PHOTOMETRY OF THE STINGRAY NEBULA (V839 ARA) FROM 1889 TO 2015 ACROSS THE IONIZATION OF ITS PLANETARY NEBULA

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ABSTRACT

Up until around 1980, the Stingray was an ordinary B1 post-AGB star, but then it suddenly sprouted bright emission lines like in a planetary nebula (PN), and soon after this the Hubble Space Telescope (HST) discovered a small PN around the star, so apparently we have caught a star in the act of ionizing a PN. We report here on a well-sampled light curve from 1889 to 2015, with unique coverage of the entire duration of the PN formation plus three decades of its aftermath. Surprisingly, the star anticipated the 1980s ionization event by declining from \( B = 10.30 \) in 1889 to \( B = 10.76 \) in 1980. Starting in 1980, the central star faded fast, at a rate of 0.20 mag year\(^{-1}\), reaching \( B = 14.64 \) in 1996. This fast fading is apparently caused by the central star shrinking in size. From 1994 to 2015, the \( V \)-band light curve is almost entirely from the flux of two bright [O \( \text{iii} \)] emission lines from the unresolved nebula, and it shows a consistent decline at a rate of 0.090 mag year\(^{-1}\). This steady fading (also seen in the radio and infrared) has a timescale equal to that expected for ordinary recombination within the nebula, immediately after a short-duration ionizing event in the 1980s. We are providing the first direct measure of the rapidly changing luminosity of the central star on both sides of a presumed thermal pulse in 1980, with this providing a strong and critical set of constraints, and these are found to sharply disagree with theoretical models of PN evolution.

Key words: planetary nebulae: general – planetary nebulae: individual (Stingray Nebula) – stars: AGB and post-AGB – stars: individual (V839 Ara)

Supporting material: machine-readable table

1. BACKGROUND

The “Stingray Nebula” (V839 Ara, SAO 244567, CD \( -59^\circ 6479, \) CPD \( -59^\circ 6926, \) Hen 3-1357, and PN G331-12.1) is a unique case where an ordinary post asymptotic giant branch (post-AGB) star suddenly changed its appearance to that of a young planetary nebula (PN). This ejection of the PN shell was roughly one millennium ago, but the nebula turned on suddenly around 1980 with some sharp increase in ionizing radiation. The Stingray represents our one opportunity to actually watch the turn-on of a PN.

Before 1980, five spectra of the Stingray have been published, all showing either very weak Balmer emission lines or no emission lines (see the timeline in Table 1). During this time, as best seen in the 1971 spectrum (Parthasarathy et al. 1995), the spectrum was that of a normal B0 or B1 star, placed into luminosity class I or II, with possible weak emission at H\( \beta \) only. The star slowly began to attract attention, first for having just some H\( \alpha \) emission (Henize 1976), then as an IRAS far-infrared source selected out as a proto-PN (Parthasarathy & Pottasch 1989; Volk & Kwok 1989), then as a star that had a sudden appearance of a PN shell within the previous few years (Parthasarathy et al. 1993). By 1990 and 1992, the Stingray spectral window was dominated by very bright and narrow [O \( \text{iii} \)] emission lines, plus other lines that are characteristic of a young PN (Parthasarathy et al. 1993, 1995). The stark difference between the 1971 spectrum (a B1I star with weak emission only) and the 1990 spectrum (very bright PN emission lines) impresses that the Stingray is evolving fast and apparently the PN has just turned-on.

From the start of the 1980s event with the fast turn-on of the PN spectrum, the Stingray has been fast evolving (see Table 1). At the start, a B0 spectrum gives a surface temperature of around 30,000 K. From the time of the first International Ultraviolet Explorer (IUE) spectrum, the effective temperature of the star has been heating up greatly (Parthasarathy et al. 1995), going from 38,000 K in 1988 to 55,000 K in 2006 (Reindl et al. 2014). The surface gravity has increased from \( 10^{4.8} \) cm s\(^{-2} \) in 1988 to \( 10^{6.0} \) cm s\(^{-2} \) in 2006 (Reindl et al. 2014). The ultraviolet continuum brightness has fallen by a factor of three from 1988 to 1994 (Feibelman 1995; Parthasarathy et al. 1995), continued to fall by another factor of three to 1997, but then brightened by a factor of two in 2002 and 2006 (Reindl et al. 2014). We have a clear picture of a star in 1988 with a high stellar wind that rapidly tapered off, while the star shrunk in size (by a factor of four) and heated up. The shrinking and heating of the central star is what would be expected for a simple picture of a stellar core following along the evolutionary track that leads to a white dwarf.

The first distance measure to the Stingray was 5.64 kpc (Kozok 1985b), based on a presumed absolute magnitude appropriate for the star’s color, and as such this estimate has a very large real uncertainty. Fresneau et al. (2007) measure the proper motion of the Stingray, and from this derive a statistical parallax of \( 1.21 \pm 0.21 \) mas (for a distance of 830 pc and an uncertainty of 17%), while the possible deviation from their statistical model makes for a possibly large error in this distance. The best distance to the Stingray is based on the luminosity calculated from the measured temperature and surface gravity, with resulting distances of \( 1.6^{+0.5}_{-1.3} \) kpc (Reindl et al. 2014) and \( 1.8 \) kpc (Arkhipova et al. 2013). The interstellar extinction has \( E(B - V) = 0.20 \pm 0.05 \) mag (based on the 2200 Å feature in the ultraviolet) and 0.14 mag (based on the observed Balmer decrement) (Parthasarathy et al. 2014).
The expanding PN shell was resolved in 1992 by the Hubble Space Telescope (HST) to be bipolar shaped with an embedded "equatorial ring," where the largest radius was 0.8 arcsec (Bobrowsky 1994; Bobrowsky et al. 1998). The inclination of the ring is 56°. Just inside this ring, a V = 17.0 ± 0.2 mag star is a possible wide companion star, making the Stingray a binary with a separation of ~2200 AU. The presence of the companion star has been suggested to have some effect on the formation of the bipolar shape, but the very wide separation makes it hard for any such effects to be substantial. Importantly, the visible size of the PN requires an ejection many hundreds or thousands of years ago. Given an angular size of 1°15, a distance of 1.6 kpc, and an expansion velocity of 8.4 km s⁻¹ from the [O III] line width, we get the kinematic age of the main PN shell to be 1013±287 years (Reindl et al. 2014). So we have a clear picture that the PN shell was ejected about a millennium ago, but was only ionized in 1980.

The Stingray has reasonable coverage from around 1920 to the present with ground-based spectroscopic monitoring, from 1988 to 1996 with IUE spectra, and from 1992 to 2000 with HST ultraviolet spectroscopy and high-resolution imaging. But no one has reported any photometry past a few isolated magnitudes, all with large problems, spread over various magnitude systems. We realized that a full light curve was needed, and we had means for measuring full light curves all the way back to 1889, so as to cover over eight decades of time before the 1980s ionization event, the transition time of the PN turn-on, and three decades of the coasting phase after the turn-on. Nor has anyone looked for an outer shell far away from the central star such as are seen around many ordinary PNe, so we wondered whether the Stingray has any far outer shells. This paper reports on our results of the light curve of the Stingray from 1889 to 2015, plus our searches for any outer halo.

### Table 1

| Year | Reference | Event |
|------|-----------|-------|
| 15 | a distance of 1.6 kpc, and an expansion velocity of 8.4 km s⁻¹ from the [O III] line width, we get the kinematic age of the main PN shell to be 1013±287 years (Reindl et al. 2014). | Ejection of visible PN shell (assuming 8.4 km s⁻¹ velocity) |
| 1980 | Section 2.1 | Ejection of visible PN shell (assuming 8.4 km s⁻¹ velocity) |
| c. 1920 | HD catalog (Jackson & Stoy 1958) | Ejection of visible PN shell (assuming 8.4 km s⁻¹ velocity) |
| 1950 | Henize (1976) | B0 spectrum, no emission lines |
| c. 1968 | Hill et al. (1974) | B3 spectrum ("e" is from Henize) |
| 1971 | Parthasarathy et al. (1995) | B1 or B2, class I or II, only emission is very weak Hβ |
| 1979.49 | Drilling & Bergeron (1995) | O or B spectrum, no emission line |
| 1980 | Section 2.1 | B = 10.8, starts fast fade at 0.20 mag year⁻¹ |
| 1988.5 | Section 2.1 | B = 12.5, central star is fading fast |
| 1988 | Feibelman (1995) | Bright UV continuum with P Cygni profile |
| 1990, 1992 | Parthasarathy et al. (1993, 1995) | Very bright emission lines dominates optical spectrum |
| 1992–1994 | Feibelman (1995) | Bright UV emission lines with no P Cygni profile |
| 1996.3 | Section 2.5 | B = 14.64, V = 14.96 for central star alone |
| 1994–2015 | Sections 2.2, 2.3, and 2.4 | V-band (i.e., [O III] lines) fades steadily by 0.081 mag year⁻¹ |

### Table 2

| Julian Date | Year | Band | Magnitude | Sigma | Source |
|-------------|------|------|-----------|-------|--------|
| 2411191.6463 | 1889.520 | B | 10.1 | 0.10 | HCO (B 3743) |
| 2411895.7797 | 1891.448 | B | 10.5 | 0.10 | HCO (B 6263) |
| 2411896.7927 | 1891.450 | B | 10.1 | 0.10 | HCO (B 6284) |
| 2412637.6167 | 1893.479 | B | 10.5 | 0.10 | HCO (B 9644) |
| 2412637.6247 | 1893.479 | B | 10.3 | 0.10 | HCO (B 9645) |
| 2412994.6657 | 1894.456 | B | 10.5 | 0.10 | HCO (B 11416) |
| 2413055.6143 | 1894.623 | B | 10.4 | 0.10 | HCO (B 11901) |
| 2413293.8362 | 1895.275 | B | 10.5 | 0.10 | HCO (B 12968) |
| 2413826.5242 | 1896.734 | B | 10.5 | 0.10 | HCO (B 17442) |
| 2414190.5165 | 1897.730 | B | 10.6 | 0.10 | HCO (B 20488) |

(This table is available in its entirety in machine-readable form.)

1993). The measured extinction has not changed significantly from 1980 to 2011 (Reindl et al. 2014). The deduced mass for the star is variously given as <0.55 M☉ (Reindl et al. 2014) or 0.2 + 0.59 M☉ for the ionized mass plus the core mass (Bobrowsky 1994).

To get broad-band magnitudes for the Stingray, we have pulled from a wide variety of sources—the Harvard photographic plate collection from 1889 to 1989, the visual magnitude estimates of Albert Jones as archived by the American Association of Variable Star Observers (AAVSO) from 1994 to 2007, the All Sky Automated Survey (ASAS) from 2001 to 2009, the AAVSO telescopes going into the All Sky Automated Photometric All-sky Survey (APASS) from 2011 to 2015, plus our own photometry from CCD images with DECam on the Cerro Tololo 4-m Blanco telescope from 2014. In all, we have 1026 magnitudes, mainly in B and V, with good coverage from 1889 to 2015. We have added 15 mag from the literature or
derived by us from the literature, all on six nights from 1969 to 1996. All 1041 mag are presented in Table 2.

A critical realization is that the magnitudes before 1980 are all measures of the continuum of the star, while all magnitudes after roughly 1989 are essentially measures of the \([\text{O} \text{~III}]\) emission line strengths. The reason is that before this cutoff date there were no significant emission lines seen in the spectrum so the brightness is of the observed stellar continuum, whereas after that date we see the optical fluxes dominated by emission lines. So before 1980, we are measuring the brightness of the star alone, and this depends only on the effective size and temperature of the photosphere minus any extinction by dust. After 1989, the emission lines dominate, with the brightness depending on both emission line fluxes and the exact spectral sensitivity of the detector. The nebular light in the \(V\)-band is entirely dominated by just three emission lines; \([\text{O} \text{~III}]\) at 5007 Å as the brightest with 77% of the \(V\)-band detected flux, \([\text{O} \text{~III}]\) 4959 Å with 21% of the flux, and \(H\beta\) at 4861 Å as the faintest with only 2% of the flux. So Jones, \(\text{ASAS}\), and \(\text{APASS}\) are essentially reporting the brightness of the \([\text{O} \text{~III}]\) emission lines.

A further realization from this is that there will likely be systematic differences in the post-1980s magnitudes from observer to observer. For example, the exact width of the spectral sensitivity curve for Albert Jones’ eyes is somewhat different from the \(\text{ASAS} \text{ CCD/telescope/longitude}\) combination, so Jones will detect somewhat more \([\text{O} \text{~III}]\) light relative to what he detects for the nearby comparison stars as compared to the \(\text{ASAS}\) measures. These systematic observer-to-observer offset are real, and apparently at the quarter-of-a-magnitude level.

Another critical realization is that the emission line spectrum for V839 Ara makes its measured brightness respond slightly differently to atmospheric extinction than do the brightnesses of the nearby comparison stars. The reason is that V839 Ara has all of its light on the blue side of the \(V\)-band, while the ordinary comparison stars have a continuum that fairly evenly covers the entire \(V\) bandpass. Ordinary atmospheric extinction dims the blue side of the \(V\) bandpass more than the red side. Extinction from the ground changes on many timescales due to differing airmass (as the Stingray is looked at with varying zenith distances) and with ordinary changes in the atmosphere aerosol content. Thus, if atmospheric extinction increases for any reason, then the blueish emission light of V839 Ara will be dimmed somewhat more than the light from the normal comparison stars will be dimmed. All of the ground-based photometry reported here is straight differential photometry with respect to an ensemble of nearby comparison stars, so V839 Ara will appear to slightly dim in our derived \(V\) magnitude as the atmospheric extinction increases. This effect cannot be taken out with the usual color terms derived from the comparison stars for the CCD/filter/telescope combination, and indeed, an exact correction is not possible without more information on the atmosphere and spectral sensitivities than is available. So we are left with a relatively small atmospheric source of variability superposed on the real underlying light curve. From the \(\text{APASS}\) time series, we see that the effect can get up to around 0.05 mag in amplitude. For all other ground-based telescopes, we cannot recover from this atmospheric variation, so we just have to acknowledge that the measured magnitudes have a non-astrophysical variability of roughly 0.05 mag superposed. This problem arises from the nearly unique nature of the Stingray’s emission line spectrum. Importantly, this mechanism does not apply to the pre-1980s Harvard magnitudes, because the star dominated with no significant emission lines. Fortunately, for the post-1980s light curve, fast variations are impossible (because the visible light is coming from emission lines spread out over a region one light-month in size), so we can use our many magnitudes to get time-averaged variations with atmospheric effects well-averaged out.

2.1. Harvard Plates

The Harvard College Observatory has a collection of over 500,000 archival photographic plates that cover the entire sky from 1889 to 1953, plus a smaller collection from around 1969 to 1989. (The years 1953–1969 are the notorious Menzel Gap.) These plates are mostly in the \(B\) band, with limiting magnitudes typically ranging from 14 to 18 mag. Any one position will have typically from 1000 to 4000 plates for coverage. The \(\text{Digital Access to a Sky Century @ Harvard program (\text{DASCH})}\) is currently ~10% through digitizing all the Harvard plates, but it will reach the Stingray (in the constellation Ara at low galactic latitude) only some years from now.

We have constructed a light curve from 108 Harvard patrol plates, all in the \(B\) band. The plates were all from the \(B\) series as well as on patrol plates of the RB, AM, AX, and DSB series. (We could have measured many more magnitudes for such a bright star as the Stingray, but the patrol plates taken have the
complete coverage in time and already well-define the star’s variability, so adding more plates would provide little new information.) The comparison stars were chosen from nearby stars of similar magnitude, with their $B$ magnitudes taken from the APASS survey of the AAVSO. The Harvard plates formed part of the original definition of the $B$ magnitude system, and they have been measured many times to have a near-zero color term for transformations from their native system to the Johnson $B$ magnitude system. With this, we can be very confident that our resultant magnitudes are in the Johnson $B$ magnitude system.

The visual comparison of targets to the comparison stars is a long well-developed practice, now largely lost among living astronomers. Nevertheless, extensive experimentation over the last thirty years has proven that the visual estimation of magnitudes has an accuracy essentially equal to that obtained from digital scans and from iris diaphragm photometers. Importantly, an experienced eye will produce a real uncertainty from digital scans and from iris diaphragm photometers. Imprecision and low-cost, the visual estimation method is to be preferred. For an average case with a good sequence and a target well above the plate limit (as for the case of the Stingray), the real $1\sigma$ error bar is close to $\pm 0.10$ mag.

The Harvard plates light curve from 1889 to 1989 is presented in Table 2 and Figure 1. The behavior of the Stingray was startlingly unexpected. From 1889 to 1980, the star slowly faded, with significant modulation. The fading is consistent with a linear decline in magnitude, going from $B = 10.30$ in 1889 to $B = 10.76$ in 1980, for a decline at a rate of $0.0051$ mag year$^{-1}$. Superposed on this linear decline are apparent fluctuations on the decadal timescale with a total amplitude of near half a magnitude. Then, starting suddenly around 1980, the Stingray central star faded fast at least until 1989. The rate of decline was approximately $0.20$ mag year$^{-1}$.

2.2. Albert Jones

From early 1994 until the middle of 2007, Albert Jones reported 128 visual measures of the Stingray. These are all visual measures, through his 12.5-inch reflector telescope in Nelson New Zealand, made using a sequence of comparison stars that is accurate on the modern magnitude scale. Thus, his measures are closely on the Johnson $V$-magnitude system. Jones’ magnitudes were reported through the Variable Stars Section of the Royal Astronomical Society of New Zealand, and are now available in the AAVSO database.

Albert Jones has been the world’s best observer of variable stars for much of the last sixty years. (He died in 2013.) Some of his exploits include the discovery of the highly important SN 1987A, the discovery of two recurrent nova eruptions (T Pyx in 1966 and V3890 Sgr in 1990), and the discovery of two comets. In the early 1990s, Janet Mattei (then AAVSO Director) pointed him out as being the all-time best variable star observer with incredibly accurate eyes, while Daniel W. E. Green (now the Director of the Central Bureau for Astronomical Telegrams) pointed him out as being the world’s best observer of comet magnitudes. And he not only has an incredible accuracy, but he also has made over 500,000 variable star magnitude measures, nearly a factor of two times more observations than any other visual observer. The authors of this paper have used Jones’ observations in many prior studies for a wide range of stars, and we have always been deeply impressed by both his quality and quantity of observations, as well as by his characteristic of always looking at the fun, exciting, and useful variables. Results from our prior work, and from others, give Jones as having a $1\sigma$ photometric accuracy of $0.05-0.10$ mag. The reason for this recital is to point to Jones’ reliability and accuracy.

The rms scatter of the differences between successive magnitudes in the light curve is $0.21$ mag for pairs within 10 days. Jones is only measuring the [O ii] emission lines, and these cannot vary substantially on such fast timescales. (This is because the [O ii] light comes from all around the PN, with near-zero from the central star, and the nebula is about a light-month in radius.) As $0.21$ mag is the difference between two magnitudes, the $1\sigma$ uncertainty for measuring one magnitude will be $0.15$ mag. This variation is significantly larger than Jones’ photometric accuracy. So we take the excess variance to be due to the effects of variations in the atmospheric extinction, where the emission lines from V839 Ara are dimmed more than the continuum light from the comparison stars. Thus, the extinction effect is somewhat smaller than $0.15$ mag in size.

Jones’ visual light curve is plotted in Figure 2, with circles representing his measures. His light curves shows a steady decline with superposed apparently random fluctuations. His observations are reasonably fit with a linear decline, from $V = 10.71$ in 1994 to $V = 11.77$ in 2007, for a decline rate of $0.081$ mag year$^{-1}$. The rms scatter around this linear decline is $0.22$ mag.

2.3. ASAS

ASAS has been running an all-sky survey, measuring $V$ magnitudes for approximately 10 million stars on a nightly
basis (Pojmanski 2002). The telescopes all have lenses of aperture 200 millimeters and f-ratio of 2.8, forming an $8.5 \times 8.5$ field of view, while the CCD has a pixel size of 15". With 180 s integrations, the limiting magnitude is roughly $V = 14$. For observations in $V$ of the Stingray, the telescope is at Las Campanas Observatory in Chile. The publicly available light curve is from early 2001 to late 2009, and we will have 425 $V$ magnitudes.

For the reported ASAS $V$ magnitudes, we selected out only the grade $A$ and $B$ values. These magnitudes show a slow secular decline from 2001 to 2009, plus a large scatter superposed on top. Uncrowded neighboring stars of similar brightness show a good flat light curve with an rms scatter of 0.06 mag. The publicly reported magnitudes are divided into ten blocks, where each block was made with a different field center and slightly different positions for the centers of the photometry apertures. Each field center produces a scattered light curve that parallels the light curves from the other centers, yet the field centers have offsets that vary by 1.6 mag (with an rms scatter in the intercepts of 0.57 mag). The cause for this variations is that a $V = 10.73$ star is 35" from the Stingray, so small changes in the center of the photometry aperture will make for a varying contribution from the nearby star. To pull out this effect, we have constructed a model with a presumed Gaussian point-spread function (PSF) for the ASAS star profiles. For the known aperture radii, the known star positions, and the known centers for the photometry aperture, this model has only one fit parameter, the Gaussian width of the PSF. The ASAS literature gives typical values from 10" to 15" (e.g., Pojmanski 2002). We have made a chi-square fit for the reported brightness for each of the 10 field centers and the 5 aperture diameters (30", 45", 60", 75", and 90"). Our best fit is with a Gaussian sigma value of 14". With this value plus our model, we have derived the $V$ magnitude for the Stingray.

The resultant light curve still shows substantial scatter. For pairs of magnitudes taken within 10 days of each other (so that the nebular $[O III]$ light cannot vary significantly), the rms scatter of the magnitude differences is 0.31 mag. The 1σ measurement uncertainty for one magnitude is 0.22 mag. This large scatter is much larger than dictated by photon statistics. The cause for this scatter can be due to the atmospheric extinction variations (as discussed previously) as well as the circumstance of having imperfect correction for a relatively bright star just near the edge of the photometry aperture. Small variations in the PSF width and the center of the photometry aperture can make for substantial changes in the derived brightness for the Stingray, and we have no way to recover this from the publicly available data.

The ASAS light curve from 2001 to 2009 (see Figure 2) shows a steady decline, with this being highly significant despite the substantial measurement errors. This decline is consistent with a linear change in the magnitude, going from 11.41 in 2001.0 to 12.53 in 2010.0, at a rate of 0.124 mag year$^{-1}$. The rms scatter around this trend line is 0.23 mag.

Figure 2 shows us that the ASAS light curve has a similar slope from 2001 to 2009 as does Jones from 1994 to 2007, but that there is an offset by 0.2–0.4 mag in the overlap time interval. It is possible that our model of the Stingray produced a systematic underestimate of its contribution to the smallest photometry aperture. However, we think that it is more likely due to Jones and ASAS having different spectral sensitivities. That is, the photochemicals in Jones’ eye will produce a distinctly different relative sensitivity for the $[O III]$ lines (when compared to the mean sensitivity for the continuum from the comparison stars) than will the ASAS CCD-plus-filter. In this case, the observed offset is just the result of normal color terms between two different detectors, with this being exaggerated for an emission line source. In all cases, the photometric uncertainties are below the quarter-magnitude level, and we can easily see the overall behavior of the Stingray.

### 2.4. APASS

APASS is measuring the $B, V, g’, r’, i’$ and $i’$ magnitudes of all stars in the sky with approximately $10 < V < 16$, with several telescopes in both the northern and southern hemisphere. This has provided us with a reliable source of comparison stars for our differential photometry. This has also provided us with magnitudes in the five filters on two nights in 2011 (see Table 2).

At our request, A. Henden has put the Stingray in the queue for time series photometry on the 0.61-m Optical Craftsman Telescope at the Mount John Observatory in New Zealand. The 1-minute CCD integrations were through a Johnson $V$ filter on the nights of 2015 March 23, 26, and 27. The quoted magnitudes were based on differential aperture photometry with respect to 5–8 nearby comparison stars previously calibrated with APASS. On the first night, as the Stingray rose from an altitude of $31^\circ–54^\circ$, the apparent brightness of the Stingray suffered a dip in brightness by about 0.05 mag for one hour. The Stingray was constant, with an rms scatter of 0.008 mag, on the other two nights. During the time of the dip, the statistical error for the star increased from 0.012 mag up to 0.06 mag, indicating that some large atmospheric extinction had dimmed the target by much more than 0.05 mag. For the time through the dip and for all the nights, we found a tight correlation between the calculated statistical error and the differential magnitude of the target. This has the easy interpretation that ordinary changes in the atmospheric aerosols substantially dimmed both the Stingray and its comparison stars (making for large statistical errors), while the Stingray’s $[O III]$ emission lines (all on the blue side of the $V$ bandpass) were dimmed more than the continuum light from the comparison stars (making for the small dip in the differential magnitude). This effect is undoubtedly happening on all timescales to all ground-based observers, but we can see this effect only in a time series from one telescope. With this correlation, we can reduce all the APASS magnitudes to those of some constant condition with minimal aerosols. For the measures with statistical error greater than 0.020 mag, this correction could not be done with high accuracy, so we have chosen to delete these data. The result is a time series on three nights with 352 $V$-band magnitudes (see Table 2), with nightly averages of 12.62, 12.57, and 12.61.

The APASS magnitudes extends the $V$-band light curve past 2009 up until 2015 March (see Figure 2). From the APASS magnitudes alone, we see a significant decline from 2011 to 2015. This is just a smooth extension of the earlier decline. The various observers are not expected to report the same $V$ magnitudes to within a quarter of a magnitude or so, due to the emission line nature of the Stingray. Nevertheless, all observers show a consistent and highly significant steady fading from 1994 to 2015. This fading goes from $V = 10.71$ in 1994.1 to
V = 12.61 in 2015.3, for an average decline rate of 0.090 mag year$^{-1}$.

2.5. DECam on Cerro Tololo 4-m

With the Cerro Tololo 4-m Blanco Telescope, DECam CCD images were taken on 2014 June 30, the main goal being to search for any outlying faint optical shell. The large size ($9' \times 17'$) of one individual chip allows for V839 Ara, comparison stars, and for any far out shell to be contained on a single CCD (out of the 64 CCD array). Observations were made using the $u'$, $g'$, $r'$, $i'$ (which are the Sloan Digital Sky Survey, SDSS, filters) with pairs of exposure time of 20 and 90 s in each band.

Standard procedures were used in the IRAF data reduction package to extract magnitudes for V839 Ara utilizing the PHOT package. Differential photometry was performed on V839 Ara using multiple APASS comparison stars, carefully avoiding saturated stars, and only with the short exposures. These comparison stars were chosen such that they fell on the same chip as V839 Ara, have similar brightness, and not crowded by surrounding stars. Since APASS only provides information for $g'$, $r'$, and $i'$ filters, a magnitude for the $u'$ observations could not be derived. We measured the magnitudes of V839 Ara to be 12.52 ± 0.01, 12.18 ± 0.01, and 13.35 ± 0.01 for $g'$, $r'$, and $i'$ respectively. The formal statistical error bars are smaller than 0.01 mag, while various systematic sources of error are likely around the 0.05 mag level.

2.6. Additional Optical Magnitudes

Hill et al. (1974) and Kozok (1985a) report on UBV photometry on four separate nights. These magnitudes are of the central star, with any contributions from emission lines and the PN being negligibly small. These four $B$ magnitudes closely fit with the light curve from the Harvard plates.

Bobrowsky et al. (1998) used HST to resolve the central star and report $V = 15.4$ as deduced from the flux measured in a continuum filter centered at 6193 Å. This magnitude is of the central star alone (with no emission lines and no PN shell) and was made in 1996 March. Around this time, Albert Jones was reporting the Stingray to be $V = 10.8$ mag. The difference of 4.6 mag is because Jones is including the shell light, almost entirely [O III] emission lines. This shows that the two [O III] lines are contributing ~70% as much flux as the star over the entire broad V-band.

Reindl et al. (2014) report on an HST spectrum from 1996 March with the FOS. We have taken the continuum flux for the center of the $B$- and $V$-bands, and converted these into magnitudes. We get $B = 14.64$ and $V = 14.96$, with this applying to the star alone. The $V$ magnitude is 0.44 brighter with the FOS spectrum than with Bobrowsky’s continuum flux, despite there being only two days of separation in time. It is unclear if the difference arises from variability or from the ordinary uncertainties in extracting magnitudes with two different non-standard methods.

Other published magnitudes (like the estimates from the Cape Durchmusterungen and HD catalogs) have problems with their comparison stars that can be as large as one magnitude, and hence cannot be used with any useful accuracy or confidence. The presentation of the ASAS magnitudes by Arkhipova et al. (2013) has not realized any of the problems or solutions caused by the varying centers and the nearby star, so their light curve is now to be replaced by our light curve described in Section 2.3.

2.7. Infrared and Radio Brightnesses

From the 1992 PhD thesis of P. Garcia-Lario (as quoted in Parthasarathy et al. 1993) the $J$, $H$, and $K$ magnitudes were 11.37, 11.97, and 11.38. These magnitudes presumably date from around 1991. Like all the brightnesses in this subsection, these refer to the entire nebula, with near-zero contribution from the central star.

The 2MASS magnitudes were $J = 12.098 \pm 0.034$, $H = 12.248 \pm 0.048$, $K = 11.506 \pm 0.029$ (Cutri et al. 2003). The magnitudes are from 2000 May.

The IRAS fluxes were 0.65 Jy at 12 µm, 15.59 Jy at 25 µm, 8.05 Jy at 60 µm, and 3.39 Jy at 100 µm (Parthasarathy & Pottasch 1989). These observations were made from 1983 January to 1983 November. This spectral energy distribution has the obvious interpretation as thermal emission from dust in the shell, with an average temperature of 125 K (Parthasarathy & Pottasch 1989).

The Akari satellite all-sky survey gives the 9 µm flux to be 0.089 ± 0.009 Jy and the 18 µm flux to be 2.57 ± 0.05 Jy (Ishihara et al. 2010). These brightnesses come from a survey running from 2006 May until 2007 August.

The WISE all-sky survey provides magnitudes (on the Vega magnitude system) for the various WISE bands to be 11.144 ± 0.0022, 10.373 ± 0.019, 5.161 ± 0.014, 0.902 ± 0.01 for the $W1$ (3.4 µm), $W2$ (4.6 µm), $W3$ (12 µm), and $W4$ (22 µm) bands respectively. The WISE survey ran from 2010 to 2011 January.

The ATCA radio light curve, from 1991 to 2002, has the Stingray declining steadily in flux density from 63.6 ± 1.8 mJy (Parthasarathy et al. 1993) to 48.8 ± 1.5 mJy at 4800 MHz (Umana et al. 2008).

3. IMAGES

Roughly 50% of classical PNe have halos, faint roughly circular shells far outside the bright well-known nebulosity (Chu et al. 1987). For example, NGC 6720 (the famous Ring Nebula) has the obvious shell (with outer dimensions $90'' \times 65''$) surrounded by a faint shell extending $162'' \times 147''$ filled with fairly uniform mottling and arcs, with this outer halo being bright in WISE images. Corradi et al. (2003) and Chu et al. (1987) have catalogs with pictures and intensity profiles. The typical surface brightness is a thousandth that of the inner classical PN. The estimated ages for these outer shells are many tens of thousands of years as based on expansion velocities that default to 20 km s$^{-1}$ when not otherwise known. Corradi et al. (2003) call these faint shell structures outside the classic PN “AGB halos,” where the ordinary stellar wind of the star during its AGB phase has become ionized. They claim that the outer edge of the AGB halo results from the last thermal pulse in the AGB star.

It is possible that the Stingray might have an AGB halo outside its small classical PN shell. Such a shell might be too large to be visible in the HST images. So we thought it worthwhile to search for any AGB halo around the Stingray. We examined deep images from DECam, Southern Ho Sky Survey Atlas (SHASSA), 2MASS, and WISE, as reported below. We have also examined the various available images from the Digital Sky Survey and from HST, but our negative
results for any shell structure or circular arcs centered on the Stingray do not provide useful constraints. No images were taken with GALEX or Swift.

3.1. DECam Images

Our DECam images in $u'$, $g'$, $r'$, and $i'$ were examined for any nebulosity surrounding the Stingray. In our images, the classical PN is entirely in the near-saturated inner core of the normal stellar image. So we are only sensitive to any outlying outer shell. Our examination was visual, mainly because there is no way to automate or quantify a shell search when we have no idea of the size or shape. We have very long experience searching for shells or light echoes around stars, and we know that the human eye/brain combination is very sensitive to detecting shells. Indeed, for irregular shells, visual examination is greatly better at detecting any nebulosity by pushing down toward the background noise limit. With this, we detect no shell or nebulosity in any of our DECam images. The $r'$ image would record any Hα emission, while the $g'$ image would record any [O III] emission.

3.2. SHASSA Images

The SHASSA is a robotic wide-angle CCD survey in the Hα line covering declinations south of $+15^\circ$ (Gautest et al. 2001). Images have pixels that are 47.64 arcsec on a side, with a sensitivity down to about 0.5 Rayleigh. The Stingray appears prominently about 4″ from the center of their Field 38. The point spread function has an FWHM of around 1 arcmin, so all the known shell appears as a point source, and any detectable shell would have to be larger than several arcminutes in radius. The continuum-subtracted and smoothed image shows no shells, circular arcs centered near the Stingray, or any structure associated with the Stingray out to a radius of over 1″.

3.3. 2MASS Images

There are also 2MASS observations of V839 Ara in $J$, $H$, and $K$ bands taken in 2000 May. The radius of emission in each of these three bands are less than 3″. No outer shell was seen in $J$, $H$, or $K$.

3.4. WISE Images

The archival WISE images covers V839 Ara in four different bands centered on 3.3 μm (W1), 4.6 μm (W2), 12.1 μm (W3), and 22.2 μm (W4). V839 Ara is positioned near a star (identified as TYC 8739-1088-1 with $V = 10.83$) which is bright in both the W1 and W2 bands; however, it is noted that PNe are expected to show strong emissions in the far-infrared. In the W1 band, the emission is centered on the location of V839 Ara with a radius of 11″. Going further out into the infrared, the emission centered on V839 Ara extends out to a radius of 14″ in W2, 34″ in W4, and a finally a very large “halo” with a radius of 81″ in W4. It should be noted that this “halo” seen out in 22 μm is consistent with PSF rings around sources bright in the W4 band, and is not astrophysical. This can be seen in Figure 3.

4. LIGHT CURVE ANALYSIS FOR THE CENTRAL STAR

From 1889 to 1980, the Stingray’s central star exhibits a linear decline in its light curve, with substantial variability superposed. The best fit line goes from 10.30 mag in 1889 to 10.76 mag in 1980, for a total drop of 0.46 mag. This is the same as the apparent amplitude for the decade-long variations. Over this time, with no substantial emission lines providing any significant fraction of the flux, the variability can only be caused by changes in the photosphere, either by variations in the effective temperature or radius. (Changes in the dust column seem unlikely given that the stellar wind must be weak, while even large winds in the 1980s led to no change in the extinction.) From c.1920 to 1980, the spectral type remained largely unchanged, with everyone reporting spectral types from B0 to B3, so the star’s surface temperature was not changing by any large factor. For the B-band flux to change by 0.46 mag, the radius would have to change by 20%. This is a large change.

How can the Stingray star have “anticipated” the 1980s ionization event? Apparently, some prelude to the sudden event had a surface manifestation at least a century in advance. The anticipation cooling and/or shrinking of the central star could not have been going on for many centuries. At its rate of fading by near half a magnitude per century, a millennium duration would imply that the central star was five magnitudes more luminous at the start of the anticipation. Such would imply a luminosity higher than supergiants. So this anticipation fading can only have been going on from one century to a few centuries. Detailed calculations of the variations of the central star luminosity can have substantial changes in the century preceding thermal pulses (Schönberner 1983; Blocker 1995). For a 0.553 $M_\odot$ star, before a thermal pulse at 45,000 K, the luminosity will drop by a factor of 2.2 in the preceding century (Schönberner 1983). For a 0.836 $M_\odot$ star, the luminosity will drop by a factor of 6 in the century preceding a thermal pulse at 200,000 K (Blocker 1995).

Handler (2003) has defined a new class of variable stars, called the “ZZ Leporis” stars, which consist of the central stars of young PN with temperatures <50,000 K. The physical mechanism for these brightness changes is not known, but it is likely some combination of stellar pulsations and fluctuations in a stellar wind. Arkhipova et al. (2013) have already identified the central star of the Stingray as being in this ZZ Lep class. However, although the variations are fast and aperiodic in both cases, the ZZ Lep stars have greatly different
light curve properties than what we see for the Stingray. In particular, ZZ Lep stars have timescales of 4–10 hr and amplitudes <0.03 mag (Handler 2003; Handler et al. 2013). This is greatly different from the Stingray’s behavior in 1889 to 1980, which has a timescale of around one decade and amplitude 0.5 mag. From 1994 to 2009, our V-band light curve is not coming from the central star, while the central star may or may not have ZZ Lep behavior.

The fast decline for the light from the central star alone from 1980 ($B = 10.8$) to 1988.5 ($B = 12.5$) to 1996.3 ($B = 14.64$) is stark and unprecedented. This cannot be due to changing extinction, because the dimming, as measured by many methods, is essentially unchanged from 1980 to 2011 (Reindl et al. 2014). So this fast fading star can only be due to some combination of the decrease of the stellar radius and a decrease in the temperature. For the case of the Stingray, Reindl et al. (2014) show that the stellar temperature increased greatly while the star’s radius decreased greatly from 1988 to 2006. The radius and temperature changes run against each other. So it needs detailed calculation as to whether these observed changes translate into the observed magnitude changes. If we go by the usual luminosity equation, we have $L \propto R^2T_\text{eff}^4$, where $L$ is the luminosity, $R$ is the stellar radius, and $T_\text{eff}$ is the effective temperature of the photosphere. We do not have direct measurements of the radius, but the star’s surface gravity, $g$, will scale as $g \propto R^{-2}$. And we should not be using the luminosity, but rather the blackbody flux in the $B$-band, $F_{\text{BB}}$, at $\lambda = 4400\,\text{Å}$, with this being the usual Planck function of $\lambda$ and $T_\text{eff}$. We can then get a $B$ magnitude as $B = B_0 - 2.5 \log(F_{\text{BB}}/g)$, for some zero magnitude function $B_0$. Reindl et al. (2014) list measured values for $\log(g)$ and $T_\text{eff}$ for many years from 1988 to 2006. Taking $B_0 = 43.55$ so that $B = 12.5$ in 1988, we get $B = 13.1$ mag in 1996, and $B = 14.9$ in 2006. We see that in this case for a shrinking star that is getting hotter, it is the shrinking that is the dominant effect, leading to the star dropping in $B$-band brightness. However, the effect predicted from the measured $\log(g)$ and $T_\text{eff}$ is a much slower decline than is actually observed. That is, from 1988 to 1996, the prediction is that the central star will dim by 0.6 mag, while the observed dimming is by 2.14 mag. This is a large difference. This points to the central star having additional light above the photosphere in 1988 that went away by 1996, or to changing systematic errors in measures of the surface gravity (perhaps associated with the changing stellar wind rate). From this analysis, we take the basic cause for the fading of the central star to be due to the shrinking of the stellar radius, although detailed calculations do not predict the central star to be fading as much as is observed.

5. THE FADING NEBULA

The $V$-band light curve (essentially the nebula’s brightness) from 1994 to 2015 has been steadily fading at the rate of 0.090 mag year$^{-1}$. This is a highly significant result from three independent sources and has no prospect of being due to any artifact. So we have the [O III] emission line flux fading with a half-life of around eight years. From 1994 to 2015, the Stingray emission lines have faded by near 2.0 mag, a factor of near 6×. This is the nebula fading, not the central star.

The fading of the nebula is also seen for wavelengths from the near-infrared, the middle-infrared, and the radio. (1) From around 1991 to 2000.4, the Stingray faded by 0.73, 0.28, and 0.13 mag for the $J$, $H$, and $K$ bands respectively. These correspond to half-lives of 9.3, 24, and 54 years respectively. (2) We can use the IRAS, Akari, and WISE mid-IR fluxes to chart the changes in the $12\,\mu$m flux. For this, the WISE magnitude must be converted to Jansky, and the $Akari$ flux must be interpolated to $12\,\mu$m. With this, we have 12 $\mu$m fluxes of 0.65 Jy in 1983.5, 0.36 Jy in 2007.0, and 0.226 Jy in 2010.6. This shows a steady decline over 27.1 years with a half-life of 20.4 years. (3) Similarly, for 22 $\mu$m, we have fluxes of 8.96 Jy in 1983.5 and 3.20 Jy in 2010.6. The extrapolation of the Akari $18\,\mu$m flux to 22 $\mu$m is just where the spectral energy distribution is turning over, so the uncertainty is too large for this to be useful. This shows a decline in flux with a half-life of 18 years. (4) From 1991.3 to 2002.7, the ATCA radio flux at 4800 MHz (6 cm) declined from 63.6 mJy to 48.8 mJy. This corresponds to a half-life of 30 years.

We see a consistent picture for the light curves from 1994 to 2015, where the optical, near-infrared, middle-infrared, and radio fluxes have all been smoothly fading with a characteristic timescale of a decade or so. The nebula had a sudden turn-on sometime between 1979.49 and 1988, and the brightening of the nebula likely stopped in the early 1990s with the turn-off of the fast stellar wind associated with the 1980s ionization event. The fading of the nebula started after the end of the ionizing event and its fast stellar wind, in the early 1990s. At this time, the central star underwent fast fading (see Figure 1), so its illumination of the nebula started to decline fast. It is easy to ascribe the fading of the nebular light to the sharp fall off in its illumination by the central star. Even with the rise of surface temperature of the star, the fall in its surface area means that it is giving off much less ionizing radiation. With the turn-off of the illuminating source, the nebula light should start fading at some sort of a re-ionization timescale. There is precedent for this fading and this interpretation for Sakurai’s Object (V4334 Sgr, a very-late-thermal-pulse born-again star). Its emission line fluxes have also been seen to decline fairly rapidly (with a half-life just under two years) from 2001 to 2006, with the fading attributed to cooling and recombination in the shell after the heating and ionization ended (Van Hoof et al. 2007).

For the usual nebula conditions, the recombination timescale is around 80,000 years divided by the electron number density (in units of cm$^{-3}$). (The nebula will have a range of densities, each recombining and fading on their own timescale, with continual-but-fading illumination from the central star, so the connection between the average electron density and the effective recombination times and the fading rate has substantial uncertainty and change over time.) For the Stingray, Parthasarathy (2000) gives an electron density of 10,000 cm$^{-3}$, so we expect a recombination timescale of around eight years. The agreement between the half-life for the fading of the optical emission lines and the recombination timescale is an indication that the slow steady fading of the nebular light from 1994 to 2015 is caused by the ordinary recombination inside a nebula that had some sort of an ionization event between 1980 and 1994.

The middle infrared emission is dominated by thermal light from warm dust in the nebula. The dust grains are not likely to be changing in number or size, so the thermal flux can only be fading due to a cooling of the dust grains. This is all consistent with a scenario where the dust was heated during the 1980s ionization event and has been cooling ever since. The dust reaches thermal equilibrium on a fast timescale, so the fading of the middle-infrared emission is a measure of the fading of the
heating radiation field. We suggest that the dust heating is dominated by the nebular emission lines, with this being in situ, and the connection is made because the nebular lines are fading at the same rate that the dust is fading.

The radio emission is free-free light, with model derived electron densities of $(1.23–2.5) \times 10^8$ cm$^{-3}$ (Parthasarathy et al. 1993; Umana et al. 2008). Like the optical line emission, with a scenario of a short-duration ionization event in the 1980s, the radio flux should fade on some sort of a recombination timescale.

6. EVOLUTION THROUGH THE HR DIAGRAM

With the results from this paper, we can construct a detailed evolutionary path of the Stingray through the HR diagram. For seven dates, we have calculated $L$ and $T_{\text{eff}}$ for the central star (see Table 3). These can be directly plotted onto the HR diagram and compared to model predictions (see Figure 4). The first point, labeled for the year 1001 AD, is meant to illustrate the approximate position where the star ejected the PN shell, just as it was leaving the AGB phase. This is useful to show that the Stingray took only around one millennium to cross from the AGB to the thermal pulse region. The two points for 1889 and 1980 have a modest uncertainty from the distance, so they can be moved up or down in the diagram, but they must be moved up or down together. Similarly, the last four points can be moved up and down together by modest amounts as the assumed stellar mass changes from the adopted 0.55 $M_\odot$. The end result is an observed evolutionary path from when the Stingray leaves the AGB until sometime during a thermal pulse.

![Figure 4](image)

The default or common idea is that the Stingray central star has evolved off the AGB with the usual nearly horizontal path across the top of the HR diagram (e.g., Parthasarathy et al. 1993), and is now undergoing a late thermal pulse (LTP) (e.g., Reindl et al. 2014). (See the next section for possible alternatives.) Late thermal pulses are when a shell of helium, just outside the carbon–oxygen core, is ignited, with the energy from this burning making the star temporarily increase back to giant size, with the result that the star forms a loop in the HR diagram. Detailed evolutionary paths through the HR diagram depend on the stellar mass, while the thermal pulses can occur anywhere along the path (e.g., Schönberner 1983, 2006; Blocker 1995, 2001). For illustrative purposes, one such LTP evolutionary track (from Schönberner 1983) has been superposed on the Stingray’s observed evolutionary track in Figure 4. This track was chosen because it is for a stellar mass that might be similar to that of the Stingray, because the thermal pulse is at a similar temperature as for the fast evolution of the Stingray, and because the track has conveniently labeled time tick marks to allow direct comparison.

The comparison between the observed and theoretical evolutionary paths in Figure 4 shows fundamental problems. (1) The timescale for the evolution from a temperature of order 5000 K (when the PN shell was ejected) to a temperature of 50,000 K (in 1996) is observed to be around one millennium, while theory dictates a timescale more like 13 millennia to cross from roughly 5000 to 50,000 K. This discrepancy can be resolved if the star is greatly more massive than 0.55 $M_\odot$, but this then raises other difficult discrepancies. (2) The Harvard
plates show the Stingray was fading from 1889 to 1980, while the spectra from 1920 to 1979.49 show a nearly unchanging spectral type, so we have a distinct vertical segment on the HR diagram lasting about a century. From the theoretical paths, this could only match the initial turn in to a thermal pulse, like from the tick marks “13” to “13.1” in the theoretical path shown in Figure 4. But if this match is made, then the further observed spectral type, so we have a distinct vertical segment on the HR plates show the Stingray was fading from 1889 to 1980, while the simple right-to-left traverse of the HR diagram (as depicted in textbooks) cannot explain the fast and complex evolution of the Stingray's central star (see Figure 4 and Table 3). So either some additional mechanism is superposing some complex evolution, or the Stingray is not the post-AGB star that it seems. Here, we will briefly discuss three possibilities.

The first possibility of the nature of the Stingray’s evolution is that it is an ordinary post-AGB star undergoing some sort of a thermal pulse, wherein a layer near the surface of the star suddenly ignites nuclear burning, and this influx of energy will puff up the star’s outer envelope to giant proportions. Thermal pulses will make a star appear to go through loops in the HR diagram. Perhaps the Stingray is caught just at the time of a thermal pulse, already having completed part of the loop? Thermal pulses come in two types, called “late thermal pulses” (LTP) and “very late thermal pulses” (VLTP). The later starts only after hydrogen burning has become extinct, and a critical feature of distinction is that the stellar surface is virtually free of hydrogen (Schönberner 2008). The known VLTP examples are V605 Aql, Sakurai’s object (V4334 Sgr), and perhaps FG Sge (Lawlor & MacDonald 2003; Schönberner 2008). But the Stingray certainly cannot be a VLTP star because it has only evolved off the AGB by roughly a millennium (when it ejected the PN shell), and because the central star has high abundance of hydrogen (as shown by the prominent Balmer absorption lines visible before 1980). So for this solution, the Stingray would have to be an LTP star. The LTP can make the star trace out a wide variety of loops through the HR diagram (Schönberner 1983; Blocker 1995; Blocker & Schönberner 1997; Van Winckel 2003). In an extreme case (see Figure 2 of Blocker & Schönberner 1997), the star’s track has nine reversals of direction in the HR diagram. For all these published loops, none match the observed track of the Stingray, as detailed in the previous section. None of the published LTP tracks can account for the Stingray, and this is the fundamental problem. Part of this fundamental mismatch between observation and model is that the Stingray is moving in the HR diagram at much faster rates than is allowed by theory. Gesicki et al. (2014) has found similar problems in accounting for the white dwarf mass distribution, and they have had to postulate an acceleration by a factor of 3 in the evolutionary timescales of Blocker (1995). In his major review on post-AGB stars, Van Winckel (2003) says “the detailed description of the badly known external post-AGB mass loss on top of the mass loss from the nucleosynthetic consumption is crucial for the transition time estimates” for the star crossing the HR diagram in various phases. It might yet be possible for some new model
calculation to match the Stingray’s evolution, but until then, the LTP idea has a fundamental problem. The second possibility is that the Stingray is a product of a common envelope ejection of the outer envelope of a giant star. That is, in ordinary binary evolution involving a red giant star, a binary can get entangled inside a common envelope, the stars will spiral close together, and the main sequence star can eject the outer envelope of the red giant, leaving a bare stellar core. The ejected envelope will expand, and the hot red giant core will ionize the shell. Reindl et al. (2014) suggested this post-common-envelope (post-CE) state for the Stingray, with the evidence being that the apparent luminosity was consistent with the models of Hall et al. (2013). Hall et al. make a variety of predictions that can be used to distinguish the post-CE systems. (1) The luminosity of the post-CE stars will always be less than about $3.16 \times 10^3 L_\odot$ while traversing across the HR diagram from right to left. In sharp contrast, the Stingray had a luminosity of $5.4 \times 10^3 L_\odot$ in 1889. It is only after the central star has faded by an order of magnitude does the observed luminosity come into agreement with the post-CE tracks. It is possible to overcome this argument by merely having the Stingray at a closer distance, with $<1.2$ kpc being adequate and within the uncertainty for the distance. (2) The post-CE central star would be a close binary with an orbital period from a fraction of a day up to weeks. We know of no observational tests for this prediction. (3) The evolution through the post-CE phase is greatly slower than for an LTP. Hall et al. calculate that the timescale from the ejection of the shell until the central star is $30,000 K$ is around $10,000$ years, while the timescale for the small turn in the motion along the HR diagram (with the central star hotter than $30,000 K$) is $0.1$–$10$ million years. This model prediction is greatly against the observed timescales of one millennium from ejection to $30,000 \text{K}$ and decades for the Stingray to turn around in the HR diagram. The stark failure of this post-CE model prediction makes for a strong argument against the second possibility.

The third possibility is that the Stingray is not a PN at all, but is rather a “PN mimic” (see Frew & Parker 2010 for a review). This has been casually suggested by Zijlstra (2015) in just one short sentence. A PN mimic is a star with a surrounding ionized shell that does not come from the ejection of the outer envelope of an AGB star. PN mimics include Wolf–Rayet stars, “young stellar objects,” symbiotic stars, B[e] stars, Herbig–Haro objects, reflection nebulae, diffuse H ii regions, old novae, and supernova remnants. With such a wide diversity of mimics, it is difficult to absolutely reject all mimic classes for the Stingray. Nevertheless, the observed properties of the Stingray have little in common with any of the classes of mimics. In detail, Frew & Parker point out how optical emission line ratios can discriminate between a typical PN and the various types of mimics. For this, taking the line fluxes from Parthasarathy et al. (1993), for the particular lines as defined by Frew & Parker, we have $\log \left(F_{\text{H} \alpha}/F_{\text{N} \text{ii}}\right) = 1.83$, $\log \left(F_{\text{H} \alpha}/F_{\text{N} \text{ii}}\right) = 0.48$, $\log \left(F_{\text{N} \text{ii}}/F_{\text{H} \alpha}\right) = -0.59$, and $\log \left(F_{\text{O} \text{m} \text{II}}/F_{\text{H} \alpha}\right) = 0.97$. With these, we can look in their Figures 4 and 5, seeing that the Stingray is right in the middle of the PN region, and is far away from the various mimic class regions. That is, the Stingray’s emission line spectrum is a classical PN spectrum, and greatly different from the mimics. Further, many properties of the Stingray are characteristic for PNe and are not found in many classes of mimics, including the position of the central star on the HR diagram near B1 II, a classic bipolar point-symmetric shaped shell, the $\sim10 \text{km} \text{s}^{-1}$ expansion velocity of the shell, dust with a temperature of $125 \text{K}$, thermal free–free radio emission, a distance of around $340 \text{pc}$ from the galactic plane, and the lack of any nearby ISM clouds or young stars. With all these, we have strong confidence that the Stingray is not a PN mimic.

After considering all proposals for the nature of the Stingray’s evolution, we have eliminated all but one, with the remaining idea being the common idea that the Stingray is a post-AGB star traversing the upper HR diagram while undergoing some sort of a thermal pulse. The fundamental problem is that there is no published model for a thermal pulse that comes anywhere near the fast timescale for evolution or the large vertical motion in the HR diagram.

8. CRITICAL OBSERVATIONS

We can propose four sets of observations that are currently ongoing or feasible in the near future. First, it would be good to get optical and ultraviolet spectra of the shell and the central star, so as to measure the temperature while keeping up with the fast evolution of the system. For this, a program with the HST in Cycle 22, with N. Reindl as the principal investigator, will get near- and far-ultraviolet spectroscopy with the COS instrument. Second, further HST images in 2016 would provide a long enough time baseline so as to measure an accurate expansion age for the ordinary PN shell. These same HST images might show the fast wind from the 1980s event. This short duration wind has a velocity and total mass like that of the shell ejected by the recurrent nova T Pyx, for which we see the impact of the wind onto a prior more-massive shell (Schaefer et al. 2010). So we might expect to see this impact lighting up the inside of the old PN shell with bright emission lines. New HST images will also allow for resolving the central star and placing it onto the HR diagram, so we can see the evolution from 2006 to 2016. For this second set of observations, we have just been awarded time during Cycle 23 of HST, with Z. Edwards as principal investigator, to use the WFC3 to take all these needed images. Third, the outer halo of the Stingray can be sought in the radio regime (c.f. Oettl et al. 2015). Fourth, time series spectra exposed to show photospheric absorption features of the central star might show a sinusoidal radial velocity curve that will discover a close-in companion star (as needed to shape the bipolar nebula) as well as define the separation and mass of the close-in companion. This observing task could also discover a close binary remnant of a post-CE system.

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