



APPLICATION FOR OBSERVING TIME

PERIOD: **96A**

Important Notice:

ToO

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 presents an extraordinary opportunity for the detection of 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. We expect to discover ~ 50 new SNe over the entire 3-year program, including ~ 5 SNe Ia at $z > 1.5$ and ~ 10 SNe Ia at $z > 0.5$ with strong lensing magnification. During the first 1 year of the HFF program we have discovered 21 new SNe. These samples are small but special: the high- z SN Ia set has unique leverage for testing SN Ia progenitor models through the delay time distribution while the lensed SNe Ia offer a 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 a) already awarded to this project: b) still required to complete this project:	Telescope(s) VLT UT2	Amount of time 20.2h awarded in P92–P93. ~ 15 h in total (P96–P97)									
5. Special remarks:	This proposal is part of a larger collaborative effort, involving a dedicated 40-orbit HST program (PID 13386, PID 13790, PI Rodney) to improve the characterisation of candidate SNe discovered in the Hubble Frontier Fields. Some of the spectroscopy could possibly be obtained in 'normal' service mode (see Box 8b).										
6. Principal Investigator: JHJORTH											
6a. Co-investigators:	<table><tr><td>S.</td><td>Rodney</td><td>1698</td></tr><tr><td>J.</td><td>Selsing</td><td>1227</td></tr><tr><td>L.</td><td>Christensen</td><td>1227</td></tr></table>		S.	Rodney	1698	J.	Selsing	1227	L.	Christensen	1227
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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). 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 $m_{lim,3\sigma}(F160W) \approx 27.9$ (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 easier 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.*

As the HFF HST data are obtained, we are searching for SNe at all redshifts – 840 HST orbits in total at the end of the program. We also search for SNe in supplemental imaging. We have already been awarded 40 HST orbits for ToO follow-up to observe SN light curves (PID 13386, PID 13790, PI Rodney).

There is an uncomfortable ambiguity about the nature of SN Ia progenitor systems (e.g., Maoz & Mannucci 2012, PASA, 29, 447). Models differ on the identity of the companion star, the time scale for mass-accretion (or merger), and the time from progenitor formation to explosion (the “delay time”). Resolving the progenitor problem has tremendous astrophysical implications touching on heavy element enrichment over cosmic history, the origins of galactic winds and galaxy formation, and the robustness of SNe Ia as standard candles.

Volumetric SN Ia rates provide important constraints on the progenitor. 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 $\sim 50\%$.

B – Immediate Objective: Our primary science goal is to provide a real measurement of SN Ia rates to $z \approx 2.5$, yielding improved constraints on SN Ia progenitor models. A secondary goal is to build a sample of about 10 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.

We process the HFF data 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. A prime example of this is shown in Figure 2.

In its comments to our P92, P93 and P94 proposals, the OPC noted the uncertain number of events. We agree that the rates in any given period are uncertain. In P92 and P93 we discovered 21 new SNe and triggered the VLT on four events. Based on our detailed simulations we expect 3 ± 3 SNe to be detectable with VLT during P95, but given past experience we will likely only trigger on 2 systems, which is what we apply for here. We will observe either the SNe or the host galaxies, or both. In terms of observational efficiency, the host is much more reliable, as we typically have good emission lines for our high- z host targets, while the SN spectrum requires template matching to broad absorption features. In our previous X-shooter programs, most redshifts were indeed obtained through host galaxy spectroscopy and we expect the same to be the case for this X-shooter/HFF program. However, a SN spectrum is valuable 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 ~ 11 objects: 3 from GOODS and 8 from the nearly completed CANDELS+CLASH survey. The expected yield of ~ 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).

Testing Lens Models: We expect to find ~ 10 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). 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.

7. Description of the proposed programme and attachments

Description of the proposed programme (continued)

Star Formation From CC SNe: CC SN volumetric rates have a much closer connection to the star-formation rate density than do SNe Ia, because CC SNe have essentially no delay from formation to explosion. CC SN rates, therefore, allow a means for measuring the star formation rate history independent from galaxy UV luminosities (Dahlén et al. 2012, ApJ, 757, 70) and will allow a direct comparison of CC SN rates and star formation rates (Horiuchi et al. 2011, ApJ, 738, 154; Madau & Dickinson, ARAA, 2014, 52:41586). Approximately half of the HFF discoveries will be CC SNe, allowing us to extend CC SN rates measurements to $z > 1$, probing closer to the peak of the cosmic star formation rate history.

Attachments (Figures)

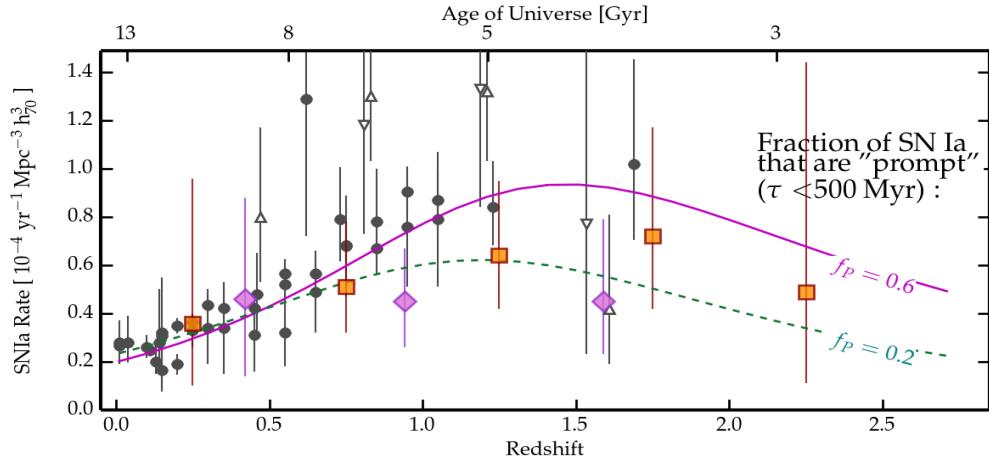


Figure 1. *SN Ia rates constrain progenitor models.* Measured volumetric SN Ia rates as a function of redshift, comparing observed SN rates against two progenitor models from Rodney et al. (2014). Large purple diamonds show the CLASH rates from Graur et al. (2014) and large orange squares show the CANDELS 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.

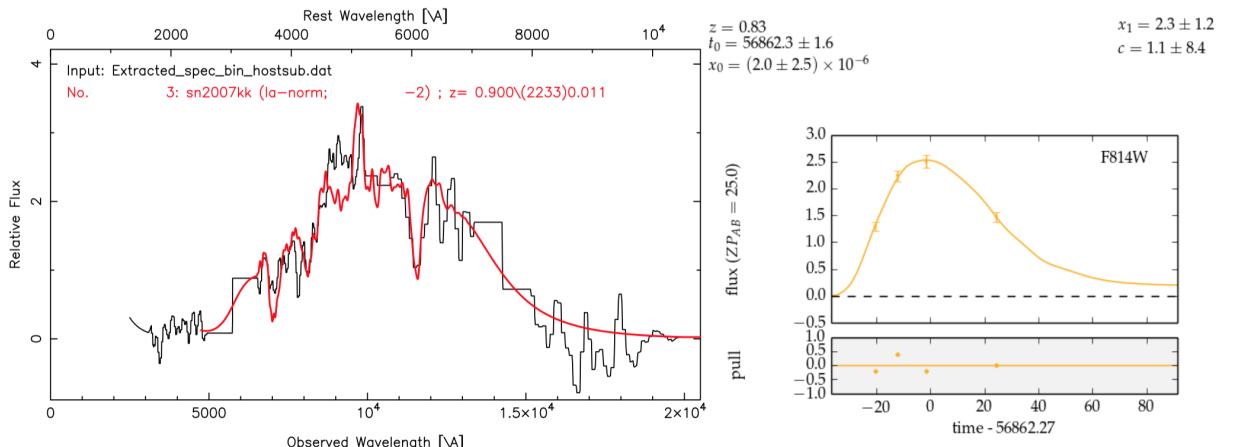


Figure 2. Left: *X-shooter spectrum of SN Preston.* In a 3.2h X-shooter spectrum we detect clear SN-features after a host template spectrum has been subtracted. Right: The photometric redshift of the host is $z \sim 0.83$ which agrees with the *SALT2* SN Ia light curve fit. This is also in rough agreement with the spectroscopically determined redshift of a SN Ia at $z \sim 0.9$ obtained from template matching with SNID (Blondin & Tonry, 2007, ApJ, 666, 1024). 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 $\lambda 6150$ 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 $\lambda 6150$, this can be detected at 5–10 σ 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.

090.A-0726 (PI Hjorth): High-redshift CANDELS/CLASH SNe and host galaxies. This program has led to several redshift determinations of high-redshift SNe, both Ia and CC, and in some cases have allowed a detailed study of the properties of the SN host galaxies: Rodney et al., ApJ, 746, 5, 2012; Frederiksen et al., ApJ, 760, 125, 2012; Frederiksen et al., A&A, 2014, 563, A140. The redshift of the most distant SN Ia is based on HST grism and X-shooter spectroscopy: Jones et al., ApJ, 768, 166, 2013. The inferred SN rates are presented in Graur et al., ApJ, 783, 28, 2014 and Rodney et al., 2014, ApJ, 148, 13.

090.D-0719 (PI Hjorth): Supernova dust extinction. Results so far include Gall et al., ATel 4454, 2012; Margutti et al., ApJ, 780, 21, 2014; Gall et al., Nature 511, 326 - 329, 2014

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., 2012, ApJ, 760, 125: The dwarf starburst host galaxy of a Type Ia supernova at $z = 1.55$ from CANDELS

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

Hjorth, J. et al., 2012, ApJ, 756, 187: The Optically Unbiased Gamma-ray burst host (TOUGH) survey. I. Survey design and catalogs

Li, Hjorth & Wojtak, 2014, ApJ, submitted (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 S. et al., 2012, ApJ, 746, 5: A Type Ia supernova at redshift 1.55 in Hubble Space Telescope infrared observations from CANDELS

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 be in the clusters of galaxies MACS0416 (RA(J2000) = 04:16:08.4, Dec(J2000) = -24:04:27.7), MACS1149 (RA(J2000) = 11:49:36.3, Dec(J2000) = +22:23:50.7) or their flanking fields a few arcmin away. 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 the 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