Hubble Space Telescope

Cycle 16 GO Proposal

SAINTS - Supernova 1987A INTensive Survey

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Scientific Category: ISM AND CIRCUMSTELLAR MATTER

Scientific Keywords: MAGELLANIC CLOUDS, SUPERNOVA REMNANTS, SUPERNOVAE

Instruments: WFPC2, NICMOS

Proprietary Period: 12

Orbit Request	Prime	Parallel
Cycle 16	25	0

Abstract

SAINTS is a program to observe SN 1987A, the brightest supernova in 383 years, as it matures into the youngest supernova remnant at age 20. HST is the essential tool for spatially-resolved observations of SN1987A's many components. A violent encounter is now underway between the fastest-moving debris and the circumstellar ring: the shock excites "hotspots." The optical, infrared and X-ray fluxes are rising rapidly on 6-month time scales: we have organized HST, SPITZER, and CHANDRA observations to understand these regions. In Cycle 16, the separate hotspots may begin to fuse as the shock fully enters the circumstellar ring. Photons from these shocks will excite previously invisible gas outside the ring, revealing the true extent of the mass loss that preceded the explosion of Sanduleak -69 202. The inner debris of the explosion, excited by radioactive isotopes from the explosion, is now resolved and seen to be aspherical, providing direct evidence on the asymmetry of the explosion. Questions about SN 1987A remain unanswered. How did the enigmatic three rings form? Precisely what happened during the core collapse and bounce? Is a black hole or a neutron star left behind? The rich and deep data set from SAINTS will help answer these central questions of supernova science.

Investigators:

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Number of investigators: 22

* ESA investigators: 5

Target Summary:

Target	RA	Dec	Magnitude
SN-1987A	05 35 27.9000	-69 16 10.00	V = 23.0 +/- 4.0

Observing Summary:

Target	Config Mode and Spectral Elements	Flags	Orbits
SN-1987A	WFPC2 Imaging F255W WFPC2 Imaging F336W WFPC2 Imaging F439W WFPC2 Imaging F555W WFPC2 Imaging F675W WFPC2 Imaging F814W WFPC2 Imaging F656N WFPC2 Imaging F502N		12
SN-1987A	WFPC2 Imaging F439W WFPC2 Imaging F675W WFPC2 Imaging F656N		4
SN-1987A	WFPC2 Imaging F656N		4
SN-1987A	NIC1 Imaging F108N NIC1 Imaging F110W NIC1 Imaging F160W NIC1 Imaging F187N NIC2 Imaging F205W NIC2 Imaging F212N NIC1 Imaging F164N		5

Total prime orbits: 25

■ Scientific Justification

SN 1987A: From Supernova to Supernova Remnant

Supernova 1987A, the brightest supernova seen since Kepler's in 1604, has given us a unique opportunity to study the mechanics of a supernova explosion and now, after 20 years, to witness the birth of a supernova remnant. A blast wave driven by the explosion of SN 1987A is striking the inner circumstellar ring, exciting "hotspots" to emit in the infrared, optical, and ultraviolet. Bright spots in X-ray images from *Chandra* match these spots and change on a 6 month timescale. *Spitzer* observations show dust emission associated with SN 1987A. We want to know how stars age and explode and how the blast wave from a violent explosion affects the surroundings. SN 1987A is the unique object for studying these questions and HST is the ideal tool for studying SN 1987A.

Our team has been observing SN 1987A since its discovery (Figure 1) and has worked vigorously to understand the data in over 60 refereed publications based on observations from HST. We interpreted the glowing radioactive debris at the center of the supernova. We derived a unique geometric distance to the LMC from the timing and angular size of the ultraviolet emission from the circumstellar ring. We predicted the impact of the blast wave with the ring and, when it happened in 1997, analyzed the optical and ultraviolet spectra of the hotspots. We predicted the onset of X-ray emission, and we now observe and analyze X-ray images and spectra obtained with *Chandra*. We have combined our data with the radio emission as observed with ACTA and MOST. Most recently, we have used the HST data together with ground-based IR and *Spitzer* data to study the infrared emission from SN 1987A. As the HST archive of SN 1987A observations has grown, we have produced coherent interpretations for many phenomena, but we have also uncovered scientific riddles whose solutions require a longer and deeper dataset: this proposal aims to continue this process into Cycle 16.

We propose a sharply focused set of Hubble observations to capture unique information on the transition from SN 1987A to the remnant SNR 1987A. These observations make it possible to realize the full scientific benefits of observing programs on *Chandra* and *Spitzer*, and from the ground at optical, IR, and radio wavelengths. This proposal is **not** precisely a "Coordinated" one as described in the Call for Proposals, but it is the result of an inclusive collaboration of experienced observers at each wavelength aimed at maximum scientific benefit.

Only HST has the resolution to observe the individual hotspots where the SN blast wave encounters the inner circumstellar ring, to distinguish the reverse shock where the supernova debris is suddenly slowed and heated to X-ray emitting temperatures, to see the innermost debris still expanding from the shredded star, and to examine the site of the explosion for a possible stellar remnant. No other telescope can separate these components: HST is essential to understanding SN 1987A. As we have shown, HST data enriches the interpretation of ground-based optical and radio observations and those from the other Great Observatories.

The Hotspots: The hotspots appear to be inward protrusions of the inner circumstellar ring that are just now being hit by the supernova blast wave (Figure 3,5). The ring is most likely gas from a red supergiant wind that was swept up by a later, faster blue supergiant wind. The explosion of Sanduleak -69 202 photoionized this ring and now, 20 years later, a mechanical collision is heating that ring again. Optical emission from the hotspots arises from shocked gas in these protrusions as it cools. There are many unanswered questions that our Cycle 16 observations will help to answer.

What are the morphologies of the hotspots? How did they get that way? Despite first appearing in 1997, the oldset hotspots are still unresolved and have not yet merged into a continuous ring. This suggests they are long compared to their cross-sections. They are also regularly distributed in azimuth, which suggests an underlying physical mechanism for their formation sets this scale. Presumably this is related to an instability in the wind-driven formation of the inner ring, but no model has yet been worked out to match this phenomenon.

What is the density distribution within the hotspots? We have shown that the optical emission comes from shocked gas that is dense and cool enough to undergo thermal collapse, as the result of slow, probably oblique, shocks. *Chandra* images show soft X-ray emission that is spatially correlated with the optical hotspots but must come from different parts of the same protrusions that are struck by faster head-on shocks. *Chandra* spectroscopic observations will measure the line widths and temperatures of these fast shocks. *Spitzer* and ground-based IR observations seem to show that dust is being heated and destroyed in these interactions. Our team continues to obtain high-resolution spectra of SN 1987A with VLT, Gemini, and Magellan. The spectra provide critical information on physical conditions in the hotspots. But to interpret them correctly, we need a spatial model that only HST can provide.

What is the distribution of gas outside the inner ring? The creation of the three circumstellar rings remains a mystery. Optical emission from the nearly-stationary triple ring nebula rings comes from a thin ionized skin. The inner ring is ionization-bounded, so there is most likely more mass present in cool, neutral, invisible gas (Figure 2). Rapidly increasing EUV and X-ray radiation from the hotspots will provide a new source of ionizing radiation to light this up the neutral gas. Our imaging observations will provide clues to the material that lies outside the dense ring and help clarify the origin of the triple-ring system.

The Debris: Emission from the center of SN 1987A comes from the shredded core of the exploded star that is excited by radioactive elements synthesized 20 years ago in the explosion itself.

What is the distribution of nucleosynthesis products in the supernova debris? Our images show that radioactive elements are moving at least as fast as 4000 km s^{-1}, but there may well be chunks of other explosion products at higher velocities. Emission in the center of the debris is heated by ^{44}Ti that was manufactured deep inside the star immediately after the explosion, so observing its expansion now is a way to see anisotropy that was set up at the time of the explosion itself. What was hinted at by polarization and speckle measurements in 1987 is now plain to see: the explosion was not spherically-symmetric. The observed ^{44}Ti distribution provides a powerful constraint on explosion models. Large dust particles condensed in the debris after one year of expansion: we hope to identify the role of dust obscuration by monitoring the time evolution of its thinning out and from limits on thermal IR emission from dust with ground-based and *Spitzer* observations. We can expect dramatic changes in the X-ray emission spectrum when newly manufactured elements in the inner debris begin to cross the reverse shock. Today, we see that the glowing inner radioactive debris extends more than halfway to the inner ring. By continuing to monitor images from HST, we will gain more detailed knowledge of the distribution of this matter, and will be able to predict when it will cross the reverse shock.

What remnant remains? Is there any fallback and accretion of debris? Cycle 16 images will place ever-more stringent limits on the elusive neutron star or black hole that must be lurking in the debris of SN 1987A. The present limits, set in our 2005 paper by Graves et al., can be improved. First, as the surface brightness of the expanding debris declines, discrimination of a point source against this background becomes easier. Second, the optical depth of the large dust particles will decline, simply due to expansion. Third, even though this is grey dust, the opportunity to place a more stringent limit in the near-IR has been enhanced by the superior performance of NICMOS since its resurrection in SM-3B. Cycle 16 will set the very best limit yet, and perhaps reveal signs of a compact source.

Other Observations by SAINTS Members

The SAINTS collaboration is broad, making these HST observations more effective. Fransson, Chevalier, Leibundgut, and Lundqvist are monitoring SN 1987A with high spectral resolution and in the near-IR with the VLT. Gaensler is on the Australian team monitoring the radio emission from SN 1987A. Crotts, Suntzeff, and collaborators continue to monitor SN 1987A with the CTIO echelle. Danziger and Bouchet are following SN 1987A in the mid-IR with Gemini-S TReCS and VLT (NACO and VISIR): their recently published results show emission from a resolved inner ring. Sonneborn and Lundqvist have studied SN 1987A using *FUSE* and will be leaders in our future use of COS. *Spitzer* observations of SN 1987A are being carried out by Dwek and other members of the SAINTS team to distinguish radiative from collisional mechanisms for heating the dust. Heng, Kirshner and Challis are continuing measurements of the reverse shock with Gemini and Magellan.

McCray, Burrows, and Park continue to obtain *Chandra* images of the X-ray source SNR 1987A (at a 6 month cadence) that show rapidly brightening X-ray emission correlated with the optical hotspots (Figure 5). Recently, this group carried out a successful 300 ks observation with the *Chandra* Low Energy Transmission Grating that provides spatially resolved X-ray spectra. These data show the kinematics of the X-ray emitting shocks in the emission-line profiles. The results confirm our suspicion that the X-ray emission is now dominated by shocks entering the hotspots with velocities $\sim$400–800 km s^{-1}. In Fall 2007, McCray's group will obtain another X-ray spectrum with a 300 ks observation with the Chandra LETG. Since the X-ray brightness has increased by a factor of 3 since the last such observation, the new spectra will give spatially resolved images of the X-ray emission lines. However, at a resolution of $0.3''$, the *Chandra* images alone are not sufficient to model the X-ray spectra. We can provide a much richer interpretation of the rapidly-evolving *Chandra* data if we make the plausible assumption that the X-ray sources are correlated with the optical hotspots monitored with HST images.

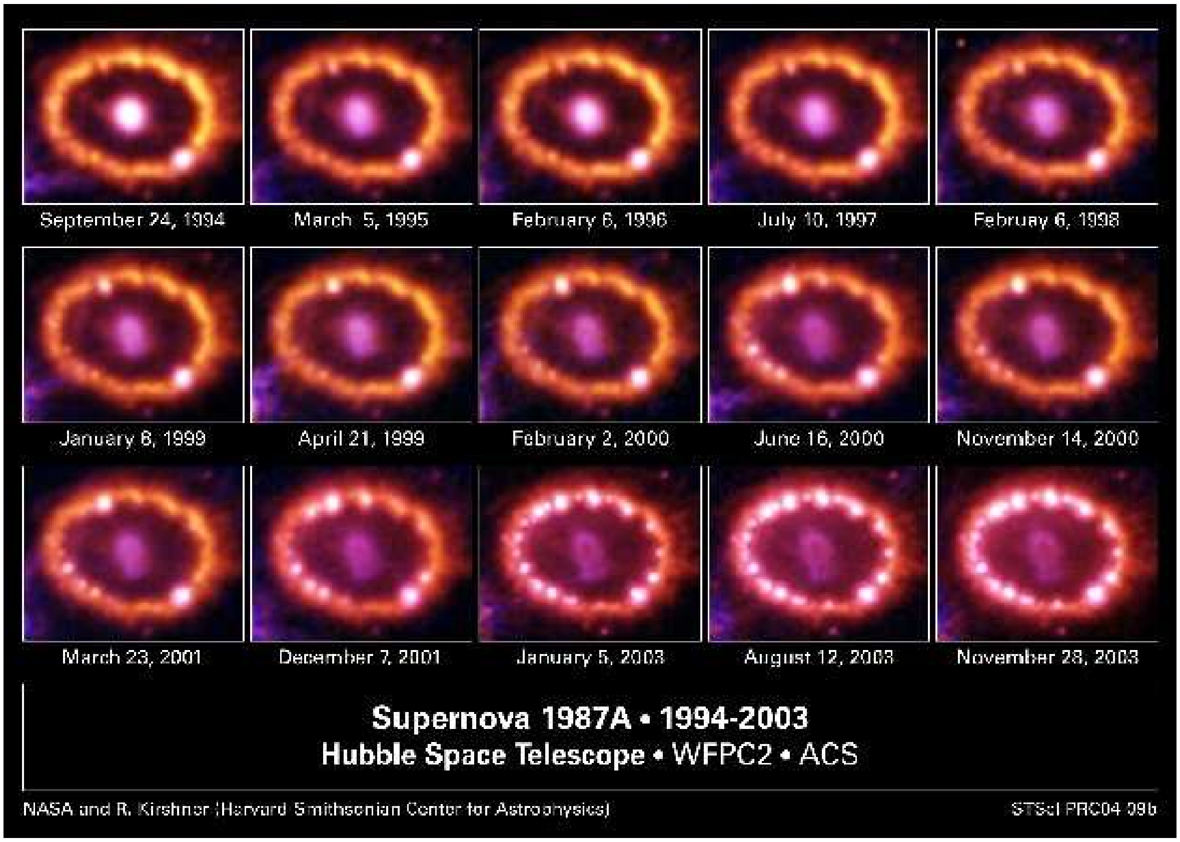


Figure 1: The HST legacy of SN 1987A. A mosaic of images constructed from WFPC2 and ACS HRC images over ten years. Note the rapid, ongoing evolution in the central ejecta and the hot spots lining the equatorial ring.

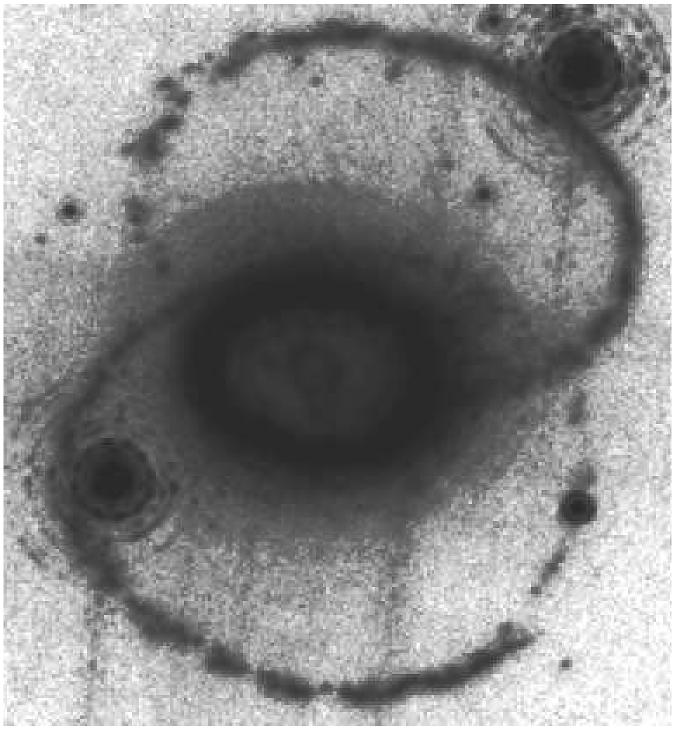
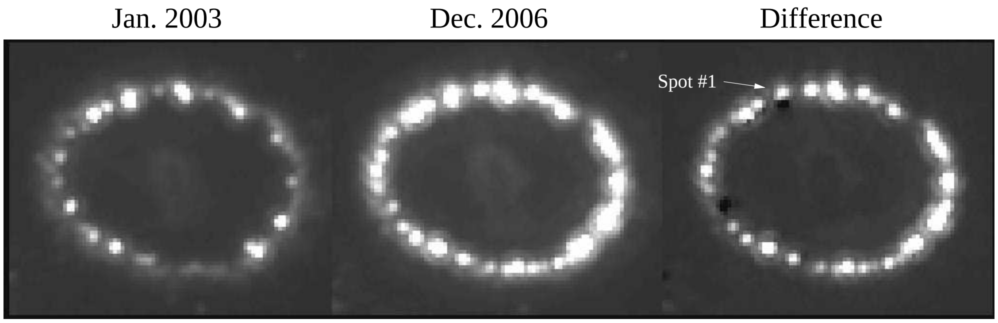


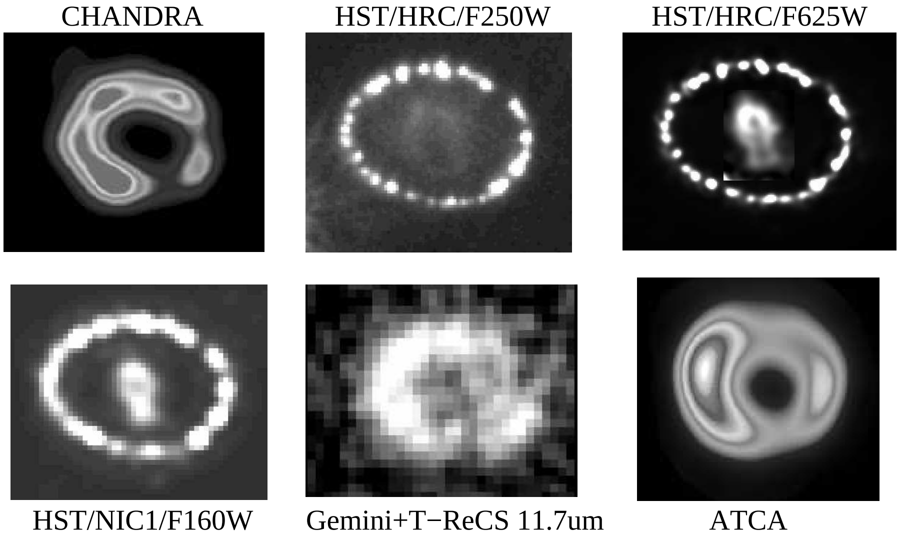
Figure 2: HST/ACS/F658N image from Dec. 2006 showing the 3 ring system with 4 orbits of exposure. With another observation late in Cycle 16, we will use difference imaging to search for unshocked gas heated by emission from shocked gas.


Jan. 2003

Dec. 2006

Difference

Figure 3: HST/ACS observations will continue to show the mushrooming of the collision hotspots. The regularly-spaced hotspots have doubled in number since 2003, but individual spots have not grown to resolvable diameters nor merged into a complete ring yet. The hotspots have not yet produced detectable photoionization in the surrounding neutral gas. Notice the hole by spot 1 which is due to proper motion of the shock.


CHANDRA

HST/HRC/F250W

HST/HRC/F625W

HST/NIC1/F160W

Gemini+T−ReCS 11.7um

ATCA

Figure 4: Multiwavelength observations produced by SAINTS collaborators. The images all have the same scale. From upper left to lower right, the panels show recent X-ray (2004), near-UV (Cycle 15), optical (Cycle 15), near-IR (Cycle 15), mid-IR (2005) and radio images (2003) of the inner ring and central debris.

Description of the Observations

Our proposed WFPC2 imaging program of SN 1987A provides continuing information on the luminosity and expansion of the debris, eruption of new hotspots, and photionization of the surroundings, all at the highest available spatial resolution. Observations in a basic set of filters (F255W, F336W, F439W, F555W, F675W, F814W, F658N, F656N, and F502N) will connect with our earlier observations at similar signal-to-noise ratio S/N. The observations in F255W,F502N and F658N will have exposures aimed at getting good $S/N \approx 30 - 100$ in the hotspots only. Observations in the other filters will provide $S/N \approx 10$ in the debris.

By using the APT to pack orbits and the instrument ETCs to estimate S/N, we request 12 orbits in cycle 16 for the entire filter set. In previous cycles, we were able to take advantage of the CVZ and use fewer orbits to obtain the observations. The reconnaissance for eruption

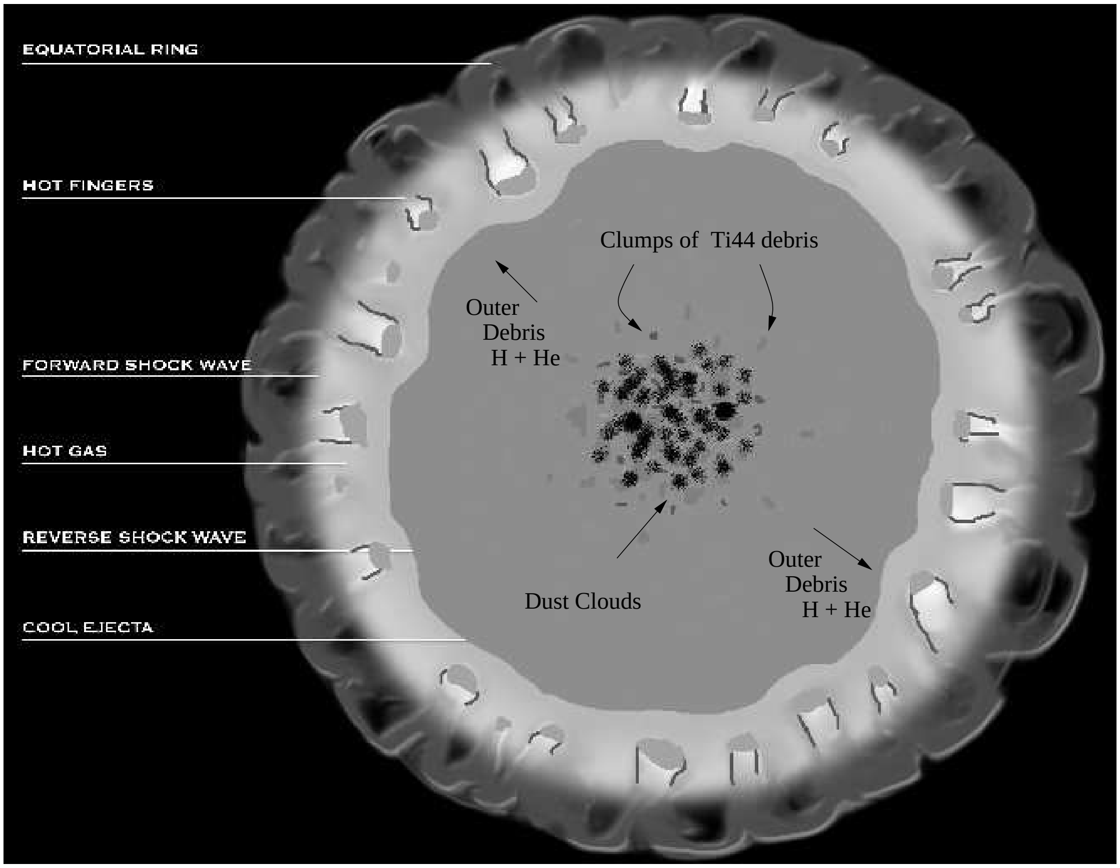


Figure 5: A Model for supernova remnant SNR 1987A. The blobs in the inner debris represent clumps of newly synthesized elements, while the black smudges represent interior dust clouds, which obscure part of the inner debris and possibly also a central compact source. The freely expanding outer debris is primarily hydrogen and helium, which then encounters the reverse shock, where the cold debris is suddenly slowed and heated to X-ray emitting temperatures. The outer boundary of the blast wave is now overtaking fingers of dense gas that protrude inwards from the inner circumstellar ring. The optical hotspots observed with HST come from the boundaries on the sides of the fingers, where the gas has been crushed by the blast wave. The X-ray emission observed with Chandra and the infrared emission observed with Spitzer and ground-based telescopes come mainly from the tips of the fingers, which are heated to X-ray emitting temperatures by the blast wave.

of new hotspots should be done again late in Cycle 16, with F439W, F675W, and F656N to match the *Chandra* cadence,which takes 4 orbits.

To make a sensitive search for brightening of as-yet unseen structures outside the ring, we request 4 additional orbits to obtain a deep H-α image (F656N), to be taken about the same time as the second reconnaissance observations (to add the exposures togethor). We expect that the rapidly increasing X-ray and EUV flux will photoionize gas in the vicinity and reveal its presence.

NICMOS observations for Cycle 16 would include F110W, F160W, F205W, F108N, F164N, F187N, and F212N, requiring 5 orbits and will yield a $S/N \approx 5-20$ in the debris and 20-100 in the hotspots. Observations in these filters were carried out in Cycles 7, 8, 14 and 15. Those observations will be used as templates to measure changes in the emission of the debris and the ring from 7 years ago. They will also provide the best limits on emission from a compact remnant in the debris.

Special Requirements

Coordinated Observations

We have taken an alternative approach to the problem of acquiring excellent sets of data from many sources for SN 1987A. We have formed a collaboration that joins the most active groups of HST observers, *Chandra* observers, ground-based observers at Magellan, Gemini, the VLT, CTIO and the Australian radio facilities with workers who have exploited the capabilities of *Spitzer*. We believe this is the most effective way to keep the responsibility for the observations in the hands of those who have been doing the most significant work and to assure that the multi-wavelength observations are done with an effective, well-coordinated strategy without imposing cumbersome scheduling constraints. The timescale for changes in the inner ring is around 6 months: not so rapid that precisely coordinated observations between observatories are needed, but short enough that it is important not to leave large gaps in the legacy record of this unique event.

Justify Duplications

The observations we propose are never duplicates, because SN 1987A is constantly changing. This is especially true for the hotspots of SN 1987A and for the reverse-shock zone, where we have seen the timescale for change is ~ 6 months. Repetition is not a defect — it is an essential tool for detecting change.

Continuity of this program has led to long-term studies of objects whose evolution spans many HST cycles. SAINTS will continue to provide material for Ph.D. theses: Philip Plait (University of Virginia), Cecilia Kozma (Stockholm), Martino Romaniello (Scuola Normale Superiore, Pisa), Jason Pun (Harvard University), Eli Michael (University of Colorado), Ben Sugerman (Columbia) and in 2007, Kevin Heng (University of Colorado). Undergraduate projects including Senior Theses by Ben Oppenheimer (Harvard, now at AMNH), Genevieve Graves (Harvard, now at UC Santa Cruz) and Maurice Hayon (Hofstra) have also come from this project.

There are over 60 refereed papers based on this series of data. Some recent publications by SAINTS authors incorporating HST observations of SN 1987A are listed here:

Graves, G. J. M., Challis, P. M., Chevalier, R. A., Crotts, A., Filippenko, A. V., Fransson, C., Garnavich, P., Kirshner, R. P., Li, W., Lundqvist, P. and 9 coauthors. 2005, Astrophys. J. 629, 944. **Limits from the Hubble Space Telescope on a Point Source in SN 1987A**

Smith, N., Zhekov, S. A., Heng, K., McCray, R., Morse, J. A., Gladders, M. 2005, Astrophys. J. Letters, 635, L141-4, **The Reverse Shock of SNR1987A at 18 Years after Outburst.**

Heng, K., McCray, R., Zhekov, S. A., Challis, P., et al. 2006, Astrophys. J., 644, 959, **Evolution of the Reverse Shock Emission from SNR1987A.**

Bouchet, P., Dwek, E., Danziger, J., Arendt, R. G., De Buizer, I.J.M., Park, S., Suntzeff, N. B., Kirshner, R. P., Challis, P. 2006, Astrophys. J. 650, 212. **SN 1987A after 18 Years: Mid-Infrared Gemini and Spitzer Observations of the Remnant.**

Heng, K., McCray, R. 2007, Astrophys. J., 654, 923-37, **Balmer-Dominated Shocks Revisited.**