Supplementary Information

***GALEX* Data Reduction** Far-ultraviolet (FUV) and near-ultraviolet (NUV) observations of the ultraviolet nebula (hereby the Blue Ring Nebula or BRN) were taken during the *Galaxy Evolution Explore* (*GALEX*) Deep Imaging Survey (DIS). Each imaging band (angular resolution) covers 1344 - 1786 Å (4.5″) and 1771 - 2831 Å (6.0″), respectively, with a spatial resolution of 1.5″ per pixel[40]. The *GALEX* images were taken between 1 - 31 July 2004. All DIS images were corrected using the relative response images of each exposure, then co-added to create the final filter image. FUV images have a total exposure time of 50,287 seconds, while NUV images were taken over a total exposure time of 68,518 seconds. The final FUV and NUV images have sensitivity limits of $\sim$25 m_{AB}. A diffuse nebula is observed in the FUV image ($m_{\mathrm{FUV,AB}} \sim$ 20.2), with the star TYC 2597-735-1[41] at the center of the nebula.

In both *GALEX* FUV and NUV images, starlight from TYC 2597-735-1 and field stars has been removed using a customized source removal routine in the python `photutils` module. The routine masks off the point-spread function (PSF) of any star that falls above a signal-to-noise (SN) threshold (for FUV, SN>5, and for NUV, SN>2) and replaces the star with a tile of random background noise representative of the surrounding sky. The sky noise is derived from sky background maps provided with each DIS exposure and co-added to create a master sky map. This exercise was done to remove excess flux from the nebular area, to derive the flux from the diffuse nebula only.

The FUV nebula appears as a ring with a slightly-elliptical shape and a clearly-defined hole at the center. The FUV emission ring of the BRN has an inner spatial extent on the sky d_{in} = $3'.7$ and an outer extent of d_{out} = $7'.3$. The geometry of the BRN is such that the FUV emission shines through where forwards and backwards outflow cones overlap (as drawn in Figure 1(f)). The viewing angle of the nebula was derived by modeling a biconical outflow from a point source and matching the geometry of the overlapping cones to reproduce the profile of the BRN. This gives $i \sim 15^\circ$ (Figure 1(f)).

Multi-Wavelength Look of the UV Nebula Extended Data (ED) Figure 1 shows a compilation of UV, visible light, and infrared images from archival surveys (*GALEX*, DSS-II, 2MASS, and *WISE*) and narrow-band Hα (Palomar-COSMIC) of the region around TYC 2597-735-1. DSS-II, 2MASS, *WISE* images were obtained from the IRSA database. Only in the *GALEX* FUV image is the inner thick band of the Blue Ring Nebula visible; no signs of the inner FUV nebula is seen in other visible light or infrared images. The outline of a shock front can is seen in the *GALEX* FUV, NUV, and Hα images. The Hα image reveals dual shocks that form two "loop"-like structures. The western-most shock in the Hα image is associated with one shock loop, while the next filamentary structure moving east (also seen as the western shock in FUV and NUV images) traces the second loop.

Properties of the Ultraviolet Nebula The count rate observed by *GALEX* is converted to flux in standard cgs units using the *GALEX* conversion factors for FUV and NUV channels[42]. We find a total flux emitted from the nebula F_{FUV} = 1.5×10^{-14} erg cm^{-2} s^{-1} Å^{-1}, corresponding to a total FUV luminosity L_{FUV} = 3×10^{33} erg s^{-1} for a distance of 1.9 kpc to the source (see *Gaia* description below). There is no detectable NUV emission counterpart associated with the nebula, except along the western boundary of the nebula, where Hα emission is also detected. We place an upper bound of NUV emission in the nebula of $F_{NUV} < 10^{-18}$ erg cm^{-2} s^{-1} Å^{-1}, corresponding to $L_{NUV} < 5\times10^{29}$ erg s^{-1}. The NUV/FUV luminosity ratio of the BRN is $<1.5\times10^{-4}$; there are $>10^{4}$ more FUV photons emitting from the smooth, uniform ring of the BRN than NUV photons.

Along the western (left-hand side) edge of the FUV nebula, a shock filament is observed in emission in both the FUV and NUV (Figure 1). Since we do not capture all of the shock emission in FUV or NUV emission, just one part of it, we present the average flux in both bandpasses, rather than the total. The average flux measured in this shock filament is $F_{FUV} \sim 10^{-18}$ erg cm^{-2} s^{-1} Å^{-1} and $F_{NUV} \sim 6\times10^{-19}$ erg cm^{-2} s^{-1} Å^{-1}; this shows less than an order of magnitude difference in FUV and NUV flux along the shock, versus over four orders of magnitude difference in flux within the ring of the BRN itself. The average shock luminosity in the FUV and NUV are $L_{FUV} \approx 5.2\times10^{28}$ erg s^{-1} and $L_{NUV} \approx 1.3\times10^{29}$ erg s^{-1}, resulting in a FUV/NUV luminosity ratio along the shock $\sim$0.4. Less than unity, this FUV/NUV ratio is more consistent with the expected *GALEX* FUV/NUV ratio for two-photon emission (0.37)[43] than dust scattering ($>$1)[44].

Emission source of the Blue Ring Nebula *GALEX* FUV grism spectra of the BRN were obtained between 23 July - 3 August 2007, corresponding to a total observing time of 14,950 seconds. The FUV grism image reveals that the BRN shines in the wavelength range $\sim$1550 - 1650Å, which is consistent with the emission processing being collisionally-induced molecular hydrogen fluorescence (ED Figure 2). We note that an exact bandpass constraint is impossible with the slitless FUV grism spectrum, given the scale of the BRN, which spreads the emission out and smears the inferred spectrum across the spatial extent of the emission region. Molecular hydrogen fluorescence (H_2F) is a natural explanation for the BRN, as the fluorescence is confined to FUV wavelengths only - it has no emission counterpart in the NUV (λ(H_2F) $<$ 1700Å). If an appreciable amount of any other atomic/ionic species resides within the nebula, the presence of a NUV emission counterpart would be expected. For example, some carbon species have strong FUV emission coincidence with H_2 fluorescence (e.g, CIV 1548,1550), but would also appear with an emission counterpart in the NUV (e.g., CIII] 1906, CII] 2324).

Neutral Hydrogen Mass in the BRN The FUV luminosity, assuming the emission is exclusively produced by an optically-thin layer of H_2, can be converted to a rate of H_2 fluorescence over the entire BRN. This conversion assumes that the nebular gas is very thin, such that the molecular density does not saturate the absorption cross-section for excitation.

To justify this assumption, we estimate the volumetric density of H_2 (n(H_2)) in the BRN. To do so, we estimate the rate that H_2 is collisionally excited by hot electrons in the medium, assuming that the source of H_2 excitation is associated with a reverse shock through the BRN (as is shown in the last panel of Figure 3). The nebula itself (excluding the shock filament) emits a total H_2 luminosity L_{H_2} = 3×10^{33} erg s^{-1}. We convert this to a total rate of H_2 collisions required to produce this luminosity, $\langle\Gamma_{H_2+e^-}\rangle$ = L_{H_2}/E(H_2F) $\sim$ 2.5×10^{44} collisions s^{-1}, where $\Gamma_{H_2+e^-}$ is the rate of H_2 fluorescence by electron collisions and E(H_2F) is the energy of the transition to produce H_2 fluorescence. The emitting surface area of the BRN is quite large (A_{BRN} $\sim$ 10^{39}

cm^2), so we calculate the average expected collision rate with electrons over the area of the nebula using derived cross sections of collisions between H_2 and free electrons: $\langle\gamma_{H_2+e^-}\rangle$ = $\langle\Gamma_{H_2+e^-}\rangle$ / (A_{BRN} / σ(H_2)) $\sim 10^{-11}$ collisions/sec, where σ(H_2) $\sim 10^{-16}$ is the cross-section between H_2 and warm-hot electrons ($E_{e^-} > 20$ eV[45]). The expected density rate of collisions between electrons and cool-warm (T $\sim$ 500 K) H_2 is $C_{H_2+e^-} \sim 10^{-11}$ cm^3 s^{-1}[46]. Setting the rates of collisions between warm H_2 and free electrons and the observed rate of H_2 fluorescence, we find: $\langle\gamma_{H_2+e^-}\rangle$ = $C_{H_2+e^-} \times n(H_2)$, which means $n(H_2) \sim 1$ cm^{-3}. This density is consistent with the diffuse, electron-impact H_2 fluorescence observed in Mira's FUV tail[16].

With the assumption that the H_2 nebula is quite diffuse, we estimate how much mass of *neutral* hydrogen has been produced in the visible area of FUV emission exposed by this H_2 fluorescence process; each time an H_2 molecule is excited collisionally by an electron, it has a non-trivial chance (10-15%) to dissociate into neutral hydrogen (HI)[47]. Assuming that the total number of H_2 fluorescence transitions equals the total number of molecules undergoing these transitions, the total amount of H_2 emitting per second in the BRN $\sim 2.5\times10^{44}$ molecules s^{-1}. We convolve the rate of transitions with model H_2 fluorescence spectra, assuming collisional excitation via electrons, and use knowledge of the transition strengths and molecular dissociation probabilities per upper electronic level cascade to ground electron level[47,48] to estimate the rate of H_2 dissociation from the BRN FUV luminosity. We find the rate of H_2 dissociation $\gamma_{H_2-HI} \sim 2.5\times10^{-14}$ solar masses ($M_\odot$) per second. If the H_2 dissociation rate in the BRN has been constant over the age of the BRN (see Age discussion below), then we can estimate the mass of HI in the BRN as: $M_{H_2-HI} \sim \gamma_{H_2-HI} \times t_{BRN}$. This places an upper limit on the total mass of the nebula that has been dissociated from H_2 to HI, $M_{H_2-HI} \lesssim 0.0008 - 0.004\ M_\odot$ = 0.8 - 4.1 Jupiter masses (assuming t_{BRN} between 1,000 - 5,000 years; see Age estimate below).

Palomar/COSMIC Hα Shock Rings After the initial discovery of the Blue Ring Nebula with *GALEX*, follow-up observations of the nebula were taken in Hα to search for nebular emission from neutral hydrogen. Hα narrow-band images were taken on 10 September 2004 with the Palomar Hale 200-inch telescope using the COSMIC instrument. A total exposure time of 2,700 seconds (3 exposures of 900 seconds each) was taken, and R-band images for continuum subtraction were taken alongside Hα narrow-band images (300 sec per exposure in R-band). Only the associated shock front of the Blue Ring Nebula is detected in Hα (Figure 1, ED Figure 1).

Keck/LRIS Observations of Shock Filaments The optical filaments bright in Hα were observed on the nights of 23 and 24 July, 2006 with the Low Resolution Imaging Spectrograph (LRIS) on the Keck I telescope using a slit-mask with nine apertures of 0.7 arcsecond width on the brightest knots in the filaments. Keck/LRIS was configured with the 600/4000 grism in the blue and with the 1200/7500 grating in the red and no filters on either channel, but using the 500 dichroic. The grating angle was tuned to optimize throughput for the Hα line on the red side, while Hβ was the primary line on the blue side. The resolution element resulting from these configurations is roughly 2 - 3 Å full width half maximum (FWHM), giving a velocity resolution of about 100 km/s. Four 2,400-second exposures were obtained on each of the two nights under good conditions and at low ($<$1.1) airmass. Each night was reduced and calibrated separately and combined to create a master spectrum for each of the knots. The wavelengths were calibrated using internal Neon calibration lamps between each exposure and also adjusted using night sky lines and corrected to the heliocentric system. Once corrected, the H-Balmer series line spectra in each LRIS slit were converted from wavelength- to velocity-space.

Selective slit spectra along the western boundary of the nebula observe hydrogen-Balmer series emission along the shock boundary. Figure 1(d,f) shows the placement of the LRIS slits in both the Hα narrow-band image and geometry schematic of the BRN and the resulting Hα velocity shifts from line center (in velocity space) as observed over different parts of the two shock loops. Maximal offsets reach ±400 km/s, which we interpret as the highest velocity of the shock filament associated with the BRN. We measure a mean Hα flux along the western filament F(Hα) = $9.7\pm3.0 \times 10^{-17}$ erg cm^{-2} s^{-1} Å^{-1} and a mean Hβ flux through the same LRIS slits along the western shock of $1.5\pm0.4 \times 10^{-16}$ erg cm^{-2} s^{-1} Å^{-1}. We measure an average Hα/Hβ = 0.74 ± 0.29 along this shock, indicating a low Hα/Hβ ratio inconsistent with local thermodynamic equilibrium. Instead, the ratio is more consistent with those observed in solar flares (Hα/Hβ $\sim$ 1), which are interpreted as being non-LTE and significantly impacted by charge exchange with free electrons[49,50]. The optical and UV emission observed along the shock are therefore consistent with a non-radiative shock front with recombination of hydrogen dominating the emission from this region[51].

Constraining the Age of the Blue Ring Nebula The maximum velocity of the BRN forward shock places constraints on the age of the nebula. Assuming that, at early times after the merger, the ejecta coasts at a constant velocity matching that of the forward shock, $v_{\rm sh}$, the source age can be estimated as $t = r_{\rm sh}/v_{\rm sh}$. As the ejecta begins to sweep up an appreciable mass of the external interstellar medium (ISM) comparable to its own, a reverse shock will pass through the ejecta. At late times, the evolution of the forward shock will approach that of Sedov-Taylor blast wave, for which $r_{\rm sh} \propto t^{2/5}$ in the case of a constant density ISM and, therefore, $v_{\rm sh} = dr_{\rm sh}/dt = (2/5)r_{\rm sh}/t$, implying a source age $t = (2/5)r_{\rm sh}/v_{\rm sh}$. The age of the source can therefore be constrained between

$$\frac{2}{5}\frac{r_{\rm sh}}{v_{\rm sh}} < t < \frac{r_{\rm sh}}{v_{\rm sh}}, \tag{1}$$

which comes out to be 2,000 years $< t <$ 5,000 years, given the inferred size and expansion rate of the BRN. As demonstrated in our MESA models (see below), the closest-matched model to the current properties of the BRN central start, TYC 2597-735-1, is best suited to an age $t \sim$ 1,000 years since the stellar merger began. Therefore, we adopt an age range for the BRN between 1,000 years $< t <$ 5,000 years throughout the course of this study.

***Gaia* distance** The *Gaia* DR2 parallax of TYC 2597-735-1 is 0.518±0.029 mas, from which employing a Bayesian method with the preferred "exponentially decreasing space density" (EDSD) prior and a distance scale corresponding to a disk population of 1000 pc at a galactic latitude[52] of +39.4°, we obtain a distance of 1935^{+127}_{-91} pc. The fractional error on the parallax is sufficiently small that the details of the method and the adopted prior only change the distance by less than one-tenth of the quoted 1σ error bars on the distance.

Archival Photometry & Spectral Energy Distribution of TYC 2597-735-1 We compile the spectral energy distribution (SED) of TYC 2597-735-1 using pre-existing photometric observations taken on a variety of UV, optical, and infrared platforms (Figure 2). The ultraviolet portion of the spectrum is taken from the *GALEX* FUV and NUV images. The optical portion of the SED comes from the Pan-STARRS[53] and Sloan Digital Sky Survey[54] surveys. Archival 2MASS, AKARI, and WISE data provide the near- to mid-IR coverage. We find no clear detection of TYC 2597-735-1 in IRAS far-IR archival data, providing only upper limits in the far-infrared.

Interstellar and Circumstellar Reddening The extinction maps and IRSA far-IR photometry towards TYC 2597-735-1 indicate a mean E(B-V) of 0.0181 magnitudes in a 5 arc-minute box centered on TYC 2597-735-1[55], with a minimum E(B-V) of 0.0167 mag and a maximum E(B-V) of 0.0204 mag. The reddening maps are based on 100 micron dust emission and represent the maximum interstellar reddening in a given direction[55]; they do not provide information on circumstellar reddening.

A second estimate of the photometric reddening towards TYC 2597-735-1 was made, including any circumstellar reddening, by analyzing the interstellar Na I D lines. The equivalent width (EW) of foreground Na D1 and Na D2 absorption has been shown to be linearly proportional to extinction[56]. We estimate the maximum EW of the D1 and D2 features to have EW(D1) $\sim$ 68 mÅand EW(D2) $\sim$ 110 mÅ. These EWs indicate E(B-V)=0.023 mag for toward TYC 2597-735-1[56], consistent with the IRSA reddening maps[55] upper limit. We adopt E(B-V)=0.02 mag and estimate its photometric properties from the corrected color-temperature relations.

Spectral Energy Distribution TYC 2597-735-1 exhibits photospheric continuum emission from the UV to J-band consistent with a stellar blackbody emission with an effective temperature

T$_{eff}$ $\sim$5,850 K. We fit ATLAS9 synthetic stellar models[36] to the spectral energy distribution (SED) of TYC 2597-735-1, using stellar parameters close to those derived for TYC 2597-735-1 (see **Stellar Properties** for more details). The ATLAS9 catalog provides a pre-set grid of synthetic stellar spectra with a defined range of stellar parameters. We fit stellar models for T$_{eff}$ = 5,750K and 600K (the grids go through T$_{eff}$ space in steps of 250K), log(g) = 2.5 and 3 (the grids go through log(g) space in steps of 0.5), and [M/H] = -1.0.

We find that, from the NUV to NIR, the synthetic stellar models fit well to the observed photometry, through we note a stark contrast between the observe FUV flux and that of the stellar model. For a star with the properties close to those reported for TYC 2597-735-1, we find that stellar synthesis models predict a range of FUV flux output by the star $F_{1500} \sim 10^{-8}$ - 10^{-7} Jy (2.6×10^{-19} - 10^{-18} erg cm^{-2} s^{-1} Å^{-1}, or $\sim$29 - 26.5 AB mag). However, *GALEX* FUV imaging observes TYC 2597-735-1 to have a FUV flux $F_{1500,\mathrm{obs}} \sim 2.0 \times 10^{-5}$ Jy (2.6×10^{-16} erg cm^{-2} s^{-1} Å^{-1}, or 20.5 AB mag); we observe $> 10^2\times$ more flux in the FUV than the stellar models predict ($\sim$6-8 AB mag).

Excess FUV emission (both in emission lines and continuum) are well-known and reported in systems with accretion disks[57,58,59]. *GALEX*-FUV imaging covers a wavelength range (1350 - 1750Å) where studies report excess FUV emission produced in accreting systems accounts for a small percentage ($<5\%$) of the total measured FUV excess[58]. Using the total accretion luminosity derived from the observed Hα emission (see **Stellar Hα Emission**), the measured FUV excess accounts for 3% of the total accretion luminosity. This is well within reason, given that the majority of TYC 2597-735-1's FUV excess is likely not measured (i.e., shorter wavelengths than were observed with *GALEX*).

From 2μm out to longer wavelength, the SED exhibits excess infrared emission relative to the single temperature stellar continuum. This IR excess likely arises from a dusty, warm circumstellar disk, similar to those seen around protostars[60] and some post-AGB systems[61]. A disk-like geometry for the dust, which lies in a plane perpendicular to our line of sight (and hence approximately perpendicular to the symmetric axis of the nebula), is further supported by the lack of circumstellar reddening of TYC 2597-735-1, inferred from our Na I D analysis (see **Interstellar and Circumstellar Reddening**). The IR excess peaks at $\lambda \sim$8 μm, corresponding to an average dust characteristic temperature $\sim$600 K.

If this temperature reflects re-radiated light from thermal dust particles in orbit around TYC 2597-735-1, then the dust peak location is $\sim$2.2 AU (depending on the albedo of the dust, which is entirely dependent on the dust grain distribution, which ranges between 0.2 - 3 AU[62,63,64]). The dust disk area is derived by modeling the dust distribution over a thin layer in the circumstellar disk to reproduce the IR SED[65]. We verify that $r_{in} \sim$0.25 AU and $r_{out} \sim$2.8 AU best reproduce the IR excess SED (Figure 2(a)). We empirically derive the dust dist mass from the infrared spectral energy distribution of TYC 2597-735-1, assuming all the dust is roughly the same temperature in a thin layer at the equilibrium distance and that the mean dust size is small[63,66]. We assume an average dust temperature T_{dust} = 600 K and take the equilibrium distance $D_{\rm dust} \sim$2.2 AU. The surface density of the dust disk is taken to be small ($\rho_{\rm dust} \approx$2.5 gm/cm^3 [66]) with an average small dust particle size ($a_{\mathrm{dust}} \sim 10^{-4}$ cm, or $\sim 1\ \mu$m) to ensure we are estimating a lower limit to the dust disk mass. Using the following relation[67],

$$M_{\mathrm{dust}} \approx \frac{16\pi}{3} \times \frac{F_{\mathrm{IR}}}{F_{\star}} \times \rho_{\mathrm{dust}} \times D^2_{\mathrm{dust}} \times a_{\mathrm{dust}} \tag{2}$$

we derive a minimum dust mass in the present-day circumstellar disk $M_{\mathrm{dust}} \gtrsim 5 \times 10^{-9} M_{\odot}$.

Keck/HIRES Observations High-resolution stellar spectra of TYC 2597-735-1 were obtained at optical wavelengths using the Keck High Resolution Echelle Spectrometer (HIRES) with the C2 Decker and iodine cell calibration[68]. The purpose of these spectra were to search for and measure a radial velocity signal from TYC 2597-735-1 to determine if its unusual characteristics were attributed to a close-in companion, but the Keck/HIRES spectra were also paramount in investigating the properties of TYC 2597-735-1 itself (see **Stellar Properties**). TYC 2957-735-1 was observed 26 times over 75 days between 25 July - 9 October, 2012. The typical observation achieved a S/N of 30 per pixel (60 per resolution element). An iodine free template spectra of 900 seconds achieved a spectral resolution of R=171,000 and S/N of ∼180 per pixel at 5500Å. The median error of the iodine calibrated velocities is 11.3 m/s.

Radial Velocity Methods & Results The systemic velocity of TYC 2957-735-1 is 8.74 km/s[17]. The iodine calibrated measurements show a detectable periodic radial velocity of semi-amplitude 199 m/s and period of 13.7 days assuming a circular orbit. Allowing eccentricity as a free parameter yields a semi-amplitude of 196 m/s, a period of 13.8 days and eccentricity of 0.124 (ED Figure 5(a)).

Hypothetically, if the measured Keck/HIRES RV using the iodine cell cross-correlation is linked to a close-in companion with ~13.7 day orbital period, we argue that this companion is not sufficiently massive enough to eject the BRN we observe today. A companion with P = 13.7 days would have a semi-major axis a ~0.1 AU. Assuming TYC 2597-735-1 has a mass 2 $\mathrm{M}_\odot$ and the orbital plane ranges from perpendicular to the axis of the Blue Ring Nebula ($i_{\rm min} \sim 15^\circ$) to edge-on to our vantage point ($i_{\rm max} \sim 90^\circ$), the companion mass will be between $M_{\rm p} \approx 3.1 - 12.1 M_{\rm J}$ (ED Figure 5). The total gravitational energy liberated as the planet inspiraled from ∞ to its final semi-major axis $a_{\rm p}$ is only

$$\Delta E \simeq \frac{GM_\star}{a_{\rm p}} \approx 10^{45}{\rm erg}\left(\frac{M_{\rm p}}{10M_{\rm J}}\right)\left(\frac{a_{\rm p}}{0.1{\rm AU}}\right)^{-1} \approx 10^{45}{\rm erg}, \qquad (3)$$

which is at least an order of magnitude smaller than the minimum kinetic energy needed to release the BRN ($E_{\rm KE} = M_{\rm ej}v_{\rm ej}^2/2 \gtrsim 10^{46}$erg, assuming $M_{\rm ej}$=0.01$\mathrm{M}_\odot$). Thus, even if the RV periodicity were from an orbiting companion which underwent an earlier phase of common envelope evolution with the primary star, the maximum energy released in bringing the companion to its present orbit would not be sufficient to explain the observed properties of the BRN. We assume the inclination of the hypothetical RV orbit is i = 15° (where i = 90° is edge-on and i = 0° is a face-on orbit), corresponding to our cone-axis inclination in our biconical model of the nebula. Only in a specific geometry where the RV orbit is completely face-on ($0^\circ < i < 2^\circ$) does the companion mass begin to approach where the energy released via gravitational insprial could release an outflow with enough kinetic energy to explain the BRN ($\sim$ 0.1 $M_\odot$).

We performed a bisector velocity span (BVS) analysis on the Keck/HIRES iodine cell-calibrated RV results, which is meant to provide a test as to whether RV signals measured from a star are tied to stellar activity, like star spots or atmospheric pulsations[13,69]. We find a statistically significant anti-correlation between the BVS and iodine radial velocities (Spearman's rank correlation coefficient = -0.76, p-value = 7.5×10^{-6}; ED Figure 5), which favors the RV signal being produced by stellar activity. Hα emission and variability (see **Stellar Hα Emission**), measurable macroturbulence affecting TYC 2597-735-1's stellar line profiles (see **Rotational Velocity & Macroturbulence**), and the presence of a dusty circumstellar disk around TYC 2597-735-1 (see **Spectral Energy Distribution**) all provide additional support that stellar activity is the main culprit of the observed HIRES iodine cell RV signal. If TYC 2597-735-1 is accreting material from a disk as suspected from these diagnostics, then it is reasonable to conjecture that the atmosphere is disturbed or that hot spots near the poles exist[13]. Indeed, the period of the HIRES RV is not consistent with that of the rotational velocity of TYC 2597-735-1 (6.5 km/s, corresponding to P∼20 days), so linking the activity near the stellar poles, where the period of revolution may better match the 13.8 days, seems a plausible explanation.

Moreover, we find that radial velocities from the same HIRES data measured with the telluric line method of Chubak et al. 2012[70] do not agree with the iodine cell calibrated measurements, as shown in ED Figure 5. There are differences of up to 600 m/s, whereas the telluric method claims to be accurate to within ∼100 m/s. We do not attempt a periodic fit to the telluric derived velocities. The reason behind this significant disagreement is not known. and it raises concerns regarding the reliability of either calibration method.

To provide an ancillary interpretation to the Keck/HIRES RV results, we obtained additional

RV data in the near-infrared with the Habitable-zone Planet Finder (HPF) to determine if the iodine based periodicity persists at longer wavelengths.

HET/HPF Observations and RV reduction HPF is a high resolution ($R \sim 55,000$) near-infrared spectrograph[71,72] that is actively temperature stabilized to the milli-Kelvin level[73], and covers the z, Y, and J bands spanning 810-1280 nm. Between 26 April – 23 July, 2018, we acquired 27 spectra of TYC 2597-735-1 using HPF. 20 of the spectra were obtained with an exposure time of 960s with a mean Signal-to-Noise (S/N) = 127 per 1D extracted pixel at $\lambda = 1000\,\mathrm{nm}$, and 7 of the spectra were obtained with an exposure time of 630 seconds with a mean S/N = 106 per 1D extracted pixel at λ = 1000 nm.

HPF has a near-infrared (NIR) laser-frequency comb (LFC) calibrator which has been shown to enable ∼20 cm/s calibration precision in 10-minute bins, and 1.5 m/s RV precision on-sky on the bright and stable M-dwarf Barnard's Star over months[74]. Due to the faintness of the target, we elected to not use the simultaneous LFC reference calibrator for these observations to minimize any possibility of scattered LFC light in the target spectrum[75]. Instead, the drift correction was performed by extrapolating the wavelength solution from other LFC exposures on the nights of the observations[75]. This methodology has been shown to enable precise wavelength calibration and drift correction down to the ∼30 cm/s level, much smaller than the RV variability observed in this system.

The HPF 1D spectra were reduced and extracted with the custom HPF data-extraction pipeline[74,76,77]. After the 1D spectral extraction, we extracted precise NIR RVs[75], using seven of HPF's cleanest (of tellurics) orders, spanning a wavelength range between 854-900 nm and 994-1058 nm. To extract the RVs, we use a modified version of the SpEctrum Radial Velocity Analyzer (SERVAL) code[78], which uses the template-matching technique to extract precise RVs, adapted for use for the HPF spectra. The stellar activity indicators used in this work – including the differential line width indicator (dLW), chromatic index (CRX), and Calcium Infrared Triplet (Ca IRT) indices – are the same as defined in the SERVAL pipeline[78].

We also see evidence of activity-induced RV variations in the HET/HPF RVs, which we interpret as features intrinsic to the star which could include stellar surface inhomogeneities (e.g., starspots, plages, and/or other active regions) and/or stellar pulsations in the evolved star. From the HPF RVs, we see clear RV variations with an amplitude of $\sim$200-250 m/s in the 13-visit sampling. ED Figure 5(c) shows evidence of clear variations in the HPF differential line width (dLW) indicator as a function of the RVswhich although not a clear 1:1 correlationthe large variations are suggestive of complex activity effects being the source of the RV variations. To this end, clear variations are further seen in the Ca II infrared triplet (IRT; 8500Å, 8545Å, 8665Å) indices, which closely correlate with the dLW indicator (ED Figure 5(d)). While the dLW traces variations in the mean stellar line profile, the Ca II IRT triplet traces activity in the chromosphere of the star. As such, the strong correlation seen in ED Figure 5(d) (correlation coefficient $>$ +0.75, p-value $< 10^{-5}$) hints at a possible link between chromospheric and line-profile effects, which could be explained as active regions rotating in and out of view and/or polar stellar hot-spots evolving at a characteristic timescale of 13.75 days.

We further note that with our current sampling with HET/HPF – which covers approximately half of the phase of the 13.75-day periodicity seen in the Keck/HIRES RVs – the amplitude of the RV variations in HPF likely represents a lower limit on the NIR RV amplitude. Generally, activity-induced RV variations are expected to show lower amplitudes in the NIR than in the optical[79]. We thus speculate that given the 5 year baseline between the HIRES and HPF RVs, that the stellar surface-features could have evolved to give rise to larger activity-induced variations seen during the HPF RV observations, although continued long-term RV observations across the optical and NIR are required to further test this hypothesis.

With the combined evidence in place from two independent RV surveys, we suspect that the RV signals observed by Keck/HIRES and HET/HPF are dominated by stellar surface activity and modulations on TYC 2597-735-1. Even if a close-in binary companion does exist, we argue that it is not sufficiently massive enough to explain the mass ejection that happened at TYC 2597-735-1 $>$1,000 years ago that is now seen as the BRN.

Stellar Hα Emission For what appears to be a red sub-giant star (see below), TYC 2597-735-1 displays a highly unusual characteristic: Hα line emission in its stellar spectrum. Hα emission from star systems can be produced by a variety of physical mechanisms, including accretion (e.g., T Tauri stars, Herbig Ae/Be, symbiotic stars), magnetic activity (e.g., low-mass stars), stellar rotation (e.g., active M-dwarfs), and stellar pulsations (e.g., Mira variables pulsating and heating part of their stellar atmosphere) - all systems with heightened levels of stellar surface activity[80,81,82]. In many cases, Hα emission is observed to be variable (e.g., shape, flux) over time (although the timescale of variability is not typically well characterized[82]) and may display both emission and absorption features (or periodic emergence of Hα emission). TYC 2597-735-1's Hα emission does not appear to coincide with a stellar Hα absorption component and has been observed in emission during all observations of TYC 2597-735-1 between 2004 and 2014. The average flux of the Hα emission line over this time is F(Hα) $\sim 10^{-13}$ erg cm^{-2} s^{-1}, implying a luminosity L(Hα) $\sim 5\times 10^{31}$ erg s^{-1}.

As shown in Figure 2(b) and ED Figure 4, the Hα line profile shape shows variability over timescales of days. One Hα observation occurred in 2004, with more regular follow-up with Keck/HIRES taken through 2012 as a part of the Keck/HIRES RV campaign. The Hα line profile tends systematically towards bluer wavelengths throughout 2012 (ED Figure 4), while the 2004 profile is fairly symmetric and centered on the line center. In the 2012 line profiles, the peak of the line emission actually fluctuates around Hα line center, but the bisector values along different points of the line profile (see below) all tend towards bluer velocity shifts away from line center. This blue-shifting line profile behavior suggests material is flowing onto TYC 2597-735-1[14], supporting the idea that TYC 2597-735-1 may be interacting and accreting material from a circumstellar disk.

We quantify the deviation of the Hα line center by calculating the line profile bisector at various points in the emission line profile. Bisectors were measured at 10% intervals of line peak. All line profiles were normalized with continuum levels matched, to best compare the line profile behavior at similar positions in the profile shape. At two points in the profiles - where the line profile is most sensitive to the line wings (continuum level - 10% of the peak flux) and near the half flux point of the profile ($\sim$50% - 70% of the peak flux), the deviation from line center bisector velocity shift $<$ -5 km/s, with an average $\sim$ -10 km/s (ED Figure 4).

Hα emission in young stars is widely associated with material from a circumstellar disk being funneled onto the star via magnetospheric accretion, or removed from the disk in the form of winds[14]. A similar reservoir of material could be fueling the Hα emission and variability of TYC 2597-735-1. As discussed, TYC 2597-735-1 exhibits an infrared excess that supports the presence of a circumstellar disk orbiting the star, which is an expected consequence in stellar merger simulations[29]. This disk provides the necessary material that would accrete onto TYC 2597-735-1 through magnetospheric accretion, creating signposts of stellar activity. If L(Hα) is a direct measure of the accretion luminosity, $L_{\rm acc}$[83], then $L_{\rm acc} \sim 10^{33}$ ergs s^{-1}. Converting $L_{\rm acc}$ to mass accretion rate ($\dot{M}$), TYC 2597-735-1 accretes $\lesssim 1.5\times10^{-7}$ $M_{\odot}$/yr of material. We note that converting L(Hα) to a mass accretion rate provides an *upper limit* for the accretion rate, as studies have shown that Hα emission is also generated by disk material itself, disk winds and other sources embedded in disks[14,84,85].

Stellar Properties of TYC 2597-735-1 We present a brief description about the determination of TYC 2597-735-1's stellar properties using Keck/HIRES spectra.

Luminosity and Radius of TYC 2597-735-1 The Johnson V-band magnitude, derived from SDSS gr photometry[86], is 11.149 mag. Using extinction laws[87] and E(B$-$V)=0.02 mag, the V-band magnitude corrected for extinction is V_0 = 11.087 mag. The absolute V-band magnitude of

BRN, based on the *Gaia* parallax, is then M_V = -0.34±0.12 mag. From bolometric corrections[88] for the Sun and TYC 2597-735-1, -0.193 and -0.219 respectively, we derive $\log(L/L_\odot)$ = 2.07 for TYC 2597-735-1[89]. Paired with the adopted T_{eff} = 5850 K and $\log(L/L_\odot)$ = 2.07, we find R = 10.5 ± 0.5 $R_\odot$ for TYC 2597-735-1.

Rotational Velocity & Macroturbulence Based on model atmosphere parameters, derived here for TYC-2597-735-1, and the spectrograph slit function of Keck/HIRES, we performed spectrum synthesis calculations to match line profiles in our HIRES spectrum. We found that the U-shaped profiles characteristic of pure rotational broadening failed to reproduce the observed line profiles, particularly in the red and blue wings of each line. Conversely, a Gaussian macroturbulent velocity distribution fit the line wings, but not the line cores. We demonstrate what these line fits look like in ED Figure 8. The final solution constrained by line full width half max (FWHM), as well as the line cores and wings, was obtained for a $vsini$= 6.5 km/s combined with a macroturbulent velocity parameter of 15 km/s. Assuming the rotation axis of TYC 2597-735-1 aligns with the symmetry axis of the BRN (i ∼15°), we derive a de-projected surface rotational velocity $v_r \approx 25$ km/s.

We find this de-projected surface rotation velocity to be larger than expected for a star which has just evolved off the main sequence ($v < 10$ km/s)[30,90,91]. However, the fact that TYC 2597-735-1 is not rotating at a much larger fraction of its break-up speed disfavors a more equal-mass merger (e.g., two $1 M_\odot$ stars).

Effective Temperature Two spectroscopic and one photometric methods to determine the effective temperature, T_{eff}, of TYC 2597-735-1 were explored.

I. Spectroscopic T_{eff}: Here, we describe two spectroscopic techniques to derive T_{eff}. The first uses a set of 35 mostly unsaturated Fe I lines with good gf values, taken from the NIST database, of class B (accuracy $<$10% error) or better. The Fe I lines chosen for TYC 2597-735-1 possesses a non-negligible covariance between microturbulent velocity (ξ) and T_{eff}, due to two saturated Fe I lines near an excitation potential of 1.0 eV (EW$\sim$100mÅ). Abundances were derived for each Fe I line, based on measured EWs, using the LTE spectrum synthesis code, MOOG, with NLTE corrections[92]. After iterating on the microturbulent velocity parameter, by requiring a flat trend of iron abundance with EW, the input model atmosphere T_{eff} was varied until there was no slope of iron abundance with line excitation potential (EP). Naturally, this minimized the Fe I abundance residuals. In this absolute analysis, we find T_{eff} = 5,800 K and ξ = 1.5 km/s, with 1σ T_{eff} uncertainty = 27 K due to random errors in EW and atomic gf values of the Fe I line transitions, which are the product of the atomic transition oscillator strength and the statistical weight of the lower level, and 1σ ξ uncertainty = 0.06 km/s due to random errors. Unfortunately, the paucity of available unsaturated Fe I lines with good gf values in TYC 2597-735-1's spectrum at low EP leads to a significant covariance between T_{eff} and ξ, which increases the total 1σ T_{eff} uncertainty = 41 K using this technique.

The second technique employs line-by-line differential abundances[93,94]. Abundances for each Fe I line are derived relative to the same line in a standard star whose atmosphere parameters, including T_{eff} and [Fe/H], are accurately known. As in the absolute analysis, the model that best estimates T_{eff} for the star provides a zero slope solution in a differential abundance versus excitation plot, relative to the standard. Ultimately, this is relative to the Sun, whose T_{eff} is accurately known and not dependent on model atmospheres. By using this technique, the adopted gf values for each line cancel-out when the difference with the standard is computed. Therefore, any measurable clean line in both target and standard star spectra can be used, even if no gf values are known. In this differential analysis we used 42 lines from the visual Keck/HIRES CCD spectrum of TYC 2597-735-1, 16 of which are in common with the absolute analysis (above). We took line abundance differences relative to star Hip 66815[94], giving a best fit T_{eff} of 5,900K, and a microturbulence velocity ξ = 1.3 km/s. We adopt a T_{eff} uncertainty of 51K, equal to the quadrature sum of the excitation temperature uncertainties for TYC 2597-735-1 and our standard. We speculate that the 0.2 km/s microturbulent velocity difference between absolute and differential methods is likely due to errors in the chosen standard.

I. Photometric T_{eff}: We adopt color–T_{eff} calibrations[95] to estimate photometric effective temperature of TYC 2597-735-1. Various photometry exists for TYC 2597-735-1, including Tycho B, V and 2MASS JHK magnitudes. The Tycho photometry of TYC 2597-735-1 have relatively large measurement uncertainties, at 0.066 and 0.071 magnitudes in B and V, respectively. Combined with the 2MASS uncertainties near 0.02 mag. per band, the T_{eff} uncertainties for B-V, V-J, and V-K are large, at 240K, 191K and 108K respectively. A further complication arises because at least part of the infrared flux observed from TYC 2597-735-1 is associated with circumstellar material (see "Spectral Energy Distribution"). Particularly, the K-band flux is significantly affected by the circumstellar material excess. In this way, the V-K color will be underestimate the stellar T_{eff}. However, the J-band contamination by circumstellar emission appears negligible. The V-band magnitude of TYC 2597-735-1 can be derived from the existing SDSS ugriz photometry using available transformations[86]. The transformation of the SDSS photometry give a Johnson V-band magnitude for TYC 2597-735-1 of 11.15 ± 0.02 magnitudes, resulting in a V-J = 1.201; the de-reddened[87] $(V\text{-}J)_0$ = 1.121 ± 0.028 mag. The color–T_{eff} relation for $(V\text{-}J)_0$ = 1.121 and [Fe/H]=-0.90 (see below) is 5,855 K, with the color uncertainty of 0.028 mag corresponding to 76 K.

Combining result from all three methods, we converge on T_{eff} = 5,850 ± 50 K.

Stellar Properties and Abundance Analysis The model atmosphere abundance analysis follows the methods described in various studies[93,96,97,98]. The analysis uses the MOOG spectrum synthesis routine[99] and a grid of model atmospheres[100]. The stellar atmosphere were linearly interpolated to the desired atmospheric parameter values. Elemental abundances and atmosphere parameters were determined iteratively. For each line, the abundance was determined by finding the input element abundance required to match the observed and theoretical equivalent width (EW). For this analysis, we focus on abundances of Fe and α-elements (e.g. O, Mg, Si, S, Ca, and Ti) relative to solar.

The LTE abundances of several elements were computed with a KURUCZ model[88], T_{eff} = 5,850 ± 50 K, log(g) = 2.75 ± 0.15 cm/s^2, [M/H] = -0.90, ξ = 1.50 km/s. The surface gravity log(g) is derived by demanding [Fe I/H] = [Fe II/H]. The microturbulent velocity parameter, ξ, was determined by requiring that derived Fe I abundances be independent of equivalent width (EW).

We find that ξ=1.5 km/s gives consistent iron abundances from the 35 optimal Fe I lines chosen to derive stellar abundances. Uncertainties on the parameters were derived from the scatter in the abundances derived from the individual Fe lines and the sensitivity of log(g) to the temperature[97].

Using the above model prescription, TYC 2597-735-1 displays low metallicity ([Fe/H] = -0.90 dex), suggesting TYC 2597-735-1 is an old, metal-poor star. Alpha-element abundances (O, Mg, Si, S, Ca, and Ti) are all consistent with [α/Fe] = +0.4 dex, similar to those in the Milky Way thick disk and halo, suggesting nucleosynthesis by core-collapse supernovae. The kinematics of TYC 2597-735-1, based on Gaia data, indicate disk-like motion, so the old thick disk is favored: chemically and kinematically, TYC 2597-735-1 appears to be an old, thick disk star.

Mass of TYC 2597-735-1 The spectroscopic gravity (log g=2.75) and stellar radius (R=10.5 $R_\odot$) of TYC 2597-735-1 imply a stellar mass M=2.17 $M_\odot$. Taken at face value, this relatively high mass, and thus young age ($<$1 Gyr), are inconsistent with membership of the thick disk population, as indicated by the chemical composition, location and kinematics of TYC 2597-735-1.

However, a reasonable gravity decrease of $\sim$0.3 dex would put the mass of TYC-2597-735-1 near 1.1$M_\odot$, with a main sequence (MS) age consistent with an old star from the Galactic thick disk population. Abundance analysis experiments of similar stars[93,94,101] show that an abundance difference between Fe I and Fe II of $\sim$0.1 dex corresponds to a surface gravity difference of $\sim$0.3 dex. For our analysis of TYC-2597-735-1, the 1-σ RMS scatter of Fe I and Fe II abundances is 0.078 and 0.053 dex, respectively; but the 1σ error on the mean difference is only 0.02 dex. Thus, random error on the means of the abundances are unlikely to be the source of a 0.1 dex ionization equilibrium difference. Systematic abundance errors, such as those due to gf value zero-points, model atmosphere effects, H-fraction, and other evolutionary effects may reduce log g to be more consistent with $\sim$1 M$_\odot$. Given the uncertainties in the mass estimate associated with using spectroscopically-derived stellar parameters, we constrain the mass of TYC 2597-735-1 between 1 – 2.1 M$_\odot$ and expect the lower mass end to be more representative of the true mass of TYC 2597-735-1, given the strong evidence linking it to the Galactic thick disk population.

MESA Models We use the stellar evolution code MESA[24] to explore the impact of a stellar merger on the long-term stellar properties displayed by TYC 2597-735-1[25]. We assume a $2.17M_\odot$ primary star and varied the mass of the merging secondary ($M_{\rm c}$) from those of Jupiter-mass planets up to low mass stars $M_{\rm c} \approx 0.3M_\odot$. We explore the merger evolution for the upper limit primary stellar mass inferred from our stellar properties analysis (see **Mass of TYC 2597-735-1**), but we expect that, if we fix the stellar radius and structure of the primary and decreased the mass by a factor of 2 (to match the lower limit of the primary mass), expect to increase the companion mass by a factor of 2 (to match the energy). The lower mass primary star and higher mass companion, still safely within the low-mass star mass range, would yield roughly the same timescales of merger evolution. We expect that the luminosity of the lower-mass primary case would change in a non-trivial way, resulting in quantitative, but likely not qualitative, changes. Future modeling efforts of the lower mass primary scenario is necessary to confirm this finding.

We consider different evolutionary stages of the primary at the time of the merger, ranging from it just leaving the main sequence, to an evolved sub-giant star on the horizontal branch.

We simulate different evolutionary stages of the primary star by changing the radius of the star, ranging from 3 – 10 $R_{\odot}$. For each simulation, right after the companion star plunges into the primary, we deposit energy into the envelope following the dynamical friction-driven inspiral. We follow the star's subsequent evolution over a long timescale, $\sim$10,000 years. We then search for the combination of pre-merger parameters that best reproduce the present-day properties of TYC 2597-735-1, namely its luminosity, effective temperature, and surface gravity. We find where along in the merger's evolutionary track that the present-day properties of TYC 2597-735-1 best match its simulated progenitor model to independently estimate the time elapsed since the merger took place. The change in luminosity over time (dM_B/dt) is provided as a change in Johnson B-magnitude over the time of the merger and is used to independently verify the expected change in luminosity of TYC 2597-735-1 over a long time frame.

ED Figure 7 shows the evolution of the `MESA` models following the deposition of energy during the merger and assumes a $0.1\,M_{\odot}$ companion. Different colored lines correspond to different sizes of the $2.17\,M_{\odot}$ primary star at the time of merger, ranging from $3-10\,R_{\odot}$. We see that the moderately evolved sub-giant star with a radius of $5R_{\odot}$ does the best job at reproducing the present-day properties of TYC 2597-735-1 for an assumed time since merger of 1,000 years. This age is a factor of $\sim$ 2 smaller than that estimated for the BRN of $\gtrsim$2,000 years.

We note that both the primary star's effective temperature and surface gravity 1,000 years after the merger energy injection adequately match the present-day derived values measured from optical spectroscopy and photometry of TYC 2597-735-1, which explains why TYC 2597-735-

1's stellar properties are slightly skewed away from the bulk of moderately-evolved stars in the T_{eff}-log$g$ plane[39] (ED Figure 3). As demonstrated in ED Figure 7, the primary stellar properties continue to settle back towards equilibrium after the modeled merger takes place, its surface gravity increases, shifting TYC 2597-735-1's T_{eff}-log$g$ relationship in-line with other moderately-evolved stars around its effective temperature.

Our simple one-dimensional models neglect a variety of effects, which if improved upon in future work would enable a more precise comparison to data. These include, for example, the back reaction of the addition of mass (particularly unprocessed hydrogen) on the long-term stellar structure, as well as multi-D effects due to rotational mixing and the delayed accretion of mass from the remnant accretion disk. More detailed models for angular momentum transport in the remnant will also be required to make specific predictions for the present-day rotation rate of TYC 2597-735-1.

Long Term Light Curve of TYC 2597-735-1 With the possibility of a merger millennia ago, it is reasonable to search for residual slow fading in TYC 2597-735-1's luminosity. Slow evolutionary fading can only be detected with something like a century-long, well-calibrated light curve, and that essentially requires the use the photographic plates now archived at Harvard. Examples include the sporadic fading of the Boyajian Star (KIC 8462852)[102,103], brightening and fading of four "Hot RCB stars"[104], and the slow-then-fast fading of the 'Stingray' planetary nebula nucleus[105].

The photometric accuracy must be around 0.01 mag, for binned magnitudes, and both the old and modern magnitudes must be very carefully placed onto the identical magnitude scale. Our procedure is to perform differential photometry of TYC 2597-735-1 with respect to the average of three nearby comparison stars of closely similar color and magnitude. We chose TYC 2597-1026-1, TYC 2597-458-1, and TYC 2588-182-1, and adopted B magnitudes from the AAVSO Photometric All-Sky Survey (APASS) of 11.506, 11.513, and 11.912 mag respectively. By using the same three comparison stars with similar color and only detectors with a sensitivity close to the Johnson B system, all color terms and systematic errors will be negligibly small, despite the many plates and detectors over the last century. By averaging together many images from many nights, we can beat down measurement and systematic errors to usefully small values.

For TYC 2597-735-1, over two thousand plates from 1892–1989 exist. The native spectral sensitivity of almost all the plates is effectively the original definition of the Johnson B magnitude system, and the comparison star magnitudes from APASS are accurately in the Johnson B band, so the resultant magnitudes are closely modern B magnitudes. Fortunately, the Digital Access to a Sky Century @ Harvard (DASCH) program has already scanned all the relevant plates, and performed a good photometric analysis. Critically, the DASCH calibration with the B-band APASS input catalog must be used, as the other calibrations lead to substantial systematic errors from imperfectly-corrected color terms. The DASCH magnitudes were rejected for photometric uncertainty >0.30 mag, yellow and red sensitive plates, problem flag (AFLAG) values $>50{,}000$, plates where the target is within 0.30 mag of the measured plate limit, and >5-σ outliers. This leaves us with 2,077 B magnitudes. These have no evidence of fast variations, so the light curve was averaged into 5-year bins. The five-year bins from 1890–1895 and 1955–1970 were not used further because they have few plates. The uncertainty in the binned magnitudes is the RMS scatter divided by the square root of the number of plates, with these uncertainties being consistent with a reduced chi-square of unity for a smooth curve.

To get a post-1989 light curve, the modern data must have a B-band spectral sensitivity, and a photometric error of around 0.01 mag or so. Unfortunately, most modern data, either published or on-line, are not useable. Gaia, ATLAS, ZTF, Pan-STARRS, ROTSE, and the Catalina Sky Survey have native photometric systems far from the B-band, so they cannot be reliably transformed to B-band with the needed accuracy. Neither the literature, ASAS, nor the AAVSO database include our target star. The Tycho BT magnitude has too large a quoted uncertainty (±0.07 mag) to be useful. The only useable B magnitude that we can find is from APASS with two observations on 2012.2, for B equal to 11.756±0.004 mag.

Given the lack of pre-existing B magnitudes that can be accurately cross-calibrated with other detectors, we have commissioned CCD photometry. Andrew Monson used the Three-hundred MilliMeter Telescope (TMMT[106]) in California to get 65 images on 22 nights from May 2014 to September 2015. Lee McDonald used the 0.25-meter iTelescope 5 system in New Mexico to get 10 images on two nights in November 2019. Kenneth Menzies used the 0.50-meter iTelescope 11 system in New Mexico to get 20 images on two nights in November 2019. Ray Tomlin used an 8-inch f/6.3 Schmidt Cassegrain telescope in Illinois to get 25 images on two nights in November 2019. All images were taken through a B filter, processed with the usual bias/dark/flat corrections, star magnitudes measured with aperture photometry, TYC 2597-735-1's magnitudes derived as differential from the same three comparison stars, the final magnitude taken as the average of all input images, and the formal uncertainty taken as the RMS scatter divided by the square root of the number of input images. The RMS scatter between the magnitudes for the latter four observational runs is 0.008 mag, which is substantially larger than the formal error bars. TYC 2597-735-1 is likely not varying on any fast time scales, so 0.008 mag is a measure of how accurately photometry can be compared between observers with different systems, despite having the best possible conditions and procedures. These observer-to-observer differences can be beaten down by averaging over the four observers, to get a modern 2015–2019 B magnitude of 11.767±0.004.

Our final light curve is presented in Supplemental Table 1 and ED Figure 6. We see a steady decline, from 1897.5 to 1952.5, consistent with a simple linear function with a slope of 0.127±0.016 mag/century (with a reduced-χ^2 near unity). This decline is significant at the 6-σ level, as taken from an F-Test. A linear fading of a light curve in magnitudes is the same as an exponential decline in the flux. Between 1952.5 and 2019.9, the slope has flattened out and is consistent with a zero slope. The two high points in the 1970s might represent some variability during the 1952.5–2019.9 interval, or maybe some residual errors of some sort, or perhaps a shallow decline from 1940 to 2019.9. In all cases, TYC 2597-735-1 starts with a fast decline in the first half of the 1900s, and a slow-or-zero decline from 1950 to now. A formal χ^2 fit to a bent line gives a break around 1940, with slopes of 0.131±0.014 and 0.040±0.006 mag/century before and after the break. An F-test shows the break to be significant at the 3.2-σ level. The total B-mag decay is found to be between 0.11-0.12 mag from 1895-2020, consistent with ∼0.09 - 0.1 mag/century.

Rates of BRN Formation A fraction $f_{\rm bin} = 0.2 - 0.4$ of $\sim$ solar-mass stars have binary companions of mass $\gtrsim 0.1M_{\odot}$[107], of which a fraction $f_{\rm interact} \sim 0.1$ of these are on sufficiently short orbital separations $\lesssim 0.1 - 1$ AU to interact with the star due to tidal inspiral following its post-main sequence evolution[108]. Also assume that the current state of the system is observable for a time comparable to its present age, e.g. $t_{\rm obs} \sim 2t_{\rm age} \sim 10^4$ yr; this is motivated in part by the fact that in older sources the shock-heated electrons potentially responsible for exciting the H_2 would have adiabatically cooled by further expansion of the ejecta. Given the lifetime of a $2M_{\odot}$ star of $t_{\star} \sim 1$ Gyr, we then expect that only a fraction

$$f_{\rm BRN} \approx f_{\rm bin} f_{\rm interact} \frac{t_{\rm obs}}{t_{\star}} \sim 5 \times 10^{-8}. \tag{4}$$

of A-stars to contain a BRN. The number density of stars in the stellar neighborhood of mass $\gtrsim 2M_{\odot}$ is $n_{\star} \sim 5 \times 10^{-4}$ pc^{-3}[109]. Therefore, the total number of stars within a radius $R = D = 1.93$ kpc and scale-height $H \sim 1.5$ kpc is approximately $N_{\star} = n_{\star}\pi D^2 H \sim 10^7$. Thus, the number of candidate A-stars as close as TYC 2597-735-1 that we would expect to show a BRN is

$$N_{\rm BRN} = N_{\star} f_{\rm BRN} \sim 0.4, \tag{5}$$

i.e. of order unity.

A second independent constraint on the rate comes from the Galactic rate of stellar merger events, as inferred from observations of luminous red nova transients, which Kochanek et al. 2014[110] estimate to be $\mathcal{R} \sim 0.3 - 0.5$ yr^{-1}. We would therefore expect a total number $\tilde{N}_{\rm BRN} \sim \mathcal{R} t_{\rm obs} \sim 3,000$ Galactic A-stars in a BRN-bearing present state similar to TYC 2597-735-1 out of the total number $\tilde{N}_{\star} \sim 10^9$ of A-stars in the Milky Way (which we take to be a fraction $\sim 1\%$

of the total number 4×10^{11} of stars). If every merger produced a BRN, then the expected BRN fraction would therefore be

$$\tilde{f}_{\rm BRN} \sim \frac{\tilde{N}_{\rm BRN}}{\tilde{N}_\star} \sim 10^{-6}, \tag{6}$$

which is consistent (within an order of magnitude) with the equally-uncertain estimate (4). The number of candidate A-stars from the rate of Galactic stellar mergers is then

$$N_{\rm BRN} = N_\star f_{\rm BRN} \sim 10. \tag{7}$$

Therefore, we expect from our two independent methods to find anywhere between 0.4 - 10 BRNs. Our finding of one BRN is consistent with this rate.

Analytic Processes Describing Mergers The process of the companion falling into the stellar envelope causes the ejection of mass in a rotationally supported disk (or decretion disk) near or above the surface of the star. Mass ejected from the L_2 point during the earliest stages of a stellar merger can remain gravitationally bound[28,111], particularly for binary mass ratios $q \equiv M_{\rm c}/M_\star \lesssim 0.06$, as would be satisfied in our case for $M_{\rm c} \lesssim 0.1 M_\odot$. The equatorial outflow acts to shape matter which is ejected at higher velocities during the final, plunge phase of the merger, into a bipolar outflow[29,112]. Our MESA calculations demonstrate that the merger process could eject a mass $M_{\rm ej} \sim 0.01 M_\odot$ from the stellar envelope.

After forming a disk of radius $\sim R_{\star,0}$ and mass (of, say) $M_{\rm d,0} \sim M_{\rm c} \sim 0. - 1 M_\odot$, the disk will accrete onto the star at a characteristic rate[113]

$$\dot{M}_{\rm pk} \sim \frac{M_{\rm d,0}}{t_{\rm visc}} \sim 6 \times 10^{25} {\rm g\,s^{-1}} \left(\frac{\alpha}{0.1}\right)\left(\frac{M_{\rm d,0}}{0.1 M_\odot}\right)\left(\frac{M_\star}{M_\odot}\right)^{1/2}\left(\frac{R_{\rm d}}{3 R_\odot}\right)^{-3/2}\left(\frac{H/R_{\rm d}}{0.5}\right)^{2}, \tag{8}$$

over a timescale set by the viscosity of the disk

$$t_{\rm visc} \sim 4 \times 10^5 {\rm s} \left(\frac{\alpha}{0.1}\right)^{-1} \left(\frac{M_\star}{M_\odot}\right)^{-1/2} \left(\frac{R_{\rm d}}{3R_\odot}\right)^{3/2} \left(\frac{H/R_{\rm d}}{0.5}\right)^{-2} \sim {\rm days}, \tag{9}$$

where α is the Shakura-Sunyaev viscosity parameter. We have assumed a thick disk with a scale-height $H \sim R_{\rm d}/2$, which is justified because the peak accretion luminosity

$$L_{\rm acc,pk} = \frac{GM_\star \dot{M}_{\rm pk}}{R_\star} \sim 10^{41} {\rm erg\,s^{-1}} \tag{10}$$

is several orders of magnitude larger than the Eddington luminosity of the star $\sim 10^{38}$ erg/s.

At such highly super-Eddington accretion rates, the disk cannot cool on the accretion timescale and is therefore subject to powerful outflows[114]. These outflows may carry away an order unity fraction of the initial disk mass in the form of a wind, i.e. $\sim 0.01 M_\odot$. This wind would also be funneled by the disk geometry into bipolar conical geometry, perhaps contributing to the BRN ejecta on top of the material ejected dynamically during the merger itself.

What happens to the disk that remains bound to the star? For a thick disk with constant $H/R_{\rm d}$ that evolves due to the viscous redistribution of angular momentum, the accretion rate onto the star evolves with time approximately as[115,116]

$$\dot{M}(t) = \dot{M}_{\rm pk} \left(\frac{t}{t_{\rm visc}}\right)^{-4/3}, t \gg t_{\rm visc} \tag{11}$$

and therefore the disk will evolve to become sub-Eddington ($L_{\rm acc} \lesssim 2\times 10^{38}$ erg/s) after a timescale

$$t_{\rm Edd} \sim 100 t_{\rm visc} \sim 1 \text{ year} \tag{12}$$

The current accretion rate would be estimated as

$$\dot{M}(t_{\rm age}) = \dot{M}_{\rm pk}\left(\frac{t_{\rm age}}{t_{\rm visc}}\right)^{-4/3} \sim 10^{19}{\rm g/s}, \tag{13}$$

comparable to that inferred from the present-day Hα luminosity (see **Methods**).

As the disk accretes, it will also viscously spread outwards in radius due to the redistribution of angular momentum. If the evolution of the disk conserves total angular momentum $J_d \propto M_{\rm d}(GM_\star R_{\rm d})^{1/2}$, where $M_{\rm d}$ and $R_{\rm d}$ are the total mass and outer disk radius, then the outer edge of the disk viscously spreads outwards in time as $R_{\rm d} \propto M_{\rm d}^{-2}$, i.e.

$$R_{\rm d} = R_\star\left(\frac{t}{t_{\rm visc}}\right)^{2/3} \tag{14}$$

By the time the disk has become sub-Eddington ($t \sim t_{\rm Edd}$) its outer edge would reach a radius $R_{\rm d}(t_{\rm Edd}) \sim 1$ AU. The disk may spread a bit further than this after $t_{\rm Edd}$, but since the disk will become geometrically thin ($H/R_{\rm d} \ll 1$) after becoming sub-Eddington the viscous timescale over which the spreading occurs $t_{\rm visc} \propto (H/R_{\rm d})^{-2}$ (eq. 9) will increase significantly. Thus, we expect $R_{\rm d}(t_{\rm age}) \sim$ few 10^{13} cm. The equilibrium temperature at the outer disk edge

$$T_{\rm eq} = \left(\frac{L_\star}{4\pi\sigma R_{\rm d}^2}\right)^{1/4} \sim 500{\rm K}, \tag{15}$$

i.e. sufficiently low to allow dust formation and consistent with the inferred temperatures of the NIR excess of TYC 2597-735-1 (see **Spectral Energy Distribution**).

The current mass of the disk in such a scenario is approximately $M_{\rm d,0}(t_{\rm Edd}/t_{\rm visc})^{-1/3} \sim 0.1 M_{\rm d,0} \sim 10^{-3}M_\odot$, which, assuming the standard $1:100$ value for the dust-gas mass ratio, would imply a present dust mass of $\sim 10^{-5} M_{\odot}$. This is consistent with the minimum mass of dust *only* $\gtrsim 5 \times 10^{-9} M_{\odot}$ we derive from model-fitting the IR excess[117] (see **Spectral Energy Distribution**).

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Supplemental Table 1: TYC 2597-735-1 light curve.

Source	⟨Year⟩	⟨B$_{BRN}$⟩ (mag)
DASCH	1897.5	11.660 ± 0.023
DASCH	1902.5	11.675 ± 0.014
DASCH	1907.5	11.708 ± 0.015
DASCH	1912.5	11.719 ± 0.023
DASCH	1917.5	11.709 ± 0.016
DASCH	1922.5	11.722 ± 0.023
DASCH	1927.5	11.709 ± 0.015
DASCH	1932.5	11.726 ± 0.010
DASCH	1937.5	11.734 ± 0.007
DASCH	1942.5	11.737 ± 0.007
DASCH	1947.5	11.724 ± 0.008
DASCH	1952.5	11.764 ± 0.012
DASCH	1972.5	11.731 ± 0.016
DASCH	1977.5	11.747 ± 0.011
DASCH	1982.5	11.759 ± 0.012
DASCH	1987.5	11.761 ± 0.011
APASS	2012.5	11.756 ± 0.004
TMMT	2015.5	11.764 ± 0.001
AAVSO	2019.9	11.780 ± 0.003
AAVSO	2019.9	11.758 ± 0.003
AAVSO	2019.9	11.764 ± 0.003