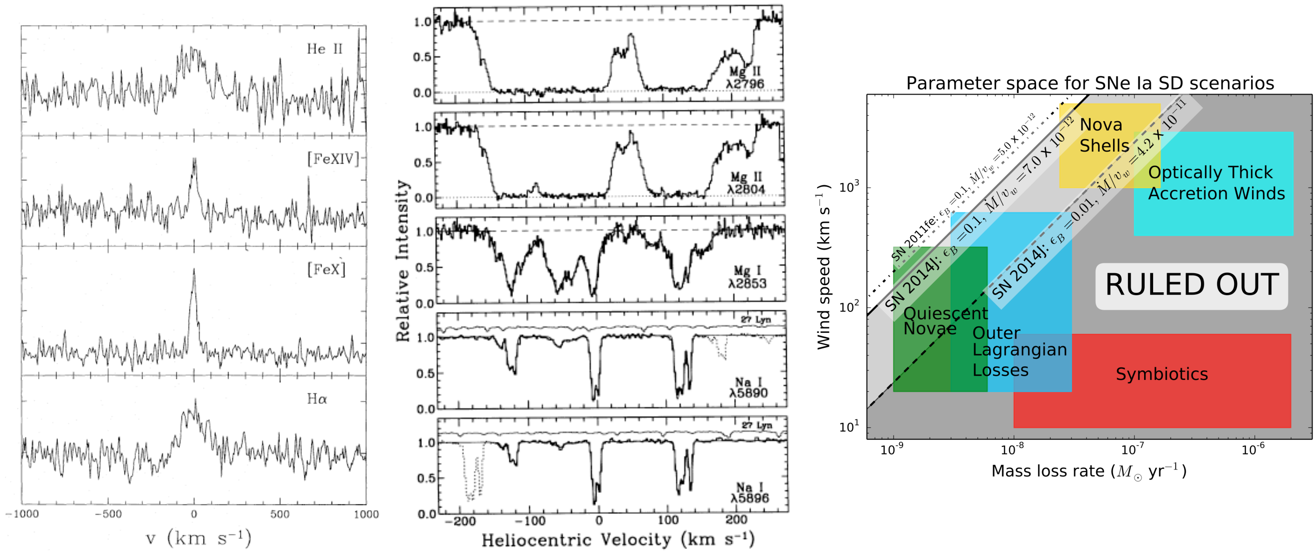

Fig.1 (Left) High-excitation circumstellar emission lines seen for SN 1993J (Benetti et al. 1994). **(Middle)** Multitude of narrow interstellar absorption features seen in spectra of SN 1993J (Bowen et al. 1994). **(Right)** Limits on the parameter space (wind speed vs. mass loss rate) for SD scenarios for SNe 2011fe and 2014J. 3σ limits on the mass loss rate over wind speed are shown. Mass loss scenarios falling into the gray-shaded areas should have been detected by past radio observations and are therefore ruled out (Pérez-Torres et al. 2014). This essentially only leaves room for quiescent nova emission as a viable alternative among the SD scenarios, at least for the Type Ia SN 2011fe.

4. The Intervening Circumstellar and Interstellar Media: SNe offer a unique opportunity to probe diffuse gas in galaxies beyond the local group. The ISM appears as absorption in the continuum emission from the SN. Since the absorbing materials likely have complicated kinematics (with velocity dispersion of $<$ 50 km s^{-1}) and many have too small equivalent widths to be seen in low resolution. For the CS medium one expects a blueshift of 10−1000 km s^{-1} due to outflow, while ISM components have $<$ 200 km s^{-1}). Strong DIBs are believed to originate in the ISM and can thus be used as tracers of the ISM. Investigating variability of Na I D, Ca II H&K, and other lines allows us to conclusively distinguish the CS medium (e.g., Patat et al. 2007). Once temporal variability is detected, one can derive the location and the amount of the CS material. With the standard set up in our proposal, we will cover the spectral region in 3726−6379 Å, with a resolution of 3.3 km s^{-1}. Thus we will be able to analyze various features, including Ca II H&K, Ca I λ4226, CH^+ λ4232, CH λ4300, Na ID and the DIBs at 4428 Å, 5780 Å, 5797 Å and 6283Å.

5. Observing Strategy: We propose to observe 4 SNe. Each SN will be observed at 3 epochs, each epoch being separated by about one month. The first spectrum will be taken well before maximum in the visual. Of the four SNe, two SNe are ideally SNe Ia and two are stripped-envelope SNe. There are a sufficient number of bright SN which can be followed multiple times within this program. In 2013, 55 SNe Ia and 31 SNCC with peak magnitude brighter than V=16 were discovered. We will thus have approximately have ~9 SNe Ia and ~5 SNCC discovered within the first four months (to be able to get all three epochs for each supernova within the 6-month period). The estimated S/N (per pix) $>$ 40 at the peak (V~16) and $>$ 25 in later phases (V~17**).** We note that more than one third of these targets will be brighter than V~15 at the peak, providing a S/N better than 70. We are aiming for SNe Ia of this brightness. Since stripped-envelope SNCC (including Type IIb) constitute almost 1/3 of all SNCC (e.g., Shivvers et al. 2017), we are aiming for such SNe with a peak magnitude of V~16. Noting that these SNe occur in dusty environments, we expect stronger IS signatures, and S/N~25 at late epochs for the stripped-envelope SNe is fully acceptable.

References: **Benetti, S.**, et al. 1994, A&A, 285, L13; **Bowen, D. V.**, et al., 1994, ApJ, 400, L71; **Chomiuk, L.**, et al. 2016, ApJ, 821, 119; **Ferretti, R.**, et al. 2016, A&A, 592, 40; **Galbany, L.,** et al. 2017, MNRAS, 468, 628; **Kundu, E.,** et al. 2017, ApJ, 842, 17; **Lundqvist, P.** & Fransson, C. 1996, ApJ, 464, 924; **Lundqvist, P.,** et al. 2013, MNRAS, 435, 329; **Maeda, K.,** et al. 2016, ApJ, 816, 57; **Margutti, R.,** et al. 2014, ApJ, 790, 52; **Mattila, S.,** et al. 2005, A&A, 443, 649; **Mattila, S.,** et al. 2016, ATel #8669; **Milisavljevic, D.,** et al. 2014, ApJ, 782, L5; **Patat, F.,** et al. 2007, Science, 317, 924; **Pérez-Torres, M. A.,** et al. 2014, ApJ, 792; **Shivvers, I.,** et al. 2017, PASP, 129, 975; **Simon, J.D.,** et al. 2009, ApJ, 702, 1157; **Sternberg, A.,** et al. 2011, Science, 333, 856; **Stritzinger, M.,** et al. 2010, AJ, 140, 2036; **Stritzinger, M.,** et al. 2017, arXiv:1707.07615