natureresearch

Peer Review File

Manuscript Title: A blue ring nebula from a stellar merger several thousand years old

Editorial Notes:

Reviewer Comments & Author Rebuttals

Reviewer Reports on the Initial Version:

Referees' comments:

Referee #1 (Remarks to the Author):

It has been my pleasure to review the manuscript "A blue ring nebula reveals a thousands of years old stellar merger" by Hoadley et al. Clearly BLN is a very interesting object, all the more so given the presence of an exposed central star which the authors suggest to be the remnant of a merger. Such a unique object providing insight into a very active field of binary mergers merits discussion in Nature.

The paper is a combination of comprehensive empirical work defining the system and phenomenological speculation on its nature and history. Some of the latter is not justified physically in the paper; sometimes the argument seems to rest on analogy. This is an issue that will need to be resolved before this manuscript should be considered for publication.

One example is the discussion of an accretion disk around the central star. That there is circumstellar material seems well supported by the infrared excess, and certainly is a very interesting find. However this in itself is not evidence for a disk geometry. That there may be infall begins from a blue-shifted component in the Hα profile. While an infall interpretation is not unreasonable, Hα profiles are notoriously difficult to interpret uniquely. There appears to be evidence of stellar activity, but there is as yet no empirical evidence of a strong organized magnetic field, as found on the oft-referenced pre-main sequence stars. All in all, the jump to magnetospheric accretion from a circumstellar disk is a large one. Finally, the authors then use this disk to collimate their suggested bipolar outflow, with no discussion or mention of the collimating mechanism, mass of the disk, accretion rates, or disk angular momentum.

(As a more specific aside, the authors write "The balance of the mass lost during primary-companion interactions remains as a circumstellar disk, which spreads out and cools over time, forming dust and molecules" and then in the next sentences they write about accretion processes onto the star. Similarly with the outward arrows in their accreting disk of Figure 5. Certainly there is physics here to be clarified for the reader.)

Notes:
1) The derived distance for the star in the Methods is 1935+127, -91 pc. The authors should not be providing the distance in the main text to 4 significant digits.

2) The authors note that the central star "occupies an outlier position" in the Teff - log g plane, but then make no further comment on the significance of this point. I might suggest connecting this with the Metzger et al. analysis rather than leaving the point hanging.

3) "in other systems exhibiting Hα emission, such as T Tauri stars, magnetospheric accretion is fed by

a gaseous circumstellar disk". This sentence is where the big leap is taken from the Hα lineshape. At the least, the authors need to recognize that there are many systems exhibiting Hα emission whose sources are not magnetospheric accretion.

4) "This activity is likely fueled by the star-disk interactions … " - This merits some explanation. Often the argument goes the other way around, something akin to (rapid rotation =>) stellar activity => evidence for strong stellar magnetic fields => perhaps also a strong organized field => magnetospheric accretion."

5) The Metzger et al. analysis is critical to the conclusions of the paper. Unfortunately I was not able to find the referenced Supplementary Information where the analysis is at least conceptually described. This needs to be added.

6) The authors say very little about the initial binary, except for the very small companion mass, so it is very hard to ascertain the likelihood of such a system existing. Some discussion of this in the context of binary frequencies with (very short?) periods is merited.

7) The authors are silent on the mass of the circumstellar or circumbinary disks. I realize that they don't have an empirical measure, but as the reader I don't have a clue of even what order(s) of magnitude that they have in mind. The only hint is that in the final paragraph they talk about further planet formation. Both for that statement, and for better understanding of the entire scenario they are putting forward, they should speak to the disk masses that they are suggesting.

8) Curiously, the Summary does not say anything about their proposed scenario. If the concerns above are resolved, I might note that the last three lines do not have much content, and could be used for this purpose without any increase in length.

9) The set of references is very good, and gives appropriate acknowledgement to previous work.

Referee #2 (Remarks to the Author):

This paper reports the discovery of a ring nebula seen only in the ultraviolet. This is a very comprehensive paper covering multi wavelength imaging, spectroscopy, multi-epoch photometry, and radial velocities observations. In addition to new observations (GALEX, HPF, Keck, Palomar, small telescopes), extensive archival data were used in the analysis. From these observations, the authors derive the temperature, luminosity, mass, radius and chemical abundance of the underlying star.

I find the discovery significant as it shows how much we may be missing in the ultraviolet view of the Universe.

The paper itself is concise and summarizes the highlights of the discovery. The evolutionary scenario outlined in Figure 3 is reasonable. The analysis as detailed in the Methods section is competently done. These results warrant rapid publication in Nature.

I have only very minor comments on the manuscript.

The most uncertain aspect of the paper is the origin of the radial velocity variations. Given the data available, I agree with the authors' interpretation that they are due to stellar surface activity. A quantitative fitting of the long-term photometric light curve (extended data figure 9) is also difficult as more than one process could be responsible for decline. Slow optical decline can be due to changing colors as the result of gradual exposure of the core by stellar wind. The MESA modelling provides a consistency check, not a proof. But given the low luminosity of the object, I agree that merger is the most likely interpretation.

The observed ring morphology of BRN resembles ring-shaped planetary nebulae, which are now interpreted as manifestations of bipolar objects. The most well-known example is NGC 6720 (the Ring Nebula, Bryce et al. 1994, MNRAS, 266, 721). The model presented for BRN in Figure 1f is similar to biconical models for planetary nebulae (e.g., NGC 3132, Monteiro et al. 2000, ApJ, 537, 853) as the result of the interacting stellar winds process.

p. 27 "constraining the age of the BRN": estimating the kinematic age in an interacting system can be tricky as it depends on the density distributions of the interacting systems (see Chapter 16 of Kwok, S.: Physics and Chemistry of the Interstellar Medium).

Referee #3 (Remarks to the Author):

A blue ring nebula reveals a thousands of years old stellar merger by Hoadley et al.

This is a very nice paper describing the properties of the possible remnant of a stellar merger. The authors did an excellent work in collecting all the relevant observational properties of the nebula and the stellar merger remnant to construct a convincing scenario for its formation. I really appreciated the work and I have no specific points of criticism to raise.

My only concern is that this nice piece of work tells us the story of a peculiar object, which is a quite rare stellar system: it certainly has a relevant importance for people interested in binary evolution and merger processes, but I'm not sure it would be interesting to a general audience. Indeed, from the manuscript I cannot see the broad impact of the result. This is my only hesitation in recommending the publication in Nature.

Minor points:
Can the authors add some comments on the "outlier" position of TYC25597-735-1 in the Teff-logg plane? Did the authors compare the TYC25597-735-1 position in the HR diagram with that of an unperturbed 1-2 Msun star in the same evolutionary stage? In other words, is there any photometric (luminosity and color) signature of deviation with respect to the single-star evolutionary path that allows the authors identify this object as the result of a merger event?

At page 41, the authors admit that a mass of 2.1 Msun "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 in the analysis (see for instance p.42) they adopt the primary mass as large as 2.17 Msun, without considering the possibility that it is less massive than 2 Msun.

Author Rebuttals to Initial Comments:

<u>Response to Referee 1:</u>

We thank Referee 1 for their constructive comments and suggestions for clarifying some of the physics we describe in our manuscript. Please find our responses to the numerical points presented by Referee 1, as well as the changes made to the manuscript in response to Referee 1's concerns. The referee's comments are bolded, and our responses are in plain text.

1) The derived distance for the star in the Methods is 1935+127, -91 pc. The authors should not be providing the distance in the main text to 4 significant digits.

We agree with the Referee and have changed the stated distance to reflect two significant digits in the main text (1.9 kpc). This can be found on line 40.

2) The authors note that the central star "occupies an outlier position" in the Teff - log g plane, but then make no further comment on the significance of this point. I might suggest connecting this with the Metzger et al. analysis rather than leaving the point hanging.

We have now added text that connects TYC 2597-735-1's outlier position on the Teff- logg plane of early evolved stars to the discussion of the MESA model results in the main text. We realized this was a key missing connection that helps make our interpretation stronger - the MESA evolutionary models reproduce the current stellar properties of TYC 2597-735-1 well, but they also predict that over the next thousands of year, TYC 2597-735-1 should relax back to an equilibrium state that moves its position on the Teff-logg plane in line with the majority of other evolving stars. Specifically, in the main text, when describing the model outcome, we add the following line 90-91:

> "We find that either a massive brown dwarf or low-mass stellar companion (Mc ~ 0.1 Msun) reasonably reproduce TYC 2597-735-1's effective temperature, luminosity, and surface gravity at a post-merger age of t ~ 1,000 years, accounting for TYC 2597-735-1's in Teff-logg space."

In the Methods section, under the heading "MESA Modeling", we also add the following paragraph (starting on line 845):

> "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 properties of moderately-evolved stars in the Teff - log g plane [Afsar+18]. As demonstrated in ED Figure 8, 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 Teff - log g relationship in-line with other moderately- evolved stars of similar effective temperature."

3) "in other systems exhibiting Hα emission, such as T Tauri stars, magnetospheric accretion is fed by a gaseous circumstellar disk". This sentence is where the big leap is taken from the Hα lineshape. At the least, the authors need to recognize that there are many systems exhibiting Hα emission whose sources are not magnetospheric accretion.

The referee's point is well-taken, that stellar H-alpha emission can arise from many types of stellar phenomena, not just those related to circumstellar disks. However, in light of the infrared excess seen on large scales surrounding TYC 2597-735-1, the RV variations that correlate well with stellar rotation, a new result we are presenting - that TYC 2597-735-1 exhibits >100x brighter FUV flux than expected from stellar synthetic spectral fitting – as well as the substantial angular momentum likely to be present in the system given our favored interpretation of a stellar merger, an accretion disk origin remains the most natural conclusion to us. However, it is also worth noting is that many other sources of H-alpha emission share a related cause: stellar surface activity, whether that be attributed to accretion (e.g., T Tauri stars), magnetic activity (e.g., low-mass stars), stellar rotation (e.g., active M-dwarfs), or other mechanisms (e.g., Mira variables pulsating and heating part of their stellar atmosphere), which we now mention in the Methods section on the Stellar H-alpha Emission (see below).

To expand on the point above, we have evidence to suggest that the circumstellar material revealed by the IR excess exists around TYC 2597-735-1 in a disk-like geometry. Our analysis of both the circumstellar-sensitive reddening from the stellar Na I D-doublet and far-infrared IRSA extinction maps, from which we derive consistent E(B-V) values, disfavors the dust generating the IR excess emission existing in a spherical shell. Instead, it appears that circumstellar dust does not lead to additional reddening in the sightline, leading us to conclude that the culprit of the IR excess is geometrically perpendicular (or close to this) to our line of sight. Assuming the IR excess culprit is bound to the star, it very likely exists in a rotating configuration in order to survive for such a long time since the dynamical event forming the ultraviolet nebula.

To better justify and clarify our interpretation of the H-alpha emission, in conjunction with the other unusual observables of TYC 2597-735-1, we have amended two paragraphs in the Main Text, starting on line 54:

> "TYC 2597-735-1 also displays prominent H-alpha line emission, excess far-ultraviolet flux, and radial velocity variations. The H-alpha emission varies in both line shape and amplitude on timescales of days, showing an enhanced blue-shifted component (see Methods, Figure 2(b)). The observed far-ultraviolet magnitude of TYC 2597-735-1 is over 6 orders of magnitude brighter than is expected from synthetic stellar models (Figure 2(a); see Methods). Radial velocity measurements of TYC 2597-735-1 find ~200 meters per second Doppler shift, yet exclude the presence of a binary companion with mass $\gtrsim$0.01 Msun in tight orbit around TYC 2597-735-1 (a $\lesssim$ 0.1 astronomical units; see ED Figure 5 and Methods). Altogether, these signatures point to heightened stellar surface activity at TYC 2597-735-1.
>
> In addition, TYC 2597-735-1 exhibits a prominent infrared excess in its spectral energy distribution (Figure 2(a); see Methods), a tell-tale sign of a dusty circumstellar disk [Rucinski+85,Adams+87]. A disk-like geometry (which lies in a plane perpendicular to our line of sight and the symmetric axis of the nebula) is favored for TYC 2597-735-1 because it lacks evidence of circumstellar reddening, as measured from TYC 2597-735-1's optical spectrum (see Methods). The combination of infrared emission and surface activity paints a picture where TYC 2597-735-1 is actively accreting material from a disk of gas and dust extending to several astronomical units (see Methods). Other systems with similar observable traits (e.g., T Tauri stars [Edwards+1987,Kurosawa+2006,France+2014]; AGB stars with accretion disks [Sahai+2008,SC2008,Ortiz+2016]), are also often interpreted as actively accreting material from circumstellar disks [Lima+10,Sahai+2015]. "

In the Methods, Section "Stellar H-alpha Emission", we have revised the first paragraph to acknowledge different physical mechanisms that could lead to the formation of H-alpha emission on a star/stellar systems:

> "H-alpha 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 [Bertout89, Witham+06, Hamilton+12]. "

4) "This activity is likely fueled by the star-disk interactions ... " - This merits some explanation. Often the argument goes the other way around, something akin to (rapid rotation =>) stellar activity => evidence for strong stellar magnetic fields => perhaps also a strong organized field => magnetospheric accretion."

As the referee pointed out above, our assumption that the H-alpha activity is due to disk-star interactions may be somewhat premature. We do infer a relatively fast rotation rate of the star ~25 km/s (much higher than would be expected for a star which has just evolved off the main sequence), though this inference relies on assuming the stellar rotation axis is aligned with the symmetry axis of the blue ring nebula (a very reasonable, but not rock solid, assumption).

With the changes already implemented in comment 3 above, we hope that the interpretation stated in the text is now sufficient to accommodate these concerns.

5) The Metzger et al. analysis is critical to the conclusions of the paper. Unfortunately I was not able to find the referenced Supplementary Information where the analysis is at least conceptually described. This needs to be added.

We thank the referee for pointing out this erroneous label in the main text. The description of the Metzger et al. analysis for this particular merger scenario is described in the Methods, the Section labeled “MESA Modeling”, starting on line 812.

6) The authors say very little about the initial binary, except for the very small companion mass, so it is very hard to ascertain the likelihood of such a system existing. Some discussion of this in the context of binary frequencies with (very short?) periods is merited.

We are somewhat agnostic about the physical process drove the secondary into merging with the primary star, which in principle could range from tidally induced orbital decay (Darwin instability) to 3-body secular interactions (e.g. Kozai-Lidov oscillations due to the presence of a long-period tertiary companion).

As we currently mention in the main text, we favor tidally induced orbital decay because that more naturally explains why the merger took place relatively quickly after the primary evolved off the main sequence (our favored scenario fitting the stellar properties employing the Metzger et al. 2017 model). In this case, we likely require an initial orbital semi-major axis smaller than ~0.5 AU (P < 100 d) for the tidal inspiral time to be comparable to the evolutionary time of the star (Sato et al. 2008, PASJ, 60, 539). According to Mo & diStefano (2017; their Fig. 31), roughly 4% of solar-type main sequence stars have stellar binary companions on orbits P < 100 d and ~10% have mass ratios less than 0.2 (their Fig. 30).

More directly, using the observed rate of luminous red novae (LRN) in the Milky Way (Kochanek 2014) we estimate in the Methods the rate of stellar mergers out to distances comparable to the BRN to be ~10. Perhaps the most well-studied Galactic LRN is V1309 Sco (Tylenda et al. 2011), for which OGLE pre-imaging of the system a decade prior to the merger allowed a detection of the progenitor contact binary. Several studies (Stepien 2011, https://ui.adsabs.harvard.edu/abs/2011A%26A...531A..18S/abstract , Pejcha et al. 2017, http://adsabs.net/abs/2017ApJ...850...59P) agree that the progenitor system was a ~1.5-2 Msun binary with a mass-ratio ~0.1, similar to those we favor to explain the properties of the central star in BRN.

We have augmented the discussion on these points in the “Rates of BRN Formation” in the Methods Section, starting on line 928.

7) The authors are silent on the mass of the circumstellar or circumbinary disks. I realize that they don’t have an empirical measure, but as the reader I don’t have a clue of even what order(s) of magnitude that they have in mind. The only hint is that in the final paragraph they talk about further planet formation. Both for that statement, and for better understanding of the entire scenario they are putting forward, they should speak to the disk masses that they are suggesting.

We thank the reviewer for pointing this out, as this is an important component of our study and justification. We now provide a lower mass limit estimate of the inferred circumstellar disk from the presumed present-day mass accretion rate of material from said disk onto TYC 2597-735-1, under the assumption that the H-alpha emission seen on TYC 2597-735-1 is due to accretion. Based on the H-alpha luminosity, we estimate the gaseous accretion rate onto the star using a commonly applied method from proto-star literature (Methods, Section “Stellar H-alpha Emission”). Then, using the estimated age of the system and assuming a roughly constant accretion rate over that time, we derive a lower limit on the present-day disk mass of ~few 1e-4 Msun. This estimate assumes a constant accretion rate since the merger happened several thousand years ago.

In the SI, we have now added detailed estimates of the evolution of the gaseous disk under the action of internal viscosity after its formation in the merger, including an estimate of the present-day mass of the remaining material. We show that, even if the disk starts compact initially after the merger (right outside the surface of the merged star), that it has sufficient time - over the thousand years since - to spread outwards due to internal viscosity to a large enough radius where the equilibrium temperature allows the formation of dust, similar to that inferred to our fits to the IR SED.

Finally, we use the IR excess flux observed in TYC 2597-735-1’s SED with Equation 1 of Jura & Turner 1998 [https://ui.adsabs.harvard.edu/abs/1998Natur.395..144J/abstract] to provide an independent estimate of the *dust* disk mass, which is described in the Methods, Section “Spectral Energy Distribution”. We show that this minimum present day dust mass (~few

1e-9 Msun) is consistent with our analytic estimates above.

We had added the following corrections to the Main text to reflect estimates of the circumstellar mass estimates (line 114):

> "A simple analytic model, which follows the spreading evolution of the gaseous disk due to internal viscosity over the thousands of years since the merger (see SI), is broadly consistent with both the present-day gas accretion rate (as estimated from H-alpha emission; see Methods) and a lower limit on the present-day disk mass obtained by fitting the infrared spectral energy distribution of TYC 2597-735-1 (Mdust > 5x10^{-9} Msun; see Methods). Accretion of disk material onto TYC 2597-735-1 could account for its observed stellar activity (e.g., H-alpha emission and far-ultraviolet excess)."

In the Methods, the Section "Spectral Energy Distribution" (starting on line 509) has been significantly modified to reflect and describe the dust disk mass estimation.

8) Curiously, the Summary does not say anything about their proposed scenario. If the concerns above are resolved, I might note that the last three lines do not have much content, and could be used for this purpose without any increase in length.

We have revised the Summary paragraph, particularly the entirety of the paragraph after the "Here we report..." sentence, to structure the Summary around the story of the stellar merger. Within the framework of the events leading up to and proceeding the merger, we present small details of the observational evidence supporting this scenario. The Summary now reads as follows (changes in bold, and with references removed for readability), and we hope that the referee is more satisfied with the tie-back to the proposed scenario throughout:

> "Luminous red novae, like V1309 Sco and V838 Mon, are optical transients that arise when binary stars merge. However, these stellar mergers quickly become shrouded by an opaque shell of dust and molecules as their ejecta expands and cools, making it difficult to ascertain their ultimate fates. Here we report the detection of an ancient stellar merger remnant, TYC 2597-735-1, uncovered by an unusual ring-shaped far-ultraviolet nebula observed by the *Galaxy Evolution Explorer*. The nebula is the result of a bipolar outflow ejected from the merger and shines today because its molecular hydrogen is excited by electrons heated as the outflow collides with interstellar gas. The matter left bound to TYC 2597-735-1 remains today as circumstellar material, observed as excess infrared emission around the star and potentially accounting for the stellar H-alpha emission, radial velocity variations, and excess ultraviolet radiation. Today, TYC 2597-735-1 still exhibits uncharacteristic properties inconsistent with its likely evolutionary phase, including an unexpectedly low surface gravity (for its effective temperature) and long-term luminosity decay. Following the long-term evolution of the merger with 1-D MESA stellar evolution models, we identify the initial binary properties consistent with the present-day appearance of TYC 2597-735-1. TYC 2597-735-1 and its ultraviolet nebula provide a unique look at an unobstructed stellar merger remnant, complementing the view provided by luminous red novae at much earlier stages of these events."

<u>Response to Referee 2</u>:

We thank Referee 2 for their constructive comments. Please find our responses (plain text) below each of the Referee's comments (bolded).

The most uncertain aspect of the paper is the origin of the radial velocity variations. Given the data available, I agree with the authors' interpretation that they are due to stellar surface activity. A quantitative fitting of the long-term photometric light curve (extended data figure 9) is also difficult as more than one process could be responsible for decline.

Slow optical decline can be due to changing colors as the result of gradual exposure of the core by stellar wind. The MESA modelling provides a consistency check, not a proof. But

given the low luminosity of the object, I agree that merger is the most likely interpretation.

We agree that the long-term light curve is very difficult to interpret on its own, and we find that the decline in luminosity is not linear or steady - the physics happening to explain what is going with this light curve behavior are not captured in our simplified models. We also acknowledge that the MESA modeling provides a consistency check for our proposed origin story, not that the models prove our result. We invoke the modeling framework to demonstrate that a stellar merger origin for the BRN and the resulting unusual traits of TYC 2597-735-1 are even plausible. In that same vein of reasoning, we very consciously explored the long-term photometric light curve as a proof of concept for the qualitative results from our MESA 1D modeling - the models predicted the luminosity decay, which we then explored separately (and happened to find that it was the case that TYC 2597-735-1 has dimmed over a long baseline).

The observed ring morphology of BRN resembles ring-shaped planetary nebulae, which are now interpreted as manifestations of bipolar objects. The most well-known example is NGC 6720 (the Ring Nebula, Bryce et al. 1994, MNRAS, 266, 721). The model presented for BRN in Figure 1f is similar to biconical models for planetary nebulae (e.g., NGC 3132, Monteiro et al. 2000, ApJ, 537, 853) as the result of the interacting stellar winds process.

Although the comparison to planetary nebulae is a reasonable one *a priori*, our system is not in a PN stage because the central star TYC 2597-735-1 is not a post-PN object. Its properties are closer to a moderately evolved (e.g. sub-giant) or post-red giant horizontal branch star, but normal stellar tracks do a poor job of fitting its properties. We considered stellar winds from a red giant as a scenario to explain the UV nebula; however, the typical velocities of a red giant wind ~ tens of km/s are much smaller than the inferred expansion rate of the BRN of 400 km/s. The latter velocity is in fact comparable to the outflow speed of winds from a star which is *even more compact* than the current configuration of TYC 2597-735-1. This was additional motivation for invoking the hypothesis of a stellar merger which occurred during the sub-giant branch phase of the primary (in which case the thermal energy released during the merger has caused TYC 2597-735-1 to swell up moderately to its current size, as explored by the Metzger+17 models).

p. 27 "constraining the age of the BRN": estimating the kinematic age in an interacting system can be tricky as it depends on the density distributions of the interacting systems (see Chapter 16 of Kwok, S.: Physics and Chemistry of the Interstellar Medium).

As the referee points out, this is hard to do accurately. Our best effort was to provide an upper limit on the age by assuming the current observed velocity of the shock filaments outlining the nebula has been constant since the nebula was ejected by TYC 2597-735-1. While we can think of scenarios which would decelerate the outflowing material as it travels through the intervening ISM, it is difficult to imagine any scenario where the nebula velocity would have been less than it is now (i.e., it was traveling slower at some point before these observations were made). Therefore, assuming a constant velocity traveled by the blue ring nebula to its current position on the sky constrains the age to, at most, 5,000 years.

Response to Referee 3:

We thank Referee 3 for their constructive comments and suggestions for adding clarification to the text. Please find our responses (plain text) below each point raised by Referee 3 (bold face), as well as the changes made to the manuscript in response to Referee 3's concerns.

Can the authors add some comments on the "outlier" position of TYC25597-735-1 in the Teff-logg plane? Did the authors compare the TYC25597-735-1 position in the HR

diagram with that of an unperturbed 1-2 Msun star in the same evolutionary stage? In other words, is there any photometric (luminosity and color) signature of deviation with respect to the single-star evolutionary path that allows the authors identify this object as the result of a merger event?

Yes, we had considered where TYC 2597-735-1 falls on the HR diagram, given its derived Teff and Luminosity (using the Gaia DR2 parallax). We found that it falls within the rising red subgiant stage of stellar evolutionary tracks, but its luminosity is much too high for a 1-2 Msun star, given its Teff. We also found that a younger, pre-main sequence star of 2 Msun and ~500 Myr fit the stellar parameters of TYC 2597-735-1, but its proximity above the Galactic plane, kinematics, and abundances better match those of other thick-disk population Galactic stars, making a pre-main sequence interpretation very unlikely.

Our intention of demonstrating that TYC 2597-735-1 is an "outlier" when compared with other evolved stars with similar Teff and log(g) was to show that TYC 2597-735-1 doesn't exactly fall into a category nicely - some of its parameters better fit early evolved stars, while others look more like pre-main sequence. Since the argument for TYC 2597-735-1 being more likely an evolved star than a pre-main sequence star, we wanted to demonstrate that while this was the case, it is still "off": it appears "puffier" (lower log(g)) than it should for its current inferred evolutionary phase.

We realize that this point may not have been made sufficiently clearly in the text. We now have changed line 46-48 in the main text to read as follows:

> "Notably, TYC 2597-735-1 appears puffier for its temperature than other evolved stars of similar luminosity (ED Figure 8)."

At page 41, the authors admit that a mass of 2.1 Msun "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 in the analysis (see for instance p.42) they adopt the primary mass as large as 2.17 Msun, without considering the possibility that it is less massive than 2 Msun.

The 2.17 Msun mass for TYC 2597-735-1 is the derived mass for the star from its stellar spectrum, when compared with stellar synthetic models. The lower mass limit comes from systematic errors associated with using spectroscopic log(g) to estimate stellar mass. In this way, our MESA models are true to the derived mass of TYC 2597-735-1, though we acknowledge this mass is likely too high to explain its proximity in the Galactic thick disk.

The primary purpose of the MESA models was to demonstrate that a stellar merger was a viable explanation for the strange properties of TYC 2597-735-1 and the presence of an ultraviolet nebula with the properties we report. We felt this was accomplished when the 2.17 Msun MESA evolutionary models reproduced many of the observed properties of the star (e.g. low surface gravity for its effective temperature; and the luminosity, given the new measurements of its distance with Gaia DR2) at roughly the same time after the merger occurred to be consistent with the ultraviolet nebula. We decided that the effort to run additional grids of models was not worth exploring because there exist fairly large uncertainties associated with our approach (e.g. 1D modeling, which only become exacerbated for lower mass primaries; see below) and we do not expect qualitatively different conclusions if had instead assumed a lower primary mass.

We comment here and in the text on how we expect the qualitative evolution to be preserved, if we were to decrease the primary star's mass. In essence, as long as we conserve the energy deposited into the primary star at the time of merging, we expect the qualitative results to remain the same over roughly the same timeframe. This means, for a 1 Msun case with the same radius and internal structure at the point of merger assumed for the 2 Msun case, a 0.2 Msun companion would be required in the models. This companion still falls within the "low-mass stars" category, which does not change our broad conclusions.

We have added the following text in the Methods, Section "MESA Models" to address this issue, which starts at line 816:

"We explore the merger evolution for the upper limit primary stellar mass inferred from our stellar properties analysis (see Methods, Section ``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."

Reviewer Reports on the First Revision:

Referees' comments:

Referee 1 provided only remarks to the editor -- he is happy with the changes, though he notes that the Methods section has become very long.

Author Rebuttals to First Revision:

N/A