European Organisation for Astronomical Research in the Southern Hemisphere

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APPLICATION FOR OBSERVING TIME

PERIOD: **96A**

ToO

Important Notice:

By submitting this proposal, the PI takes full responsibility for the content of the proposal, in particular with regard to the names of CoIs and the agreement to act according to the ESO policy and regulations, should observing time be granted.

1. Title

Category: **A–4**

Hubble Frontier Field Supernova Spectroscopy

2. Abstract / Total Time Requested

Total Amount of Time:

The HST Frontier Fields (HFF) program present an extraordinary opportunity for the detection of lensed, high redshift supernovae (SNe) out to $z \sim 3$. We propose to capitalize on this unique asset by searching the HFF data and triggering ToO follow-up for SNe of interest. Over the first 7 Frontier Fields observing windows we have found 17 SNe, including the multiply imaged SN Refsdal, and we expect this number to increase. The number of detected high-z SNe Ia is small, but carry great leverage for testing progenitor model through the delay time distribution while the lensed SNe Ia offer a unique chance to validate cluster mass models by directly measuring the lensing magnification. We will also be able to extend core-collapse SN rate measurements for the first time beyond $z \sim 1$. This follow-up program provides the spectroscopic information necessary to unlock the science potential of these SNe.

3. Run	Period	Instrument	Time	Month	Moon	Seeing	Sky	Mode	Type
A	96	XSHOOTER	6.4h	any	n	1.0	THN	s	TOO

4. Number of nights/hours	Telescope(s)	Amount of time
a) already awarded to this project:	XSHOOTER	20.2h awarded in P92–P93.
b) still required to complete this project:	XSHOOTER	$\sim$ 10 h in total (P97)

5. Special remarks:

This proposal is part of a larger collaborative effort, and involves a dedicated 60-orbit HST program (PI:Rodney, PID:13386,13790) to improve the characterisation of candidate SNe discovered in the Hubble Frontier Fields plus additional orbits dedicated to the follow-up of SN Refsdal in MACSJ1149, all piggybacking on 840 orbits of HST time for the Frontier Fields. Some of the spectroscopy could possibly be obtained in 'normal' service mode (see Box 8b).

6. Principal Investigator: JHJORTH

6a. Co-investigators:

S.	Rodney	1698
J.	Selsing	1227
L.	Christensen	1227

7. Description of the proposed programme

A – Scientific Rationale:

Over the past decade, the deep HST Treasury surveys (GOODS, CANDELS, CLASH) have all enabled "piggyback" Type Ia SN searches (hereafter, the HST-SN surveys), which have collectively accumulated scores of SN detections that reach to uniquely high redshifts (Riess et al. 2007, ApJ, 659, 98; Dahlén et al. 2008, ApJ, 681, 462; Suzuki et al. 2012, ApJ, 746, 85). The ongoing HFF program now provides a powerful new tool for the discovery of particularly high-z SNe. What sets this survey apart from the previous HST-SN surveys is the unique depth of each visit, reaching $m_{lim,3\sigma}$(F160W) ≈ 27.9 (AB), ~ 1 mag deeper than CANDELS/CLASH per epoch. Gravitational lensing in the prime fields can also magnify fluxes by about a factor of 2, making it possible to detect distant background events. *The Hubble Frontier Field survey thus provides the first opportunity to discover SNe at $2 < z < 3$, building up a small but important "New Frontier" sample.*

There is a long-standing and uncomfortable ambiguity about the nature of SNIa progenitor systems, and the mechanisms by which they reach the point of explosion (e.g., Maoz & Mannucci 2012, PASA, 29, 447). Most models assume that the primary progenitor star is a white dwarf (WD), but they differ on the identity of the companion (mass donating) star, the time scale for mass-accretion (or merger), and ultimately the time required to go from progenitor formation to explosion (or the delay time). There are two principal families of models: the "double degenerate" models, in which orbital decay causes two WDs in a binary system to merge; and the "single degenerate" models, wherein the WD accretes mass gradually from a main sequence or evolved giant companion star. It is unclear what scenario(s) are ultimately responsible for the creation of Ia SNe, but resolving this question has tremendous astrophysical implications touching on heavy element enrichment over cosmic history, the origins of galactic winds and galaxy formation, and the robustness of SNIa as standard candles over cosmic time. Volumetric SN Ia rates provide important constraints on the progenitor systems. Each scenario predicts different delay-time distributions, which can be constrained by measuring the SN Ia rate with z. Our HST-SN surveys now reach $z \approx 2$ with large uncertainties (Graur et al., 2014, ApJ, 783, 28; Rodney et al., 2014, ApJ, 148, 13 see Figure 1). It is here that the HFFs will have the greatest impact, adding about 5 new SNe Ia, and increasing the $z > 1.5$ sample size by $\sim 50\%$.

Observations of SNe Ia lensed by clusters of galaxies allows a measure of the true lensing magnifications and thereby a critical test for the existing mass models. Mass models are based on assumptions about the distribution of dark matter and confronting these will significantly improve our understanding og the nature of dark matter. A strongly lensed SN Ia at $z = 1.31$, have recently been observed in exactly our program (Rodney et al. 2015, in prep.) and with a magnification $\mu = 2.0$, we have found that all existing mass models for this cluster significantly overestimates the magnification.

B – Immediate Objective:

Our primary science goal is to provide a real measurement of SN Ia rates at $z > 1.0$, yielding improved constraints on SN Ia progenitor models. A secondary goal is to build a sample of lensed SNe Ia to provide independent validation tests of cluster lensing models. Furthermore, this sample will extend the measurement of CC SN rates to $z > 1$, find SNe Ia for cosmological analyses, and possibly discover rare events such as multiply lensed SNe. The latter have recently been achieved when our collaboration discovered *the first ever multiply imaged transient* dubbed SN Refsdal (Kelly, P. L., et al. 2015, Science, 347, 1123), which already have provided refined mass models (Oguri 2015 MNRAS, 449, L86) and is expected to reappear with the next 5 years.

As the HFF HST data are obtained we process it through a pipeline that we have developed and battle-tested for SN discovery in the HST-SN surveys. When a SN has been detected the HST ToO program is triggered to obtain a photo-z for the host galaxy and a rough estimate of the redshift from the SN colours. From the photometry we assess whether we can determine a spectroscopic redshift and in some cases classify the event from an X-shooter spectrum. In its comments to our previous proposals, the OPC noted the uncertain number of events and the thereby potential lack of quantitative constraints. We agree that the rates in any given period are uncertain, but given the proven unique leverage of these events, we believe that the importance of spectroscopic follow-up have been shown. In P92 and P93 we triggered the VLT on four events. Based on our detailed simulations we expect 3 ± 3 SNe to be detectable with VLT during P96, but given past experience we will likely only trigger on 2 systems, which is what we apply for here. A SN spectrum is invaluable for classification, and is critical in cases where the SN is "hostless" or the host association is ambiguous, about 15% of the time. This is highlighted for SN Preston (Figure 2) where the capability of doing ToO spectroscopy proved invaluable for typing and redshift determination.

SN Ia Rates: The HST-SN sample in the highest redshift bin currently comprises only $\sim$11 objects: 3 from GOODS and 8 from the nearly completed CANDELS+CLASH survey. The expected yield of $\sim$5 new SNe Ia at $z > 1.5$ from the HFFs therefore represents an increase in the sample size of nearly 50%. This could reduce the overall measurement error (statistical and systematic) from 55% to $\sim$30%. With this improved precision we could potentially reject any models dominated by very prompt explosions (see Figure 1).

7. Description of the proposed programme and attachments

Description of the proposed programme (continued)

Testing Lens Models: We expect to find several magnified SNe Ia behind the HFF clusters, and by measuring their light curve shapes with our follow-up orbits we will determine their absolute luminosities to ± 0.2 mags, providing a direct measurement of the lensing magnification (Patel et al., 2014, ApJ, 786, 9; Nordin, J., et al. 2014, MNRAS, 440, 2742). The precision of these SN Ia magnification measures will be on par with the magnification predictions available from existing mass models. Agreement between the SNe and the mass models will provide an important validation of the models. Any disagreement can provide interesting insights into the local clumpiness of the dark matter halo. For a proof of concept, this exercise has been done for a strongly lensed SN Ia at $z = 1.31$ (Rodney et al. 2015, in prep.) with an inferred magnification $\mu = 2.0 \pm 0.19$, significantly different from predictions of current mass models.

Attachments (Figures)

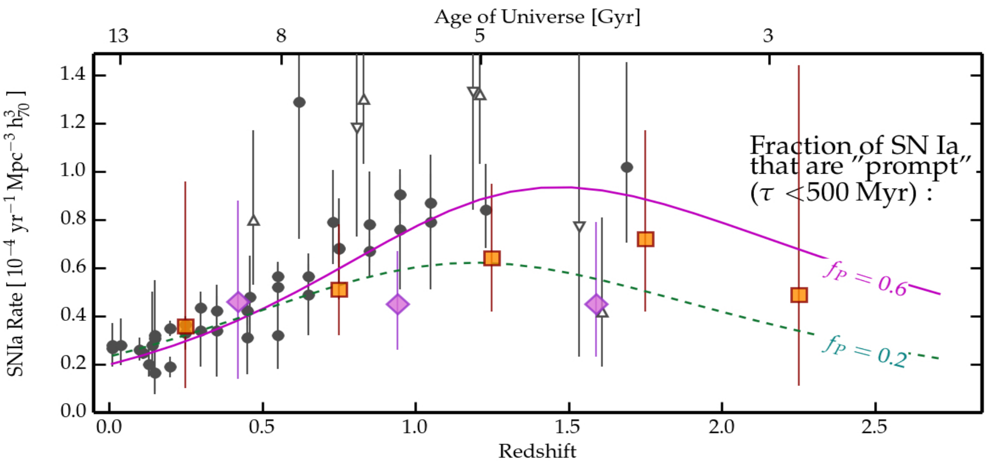

Figure 1. *SN Ia rates constrain progenitor models.* Measured volumetric SN Ia rates as a function of redshift, comparing observed SN rates against two progenitor models from Rodney et al. (2014). Large purple diamonds show the CLASH rates from Graur et al. (2014) and large orange squares show the CANDELS rates from Rodney et al. (2014). Two curves show the SN Ia rates predicted by models that allow for a variable fraction of SN Ia explosions to occur promptly, within 500 Myr after their formation. The ground-based observations (black points) prefer the model, which has $\sim$60% of all SNe Ia exploding within 500 Myr. The green dashed line is the best-fit model when using the CANDELS+CLASH data alone, for which the prompt fraction is $\sim$20%. The HFF SN sample will increase the sample size at $z > 1.5$ by about 50%, and will extend the measurement for the first time to $z \approx 3$, providing unique leverage for discriminating between these models.

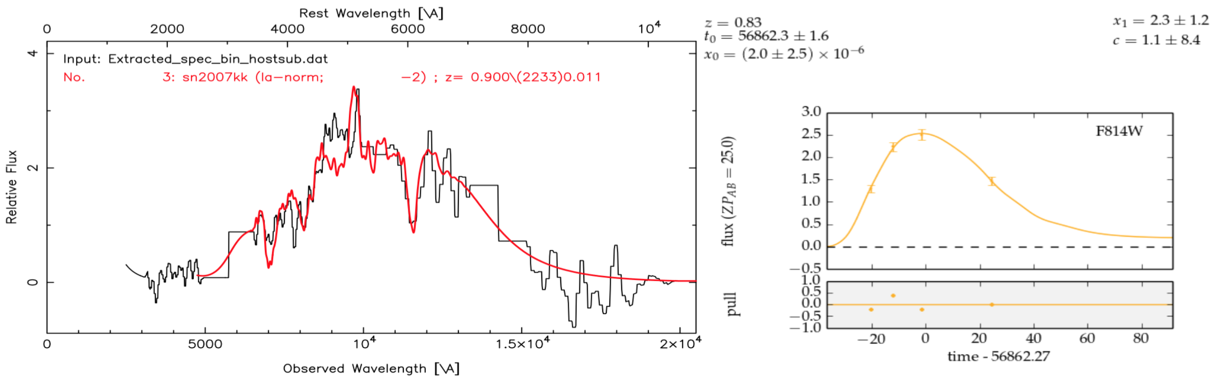

Figure 2. Left: *X-shooter spectrum of SN Preston.* In a 3.2h X-shooter spectrum we detect clear SN-features after a host template spectrum has been subtracted. Right: The photometric redshift of the host is $z \sim 0.83$ which agrees with the *SALT2 SN Ia light curve fit.* This is also in rough agreement with the spectroscopically determined redshift of a SN Ia at $z \sim 0.9$ obtained from template matching. This highlights the need for ToO observations, giving an independent measure of type and redshift. To our knowledge this is the highest redshift Ia typed from a ground-based spectrum.

8. Justification of requested observing time and observing conditions

Lunar Phase Justification: The driver for this proposal is time-critical (ToO) NIR observations and we therefore do not wish to put any restrictions on the lunar phase.

Time Justification: (including seeing overhead) For the SNe, we assume peak magnitudes of $M_B = -19.34$ and a standard cosmology ($\Omega_m = 0.3, \Omega_\Lambda = 0.7, h = 0.7$). At $z = 1$ and $z = 1.5$ the Si II λ6150 feature is redshifted to the J and H bands, respectively. At $z = 1$ J=23.25 (H=23.5) and at $z = 1.5$ H=23.7. Assuming a restframe width of 150 Å of Si II λ6150, this can be detected at 5–10σ at $z = 1$ (depending on the profile shape and depth) and half that at $z = 1.5$ according to the X-shooter ETC v.5.0.1 in 8×1200 s, corresponding to 3.2h execution time. Hence, for the SNe we adopt exposure times of 3.2h. For host galaxies which are assumed to be emission line sources our experience is that redshifts can sometimes be obtained in a 4×1200 s ABBA sequence (1.6h execution time, as used in previous periods), while at higher redshifts, usually twice that may be required (e.g., our determination of $z = 1.91$ for a SN Ia host). Given that we are probing new territory and higher redshifts, we expect that 3.2h will be required in most cases. See Figure 2 for proof of concept.

8a. Telescope Justification:

X-shooter is by far the most efficient instrument in the world to perform ground-based spectroscopy of high-redshift SNe.

8b. Observing Mode Justification (visitor or service):

ToO observations require service mode. In its comments to our P94 proposal, the OPC remarked: "The primary goal of the observations is redshifts (rather than typing), and will make use of the SN themselves, or their hosts. In principle, this could all be done targeting the hosts after". It is true that for some targets the redshift could be observed in "normal" mode and in some cases a 1 week turnaround would be sufficient, but we need the valuable ability to occasionally do a quick ToO that informs our HST follow-up choices. If we can rely on turnarounds approaching 7 days for 'normal' scheduling this would be an interesting possibility in about half the cases and we would be happy to adopt such an approach. However, we have no experience with such fast turnaround normal service observations and do not know the procedures for dealing with this on a routine basis. As can be seen in Figure 2, we have targets where the ToO capability proves invaluable for typing and redshift determination.

8c. Calibration Request:

Standard Calibration

9. Report on the use of ESO facilities during the last 2 years

092.A-0533,093.A-0667 (PI Hjorth): So far, 20.2h of X-shooter TOO time has been awarded to this effort; 14.2h have been used on four triggers, yielding a redshift of 0.41 for a cluster SN Ia, a $z = 1.32$ SN Ia in MACS1423, a SN Ia at $z \sim 0.9$ in the parallel field of Abell 2744 (see Figure 2) and SN Spock is pending observation.

093.D-0342 (PI Christensen): VIMOS-IFU observations of SN Type Ic host galaxies. Final data obtained in P93 and analysis proceeding (Selsing & Christensen in prep).

9a. ESO Archive - Are the data requested by this proposal in the ESO Archive (http://archive.eso.org)? If so, explain the need for new data.

This is a ToO proposal. The data requested are not in the archive.

9b. GTO/Public Survey Duplications:

There is no duplication of targets/regions covered by ongoing GTO and/or Public Survey programmes.

10. Applicant's publications related to the subject of this application during the last 2 years

Frederiksen T. F. et al., 2014, A&A, 563, A140: Spectroscopic identification of a redshift 1.55 supernova host galaxy from the Subaru Deep Field supernova survey

Gall C. et al., 2014, Nature 511, 326 - 329: Rapid formation of large dust grains in the luminous supernova SN 2010jl

Graur O. et al., 2014, ApJ, 783, 28: Type-Ia supernova rates to redshift 2.4 from CLASH: The cluster lensing and supernova survey with Hubble

Li, Hjorth & Wojtak, 2014, ApJl, accepted (arXiv:1409.3567): Cosmological Parameters From Supernovae Associated With Gamma-ray Bursts

Hjorth, J., 2013, Phil. Trans. R. Soc. A, 20120275: The supernova–gamma-ray burst–jet connection

Jones D. et al., 2013, ApJ, 768, 166: The discovery of the most distant known Type Ia supernova at redshift 1.914

Margutti, R. et al., 2014, ApJ, 780, 21: A panchromatic view of the restless SN 2009ip reveals the explosive ejection of a massive star envelope

Rodney et al., 2014, ApJ, 148, 13: Type Ia supernova rate measurements to redshift 2.5 from CANDELS: Searching for prompt explosions in the early universe

11. List of targets proposed in this programme

Run	Target/Field	α(J2000)	δ(J2000)	ToT	Mag.	Diam.	Additional info	Reference star
A	SN1	00 00 00.0	+00 00 00	3.2	J=23	1"		
A	SN2	00 00 00.0	+00 00 00	3.2	J=23	1"		

Target Notes: The targets will primarily be in the clusters of galaxies Abell S1063 (RA(J2000) = 22:48:44.4, Dec(J2000) = −44:31:48.5), Abell 370 (RA(J2000) = 02:39:52.4, Dec(J2000) = −01 :34:36.5), or their flanking fields a few arcmin away. The monitoring of SN Refdal in MACSJ1149 (RA(J2000) = 11:49:36.3, Dec(J2000) = +22:23:58.1) could potentially lead to more event, or other clusters may be observed from the ground and will also provide rare events. Targets will be selected as being strong SN candidates based on colours and light curve properties in the HST imaging. Targets may be either the SNe themselves or their host galaxies (or both). We reserve the right to observe each target for shorter or longer than then default 3.2h specified above, depending on brightness and results of first inspections of the data (e.g., if the observations have to be split into two visits). Each OB will be a 1.6h execution time OB, consisting of 4 × 1200 s (ABBA) in the NIR arm, with an AFC template in the middle.

12. Scheduling requirements

13. Instrument configuration

Period	Instrument	Run ID	Parameter	Value or list
96	XSHOOTER	A	300-2500nm	SLT
96	XSHOOTER	A	SLT	1.0, 0.9, 0.9JH
96	XSHOOTER	A	SLT	100k-1x1,100k-1x1,NDR

14. List of ToO runs proposed in this programme

Run	Nature	Targets per run	Triggers per target
A	ToO-soft	2	2