SAINTS - Supernova 1987A INTensive Survey

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Scientific Category: ISM AND CIRCUMSTELLAR MATTER

Scientific Keywords: SUPERNOVAE, SUPERNOVA REMNANTS, MAGELLANIC CLOUDS, INTERSTELLAR AND INTERGALACTIC MEDIUM

Instruments: ACS, NICMOS

Proprietary Period: 12

Orbit Request	Prime	Parallel
Cycle 15	25	0

Abstract

SAINTS is a program to observe SN 1987A, the brightest supernova in 383 years, as it morphs into the youngest supernova remnant at age 19. HST is a unique tool for spatially-resolved observations of the many physical components of SN 1987A. A violent encounter is now underway between the fastest-moving debris and the circumstellar ring: the collision excites "hotspots" that light up suddenly. The optical, infrared and X-ray fluxes are rising rapidly and vary significantly on 6-month time scales: regularly-spaced HST, SPITZER, and CHANDRA observations are needed to understand the physics of these shocked regions. In Cycle 15, the many separate hotspots may begin to fuse as the shock fully enters the circumstellar ring. Photons from these shocks may 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 itself, still excited by radioactive isotopes produced in the explosion, is now resolved by ACS and seen to be aspherical, providing direct evidence on the asymmetry of the explosion.

Many questions about SN 1987A remain unanswered despite our diligent efforts at observation and analysis since the launch of HST. How did the enigmatic three rings form? Precisely what took place in the core during the core collapse and bounce? Is a black hole or a neutron star left behind in the debris? The rich and deep data set from SAINTS will be a resource for current use and for future reference to help answer these central questions of supernova science.

Investigators:

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Number of investigators: 24

* ESA investigators: 5

Target Summary:

Target	RA	Dec	Magnitude
SN-1987A	05 35 28.1100	-69 16 10.85	V = 21.0 +/- 4.0

Dr. Robert P. Kirshner
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Target	RA	Dec	Magnitude

Observing Summary:

Target	Config Mode and Spectral Elements	Flags	Orbits
SN-1987A	ACS/HRC Imaging F250W		7
	ACS/HRC Imaging F330W		
	ACS/HRC Imaging F435W		
	ACS/HRC Imaging F555W		
	ACS/HRC Imaging F625W		
	ACS/HRC Imaging F775W		
	ACS/HRC Imaging F814W		
	ACS/HRC Imaging F502N		
	ACS/HRC Imaging F660N		
SN-1987A	ACS/HRC Imaging F658N		4
SN-1987A	NIC1 Imaging F110W		5
	NIC1 Imaging F160W		
	NIC2 Imaging F205W		
	NIC1 Imaging F108N		
	NIC1 Imaging F187N		
	NIC1 Imaging F164N		
	NIC2 Imaging F212N		
SN-1987A	ACS/HRC Imaging F435W		3
	ACS/HRC Imaging F555W		
	ACS/HRC Imaging F625W		
	ACS/HRC Imaging F658N		
SN-1987A	ACS/HRC Spectroscopic G800L		3
SN-1987A	ACS/HRC Spectroscopic G800L		3

Total prime orbits: 25

Scientific Justification

SN 1987A: From Supernova to Supernova Remnant

Supernova 1987A, the brightest supernova seen since Kepler's in 1604, provides a unique opportunity to study the mechanics of a supernova explosion and, now, allows us to witness the birth of a supernova remnant. Today, a blast wave driven by the explosion of SN 1987A is striking the inner circumstellar ring, exciting a rapidly increasing number of "hotspots" that emit in the infrared, optical, and ultraviolet. Bright spots in X-ray images from *Chandra* correlate with these optical hotspots that change on a timescale of 6 months. Astronomers have never before had the tools to observe a supernova event as we are observing SN 1987A, and we are unlikely to see another in our lifetimes. 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.

Our team has been observing SN 1987A since its discovery and has worked vigorously to understand the data (please see the bibliography and Figure 1). We have observed and interpreted the glowing radioactive debris at the center of the supernova. We predicted the impact of the blast wave with the ring and then interpreted the optical and ultraviolet spectra of the hotspots when this took place. We predicted the X-ray emission, and we continue to observe and analyze X-ray images and spectra obtained with *Chandra*. 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 based on our observations grows, the analysis becomes deeper: this proposal aims to continue that productive process for Cycle 15.

Our work with HST and the work of others using the data, have produced a coherent interpretation for many of the phenomena that we have observed (See Figure 5). But they have also posed an exciting set of scientific riddles that can only be addressed by further observations with HST.

We propose a sharply focused set of Hubble observations to capture unique information on the transition from SN 1987A to the remnant SNR 1987A. The data will address scientific questions we recognize today and establish the baseline to interpret major events that we foresee happening during the next several years. These observations are also needed to realize the full scientific benefits of major observing programs on other telescopes, especially *Chandra* and *Spitzer*, but also from the ground at optical and radio wavelengths. While this proposal is **not** precisely a "Coordinated" one as described in the Call for Proposals, it is the result of a wide-ranging and inclusive collaboration that aims to have experienced users make the essential observations at each wavelength and to combine them when that is useful.

Only HST allows us to observe the individual hotspots where the SN blast wave is encountering 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 has the spatial resolution to separate these components: HST is essential to understanding SN 1987A. Combining HST with other tools, as we have done, enriches the interpretation of the ground-based data and of observations made at X-ray, IR wavelengths, and radio wavelengths.

The Hotspots: The hotspots are apparently inward protrusions of the inner circumstellar ring that are just now being hit by the supernova blast wave (See Figure 3). The ring is, most likely, composed of gas from a wind that the star exhaled as a red supergiant, later swept up by the wind it blew as a blue supergiant. The explosion of Sanduleak -69 202 photoionized this ring and now, 19 years later, a mechanical collision is heating that ring again. Optical emission from the hotspots arises from shocked, relatively dense gas in these protrusions that has cooled and collapsed to high density. The hotspots remain unresolved with HST, and there are many unanswered questions that Cycle 15 observations can help to answer.

What are the morphologies of the hotspots? How did they get that way? Though the hotspots are unresolved, the long time that elapsed between the onset of the first hotspots (1997) and the merging of the spots into a continuous ring (which has not yet happened) suggests they are quite long compared to their cross-sections. They are also regularly distributed in azimuth, which suggests some underlying physical mechanism for their formation that has a characteristic length scale. Presumably this is related to an instability in the wind-driven formation of the inner ring, but no model has 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, so we see gas that has been struck by 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. Members of our team continue to obtain high-resolution spectra of SN 1987A with VLT, Gemini South, and Magellan. These spectra provide critical information on physical conditions in the hotspots. But to interpret these spectra correctly, we need a spatial model that can only be provided by HST optical, HST infrared images and grism spectra.

What is the distribution of gas beyond the hotspots? The creation of the three circumstellar rings remains a mystery (See Figure 2). Optical emission from the stationary rings comes from a thin ionized inner skin, but there is almost certainly much more mass present in cool, neutral gas that has been undetectable up to the present (except in limited dust echo detections). Rapidly increasing EUV and X-ray radiation from the hotspots provides a new source of ionizing radiation that will light this up. We hope our imaging observations will provide clues to the material outside the dense ring that will help clarify the origin of the triple-ring system. We request one deep visit to search for outlying gas newly photoionized by the hot spots.

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 19 years ago in the explosion itself (See Figures 3 and 5).

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. Since emission in the center of the debris is heated by ^{44}Ti that was manufactured deep inside the star immediately after the explosion, 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 measurements in 1987 is now plain to see: the explosion was not symmetric. The observed ^{44}Ti distribution provides a powerful constraint on explosion models. Large dust particles formed after the first year of SN 1987A's expansion: we hope to identify the role of dust obscuration by monitoring the time evolution of its thinning out and possibly by limits on thermal IR emission from dust with ground-based and Spitzer observations.

What type of compact remnant is left behind? Our Cycle 15 images will place ever-more stringent limits on the elusive compact object that must be lurking in the debris of SN 1987A. The present limits, set in our paper by Graves et al. (2005), can be improved. First, as the surface brightness of the expanding debris declines, discrimination of a point source becomes more effective. Second, as time passes, the optical depth of the large dust particles that formed around day 600 will decline 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 15 should set the very best limit yet, or perhaps reveal signs of a compact source. *Spitzer* observations at longer wavelengths are very sensitive, but do not have the resolution to distinguish a point source from extended sources at the subarcsecond scale of the structure in SN 1987A.

Other Observations by SAINTS Members

The SAINTS collaboration is engaged in a broad range of supernova studies that make 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 part of the Australian team monitoring the radio emission from SN 1987A (See Figure 5). Crotts, Suntzeff, and collaborators continue to monitor SN 1987A with the CTIO echelle. Suntzeff and Bouchet are following SN 1987A with Gemini-S TReCS mid-IR imaging; the results show emission from a resolved inner ring (See Figure 5). Sonneborn and Lundqvist are studying SN 1987A using *FUSE*. *Spitzer* observations of SN 1987A are being carried out by Dwek, Arendt, and other members of the SAINTS team. 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 (on a cadence of roughly 6 months), that show rapidly brightening X-ray emission correlated with the optical hotspots. 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}. 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 Chandra data if we make the plausible assumption that the actual sources of X-ray emission are at the optical hotspots observed with HST.

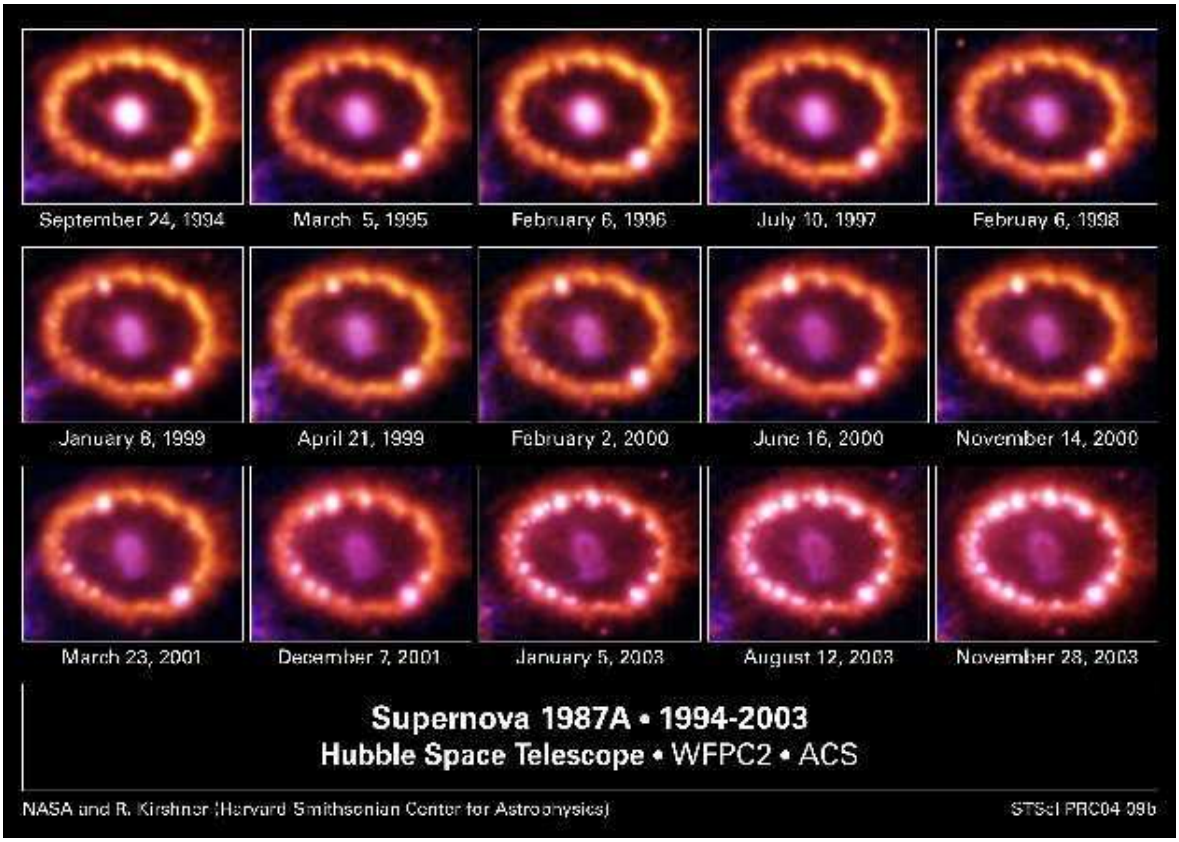
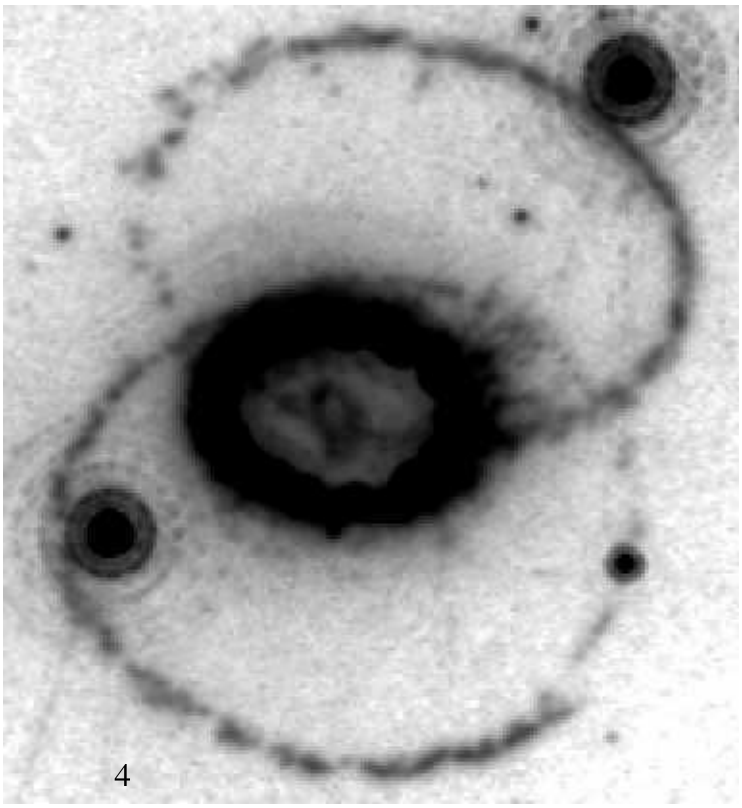


Figure 1: The HST legacy of SN 1987A. A mosaic of images constructed from WFPC2 and ACS HRC images over ten years. Note the rapid, ongoing evolution in the central ejecta and the hot spots lining the equatorial ring.

Figure 2: HST/ACS/F658N image showing the 3 ring system with 1.5 orbits of exposure. In cycle 15, we are proposing for additional exposure time to search for neutral gas being ionized by the hotspots.



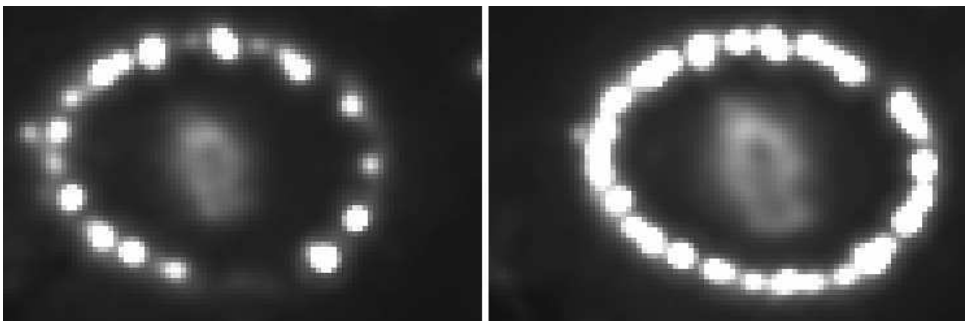


Figure 3: HST/ACS observations will continue to show the mushrooming of the collision hotspots. The almost equally spaced hotspots have doubled in number since 2003, but have not joined together or grown in size. The hotspots have not yet photoionized the nearby regions in the circumstellar ring. Further observations with ACS and NICMOS will continue the characterization of morphology and density distribution of these inward protrusions of gas.

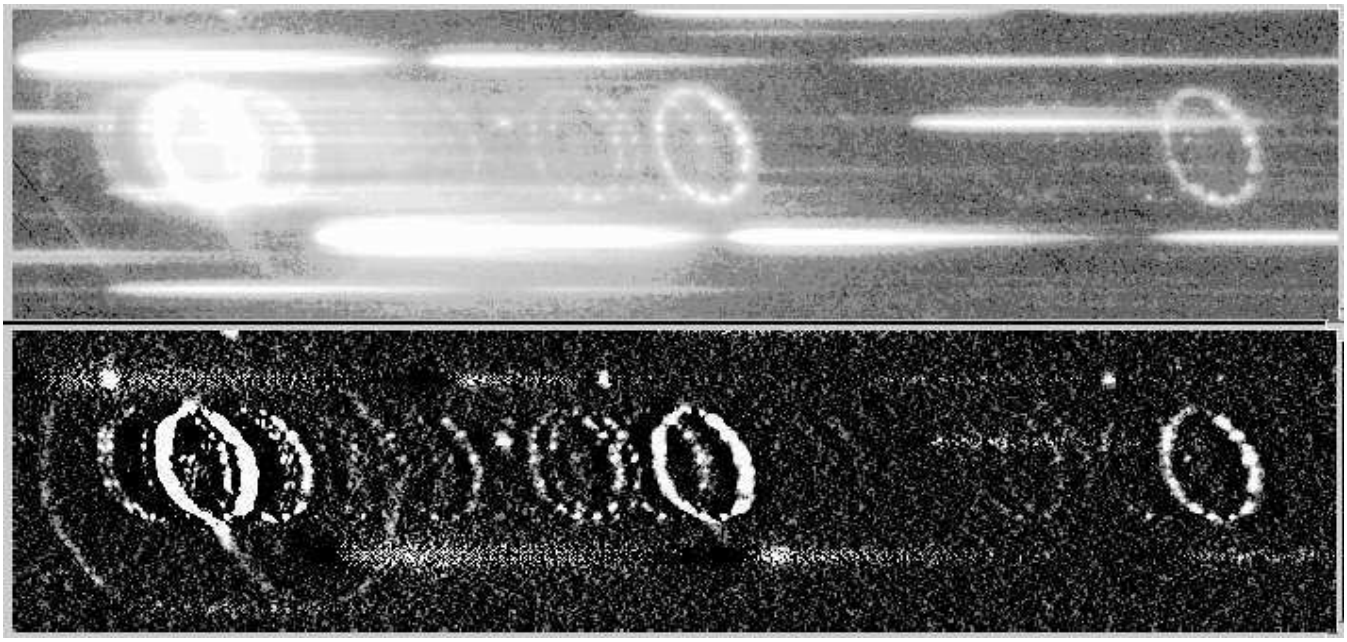


Figure 4: HRC/G800L observations from cycle 14 showing the complete 1st , 2nd and partial 3rd orders. The top panel is the sum of the dithered exposures; the bottom panel is the result of a preliminary continuum-subtraction, with further refi nements expected. The HRC/G800L records the spectra of the hotspots in the 0th through 4th orders, with detectable emission spanning [N II] 5755 through [Fe II] 9417. The fourth order images (not shown) appear to have suffi cient spectral resolution to allow de-blending of H-alpha from [N II] 6548,6583. Observations spaced by six months with 180 degree reversed orientations will eliminate most spatial-spectral overlap. Difference imaging from earlier epochs will allow us to monitor flux changes in individual emission lines in each distinct hot spot; this is not possible with broadband HRC images or with seeing-limited ground-based spectra.

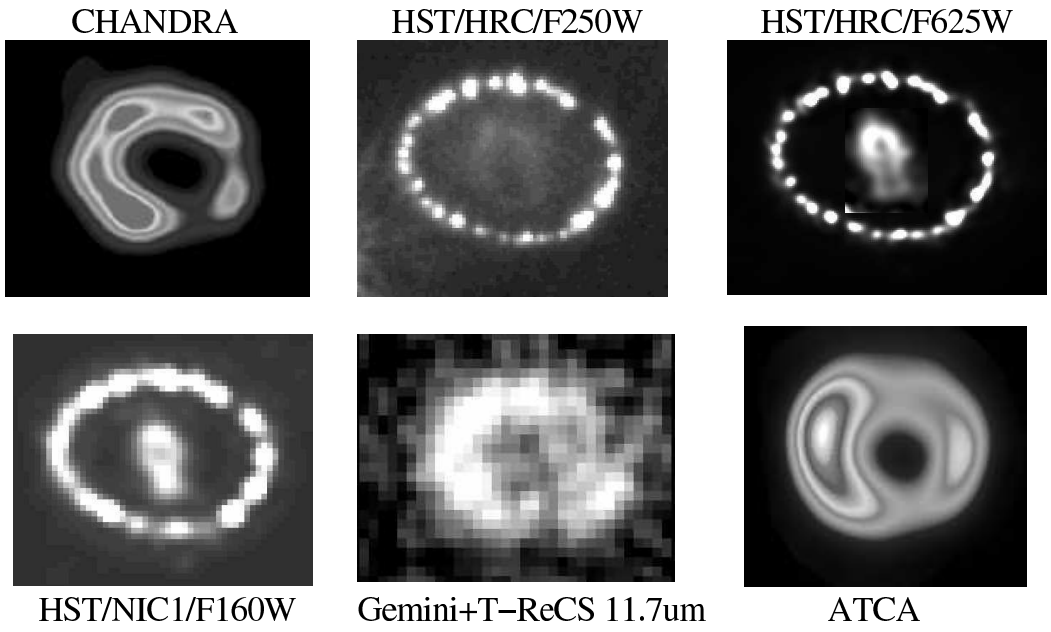


Figure 5: Multiwavelength observations produced by SAINTS collaborators. From upper left to lower right, the panels show recent X-ray (2004), near-UV (Cycle 14), optical (Cycle 14), near-IR (Cycle 14), mid-IR (2005) and radio images (2003) of the inner ring and central debris.

Description of the Observations

SN 1987A

Our ACS/HRC imaging program provides continuing information on the debris luminosity and expansion, eruption of new hotspots, and recombination of the rings, all at the highest available spatial resolution. Observations in a basic set of filters (F250W, F330W, F435W, F555W, F625W, F814W, F658N, F660N, and F502N) will connect with our earlier observations at similar signal-to-noise ratio (S/N). We have good knowledge of the exposure times needed to obtain these data. Based on our experience in Cycle 14, with 7 orbits we obtain $S/N \approx 5$–20 in the debris and 5–100 in the hotspots. In previous cycles, we were able to take advantage of the CVZ and use fewer orbits to obtain the observations. In Cycle 15, with the 2-gyro mode and possible shorter orbits, we are requesting a time allocation that is adequate to match the data from previous cycles. Since the ACS/HRC G800L grism spectra described below will pose some complications in extracting the emission-line strengths of some lines, we would like to use narrow-band images through both F658N and F660N to help extract the strengths of Hα and [N II] individually. We request 4 additional orbits to obtain a deep H-α image to make a sensitive search for brightening of as-yet unseen structures connected to the ring. We expect that the rapidly increasing X-ray and EUV flux will photoionize any gas in the vicinity and reveal its presence. The reconnaissance for eruption of new hotspots should be done again late in Cycle 15, which takes 3 additional orbits.

The ACS/HRC/G800L grism observations require 3 orbits per visit and are effective in providing spatially-resolved spectra of the individual hot spots in the 5500–9800 Åspectral range. Each orbit will consist of a set of dithered exposures with different roll orientations to help remove the complex background; we have had some preliminary success so far (See Figure 4). A second visit after a six-month delay will provide a 180-degree-reversed orientation that will remove most of the spatial-spectral confusion. These Cycle 15 grism spectra will provide a direct comparison

to the Cycle 14 data and our earlier STIS G750L spectra, in order to monitor the rapidly changing line fluxes in individual hot spots.

NICMOS observations for Cycle 15 would include F110W, F160W, F205W, F108N, F164N, F187N, and F212N, requiring 5 orbits and will yield a $S/N \approx of5$-20 in the debris and 20-100 in the hotspots. Observations in these filters were carried out in Cycles 7, 8 and 14. 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 the VLT, CTIO and the Australian radio facilities with new workers who have exploited the capabilities of *Sptizer*. 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 in the past and to assure that the multi-wavelength observations are done with an effective, well-coordinated strategy. 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 in flux, size, and spectrum. 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 of these observations 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, as SINS did, 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), and Ben Sugerman (Columbia). 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 based on HST observations of SN 1987A are listed here:

Wang, L., et al. 2002, ApJ, 579, 671. "The Axisymmetric Ejecta of Supernova 1987A." (Discusses in detail the asymmetric expanding ejecta of SN 1987A, and presents a novel model.)

Sugerman, B. E. K., Lawrence, S., Crotts, A. P. S., Bouchet, P., & Heathcote, S. R. 2002, ApJ, 572, 209. "Evolution and Geometry of Hot Spots in Supernova Remnant 1987A." (Discusses a long series of *HST* images showing the hot spots brightening as the SN ejecta collide with the ring.)

Romaniello, M., Panagia, N., Scuderi, S., & Kirshner, R. P. 2002, AJ, 123, 915. "Accurate Stellar Population Studies from Multiband Photometric Observations." (Discusses the environment of SN 1987A and other nearby SNe, as determined from images of the SNe themselves.)

Fransson, C. & Kozma, C. 2002, "Radioactivities and Nucleosynthesis in SN 1987A,"New Astronomy Reviews, 46, 487. (Analyzes evidence from the debris and its light curve for nucleosynthesis in the explosion.)

McCray, R. 2003, "Supernova 1987A" in *Supernovae and Gamma-Ray Bursters*, ed. K. W. Weiler (Berlin: Springer-Verlag), 219. (Reviews entire story of SN 1987A, including SAINTS observations.)

McCray, R. 2004, "Supernova 1987A: the Birth of a Supernova Remnant" in *Cosmic Explosions,* ed. J. M. Marcaide and K. W. Weiler (Heidelberg: Springer-Verlag), 77. (Reviews impact of debris with circumstellar rings, especially in light of HST and *Chandra* observations.)

Michael, E., McCray, R., and the SAINTS team. 2003, "HST Observations of High-Velocity Lyα and Hα from Supernova Remnant 1987A - The Structure and Development of the Reverse Shock," ApJ, 593, 809. (The study of the reverse shock in the Supernova Remnant 1987 by means of SINS HST spectroscopy.)

Romaniello, M., Robberto, M., & Panagia, N. 2004, "Low Mass Pre-Main Sequence Stars in the Large Magellanic Cloud — III: Accretion Rates from HST-WFPC2 Observations," ApJ, 608, 220 (also astro-ph/0402459). (A study of the mass accretion on PMS stars in the field of SN 1987A, based on SINS HST imaging.)

Panagia, N. 2005, "SN 1987A: The Unusual Explosion of a Normal Type II Supernova," in *1604–2004: Supernovae as Cosmological Lighthouses,* ed. M. Turatto, W. Shea, S. Benetti, & L. Zampieri (San Francisco: ASP), in press (see also astro-ph/0410275). (A review of SN 1987A including the SINS results.)

Graves, J. M. G., and the SAINTS team. 2005, "Limits from the Hubble Space Telescope on a Point Source in SN 1987A," ApJ, 629, 944. (Integrates the continuum emission in the spectrum of SN 1987A and uses SAINTS images to derive an upper limit to the flux from an embedded pulsar, or accretion on to a black hole or neutron star.)

Pun, C.-S. J., and the SAINTS team. 2006, "Hubble Space Telescope Observations of the Expansion and Shape of the SN 1987A Debris," ApJ, to be submitted. (Presents a quantitative analysis of the expanding debris of SN 1987A, showing substantial asymmetry.)

Heng, K., McCray R., and the SAINTS team "Evolution of the Reverse Shock Emission from SNR1987A" manuscript in preparation (uses overlapping STIS images to monitor Lyman α flux changes in the reverse shock.)

Sugerman, B. E. K., Crotts, A. P. S., Kunkel, W. E., Heathcote, S. R., Lawrence, S. S. 2005, Astrophys. J., 627, 888-903, "A New View of the Circumstellar Environment of SN 1987A," (Uses SAINTS WFPC2 data to observe light echoes from SN 1987A between 1994-1997 and rule out their presence thereafter.)