# SINS: The Supernova INtensive Study–Cycle 11

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Scientific category: HOT STARS
Scientific keywords: SUPERNOVAE, SUPERNOVA REMNANTS, MASSIVE STARS, CHEMICAL ABUNDANCES, COSMOLOGICAL DISTANCE SCALE
Instruments: ACS, NICMOS, STIS Proprietary period: 12
Cycle 11 primary orbits: 81
Cycle 11 parallel orbits: 0

## Abstract

Supernovae create the chemical history of the Universe, energize the interstellar gas, form the spine of the extragalactic distance scale, and provide the only direct evidence for an accelerating universe. SINS is a program to study supernovae, near and far. HST is the perfect match in field and scale for spatially-resolved observations of SN 1987A. There, a violent encounter between the fast-moving debris and the stationary inner ring is well underway. Monitoring this interaction will help solve the riddles of stellar evolution posed by the enigmatic three-ring system of SN 1987A. Our UV observations of Ly-$\alpha$ emission reveal a remarkable reverse shock that provides a unique laboratory for studying fast shocks and a powerful tool for dissecting the structure of the vanished star. For more distant events, we propose Target-of-Opportunity observations. In addition to one bright new supernova in Cycle 11 discovered by any search at any time, we propose to discover two supernovae for study in the ultraviolet *at times specificed in advance*, using the Lick Observatory Supernova Search. SINS will study the historic SN 1987A, explore UV emission from supernovae, and press late-time observations of supernovae into uncharted territory of infrared catastrophes, light echos, and stellar remnants.

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Total number of investigators: 23
Number of ESA investigators: 4 (indicated by * after name)

**Observing Summary:**

| Target | RA | DEC | V | Configuration,mode,aperture spectral elements | Total orbits | Flags |
|---|---|---|---|---|---|---|
| SN1987A-SPOT1 | 05 35 | -69 17 | 21 | STIS SPECTRA<br>G140M(1222) | 5 | CPAR DUP |
| SN1987A-HOTSPOTS | 05 35 | -69 17 | 21 | STIS SPECTRA<br>G140L(1425),G230L(2375) | 8 | CPAR DUP |
| SN1987A-HOTSPOTS | 05 35 | -69 17 | 21 | STIS SPECTRA<br>G430L(4300),G750L(7500),G750M(6581) | 10 | CPAR DUP |
| SN1987A-NIC | 05 35 | -69 17 | 21 | NIC1,NIC2 IMAGING<br>F110W,F160W,F205W,<br>F108N | 3 | CVZ CPAR DUP |
| SN1987A-ACS | 05 35 | -69 17 | 21 | ACS/HRC IMAGING<br>F330W,F435W,F555W,F625W,F814W | 2 | CVZ CPAR DUP |
| SN1987A-ACS | 05 35 | -69 17 | 21 | ACS/HRC IMAGING<br>F502N,F658N,FR656N | 4 | CVZ CPAR DUP |

**Observing Summary:**

| Target | RA | DEC | V | Configuration,mode,aperture<br>spectral elements | Total orbits | Flags |
|---|---|---|---|---|---|---|
| SN1987A-EPOCH2 | 05 35 | -69 17 | 21 | ACS/HRC IMAGING<br>F435W,F555W,F625W,FR656N | 2 | CPAR DUP |
| SN1987A-INTERACTION | 05 35 | -69 17 | 21 | STIS/FUV SPECTRA<br>G140L(1425) | 4 | CPAR DUP |
| SN2002TOO | 00 00 | 00 00 | 14.0 | STIS/FUV,STIS/NUV,STIS/CCD SPECTRA<br>G140L(1425),G230L(2375),G430L(4300) | 18 | TOO |
| SN2002TOO | 00 00 | 00 00 | 14.0 | ACS/HRC IMAGING<br>F435W,F555W,F625W,F814W | 1 | DUP |
| SN2002KAIT1 | 00 00 | 00 00 | 16.0 | STIS/FUV,STIS/NUV,STIS/CCD SPECTRA<br>G140L(1425),G230L(2375),G430L(4300) | 8 | TOO |
| SN2002KAIT2 | 00 00 | 00 00 | 16.0 | STIS/FUV,STIS/NUV,STIS/CCD SPECTRA<br>G140L(1425),G230L(2375),G430L(4300) | 8 | TOO |
| SN2001V | 11 57 | 25 12 | 24.0,26.5 | ACS/HRC IMAGING<br>F435W,F555W | 3 | |
| SN-CYCLE10-TOO | 00 00 | 00 00 | 20.0 | SITS/FUV,STIS/NUV/STIS/CCD SPECTRA<br>G140L(1425),G230L(2375),G430L(4300) | 5 | DUP |
| | | | | Grand total orbit request | 81 | |

## ■ Scientific Justification

### 1 SN 1987A

Supernova 1987A is a once-in-a-lifetime event which deserves careful study with HST for current investigation and as a legacy for the future. Studying SN 1987A in the same program with extragalactic supernovae makes sense because the lessons from SN 1987A alert us to issues of circumstellar interaction and asymmetry of the explosion that we might otherwise ignore. The best-observed death of a star is now the first birth of a supernova remnant to be observed in real time. The data so far, which we have analyzed extensively (see the SINS publications), challenge our understanding of exactly how supernovae explode. We want to understand the dynamics of the SN 1987A explosion by observing its expanding asymmetric debris, now well resolved by HST. The shape of the debris embeds clues to the explosion mechanism. The fastest debris are now smashing into "hotspots" on the inner circumstellar ring and more spots are lighting up each year (SINS 43, 44, 54, 55, 60). Observing this impact will help determine how the supernova progenitor produced the remarkable triple-ring system and reveal the physics of radiative shocks. Figure 1 illustrates the debris and the hotspots.

**Figure 1: SN 1987A Spots and Debris**

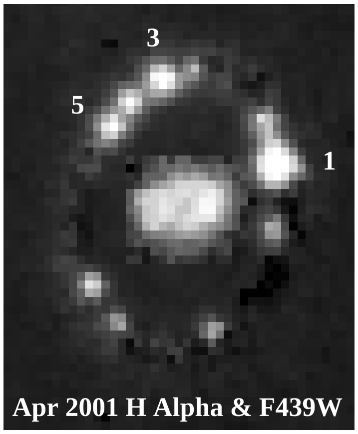
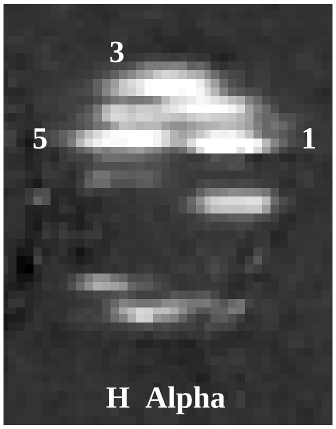


**Figure 2: STIS G750M spectra**



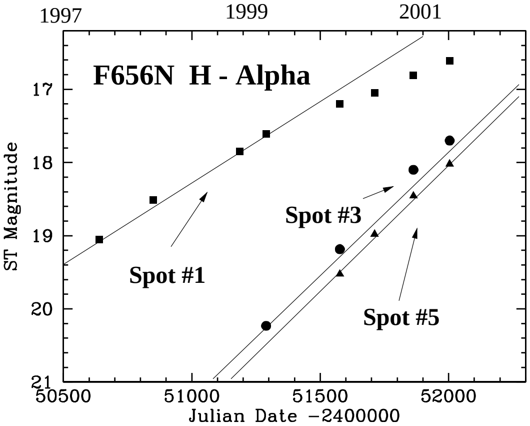


**Figure 3: Lightcurves of SN 1987A collision spots**

**Hotspots Galore:** The first "hotspot" on the inner ring brightened exponentially starting in 1995 (SINS 54). This spot evidently represents a peninsula that protrudes inward — the first place on the ring to be touched by the supernova blast wave. This process converts kinetic energy into radiation and heat as a supernova remnant forms. SINS member McCray has modelled SN 1987A to predict the emission now seen with HST and with Chandra (Borkowski et al. 1997). New spots have emerged in Cycle 10 and more are coming in Cycle 11. STIS spectra of the newly emerging spots offer a unique opportunity to watch a fast radiative shock develop and difference analysis of slitless STIS images, as perfected by SINS member Crotts, provides a powerful way to monitor the emergence of new spots, as illustrated in Fig. 2. Pun et al. (SINS 81) show that simple shock models cannot account simultaneously for the line profiles and line ratios we observe. We suspect that the discrepancy can be attributed to the complex geometry of the protrusion responsible for a hotspot. If so, we may find differences in the spectrum and time development for each hotspot as Figure 3 suggests. We need to look at the profile of the highly ionized N V 1240Å line for clues to the shock geometry. Our analysis will be enriched by Chandra observations, already allocated, which will resolve X-ray and OVI emission, respectively, from the hotspots. As time passes, many more hotspots will appear, brighten, and eventually merge until the entire ring is blazing brighter than Spot 1. In a decade, SN 1987A will be an extraordinary source of UV emission more than 30 times brighter than it is today (Luo et al. 1994) Careful examination of new spots may reveal whether knots formed due to instabilities when the ring was created by presupernova interacting winds and photoionization.

**The Debris:** SN 1987A, 10 million times fainter than at maximum light, requires HST photometry because of its bright neighbors and the brightening inner ring. SINS member Suntzeff leads our work to measure the UBVRIJHK magnitudes of SN 1987A, shown in Figure 4, where scrupulous connection of the ground-based and HST data has now been achieved. Delayed recombination and radioactivity, most likely from $^{44}$Ti, now power the emission. As time passes, continued HST imaging provides the clues to solve a deep mystery — where is the neutron star whose formation was inferred from the neutrino flash of February 1987? Our observations would detect energy emitted from a pulsar, an accreting neutron star, a black hole, or even a surviving binary companion. The expansion of the debris reveals asymmetry in the explosion mechanism (SINS 71). The irregular shape of the optical emission suggests fresh dust in the inner debris affects what we see.

**Figure 4: SN 1987A light curve in B R and J**

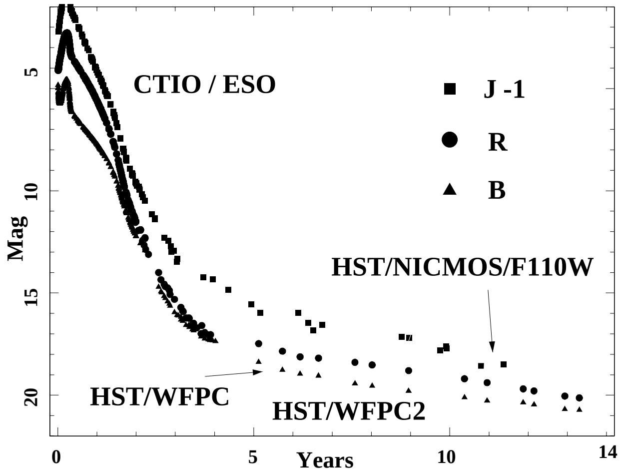
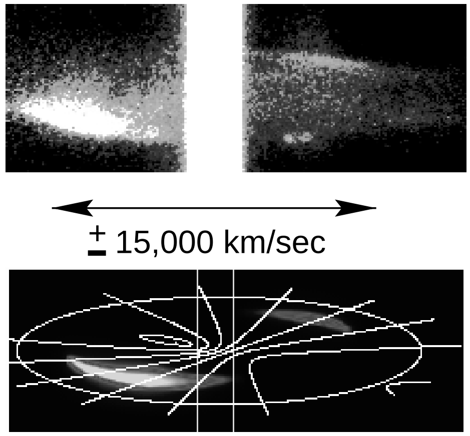


**Figure 5: SN 1987A L$\alpha$ emission**



**The 15,000 km s$^{-1}$ Shock:** Figure 5 shows the spatially resolved Ly-$\alpha$ emission produced as fast-moving neutral hydrogen atoms of the cold outer debris cross a shock at $\sim 15,000$ km s$^{-1}$. STIS is the perfect instrument for this work, matched in spatial and spectral resolution to the properties of SN 1987A. The observations now show that this emission is concentrated in the equatorial plane and is several times brighter on the near (blueshifted) side than on the far side (SINS 36, 56). Maps obtained in Cycle 9 show that this emission is also much brighter on the east side than on the west. Since the flux in this emission measures the amount of neutral gas crossing the shock, this suggests the outer supernova debris has large departures from axial symmetry. The nonthermal radio and X-ray emission (SINS 69) have similar asymmetry and probably come from the zone of hot gas bounded on the inside by the 15,000 km $s^{-1}$ shock and on the outside by the blast wave. By comparing maps of the 15,000 km $s^{-1}$ shock with those of the radio and X-ray emission, we can investigate the cause of the asymmetry of the shock, study the way relativistic particles are accelerated by the shock, and examine the physics of particle isotropization in a collisionless shock. This development bears close watching, as the fluxes are doubling on timescales of $\sim 1$ year.

As time passes, we should see the velocity of the 15,000 km $s^{-1}$ shock decrease as slower moving gas from deeper within the debris crosses the shock. By measuring the change of the Ly-$\alpha$ flux, we can reconstruct the density profile of the shattered star. In the next decade, we expect to see this spectrum change suddenly as clumps of heavy elements from deep within the chemically inhomogeneous envelope of SN 1987A cross the shock and reveal the distribution of nucleosynthetic products in the supernova debris. Perhaps helium will be next.

## 2 Opportunity Knocks

The greatest adventure for SINS has been to observe newly discovered supernovae with HST as targets of opportunity. The only other UV spectra of supernovae are from SN 1987A and work with IUE. In Cycles 7 and 8, we obtained exquisite UV spectra of SN 1998S and SN 1999em and we have already analyzed the spectra (SINS 53, 62). But the world's entire supply of good UV observations, displayed in Figure 6, is much smaller than we need to determine the bolometric behavior of supernovae, or to understand the circumstellar interactions of core-collapse supernovae, or to learn the restframe UV behavior of SN Ia so they can be used as cosmological probes at high redshift (Schmidt et al. 1998; Coil et al. 2000). HST is the only way to observe these UV spectra. We propose to continue this work on one bright target which will be the subject of intensive study.

Because supernovae at $z \approx 1$ can only be observed with CCDs in the restframe UV, and the UV sample of local objects is slim, last year we proposed an augmented approach to the problem, based on the Lick Observatory Supernova Search, run by SINS members Weidong Li and Alex Filippenko. They have discovered 50 supernovae in the past year, most of them well before maximum light. We propose to observe two Lick objects in the UV, *supplied to STScI at times we can specify in advance* and locations that correspond to the night-time quadrant of the celestial sphere searched from Lick.

Supernovae fall into two broad categories: Type I (SN I) have no hydrogen in their spectra and Type II (SN II) show strong hydrogen lines. SINS member Craig Wheeler divides SN I into three spectroscopic classes: SN Ia, Ib, and Ic. While SN Ia probably result from a sudden thermonuclear burn in a white dwarf, SN Ib and Ic probably arise from core collapse in massive stars after extensive mass loss, which may have a conspicuous UV signature. Precise photometry shows that SN Ia display a range of luminosities and light-curve shapes which have been analyzed empirically to make SN Ia the best tools for measuring extragalactic distances. Observations with HST could help decode what leads to the observed range of luminosities and light-curve shapes. This also is important for understanding possible effects of chemistry and stellar populations on the high-$z$ Hubble diagram since theory (Hoeflich et al. 1998) predicts that these effects are largest in the UV.

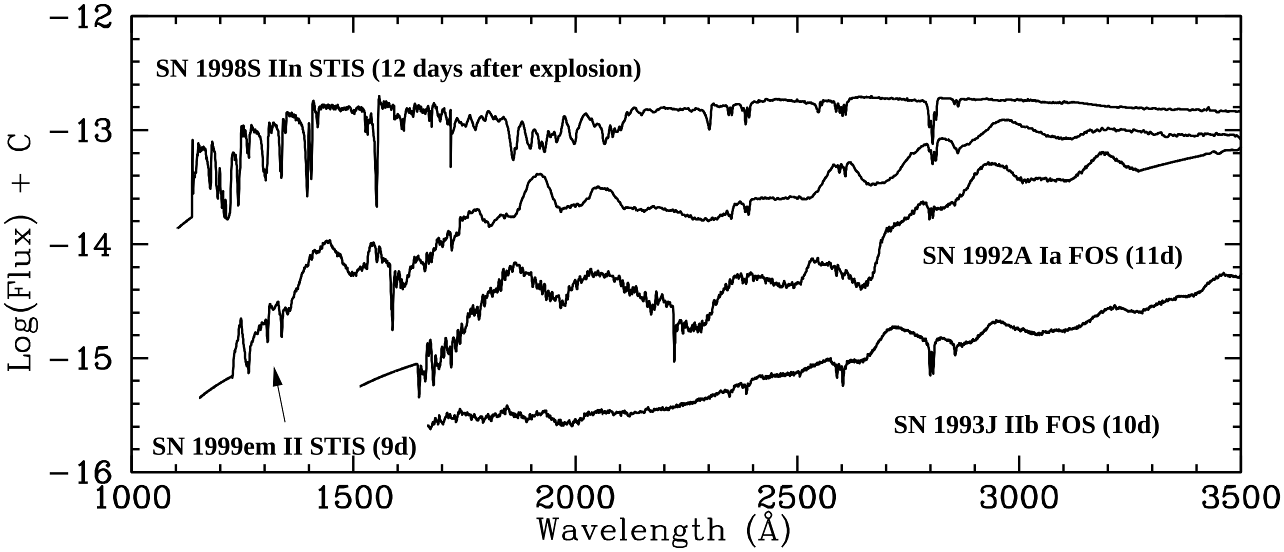
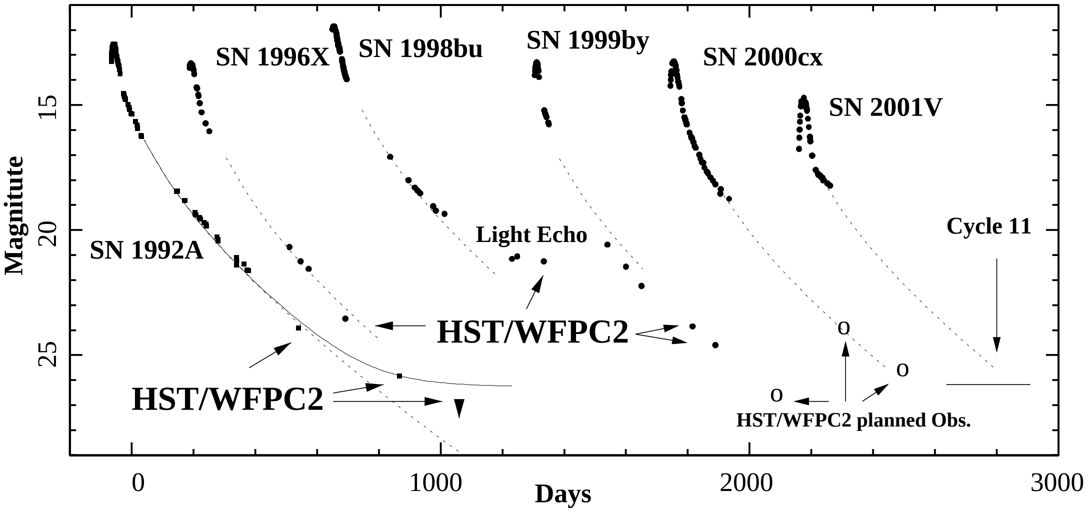


**Figure 6: SINS - First Epoch HST UV Spectra**

**Figure 7: Late-Time light curves of Ia supernovae**



## 3 A Long Slow Decline

The SINS program includes late-time followup of objects to help understand how different types of supernovae work. For example, the decay of $^{56}$Ni powers the light curve of SN Ia. After several months, the optical emission comes from a cold iron-rich gas which is excited by MeV particles. Once the gas gets cold enough, Kozma and SINS member Fransson predict an “infrared catastrophe,” with most of the energy emitted in the far infrared, while optical emission plummets. Does this really happen? SINS data shows that it did **not** for SN

1992A observed 925 and 1680 days past maximum, as illustrated in Figure 7. But perhaps conditions are slightly different in other SN Ia.

In Cycle 11 we will obtain observations of an exceptionally well-observed SN Ia, SN 2001V, as it ages and reveals its late-time behavior. The light curve is very well sampled: it was discovered 14 days before maximum at the CfA and we feel paternal pride in studying it thoroughly.

We also plan to obtain spectra at age 1 year of our Cycle 10 target-of-opportunity, which we have not yet observed. Late-time spectra of previous SINS targets-of-opportunity, like SN 1993J, have proved exceptionally interesting with evidence for a reverse shock running back into the inner layers of the exploded star.

## 4 References

See the attached SINS bibliography for copious references to SINS work.
Borkowski, K., Blondin, J. M., & McCray, R. 1997, *ApJ*, **477**, 281.
Coil, A., et al. 2000, *ApJL*, **544**, 111.
Hoeflich, P., Wheeler, J. C., & Thielemann, F. K. 1998, *ApJ*, **495**, 617.
Lawrence, S. S., et al., 2000, *ApJ*, **537**, L123.
Luo, D., McCray, R., & Slavin, J. 1994, *ApJ*, **430**, 264.
Schmidt, B. P., et al. 1998, *ApJ*, **507**, 46.

# Description of the Observations

### SN 1987A:

Cycle 11 SN 1987A STIS spectroscopy will follow the rapid development of the interaction shock and of the hotspots. All STIS visits will have a time-tested acquisition strategy, include dithers to remove cosmic rays and hot pixels, and use a short STIS/CCD image to record the telescope pointing and to search for new hot spots.

The spectrum of the interaction region will employ the same STIS setup at Ly-$\alpha$ as in our previous work. We expect that the interaction region will grow brighter and four orbits with the STIS/MAMA $0.2''$ slit with G140L will provide good signal. These spectra will give further evidence on asymmetries in the expansion. We will also use the ACS/HRC to image the interaction region, by differencing drizzled H$\alpha$ from $R$-band images to reveal the broad H$\alpha$ flux from the high-velocity regions.

STIS spectra of the hotspots should allow us to diagnose the shock that is crushing these stalactites of gas. The high-resolution spectrum at N V 1240 $\mathring{A}$ with G140M will test models of the shock structure developed by SINS member Lundqvist. Our estimates show 5 orbits will give enough signal in each resolution element to measure the line profile. We should be able to find the shock velocity, see non-equilibrium effects in regions of different density, and derive some properties of the shock geometry. We expect the hotspots will continue to brighten and that Cycle 11 observations will show significant differences from our first hotspot spectra. The first set of observations will use the G140L & G230L gratings with the 0.5″ slit to measure the UV flux in the brightest spots. The second set of observations will observe the complete SN 1987A ring and all newly discovered hot spots with STIS with the 52X2 slit and G750M, G750L, and G430L gratings. There will be two visits, separated by approximately six months, matching orientations of previous observations (GTO 7123, GO/DD 8806) for difference imaging. We will obtain spectra through the 52X2 slit in two pointings to deliver data at the full spatial and spectral resolution. Important diagnostic lines that are blended will be resolved by the G750M spectra. Each epoch will use 5 orbits: 1.5 for each of G430L and G750L, and 2 for G750M.

SINS member Nino Panagia and his students have been industrious in using the parallel images obtained during our spectroscopic visits to provide a deep multi-band survey of this interesting segment of the LMC. We would like to continue this practice, which provides information on the stellar population and star formation history of this region. We note that a very large number of stars with a range of brightness and color in these frames can be used to compare the ACS calibration with WFPC2.

Our ACS/HRC imaging program provides continuing information on the debris shape, luminosity, and expansion, the eruption of new hot spots, and the recombination of the rings. A basic set of filters that connects with our earlier observations at similar signal-to-noise ratio takes 6 orbits. The reconnaissance for eruption of new hot spots should be done again late in Cycle 11, which takes 2 additional orbits. We would use the CVZ opportunity when it is available. Our previous WFPC2 data will allow us to connect the HRC photometric system to the WFPC2 photometric system. We will also revisit SN 1987A with NICMOS; 3 orbits (0.67 NIC1/F110W, 0.67 NIC1/F160W, and 1.67 NIC2/F205W ) will be needed to make high-quality dithered images.

**SN 2001V:** Photometry of SN 2001V will test whether the predicted infrared catastrophe takes place for this exceptionally well-studied (by us) SN Ia. We will observe at $m \geq 24$ and $m \geq 26.5$ with ACS/HRC/F439W and F555W to measure the color at each epoch. A total of 3 orbits is required.

**Late-Time UV Spectrum of Cycle 10 TOO Supernova:** We will observe one supernova in Cycle 10 as our Target of Opportunity. A late-time UV spectrum, at age 1 year, has proved very interesting for previous SINS targets SN 1993J and SN 1998S. We would like to return to this Cycle 10 target in Cycle 11 to obtain that UV spectrum using STIS with G140L, G230L, and G430L for 5 orbits.

**Target of Opportunity:** We have developed a very effective set of observations which have worked well for SN 1992A (SN Ia) , SN 1993J (SN IIb), SN 1994I (SN Ic), SN 1998S (SN IIn), and SN 1999em (SN II) to gather unique spectra in the UV with HST. We observe at the earliest moment the HST system will allow, a week later, at age 2 weeks, and at an age of about 50 days. At age 1 year, we image in ACS/HRC/F439W, F555W, F675W, and F814W to examine the neighborhood of the explosion and to get a solid point on the late-time light curve. Effective target acquisition schemes have been worked out in detail during Phase 2 for earlier cycles. Low-dispersion UV spectra give the overall energy distribution, which has proved dramatically different for various types of supernovae and is a sensitive indicator of the physical state of the outermost layers of the explosion and the circumstellar surround. We need 3 orbits for the first visit (1.7 orbits with G140L, 1.0 orbits with G230L, and 0.3 orbits with the G430L), 5 orbits for the second visit [G140L (3 orbits), G230L (1.7 orbits), and G430L (0.3 orbits)], 5 orbits for each of the two later measurements, and 1 orbit for the ASC/HRC imaging, a total of 19 orbits for the ToO.

For supernovae discovered on a pre-determined schedule at Lick Observatory, the first visit will be 3 orbits with STIS with gratings G140L, G230L, and G430L. The second visit a week later will be the same low-dispersion gratings for 5 orbits.

Table 1: Observing Summary

| | | |
|---|---|---|
| SN 1987A | STIS N V G140M | 5 orbits |
| SN 1987A | STIS Ly$\alpha$ | 4 orbits |
| SN 1987A | STIS hotspots | 18 orbits |
| SN 1987A | NICMOS imaging | 3 orbits |
| SN 1987A | ACS CVZ imaging | 6 orbits |
| SN 1987A | ACS 2nd-epoch imaging | 2 orbits |
| SN 2002 TOO | STIS UV spectroscopy | 18 orbits |
| SN 2002 TOO | ACS late time | 1 orbit |
| SN 2002 KAIT1 | STIS UV spectroscopy | 8 orbits |
| SN 2002 KAIT2 | STIS UV spectroscopy | 8 orbits |
| SN 2001V | ACS imaging | 3 orbits |
| Cyc 10 TOO | Late time STIS | 5 orbits |
| | GRAND TOTAL | 81 orbits |

## Special Requirements

When SN 1987A is in the CVZ, we can make the most efficient use of the spacecraft to gather our imaging data (which doesn't require a special roll angle). The STIS observations have too many constraints to be accommodated in this way.

Our Target of Opportunity program would trigger for a supernova which we expect to reach maximum light brighter than 14 mag based on the distance and epoch of discovery, or fainter if there is also a gamma-ray localization. The probability of having a 14 mag supernova in Cycle 11 is near unity given the current rate of supernova discoveries. However, we have been scrupulous in applying high standards to our targets, avoiding crowded fields and obscuration by dust, while obtaining excellent astrometry, photometry, and diagnostic spectroscopy from sites in Arizona, Texas, California, Chile, and Australia. Early observations are desirable, but we are **not** requesting the ultra-rapid 24 hour turnaround. We depend on close cooperation with our Program Coordinator to get the best performance available from the HST system and we are willing to live with the result.

We also propose to continue our Cycle 10 "UV opportunities" program to observe the UV spectra of two new supernovae discovered by the Lick Observatory Supernova Search in September through November 2002. The Lick search has been terrifically productive, so **the time of the HST observation can be fixed in advance and the area on the sky specified in advance to the zone visible from Lick during those nights** — less than 1/4 of the celestial sphere.

These observations can be built into the HST plans, with the exact positions provided later. The advantage of "booking ahead" is that part of implementing a TOO is to check which programs would be impacted and to see whether they can be shifted to a later time. Specifying the time of the discovery in advance saves the STScI this step and creates less disruption to other programs. For this segment of the program, we would accept any supernova down to $m \approx 16$. In 1999 and 2000, the Lick system found two supernovae per month that meet this standard.

## ■ Coordinated Observations

The SINS collaboration is engaged in a broad range of supernova studies that make the HST observations more effective. There are supernova searches at Lick and Mount Stromlo to help create our own opportunity. We have regular access to Keck, Lick, CTIO, VLT, HET, Magellan, and the MMT which we devote to study of objects in the SINS program. Fransson, Lundqvist, and Leibundgut are monitoring SN 1987A with high spectral resolution and in the near-IR with the VLT. Kirshner and Sonneborn have a Target of Opportunity program approved for FUSE. Sonneborn leads a GTO program on FUSE to study SN 1987A. McCray already has time allocated for continued Chandra studies of SN 1987A. Both the reverse shock and the hot spot are powerful X-ray sources. The combination of Chandra images and spectra with the SINS data will provide tremendous scientific leverage in understanding SN 1987A. Since the source varies on timescales of months, not days, the coordination of these observations in 2001–2002 should not be too difficult. Several SINS members are part of the CHANDRA program for a TOO aimed at SN Ia, while Panagia is part of the program to observe radio emission from supernovae with the VLA. Lundqvist heads a TOO program at the VLT echelle. The study of asymmetry in supernovae, of special interest in their connection to $\gamma$-ray bursts, has been carried out by SINS members at Keck and at McDonald.

## ■ Justify Duplications

You call them duplications, but we call them repeat observations of time-varying events! The observations we propose can never be duplicated, since the source is constantly changing in flux, size, and spectrum. This is especially true for the hotspots of SN 1987A and for the 15,000 km $s^{-1}$ shock zone, where the timescale for change is 1 year.

Sonneborn has submitted a TOO proposal to study the interstellar medium using supernova light as a background source. The ISM program and SINS are complementary, not duplications. Of course, we will cooperate to make his observations as effective as possible by providing information on object positions and UV flux.

## Previous HST Programs

**"SINS: The Supernova INtensive Study." PI: Robert Kirshner**
The SINS program has been approved for each cycle of HST. Continuity of this program has led to long-term studies of objects whose evolution spans many HST cycles. SINS has provided material for the Ph.D. theses of Philip Plait (University of Virginia), Cecilia Kozma (Stockholm), Martino Romaniello (Scuola Normale Superiore, Pisa), and Jason Pun (Harvard University), and it supports the current thesis project of Eli Michael (University of Colorado). Undergraduate projects including a Senior Thesis by Ben Oppenheimer (Harvard, now at Arizona) and Genevieve Graves (Harvard, now at Cambridge) and Jennifer Millard (Oklahoma, now at Lockheed) have also come from the SINS project. Information on the SINS work is located at:

http://cfa-www.harvard.edu/cfa/oir/Research/sins.html

Selected publications are listed here, with all but the most recent AAS abstracts and IAU Circulars omitted:

**Cycle 1, Proposals 2563-4016, 36 orbits**

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