Startlingly fast evolution of the Stingray Nebula

Abstract
The Stingray Nebula provides the unique opportunity to watch the ionization of a planetary nebula, a helium shell flash, and the evolution of the central star. Importantly, before 1980 the Stingray's spectrum was characteristic of a B1I star, then in 1990 the Stingray's spectrum was dominated by bright emission lines characteristic of a young planetary nebula, indicating the fast evolution of this system. Despite its fast evolution, the Stingray has not been imaged for 15 years. We propose to use 2 orbits of HST, using WFC3, to define the evolution of this planetary nebula and its central star. These observation will address three science goals: First, measure the differential expansion of the shell from 1992 to present. Second, detect brightening from the the fast wind of the 1980s ionization event impacting the inside of the planetary nebula shell. Third, define the motion of the central star through the HR diagram to provide quantitative measures for comparison to theory. This program cannot be done from ground-based observatories since it requires HST's angular resolution to detect expansion, and resolve the central star from the surrounding nebula.
Investigators:

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<tr>
<td>PI&amp;</td>
<td>Z Edwards</td>
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Number of investigators: 5
# US Admin CoI: B Schaefer
& Phase I contacts: 1

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Total prime orbits: 2

Z Edwards: Startlingly fast evolution of the Stingray Nebula
Scientific Justification

The ‘Stingray Nebula’ (V839 Ara, SAO 244567, CD -59° 6479, Hen 3-1357, and PK 331-12.1) is a unique case where an ordinary post asymptotic giant branch (post-AGB) star suddenly changed to appear as a young planetary nebula (PN) in the 1980s. The Stingray represents our one opportunity to actually watch the ionization of a PN and a helium shell flash.

Before 1980, all spectra showed either very weak Balmer emission lines or no emission lines. During this time, the spectrum was that of a normal B0 or B1 star (Parthasarathy et al. 1995), placed into luminosity class I or II, with possible weak Balmer emission lines. The star slowly began to attract attention, first for having just some Hα emission (Henize 1976), then as an IRAS far-infrared source selected out as a proto-planetary nebula (Volk & Kwok 1989; Parthasarathy & Pottasch 1989). By 1990 and 1992, the Stingray optical spectrum was dominated by very bright and narrow [O III] emission lines, plus other lines that are those of a young PN (Parthasarathy et al. 1993; 1995). IUE observed the velocity of the fast wind during the 1980s event to be 1800 km s\(^{-1}\) or larger as based on the P Cygni profiles, with a mass loss rate of \(\sim 3 \times 10^{-8} \, M_\odot/\text{year}\) (Feilbelman 1995; Reindl et al. 2014). The stark difference between the 1971 spectrum (a B1I star with weak emission only) and the 1990 spectrum (very bright PN emission lines) shows that the Stingray is evolving fast and apparently the PN just turned on due to a large increase in ionizing flux starting in 1980.

A very small PN shell was resolved in 1992 by the Hubble Space Telescope (HST) to be bipolar shaped with an embedded ‘equatorial ring’ (see Figure 1), with an inclination of 56° (Bobrowsky 1994; Bobrowsky et al. 1998). The central star was resolved from the nebula in March 1996 with HST, and was reported with V=15.4, as deduced from the flux measured in the continuum filter centered at 6193Å (Bobrowsky et al. 1998). As seen from our light curve (Figure 2), starting in 1980 the central star faded at a rate of 0.20 mag/year extending till at least 1996. Reindl et al. (2014) present an analysis in which they derived a kinematic age of the observed PN shell to be 1013 \(+488\)\(^{-793}\) years, given an angular radius of 1.15 arc-seconds, a derived spectroscopic distance of 1.6 \(+0.8\)\(^{-1.2}\) kpc, and an expansion velocity of 8.4 km s\(^{-1}\) (based on the [O III] 5007Å line width). This shows that the observed PN shell is many centuries old and was ejected long before the 1980s ionization event.

We propose to obtain second epoch images of the Stingray, using the 1992, 1996, and 2000 HST images as first epochs. The first goal of these observations is to measure the expansion and the expansion age of the visible PN shell between the pairs of first and second epoch images. The second goal is to observe the brightening caused by the fast moving wind from the 1980s ionization event impacting the visible PN shell, as recognized by comparing the first and second epoch images. The third goal is to measure the current BVr magnitudes of the central star to define its evolution through the HR diagram over the last 15 years. No one has resolved the central star since the HST image in 2000, so no one has seen the start of the collision (between the fast wind from the 1980s and the pre-existing visible PN shell) lighting up the nebula. Further, the magnitude of the central star might be around 19 by extrapolation of the 1980-1996 light curve (see Figure 2), or might be around 15 if
there has been no change since 1996, while the expected evolution should have the central star brightening sometime after 1996.

We expect the visible PN shell is expanding at a rate of 8.4 km s\(^{-1}\) (based on the [O III] emission line width). This means the expected expansion rate is 1.1 milli-arc-seconds per year, or 25 milli-arc-seconds in 23 years (for the longest possible baseline, 1992-2015). Palen et al. (2002) measured expansions with HST for four very small PN (with a baseline of 4 years between epochs). For their PN sample, they were able to measure the expansion of the shell with 1-\(\sigma\) accuracy of 2-4 milli-arc-seconds (4%-8% of an HST pixel). For 7 image pairs, up to a 23 year baseline, we expect our 1\(\sigma\) error in the expansion to be 0.05 milli-arc-seconds per year, which corresponds to 1.1 milli-arc-second expansion over the full 23 year baseline. This will provide us with a \(\sim\)5\% accuracy in the expansion age of the visible PN shell.

Fast winds are expected to be present in PN (Perinotto et al. 2004), indeed the P Cygni profile for the Stingray nebula shows the velocity of this wind to be at least 1800 km s\(^{-1}\). The measured mass loss rate in 1988 was \(3 \times 10^{-8}\) M\(_{\odot}\)/year, which tapered off to \(\sim 10^{-10}\) M\(_{\odot}\)/year in 1996 (with no measurements of the mass loss rate in 1980-1988). Therefore, the total mass of the 1980 wind is on the order of \(10^{-8}\)-\(10^{-7}\) M\(_{\odot}\). This is comparable to the mass ejected in a Recurrent Nova (RN) shell where we do see fast ejecta impact slower material, causing the shocked material to radiate in [N II], H\(_{\alpha}\), [He II] and [O III] (for example, T Pyx). With similar situations from T Pyx (Shara et al. 1997) as well as SN1987A (Gröningsson et al. 2008), we expect to see the Stingray brightening in Balmer emission lines plus [N II] and [O III] as the 1980s wind impacts the pre-existing shell. For a distance of 1.6 kpc and a velocity of 1800 km s\(^{-1}\), we expect the undecellerated wind to reach 1 arc-second in 15 years (1985-2000), but no one has looked after 2000.

The current ground-based magnitudes have the central star unresolved, so all V magnitudes measured from the ground (now V=12.6) are strictly for the nebula (which is dominated by the [O III] emission lines). To obtain BVR magnitudes we need to be able to resolve the now likely-faint central star, which is tucked into the bright nebula inside a hole which is 0.2 arc-seconds at its narrowest (see Figure 1) and only HST can resolve the faint central star from the surrounding nebula. By resolving the faint central star, we will determine the temperature from the BVR colors, given that we have a well measured and small extinction (\(E_{B-V}=0.18\pm0.03\), Reindl et al. 2014). In addition, we will get the luminosity from the extinction-corrected magnitudes, plus a bolometric correction for the given temperature.

PN formation involves complex variations in the luminosity and temperature of the central star, fast stellar winds, and thermal flashes. This is seen in the evolutionary calculations of Schönberner (1983) and Blocker (1995), where the central star moves through multiple loops and turns on an HR diagram, T\(_{\text{eff}}\) versus luminosity (see Figure 3 for a typical example). The thermal pulse is represented by a loop on the HR diagram, with this also being associated with the fast wind and ionizing radiation.

We will measure the motion of the central star through the HR diagram over two segments of its evolution: First, from our measured expansion age, we will determine the time from the PN ejection to the thermal pulse in 1980. With theory predicting the time scale (c.f. Figure 3) being much longer then the apparent kinematic age of the shell. Our measured
expansion age from these observations will provide the interval on this HR diagram between the PN ejection and the first evolutionary loop. Hence, this will provide a quantitative measure which can be compared with theory. Second, we will measure the position of the central star on the HR diagram in 2015 to compare with the positions from 1996 and 2000. Comparing our new observations with the old observations, we can determine the direction and amount of motion on the HR diagram from 1996 to 2015. For the 1980 to 1996 evolution, our results show the central star to be evolving greatly faster than what theory would allow and in the wrong direction. For the 1996 to 2015 time interval, the evolution of the central star could be going in any direction. Since nobody has determined the evolution of the Stingray in the last 15 years, the fast evolution means it is imperative to get a current measure. Thus our HST observations will provide theorists with a measured position on the HR diagram for direct comparisons with models.

For our first task, measuring the expansion of the visible PN shell, only HST has the first epoch images and the required angular resolution to measure any expansion. Additionally, HST’s angular resolution will allow us to localize any collision of the 1980s fast wind impacting the pre-existing shell (with comparison being made between the first and second epoch images). Finally, only HST can resolve the likely-faint central star from the surrounding nebula which is only tenths of an arc-second away.

The Stingray has not been looked at with imaging in the last 15 years, and that is a long time for the very fast evolution of this central star. We expect to measure the expansion of the PN, the lighting up of the shell from the impact of the 1980s wind, and the possibly large change in brightness and temperature of the central star with an unknown shift in the HR diagram. Thus, we will provide the first measured segments of evolution from the PN formation and its first thermal flash, all for direct confrontation with theory.

References:
Figure 1: **The Stingray in March 1996.** This *HST* image has the [NII] emission in red, [OIII] emission in green, and Hβ emission in blue. The central star is greatly outshone by the nebula, so it is important that *HST* can resolve it inside the central nearly-blank region. We see that there are sharp features on all sides to allow for a good measure of the expansion of this shell. The fast stellar wind from the 1980s (with a total mass and velocity like in the recurrent nova T Pyx) should impact this shell soon after the year 2000, so the nebula should be lit up from this collision in 2015.
Figure 2: **B-band light curve of the central star of the Stingray Nebula.** The Harvard plates show a steady and significant decline from 1889 to 1980, followed by a sudden fast fading from 1980 to 1989 (due to the lack of emission lines in early spectra, this light is solely from the photosphere of the central star). After 1980, the B magnitude starts fading fast, with an apparent rate of 0.20 mag/year. This observed evolution from 1889-1980 and 1980-1996 are both greatly faster than possible with current theory (c.f., Figure 3). This very-fast evolution is likely caused by the observed decrease in the size of the central star. In 1996, HST resolved the central star from the surrounding nebulosity, while the B-band flux was taken from a spectrum without any emission contribution, so this magnitude is also of the central star alone. If this 1980-1996 trend continues, the central star should be $V\sim19$ for our images in 2015. However, current evolution models (e.g., see Figure 3) do not allow for a drop by 4 magnitudes, so the luminosity and brightness really should be starting to *increase*, with a magnitude in 2015 perhaps being much brighter than $V=14$. No one has resolved the central star since 2000, so our proposed magnitudes in 2015 will measure the startling and fast evolution over the last 15 years.
Description of the Observations

We propose to take WFC3 images of the Stingray to answer three main science questions: First, we will measure the differential expansion of the shell from 1992 to present. Second, we will detect the collision of the fast stellar wind from the 1980s with the PN shell. Third, we will define the current position of the central star on the HR diagram so as to follow its fast and startling evolution. All three goals can be accomplished with just two HST orbits of imaging with WFC3-UVIS. We will take short and long exposures (60 and 600 sec) through narrow band filters F502N ([O III]), F487N (Hβ), and F658N ([N II]). We will also take short and long exposures through the F438W (B), F555W (V), and F625W (SDSS r′) filters.

To accomplish the first two science goals, we will use our narrow band images in 2015 as second epoch images, for direct comparison with first epoch HST images variously from 1992, 1996, and 2000. Our analysis is to make a direct comparison to measure the expansion and to difference the images to seek the collisional brightening. Within two HST orbits, we have time for three narrow-band filters, and these must be F502N ([O III]), F487N (Hβ), and F658N ([N II]). These three filters have the highest S/N in the nebula, and they have the most first epoch images. (The 1992 data set has both [O III] and Hβ, the 1996 set has all three, while the 2000 images include [O III] and [N II].) The three sets of old first epoch images will provide multiple time baselines of 23 years, 19 years, and 15 years.

The exposures are both short and long (60 and 600 seconds) so as to nearly match the exposures from the first epoch images. Indeed, these first epoch images provide the proof that our exposure times will produce good S/N and not be saturated in the nebula.

By what accuracy can we measure the change in the shell radius? For this, there is a lot of experience in using HST for measuring the expansion of PN. For four small PN at nearly the same distance as the Stingray, Palen et al. (2002) used ~300 second exposures with WFC2 PC1 (0.046” pixels) and a 4 year baseline, being easily able to measure the expansion.
for typical PN velocities of 7-15 km s$^{-1}$ by means of two methods. One method involved calculating gradients in the difference image, while a second method involves magnifying the first epoch image by some small factor and calculating the minimal differences to the second epoch image. Their typical one-sigma uncertainties in the total change of the radius over their whole time interval are 2 and 4 milli-arc-seconds for their two methods. So this is proof that these methods on closely-similar data can measure the change of radius to 4% to 8% of the pixel size. So for our proposed WFC3 images plus the earlier WFPC and WFPC2 images, we should be able to measure radius changes of 2 and 4 milli-arc-seconds, variously over 23, 19, and 15 year baselines. (The 1992 images have the original HST spherical aberration, but the extended wings in the PSF will only somewhat degrade the quality of the correlation.) We will have 2, 3, and 2 image pairs with baselines of 23, 19, and 15 years respectively. Detailed propagation of the expected errors for our 7 first/second epoch image pairs gives an expected one-sigma uncertainty in the angular expansion rate of 0.05 milli-arc-second per year. For the Stingray at a distance of 1.6 kpc and for an expansion velocity of 8.4 km s$^{-1}$, the shell should be expanding at a rate of 1.1 milli-arc-second per year, or 25 milli-arc-seconds between 1992 and 2015. Thus, we should have a highly significant measure of the expansion, with an approximately 5% uncertainty in the expansion age.

The magnitude of the central star has not been measured for 15 years, and there is large uncertainty as to what is expected. (Note, ground-based imaging, such as our recent DECam images and those with ASAS, all show the nebula unresolved with the much fainter central star, so these total magnitudes are only measures of the emission line brightness of the shell.) For 2015, we would not be surprised by any V magnitude from 13 to 20 for the central star alone. With the WFC3-UVIS ETC, a 60 second integration with F555W will give S/N=100 when the central star is at V=20. Similarly, the F438W exposure should be 120 seconds to get S/N=100, while the F625W exposure should be 90 seconds. If the central star is much brighter, then we must have much shorter integrations to avoid saturation. For a V=13 central star, the saturation limits are 5.4, 2.7, and 4.3 seconds for B, V, and r respectively. So we will ask for a second exposure of 1 second in each of the BVr filters.

How much HST time will be needed for these observations? At the declination of the Stingray, we get 58 minutes of usable time per orbit, with 6 minutes for guide star acquisition per orbit. For each filter/exposure, we will have CR-SPLIT for an overhead of 4.7 minutes. For each filter, we will have two images, long and short, for an overhead of 9.4 minutes for each filter. With six filters, for two orbits, our total overhead is $2 \times 6 + 6 \times 9.4 = 68.4$ minutes. With the exposures given above, the total exposure time is 37.6 minutes. This makes for a total time needed of 106 minutes, and this nearly fills two HST orbits.

### Special Requirements

There are no special requirements for this proposal.

### Coordinated Observations

Not Applicable
Justify Duplications

_HST_ images in 2015 will serve as a second epoch to measure the expansion rate of the ‘Stingray Nebula’, with the first epoch given by the 1992 WFPC images, the 1996 Bobrowsky et al. (1998) images, and the WFC2 2000 archival images, which will provide baselines of 23, 19, and 15 years respectively. The WFC2 images in the year 2000 (HST Proposal 8390) do not constitute a duplication for our proposed effort to measure the expansion of the planetary nebula, because the 1992-2000 baseline is just too short to provide a measure of the expansion.

In Cycle 22, there was a UV spectroscopic program for the ‘Stingray Nebula’ (GO 13708, “Following the rapid evolution of the central star of the Stingray Nebula in real time”). Any images obtained from this program would be acquisition images only, and will not be adequate for measuring the expansion of the PN since the shell will be under-exposed. Similarly, the archival STIS data taken in 1998, 1999, & 2001 as well as the 1997 FOS data, cannot be used to measure the expansion. The Cycle 22 observations of the Stingray are all with UV spectroscopy, so they will not be able to provide BVr magnitudes the are required to extend that light curve to present day.

Past HST Usage

The primary investigator of this proposal has no accepted HST programs in the last four cycles.