YY Hya and its interstellar environment

Stefan Kimeswenger1,2, John R. Thorstensen3, Robert A. Fesen3, Marcel Drechsler4, Xavier Strottner5, Maicon Germiniani6, Thomas Steindl1, Norbert Przybilla1, Kathryn E. Weil7, and Justin Rupert8

1 Institut für Astro- und Teilchenphysik, Leopold–Franzens Universität Innsbruck, Technikerstr. 25, 6020 Innsbruck, Austria
2 Instituto de Astronomía, Universidad Católica del Norte, Av. Angamos 0610, Antofagasta, Chile
3 Department of Physics and Astronomy, 6127 Wilder Laboratory, Dartmouth College, Hanover, NH 03755-3528, USA
4 Sternwarte Bärenstein, Feldstraße 17, 09471 Bärenstein, Germany
5 Montfrazie, 01370 Saint Etienne Du Bois France
6 Leopoldo Stadtlober Street 49, 89871-000 Serra Alta, Brazil
7 Department of Physics and Astronomy, Purdue University, 525 Northwestern Avenue, West Lafayette, IN 47907 USA
8 MDM Observatory, Kitt Peak National Observatory, 950 N. Cherry Ave., Tucson, AZ 85719, USA

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ABSTRACT

Context. During a search for previously unknown Galactic emission nebulae, we discovered a faint 36’ diameter Hα emission nebula centered around the periodic variable YY Hya. Although this star has been classified as RR-Lyr variable, such a stellar classification is inconsistent with the formation of such a large nebula especially if at YY Hya’s estimated Gaia distance of ≃450 pc. GALEX image data also shows YY Hya to have a strong UV excess, suggesting the existence of a hot, compact binary companion.

Aims. We aim to clarify the nature of YY Hya and its nebula.

Methods. In addition to our discovery image data, we obtained a 2.5 × 2.5 image mosaic of the whole region with CHILESPEO facilities and time-series spectroscopy at MDM observatory. Also, we used data from various space missions to derive an exact orbital period and a spectral energy distribution (SED). The binary star model code Binary Maker 3 (B3M), and Kurucz ATLAS9 stellar atmospheres were used to derive a synthetic light curve and a model SED of the compact binary system, respectively.

Results. We find that YY Hya is a compact binary system containing a K dwarf star which is strongly irradiated by a hot white dwarf (WD) companion. The binary has a period of 4.01863 days and a semi-amplitude of 0.03479 m/s. We find evidence for a second companion with a mass of 1.35 ± 0.05 M⊙. The nebula is consistent with a binary system with a mass ratio of 0.33479 d, and classified the star as a c-type RR Lyr (RRc), based on its almost perfectly sinusoidal light curve and high amplitude of nearly one magnitude. The RRc classification implies an absolute magnitude range from 0.85 < MV < 0.55 (Catelan et al. 2004; Dambis et al. 2013). This led to an initial distance estimate of 4.05 < DRR < 4.75 kpc.

However, recent parallax measurements indicate a much shorter distance, consistent with any kind of RR Lyr star. The inverse of the parallax from Data Release 2 (DR2) of the Global Astrometric Interferometer for Astrophysics (Gaia; Gaia Collaboration et al. 2018) is 443±6 pc, about 10 times smaller than that expected for an RR Lyr star. The more recent Gaia early Data Release 3 (eDR3; ?) gives 456±3 pc. Although this new...
value does not overlap within the 1σ errors with the DR2 result, we will adopt that value as it is based on more extensive data and has correspondingly smaller uncertainties. However, up to now, the Gaia analysis solves only for the star’s position, parallax, and proper motions. Moving due to binary orbits is not yet included in Gaia as a source of possible systematic errors. But in the case of the system here as we see later, the whole orbit extends only to 0.03 mas. That is about 1σ of the given parallax error in Gaia eDR3. The distance by Gaia thus seems to be still reliable. However the orbital motion might be the cause for the significant shift between the two major data releases. Thus the realistic error, assuming some systematic component, is more likely in the order of 10 pc.

In this paper, we present follow-up imaging and time series spectroscopy, along with photometric data collected from various literature and data base resources, as well as an analysis of photometry from the Transiting Exoplanet Survey Satellite (TESS, Ricker et al. 2015). We have used these data to classify the system using radial velocities, spectral energy distribution (SED) and the UV excess found by the Galaxy Evolution Explorer (GALEX, Bianchi 1999). We furthermore put the kinematic behavior of the system into the Galactic context and derive detailed parameters for the progenitor stars. Finally, we discuss a possible link to a medieval “guest-star” observation reported by Chinese observers in this direction on the sky (Hsi 1957; Ho 1962).

2. Data and Reductions

2.1. Hα Imaging

Hα discovery images were taken in January 2020 in Serra Alta, Brazil2 using a 115mm F7 TS Proline Triple APO refractor from Teleskop–Service Ransburg3 plus a focal reducer resulting in a final f/5.5. The detector was a ZWO4 Camera ASI 1600 MM-Cool equipped with a 4656 × 3520, 3.8μm pixel CMOS Panasonic MN34230 and an OPTOLONG5 7 nm wide Hα filter. This resulted in a pixel scale of 1′′.24 pixel−1 and a field of view (FOV) of 1′.6 × 1′.21.

The image shown in Fig. 1 is a composite of 120 × 600 s exposures for a total exposure time of 20 hours. A set of matching broadband red filter images were also obtained in order to remove the stellar background. These red filter images were stretched manually by a nonlinear intensity curve to correct for differences in the calibration and were finally subtracted from the Hα image.

The resulting images show a highly structured Hα nebula with a diameter of ~36′. In addition, two smaller nebulosities in opposite directions roughly 45′ to the northeast and southwest from YY Hya are also visible. Examination of copies of the original photographic sky surveys ESO-R (West 1974) shows no more evidence for the nebula other than the small southwestern arc already seen on the H-compressed digital scans. Likewise, no part of the nebula is visible at the SERC-J (Morgan 1995).

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2 Serra Alta, Brazil: 53°04′26″ W, 26°72′85″ S
3 https://www.teleskop-express.de/
4 https://astronomy-imaging-camera.com/
5 https://www.optolong.com/
Fig. 2. The Hα image mosaic obtained at CHILESCOPE with a linear gray-scale mapping with surface brightness from zero to $1.5 \times 10^{-16} \text{ erg cm}^{-2} \text{s}^{-1} \text{arcsec}^{-2}$. The stellar limiting magnitude is about Gaia RP $\approx 21.8$. The round nebula southwards is not related to our target but the beforehand known planetary nebula StDr 47 (PN G253.7+19.4, 09h27m31.46, -23°22′34.40′′).

To investigate further, we booked time at the CHILESCOPE remotely controlled commercial observatory facilities. Details on the location, the instrumentation used and the calibration are given in Appendix B. Images with Hα, [O iii], and [S ii] filters from Astrodon6 were obtained. However, 30 minutes of exposure in the [O iii] and [S ii] bands centered at the main nebula showed no detection of even the brightest filaments. Thus the campaign, lasting from March 9th to June 13th 2021, focused finally completely on the Hα imaging. The aim was the full coverage of the field and the possible detection of further distant structures and a calibrated intensity estimate. But beside the already mentioned structures, no other distant structures related YY Hya and its nebula could be identified. Figure 2 shows the mosaic of the 294 Hα images with 1200 seconds exposure time each (98 hours integration time). The brightest nebular filaments are about $4 \times 10^{-17} \text{ erg cm}^{-2} \text{s}^{-1} \text{arcsec}^{-2}$. The faintest visible structures at $1.5\sigma$ to the background $\text{rms}$ of single pixels are around $8 \times 10^{-18} \text{ erg cm}^{-2} \text{s}^{-1} \text{arcsec}^{-2}$.

Higher-resolution images were also obtained with the 2.4m Hiltner telescope at the MDM Observatory at Kitt Peak, Arizona using the Ohio State Multi-Object Spectrograph (OSMOS;

6 https://astrodon.com/
Martini et al. (2011) in direct imaging mode. A 4k × 4k CCD provided an effective FOV of 18′ × 18′. With 2 × 2 on-chip binning, this yielded an image scale of 0.546′′ pixel⁻¹. A series of narrow passband Hα + [N ii], [O iii] λ5007, and [S ii] filter images were taken of the northeastern and southwestern outlying nebulosities with exposure times of 600 s to 1200 s. The resulting Hα images of the NE and SW outlying nebulae are shown in Fig. 3. The sharp filamentary appearance of the emission along with the lack of appreciable [O iii] and [S ii] emissions strongly suggests these filaments are Balmer-dominated shock filaments with shock velocities ≃100 km s⁻¹ or more depending on the density of the ambient interstellar medium.

2.2. UV Images

UV GALEX images (Bianchi 1999; Martin et al. 2005) were obtained from the online data bases. This nearly all-sky UV imaging survey used wide-band filters centered around 154.9 and 230.5 nm, called FUV and NUV, respectively. The full-resolution images contain mainly pixels with individual photons in about 30% of the pixels and more than 60% of the image pixels containing no photons at all. Simply averaging these images would have artificially enhanced the intensity in the overlap regions of the individual pointings, while using a smoothing filter degrades the brighter parts of the image. We therefore used a nearest-neighbor algorithm in the way normally used for investigations of stellar cluster density (Gao 2016), which preserved the nearest-neighbor algorithm in the way normally used for investigations of the individual pointings, while using a smoothing filter degrades the brighter parts of the image. Seven survey fields were combined that way to get a larger mosaic for faint background without touching the brighter regions. Seven generations were taken of the northeastern and southwestern outlying nebulosities, while using a smoothing filter degrades the brighter parts of the image. We therefore used a nearest-neighbor algorithm in the way normally used for investigations of stellar cluster density (Gao 2016), which preserved the faint background without touching the brighter regions. Seven survey fields were combined that way to get a larger mosaic for the final image (Fig. 4).

Interestingly, only the far NE and SW pair of nebulae ~45′ from the center are clearly detected in the GALEX images. The average position angle of these features is 25′ (north over east) on the sky. This is consistent with these outer emissions as being due to shocks, as suggested by the optical images. A very weak hint of parts of the main nebula in a large "S" shaped structure is visible. Although GALEX images show many reflection ghost images, the detection of the lobes in the GALEX images is convincing as the features are neither in the mirroring direction along the optical axes from other bright sources, nor are they in the image of the same telescope pointing as YY Hya. They also resemble in basic shape and location the outer nebula seen in the optical images. The FUV/NUV ≫ 1 suggests similar physics of shocked gas like found in the 4 pc wide blue ring nebula around TYC 2597-735-1 (Hoadley et al. 2020).

2.3. Optical and Infrared Photometry

The light curve data from of the Catalina Real-time Transient Survey CRTS (Drake et al. 2009) were downloaded from the online data base⁷ and converted to the solar system barycentric time frame. Additionally, we obtained the time-series photometry from the Gaia DR2 data base (Holl et al. 2018). The WISE data and a handful of data points available from the Palomar Transient Factory (PTF, Law et al. 2009) were obtained from the NASA/IPAC Infrared Science Archive (IRSA)⁸.

Furthermore, we loaded the Transiting Exoplanet Survey Satellite (TESS, Ricker et al. 2015) full frame images (FFI) of sector 8 (February 2020) and quick-look, early release of calibrated FFIs of sector 35 (February/March 2021) and derived the simple aperture photometry (SAP) flux light curve by using eleanor (Feinstein et al. 2019) and our in-house public tool smarts⁹. As the TESS pixels are very large (21′′), the source is contaminated in the SAP aperture by the slightly brighter star Gaia DR2 5675391264067546624, which has G = 13.9 ± 0.7 and a color $BP − RP = 0.6 ± 0.7$, very similar to that of YY Hya. Thus, while this data allows a time-series analysis, no absolute calibration of the magnitude and the amplitude is possible. We thus used the red Gaia RP, with nearly the same effective wavelength of the passband (see Appendix Table A.2), to derive the calibration scale factor.

Using the visual band magnitude and color of the star in the Gaia photometry to estimate a spectral class range and the apparent magnitude, the central stellar source in the Gaia DR5 source data base (Bianchi et al. 2012) at the position of YY Hya shows a clear UV excess. In total, the collection of time series spans 16 years and 16 802 periods. A complete summary of the photometry can be found in the Appendix in Table A.1. We searched the time series for periods using an own implementation of the phase-dispersion minimization (PDM, Stellingwerf 1978) algorithm. Global solutions as well as individual blocks

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⁷ http://nessi.cacr.caltech.edu/DataRelease/
⁸ https://irsa.ipac.caltech.edu/frontpage/
⁹ https://doi.org/10.5281/zenodo.3768032
of 2 years were obtained to identify possible period changes, but no such changes were found down to the 0.5σ level. The period, $P = 0.03347894 \pm 0.00000004$ (≈ to a frequency $f = 2.98695 \, \text{d}^{-1}$), is constant to better than 0.1 seconds during those 16 years. Comparing the formalism from Knigge et al. (2011), the resulting limit of the period change implies that the system does not show strong mass transfer at the moment. The PDM is very sensitive to general period changes on those long time series. But as shown for the case of WZ Sge by Patterson et al. (2018), and as discussed in there for a set of other systems as well, these stars often show wiggles of the observed-computed (O–C) timing of eclipses, typically on timescales of 10 to 30 years. As we do not see an eclipse in our system, we are not sensitive to such small changes here. The ephemeris of minimum sinusoidal optical light curve is

$$BJD2458518.5082 + 0.3347894(4)E,$$

where $E$ is the integer cycle count.

Even more surprising is the remarkably sinusoidal shape of the light curve. Fitting a single sine function gives for the TESS data a correlation coefficient of $R^2 \approx 0.9997$ and $rms = 0.00073$. The near-perfect sinusoidal light curve allowed us to normalize the amplitudes from various wavelengths to a common light curve, showing that this perfect sinusoidal behavior was valid throughout the whole data period (Fig. 5). Moreover, after the drop from a flux ratio between maximum and minimum of the optical light curve of 2.5 for the two blue bands around 500 nm to 2.2 at 600 nm the amplitude is fairly well linear with a very small slope from 2.2 to 1.95 from approximately 610 to 4600 nm. As the flux in the Rayleigh–Jeans approximation part of a spectrum depends linearly on temperature $T$, this suggests that the variability originates mostly from temperature changes similar to those found in irradiated systems (Schaffenroth et al. 2019). Near infrared (NIR) data obtained at two epochs by the Deep Near Infrared Southern Sky Survey (DENIS, Epchtein et al. 1997) and one epoch from the Two Micron All Sky Survey (2MASS, Skrutskie et al. 1997) exist. All were obtained at phases near minimum. Using the linear relation of the amplitude with wavelength from the data with existing light curve small corrections towards an estimated minimum light were obtained to be used for the SED based on ATLAS9 stellar atmospheres (Castelli & Kurucz 2003) later. As the NIR observations were obtained near minimum such an estimate for observations at maximum light would be too much of an extrapolation. Thus we did not use the NIR photometry for the SED during maximum. The filter definitions and the calibration zero points for the entire photometric data are given in the Appendix in Table A.2.

Using the newest 3D Galactic extinction map Bayestar2019 (Green et al. 2019) we derive an interstellar reddening as low as $E(B − V) = 0.002$ while the Stilism map (Lallement et al. 2019) gives a value of $E(B − V) = 0.0043 \pm 0.0017$. We thus adopt the mean value of $0.0032$ for our further investigations. Furthermore, the extinction curve by Cardelli et al. (1989) was adopted. This covers purely the extinction of the foreground and the environment. Possible internal extinction within the system itself cannot be detected that way.

### 2.4. Optical Spectra

We obtained spectra of YY Hya at the 2.4 m Hiltner telescope at the MDM Observatory at Kitt Peak, Arizona, using the Ohio State Multi-Object Spectrograph (OSMOS; Martini et al. 2011). A 1′4 slit and a blue grism yielded a resolution of $R \approx 1600$ and a wavelength coverage from 3975 to 6865 Å. For wavelength calibration we used Hg, Ne, and Ar comparison lamps and fine-tuned the wavelength scale using night-sky emission features as needed. We observed spectrophotometric standard stars for flux calibration. Reductions were accomplished using an own pipeline that included elements from astropy and IRAF/pyraf. We also obtained a few spectra with the 1.3 m McGraw-Hill telescope and modspec spectrograph. These had a poorer signal-to-
noise ratio than the 2.4 m data, but were consistent with the results.

Table 1 summarizes the observations. A few spectra were taken on three successive nights in 2020 December, all of them near maximum in the optical light curve (the period is so close to 1/3 day that observations on successive nights near meridian transit are at nearly the same phase). In 2021 February and March we obtained much more extensive data on more widely separated nights, which sampled the entire orbit.

In the upper panel of Fig. 6 the averages of the flux-calibrated OSMOS spectra from near maximum and minimum in the optical light curve are plotted on the same scale. The maximum-light spectrum is dominated by a strong blue continuum and numerous emission lines of H, He i, He ii and weaker features that appear to be mostly singly and doubly-ionized C and N. The latter are very narrow while the H and He lines appear to be Stark broadened.

This kind of mixture of wide and strong H and He lines combined with narrow emission lines of low-ionized CNO elements looks very much like that in spectra found in post common envelope pre-cataclysmic variables like EC 11575-1845 (= TW CrV), V664 Cas (the central star of the planetary nebula HFG 1, Exter et al. 2005), HS 1857+5144 (Aungwerojwit et al. 2007; Shimansky et al. 2009), BE UMa (Shimansky et al. 2010; Mitrofanova et al. 2016). However, the emission-to-continuum light contrast is much weaker in those objects than the one we find here. Also, they all show spectra signatures of a white dwarf companion in the optical and have late M-type star companions (except BE UMa, Shimansky et al. 2008). UU Sge, also belonging to that class of objects, shows predominately much higher ionization levels for the CNO elements in the spectra (Wawrzyn et al. 2009).

In Table B.1 in the Appendix a full listing including relative line strengths of the very rich emission spectrum at phase 0.5 is given. The minimum-light spectrum is much fainter overall, with much weaker emission lines and prominent absorption features of a late-type star.

To quantify the contribution of the late-type star, we used a set of spectra of late-type stars classified by Keenan & McNeil (1989), observed with the modspec. Using an interactive program we scaled various spectra from this set and subtracted them from the minimum-light spectra, varying the spectral type and scale factor to optimize the cancellation of the late-type absorption features. The lower panel of Fig. 6 shows the best result, obtained with a K2 V star. Stars within ±2 subclasses of this gave acceptable cancellations.

We measured radial velocities of the late-type star using the IRAF fxcor task, which implements cross-correlation methods described by Tonry & Davis (1979). As a template, we used the average of 76 spectra of late-type IAU velocity standards that had been shifted to zero apparent velocity before the cross-correlation. Note that in this method the wavelengths of individual features are not measured. Regions around emission lines were masked. The spectra near minimum light gave strong correlations. Near maximum, in which the late-type features were barely visible, the correlations were much weaker and the velocity uncertainties correspondingly larger, but nearly all spectra showed at least some correlation. We also measured the velocity of the Hα emission line, using a convolution technique (Schneider & Young 1980); the velocities of the other emission lines were similar.

Figure 7 shows the velocities folded with the photometric phase. The emission lines move nearly in phase with the absorption, but with a somewhat smaller velocity amplitude. Table 2 gives the parameters of the best fitting sinusoids of the form \( v(t) = \gamma + K_{\text{em}} \sin(2\pi(t - T_0)/P), \) so that \( T_0 \) corresponds to inferior conjunction of the moving object. The period was held fixed at the photometric value, which spans a much longer time base; the epochs \( T_0 \) were allowed to vary. Even with this, both the epochs in Table 2 align with the ephemeris in Eqn. 1 to within 0.01 cycles. Equation 1 is for minimum light. The velocities therefore indicate an irradiation effect, since the cool star’s
Fig. 6. Upper panel: mean OSMOS spectra from 2021 February and March; the top trace is the average of spectra taken near maximum light, and the bottom trace near minimum light. The vertical axis is the same for both traces. Lower panel: the upper, black trace shows the same minimum-light spectrum as the top trace. The red trace is a scaled spectrum of a K2 V star, while the blue trace results from subtracting the scaled K-type spectrum from the observed spectrum.

Table 2. Radial velocities derived from the \(\text{H}\alpha\) emission (em) and from numerous absorption lines (abs). The period was fixed to 0\(^d\)3347894.44 out of the 45 spectra from 2021 were usable.

| Data | \(T_0\) | \(K_{\text{em,abs}}\) | \(\gamma\) | \(\sigma\) |
|------|--------|----------------|--------|--------|
| BJD  | \([\text{km s}^{-1}]\) | \([\text{km s}^{-1}]\) | \([\text{km s}^{-1}]\) |
| em   | -2400000 | 59254.712(2) | 105(5) | 18(3) | 18 |
| abs  | 59254.708(3) | 123(7) | 30(4) | 21 |

heated face is maximally turned away from us at inferior conjunction.

In Figs. 8 and 9, we present phase-resolved spectra similar to those produced by trailing a star along a spectrograph slit. To make these, we divided the phase into 100 bins, and for each bin averaged the spectra near that phase using a narrow Gaussian window. The spectra were then formed into a two-dimensional image, repeating once for continuity. In Fig. 8, we used the flux-calibrated spectra; the colormap is set to bring out the details of the spectrum near maximum light (phase 0.5 and 1.5) and the spectrum near minimum light is invisible. Because the light curve is generally extremely regular, the finer-scale horizontal banding is almost certainly an artifact of difference in the flux calibration caused by, for example, thin cloud or variable seeing.

Fig. 7. Radial velocities of the absorption component and \(\text{H}\alpha\) emission line in YY Hya, as a function of the period and epoch derived from the photometry. To preserve continuity, the data are repeated for one cycle. The solid lines show the best-fitting sinusoids.

Fig. 8. Two-dimensional phase-resolved spectrum prepared as described in the text. The spectra used here are flux-calibrated.

The emission lines dominate this view, and their velocity variation is evident.

In Fig. 9, the original spectra were divided by their continua, suppressing the overall modulation but bringing up the spectra in the faint phase. Here, the numerous K-star absorption lines can be seen, also moving approximately with the emission, as seen also in the radial velocity graphs (Fig. 7).
3. Proposed Binary Model

The photometric modulation and the time-resolved spectra show conclusively that YY Hya is a binary system in which a late-type star is strongly irradiated by a much hotter companion. This, together with the UV excess, leads us to model the system as a compact binary system with a white dwarf (WD) causing the strong irradiation effects. Other than in the objects of the BE UMa family (see e.g. Shimansky et al. 2016), the WD is not luminous enough to contribute significantly or even to dominate the optical luminosity. The resulting WD, although providing more than 99.5% of the flux in the GALEX FUV band, contributes less than 1% in the optical even during minimum phase, when only the non-illuminated side of the K star is seen. The irradiation modelling here follows widely the methods and discussions in Hamilton-Drager et al. (2018) for the post–nova V723 Cas.

While the far side of the secondary star is near the state of the normal main-sequence star, the other side is strongly illuminated and heated. This causes the sinusoidal light curve. Such compact systems are normally in bound rotation (see e.g. Schandl et al. 1997). The recurrent nova CI Aql, although even a bit more massive and with a period of $>0.46$ a significantly larger system behaves perfectly like this as well (Lederle & Kimeswenger 2003). Similar results are found by Haefner et al. (2004) and Parsons et al. (2010) in the case of the pre-cataclysmic variable NN Ser. The latter authors write in their analysis of the light curve that there is no detectable heating of the unirradiated face, despite intercepting radiative energy from the white dwarf which exceeds its own luminosity by over a factor of 20.0. Assuming now a nearly constant temperature at the far side of the cold stellar component, together with the findings in the spectroscopy (Fig. 6), we obtained an initial guess for the system during minimum. The lack of an eclipse gives an upper boundary for the system inclination, which only marginally depends on the mass ratio $q$.

As a hot compact companion does not suffer any deformation or irradiation effects, and as it is visible always, it can be modelled as constant contribution independent from the phase. This is especially important for the GALEX FUV band, where the large secondary star does not contribute to the radiation anymore, and thus no variation is expected at all.

Using the updated online version\(^\text{10}\) of the compilation and calibration by Pecaut & Mamajek (2013) we obtain then an upper limit of $M_e \leq 0.8 M_\odot$ and an radius $R_e \approx 0.75 R_\odot$. The effective temperature then would be $T_e \leq 5000 \text{ K}$. This corresponds to the spectroscopy during minimum phase shown above. However the 0.7 to 5 $\mu$m photometric colors during the minimum phase suggest a temperature of more likely near to 4000 K. That would correspond to a K6-7 star with $M_e \approx 0.6 M_\odot$, $R_e \geq 0.63 R_\odot$ and $T_e \geq 4000 \text{ K}$. We attribute the difference to the fact, that always a small fraction of the slightly heated transition zone towards the illuminated surface will show spectral lines resembling those of a slightly hotter star than that one found in the near- and mid-infrared photometry. Due to the inclination of the system here, other than in case of NN Ser, we always are contaminated by some light from the hotter illuminated side. This is supported by the distance estimate obtained from Gaia eDR3. The sole K2V star, without additional illuminating effect, with the given magnitudes during minimum, would lie already at $>500 \text{ pc}$. However the inclination always makes some additional flux from the illuminated side contributing to the photometry even during minimum. This effect diminishes towards the red and infrared (see also the decomposition in Fig. 6).

The mass $M_{WD}$ of the compact companion and the ratio $q$ finally is defined by the orbital period $P$, the system inclination $i$ and the velocity half amplitude $K$ from our spectroscopy by the binary mass fraction

$$f = \frac{M_{WD}^3 \sin^3 i}{(M_{WD} + M_e)^2} = \frac{P K^3}{2 \pi G}$$

where $G$ is gravitational constant, resulting in $0.4 \leq M_{WD} \leq 1.2 M_\odot$.

To model the light curve in detail we used the program Binary Maker 3 (BM3, Bradstreet & Steelman 2002)\(^\text{11}\). As mentioned already and nicely shown in the case of the evolution of the post–nova V723 Cas over the years moving to a low quiescence state, strong mass transfers and accretion discs cause significant asymmetric structures in the light curves (Hamilton-Drager et al. 2018). However, as we have a perfect sinusoidal light curve, we are able to assume a system without an accretion disk here for our model. As discussed in detail by Heber et al. (2018), irradiation efficiency is not completely understood and thus a source of systematic uncertainty. Schaffenroth et al. (2019) showed in the Eclipsing Reflection Effect Binaries from Optical Surveys (EREBOS) project with a large sample of spectrosopically investigated compact binary systems with hot subdwarf (sdB) companions that the efficiency in such systems is near to complete absorption of the UV radiation by the secondary. Model atmospheres using the PHOENIX model atmo-

\(^{10}\) http://www.pas.rochester.edu/~emamajek

\(^{11}\) http://www.binarymaker.com/
sphere code for the M-type stars of the non-mass-transferring post-common-envelope binaries GD 245, NN Ser, AA Dor, and UU Sge show similar results (Barman et al. 2004). Thus we adopted a unity value here. A stochastic gradient descent method (Russell et al. 2010) led to various local solutions in the minimum χ² search in the multidimensional parameter space. Therefore we manually calculated a complete grid of light curves with inclinations varying for each mass within the above calculated range in steps of 1° and a variation of the mass 0.4 ≤ MWD ≤ 1.2 M⊙ in steps of 0.05 M⊙. The size RM5 of the secondary was varied from ≈ 80% to exactly 100% of the Roche Lobe RRL in 12 steps. However, only within a few percent below the Roche Lobe perfect sinusoidal light curves were obtained. The temperature of the compact companion was varied from 50 000 to 80 000 K. Then the luminosity of the compact star was adapted until the light curve amplitude in the TESS and the CRTS bands was recovered as observed at a phase interval of ±0.05 around minimum and maximum (ϕMIN = 0.0 and ϕMAX = 0.5) each time. As the TESS photometric band is fairly red, this modelling does not suffer from the strong emission line regions at wavelengths below 5500 Å. As next step the goodness of the fit was calculated for the remaining phase regions by

$$\sum \frac{(I_{\text{data}} - I_{\text{model}})^2}{I_{\text{model}}} \forall (0.05 < \phi < 0.45) \lor (0.55 < \phi < 0.95).$$

The phase restriction for this calculation was used to avoid a dependency from the fit in the amplitude before the step. A small sub-sample of the residuals (Idata - Imodel) of the light curves is shown in the appendix in Fig. C.1. Purely from photometry there is only one possible solution in inclination i for each temperature TWD and luminosity LWWD for each of the selected MWWD. Due to the nearly noise-free TESS light curve this is very sensitive to the inclination i. Thus around the preliminary solution the grid was refined to 0.1 degree steps. The bandwidth of solutions varies only from 36 to just above 40° as function of the WD mass (Fig. 10). The system parameters, however, give us then a radial velocity. For an illuminated star we have to expect that the emission lines originate only from the half of the star towards the mass center. Thus the observed velocity half-maximum Kem / sin(i) of the emission lines will underestimate the orbital velocity K from Eqn. 2. On the other hand the absorption lines originate from the weakly and unilluminated part, having its weighted center outside the mass center. Thus the Kabs / sin(i) from the absorption lines will be an overestimate. This is described also in detail for EC 11575-1845 and V664 Cas in Exter et al. (2005). We thus safely and very conservative may use those two extreme cases Kem / sin(i) and Kabs / sin(i) as lower and upper boundaries, respectively. As indicated in Fig. 10 this limits the mass range for the white dwarf to 0.64 < MWWD < 0.85 M⊙ with favorite mass of MWWD ≈ 0.725 M⊙. The distance of the compact companion was then derived as well. The latter varies the luminosity in the mass-temperature plane (Fig. 11). However, the above mass constraints limit our further steps of the investigation to a small region in the luminosity-mass-temperature plane.

The luminosity LWWD and the effective temperature TWD were a priori independent free parameters, but are linked to a single degree of freedom by the GALEX FUV flux and the known distance of the system. For this purpose all WDs with T > 50 000 K in the sample of Finley et al. (1997) where GALEX FUV measurements were available were used together with the new Gaia eDR3 distances to derive a relationship between those two parameters. For the GALEX photometry the entire model grid from 50 000 < T < 150 000 K; 5.0 < log(g [cgs]) < 8.0 from Rauch (2003) was downloaded and folded with the published GALEX FUV filter curve (Rodrigo et al. 2013). However, as the dependency on gravity log(g) is very small in our temperature range this dimension was ultimately neglected. We used for the absolute calibration the two hot WD stars 0004+330 (Teff = 85 000 K) and 0231+050 (Teff = 50 000 K) from the calibration sample for GALEX by Camarota & Holberg (2014) and the WD in NN Ser due to its very accurately known stellar radius (Haefner et al. 2004; Parsons et al. 2010). Although the statistical errors given for the GALEX data are very small, we used a conservative error estimate, caused from possible systematic error in the extinction correction AFUV of 50%. This leads us to the
The best model magnitude. The solution for the mass range indicated by the thick dashed lines. Conservative estimates for systematic errors are (dotted lines) are very small. Fig. 12. The best model parameters are summarized in Table 3 and Fig. 13 shows the resulting geometry together with the light curve.

Table 3. Parameters of the best model.

| Parameter                  | Value          | Error       |
|----------------------------|----------------|-------------|
| MS star mass               | $M_\ast$       | $0.62 \pm 0.05 M_\odot$ |
| MS star radius             | $R_\ast$       | $94\% \pm 2\%$ $R_{RL}$ |
| MS star temperature        | $T_\ast$       | $4.5 \pm 0.3$ kK |
| MS star luminosity         | $L_\ast$       | $0.18 \pm 0.03$ $L_\odot$ |
| WD mass                    | $M_{WD}$       | $0.725 \pm 0.12 M_\odot$ |
| WD radius                  | $R_{WD}$       | $0.019 \pm 0.004 R_\odot$ |
| WD temperature             | $T_{WD}$       | $66.55 \pm 3.5$ kK |
| WD star luminosity         | $L_{WD}$       | $5.2 \pm 1.5$ $L_\odot$ |
| absorption efficiency      | $\eta$         | $1.0$ |
| system inclination         | $i$            | $40.2^\circ \pm 0.8^\circ$ |

(a) The luminosity of the MS star was calculated from mass and Roche Lobe radius without taking into account other possible systematic effects.
(b) The luminosity of the WD star is constrained by the light curve amplitude. Thus error bars of the other parameters are not independent.
(c) adopted value

final temperature range $T_{WD} = 66500 \pm 35000$ K (Fig. 12). The best model parameters are summarized in Table 3 and Fig. 13 shows the resulting geometry together with the light curve.

4. Galactic Context

Together with our spectroscopy, the Gaia mission data allow us to derive a full 6D dynamical investigation of the source. We use the Gaia EDR3 parallax and proper motions, and the average of $\gamma$ derived from the emission and the absorption lines as system radial velocity with a conservative error estimate due to the scatter in Fig. 7 (see Table 2). For the latter we thus use $v_{rad} = 24\pm10$ km s$^{-1}$. We use the Galactic potential as described by Allen & Santillan (1991) with the code of Odenkirchen & Brosche (1992) to compute the Galactic orbit and kinematic parameters of YY Hya in analogy to Pauli et al. (2006).

The orbit in the Cartesian Galactic coordinate frame $X, Y, Z$ with the Galactic center at the origin and $\rho$ parameterizing the Galactocentric distance (Fig. 14) is nearly circular and bound to the Galactic disk. Moreover, the comparison with the local WD sample by Pauli et al. (2006) also show that the position of the radial versus the rotational velocity components and the angular component $J_\phi$ perpendicular to the disk versus the orbital eccentricity $e$ clearly puts YY Hya into the middle of the young thin disk population. The currently reached height $Z = 155$ pc above the disk plane is in fact close to the maximum elevation reached in orbit.

Consequently, we are able to use the metal-rich WD evolution tracks from the most recent calculations by Miller Bertolami (2016) for the WD component of YY Hya. The WD mass of 0.725 $M_\odot$ gives us with the initial-to-final mass relation of Cummings et al. (2018) an initial stellar mass of 3-4 $M_\odot$. As the progenitor thus was a late B-type star (Mowlavi et al. 2012; Eker et al. 2018; Serenelli et al. 2021) with a lifetime of approximately half a Gyr or slightly below that, we conclude that the K-star companion has barely evolved off the zero-age main sequence.

5. Discussion and Conclusion

From the data presented above, it is clear that YY Hya is not an RR Lyr star as classified up to now in the literature but is instead a compact binary of a late K-type main-sequence star with a hot WD companion. Due to a small separation, the system certainly went through a common envelope (CE) phase. The long term stability of the period and phase shown here, suggest that no major mass transfer is currently happening in this system. Moreover, the perfect symmetric and sinusoidal light curve supports that there is no accretion disk and no hot spot from an accretion stream.

Our spectroscopic results showing hardly any emission lines during minimum light phase means that its light curve is dominated by the irradiation of the compact hot WD on the secondary star. While the H and He emission lines are strongly broadened, other emission lines, mainly originating from the CNO group elements in low ionization states, are narrow. This is similar to the findings in the binaries of the BE UMa family formed mainly by EC 11575-1845 = TW CrV, V664 Cas = the central star of the planetary nebula HFG 1, HS 1857+5144, BE UMa, NN Ser = the central star of the PN ETHOS 1 = PN G068.1+11.0 (Exter et al. 2005; Aungwerojwit et al. 2007; Shimansky et al. 2009, 2008; Parsons et al. 2010; Mitrofanova et al. 2016; Munday et al. 2020).

BE UMa systems all exhibit sinusoidal light curves with no signatures of current mass transfer and active accretion. They also show spectra signatures of the white dwarf companion in the optical and have late M-type star companions (except BE UMa; Shimansky et al. 2008). The low-luminosity companions do not oustine the WD in the optical. Thus the emission line contrast over the continuum is much smaller. The contributing WD spectra with the wide strong H and He absorptions further reduce the emission line contrast for H and He lines. Thus all those effects we see in YY Hya are less pronounced there. But still we denote YY Hya as upper boundary case with higher mass companion within this class of BE UMa variables. UU Sge, the central star of the PN A63 (PN G053.8-03.0), also belonging to that class of objects, shows predominately much higher ionization levels for the CNO elements in the spectra (Wawrzyn et al. 2009). Older members of this physical family, with already much cooler WDs, might be MS Peg and LM Com (Shimansky et al. 2003). However, the low luminosity of the WDs in these systems result in much lower photometric amplitudes of $0^\circ1$ to $0^\circ2$ and only weak emission lines of neutral metals like Fe i, Na i, and Mg i.
Recently Kruckow et al. (2021) published a catalog from the literature containing more than 800 candidates of post-CE systems. Only the small fraction shown here belongs into our class of objects with periods below 1 day with no e -ff ects. Only the small fraction shown here belongs into our class of post-CE but pre-cataclysmic variables. Investigations systematically searching for such close binary systems in the cores of PNe in the Gaia era will certainly expand the family (Chornay et al. 2021) but will be limited to the young objects of the group.

We follow the suggestion by Shimansky et al. (2016), who used the derived position along the temperature-time evolution of post-AGB white dwarfs to derive an age since the break of the AGB due to the CE phase. With the WD mass of 0.725±0.047 M⊙, we obtain an age since leaving the AGB of 520 to 600 kyr from the most recent evolutionary tracks by Miller Bertolami (2016). Shimansky et al. (2016) furthermore define the relative luminosity excess log(A/L) as the difference between the expected luminosity using a WD evolutionary track and the observed one in the HRD at the post-CE age of the system. The value of about −0.6 lies significantly above their relation. However, as the re-analysis of the central star of the PN ETHOS 1 shows, moving from the very old evolutionary tracks of Bloecker (1995) to the faster evolving modern post-AGB evolution change the system parameters already. Moreover, all systems there, except the very young and hot central star of PN ETHOS 1, have much lower WD masses. Thus the initial masses of the stars, forming the compact companion later, were much lower with the secondary stars being late M stars. The exception is BE UMa. However, that system is very wide (Porb =2729).

The latter difference might be the main reason why YY Hya formed such a massive large nebula, while the young objects of the class all show nearly normal PNe. Two objects in the sample of Shimansky et al. (2016) with similar ages, namely EC 11575-1845 and HS 1857+5144, however, show similar spectroscopic and photometric signatures. Taking the size of the main nebula 4.8 pc and assuming a CE age of 520 to 600 kyr together with typical expansions of of 5 to 20 km s⁻¹ for CE shells from models (Clayton et al. 2017; Glanz & Perets 2018), we end up in fact with a few hundred thousand years. Moreover, Clayton et al. (2017) show that the orbital effect pronounces episodic quasi-periodic mass-loss history during CE ejection. That will give a structured nebula as we see in the case of YY Hya.

To estimate a mass we used the Hα surface brightness using NEBULAR (Schrömer 2016). Assuming the shell being a aggregate of slabs with a thickness of 1% of the radius each, and assuming the brightest fragments cover about 10% along the line of sight in each case, we end up with a density nH of about 2 to 7 hydrogen atoms per cm³. Assuming that these fragments have a volume filling factor of few percent we end up with a shell of about one solar mass. This supports the idea that this nebula is the result of an ejected CE. Recombination time scales of such a plasma would be 25 000 to 100 000 years (Osterbrock & Ferland 2006). However, a static solution of the photoionization with the model of our WD and such a shell with CLOUDY (Ferland 2006) leads to photoionization fractions of about 0.5 for the hydrogen. That, and the fact, that the WD was hotter and more luminous in recent history, slows down the recombination. The CLOUDY model also predict [O iii]5007Å/Hα line ratios of 10⁻⁴. Thus we failed to observe the nebula in that line. Moreover, this model would predict a [O iii](3726+29Å)/Hα of 0.3, promising for observations.

We carried out a multi-wavelength search, using the Aladin v11 image facilities (Bonan et al. 2000) from the radio (NVSS) over infrared (IRAS, AKARI, WISE, PLANCK), to X-rays (ROSAT) and γ-rays (FERMI). But neither the nebular center, nor the lobes appear in any of those images.
YY Hya’s high Galactic latitude and the absence of large interstellar clouds in its local vicinity, the geometry of the vis-à-vis lobes plus their enormous extent, makes the explanation of ionized interstellar matter very unlikely. Instead, they are likely termination bow shocks of jets formed during the CE phase. As the FUV flux is higher in these lobes than in the main nebula, the idea that they are termination shocks of a bipolar jet is supported by models (Chamandy et al. 2018) which show that the formation of such jets is not unusual for CE evolution. However, Chamandy et al. (2018) claim that the detailed physics near the cores still cannot be handled properly due to numerical limits on the large scale differences in the systems. Moreover, the direction defined by the lobes point toward the Galactic plane, which is located south-west of the target, there is a slight gradient of emission visible in the PLANCK and the AKARI images. The large distance of the lobes make a gradient of the ISM already likely on the target scale. This might be the reason why the south-west lobe is so much more prominent than the north-east one.

While the wide system of BD+46°442 (P > 140 days) certainly does not belong to this same class of CE objects, it currently shows such a jet formation (Bollen et al. 2017). Investigations of the young objects of the EB UMa class including UX Sge (Mitchell et al. 2007) and PN ETHOS 1 (Miszalski et al. 2011), as well as of PN G054.2-03.4 (The Necklace; Corradi et al. 2011) all show jet structures with a 3:1 size ratio compared to the main nebula. Moreover, Miszalski et al. (2011) find that all those structures are dynamically a few hundred years older than the main nebula. We note that in the case of YY Hya such a small offset will not be significant after such a long time of >500 kyr.

In summary, we find YY Hya to be a BE UMa type post-common envelope pre-cataclysmic variable. Within this family of objects, the YY Hya system extends the upper limit of mass ranges found up to now, both for the primary as well as for the secondary star. A larger stellar shell is the reason for the massive large emission nebula and the far distant vis-à-vis lobes. Moreover, its high Galactic latitude (b = +20°) has helped to keep these structures largely undisturbed for a long time. Deep and high-resolution spectroscopy of these structures is encouraged to obtain insight into the spatio-kinematic structure as well as more detailed information on the excitation and recombination state of such shells.

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The image mosaic was obtained from 294 images taken at the CHILESCOPE facilities. CHILESCOPE is a remotely controlled commercial observatory located in the Chiléean Andes (70°45'53"W, 30°28'15"S, 1567 m a.s.l.) about 25 km south of the Gemini South and LSST telescope site Cerro Pachón. We used the 50 cm Newtonian telescopes built by Astro System Austria (ASA)\textsuperscript{15}. These telescopes have a focal ratio f/3.8 and are equipped with 4 K × 4 K FLI PROLINE 16803\textsuperscript{15} CCD cameras, yielding a pixel scale of 0'963 pixel\textsuperscript{-1} and a FOV of 1°096 × 1°096. Furthermore, we used for the mosaic the Ha (FWHM 3 nm) filter from Astrodon\textsuperscript{16}. This filter is known to suppress contamination from possible [N II] to a level below 5% of the intensity of those lines. As the [N II]:[S II] ratio is about 10:1 in shocked nebulae like supernovae remnants and even lower for H ii regions (Magrini et al. 2003; Barría et al. 2018), and as [S II] was not detected in even the brightest regions, we are able to conclude, that we do not suffer from contamination by the nitrogen line.

Each individual exposure time was 20 minutes around 9 pointing positions with their FOV overlapping 50% each. A total exposure time of about 100 hours was accumulated. Due to the overlap the central regions were covered with a total exposure time of 40 hours, while the outer ring with 25% of the image width was covered only by 20 hours. However the very corners were mapped only about 11 hours. To compensate for minor variations due to weather, seeing and airmass, in the overlapping regions a common set of about 300 stars ranging from a 5σ detection level until the overexposure at the central pixels were extracted using SExtractor v 2.19.5 (2019-07-27) (Bertin & Arnouts 1996). They were used to scale the frames to a common flux calibration. The median of this calibration was used and the rms of these calibration factor was about 20%. The worst case was a set of less than 10 frames achieving only about 50% of the median flux, due to the high overlap of up to 120 fields, no special noise suppression handling for those fields after the flux scaling was required.

The astrometry was obtained by the use of a local installation of solve-field and wcs-resample of the astrometry.net\textsuperscript{17} suite v0.85 (Lang et al. 2010) with a Gaia eDR3 catalog subset of the surrounding 3' field. To get a proper distortion correction of this fast f/3.8 telescopes a 4th order projection correction prior to stacking the images was required. The final positional rms was below 1''/50 of a pixel. Resampling to this grid allowed to generate a mean image now. At each position now the image count varies from 32 to 120 frames. We used the mean value of the pixels, eliminating the 3 lowest and 3 highest values. This removed cosmics and satellite spurrs but still reduces noise by building means of a large number of frames. Thus it is superior to simply using the median value.

Lacking calibrator and standard fields in the used H$_\alpha$ filter set, Gaia data were used to derive an absolute flux estimation. About 1000 stars from the central region just outside of the main nebula and from the NE and the SW corner field were matched with Gaia eDR3 stars. The red band magnitudes Gaia $R_P$ and the $BP - BR$ color were used to derive the zero point $ZP$ and a linear color term

12 http://svo2.cab.inta-csic.es/theory/fps/


tables

| survey    | date [UTC]          | MJD$_{helio}$ | band | $N$  |
|-----------|---------------------|---------------|------|-----|
| CRTS      | from 2005-10-11 05:24 to 2013-05-09 23:52 | 53654.225 | V    | 315 |
|           |                     | 56421.995     |      |     |
| WISE      | from 2010-05-17 06:05 to 2010-11-28 22:45 | 55333.254 | W1   | 37  |
|           |                     | 55528.948     | W2   | 36  |
| PTF       | from 2013-03-11 04:22 to 2013-03-12 05:06 | 56362.182 | R    | 12  |
| Gaia      | from 2014-11-02 01:12 to 2016-05-02 19:53 | 56963.050 | G    | 27  |
|           |                     | 57510.829     | BP   | 27  |
| TESS      | from 2019-02-05 00:21 to 2019-02-27 23:52 | 58519.015 | $R_T$| 748 |
|           |                     | 58541.995     |      |     |
| DENIS     | at 1996-04-20 12:48 | 50193.534 | $I_{JK_s}$ | 2665 |
|           | at 2000-01-24 18:25 | 51567.768 | $I_{JK_s}$ | 2018 |
| 2MASS     | at 1999-02-18 14:54 | 51227.621 | $JHK_s$ |     |

In Table A.1 the summary for the observations for the time series used in this paper are given. Table A.2 gives an overview of the photometry. Passbands and zero points are taken from the continuously maintained online database\textsuperscript{12} of the SVO filter service (Rodrigo et al. 2013). In case of Gaia, where several filter sets are defined for DR2, we used the revised definition by Weiler (2018) from the data base. The interstellar extinction calculation is based on Cardelli et al. (1989) and the adopted reddening value of $E(B-V)=0.032$ using $R = 3.1$. As the line of sight is far from the Galactic plane and does not show major dense clouds in the vicinity, these values derived for the thin interstellar matter seem to be most applicable. Due to the small value of the extinction, in fact the selection of the curve type and of $R$ is not causing a significant variation of the result. For those data sets, where a full fit of the light curve was possible, the minimum, mean and maximum from the derived sinusoidal curve fit is used. For the experiments and bands where only one or two measurements were given together the phase of the measurement is given together with the magnitude $m^\text{obs}$. Furthermore we used the wavelength–magnitude relation from the large data time series to calculate an estimate for the minimum brightness and corrected for interstellar extinction leading to $m^\text{min}$. Only for the GALEX data no such amplitude correction was derived. As discussed before we do not have to assume a significant amplitude of the the far UV component.
### Table A.2. Overview of the photometric bands, used effective wavelengths $\lambda_{\text{eff}}$, calibration zero points $ZP$ and the interstellar extinction $A_\lambda$. Furthermore the overview of the magnitudes as used in the SED fitting (see text).

| band          | $\lambda_{\text{eff}}$ [nm] | $ZP$ [Jy] | $A_\lambda$ [mag] | $m_{\text{min}}^\lambda$ [mag] | $m_{\text{max}}^\lambda$ [mag] | amplitude [mag] | phase [0,1] | $m_\lambda^p$ [mag] | $m_{\text{min}}^\lambda$ [mag] |
|---------------|---------------------|----------|------------------|-------------------|-------------------|----------------|----------|-----------------|------------------|
| GALEX FUV     | 154.9               | 521      | .261             |                   |                   | 0.38           | 14.142  | 13.88          |                   |
| GALEX NUV     | 230.5               | 789      | .284             |                   |                   | 0.38           | 14.440  | 14.16          |                   |
| Gaia $BP$     | 502.1               | 3393     | .112             | 14.577            | 14.077            | 13.576         | 1.002    | 14.46          |                   |
| CRTS $V$      | 561.8               | 2690     | .0975            | 14.378            | 13.897            | 13.416         | 0.963    | 14.28          |                   |
| Gaia $G$      | 583.6               | 2835     | .0975            | 14.374            | 13.912            | 13.449         | 0.925    | 14.28          |                   |
| PTF $R$       | 612.2               | 3042     | .0887            | 14.387            | 13.955            | 13.524         | 0.864    | 14.30          |                   |
| Gaia $RP$     | 758.9               | 2485     | .0659            | 13.958            | 13.534            | 13.110         | 0.847    | 13.89          |                   |
| DENIS $I_c$   | 786.2               | 2442     | .0618            |                   |                   | 0.12           | 13.474  | 13.74          |                   |
| DENIS $J$     | 1221.1588           | .0293    |                   |                   |                   | 0.12           | 13.115  | 13.21          |                   |
| 2MASS $J$     | 1235.1594           | .0288    |                   |                   |                   | 0.78           | 12.867  | 13.20          |                   |
| DENIS $K_s$   | 2147.667            | .0118    |                   |                   |                   | 0.12           | 12.809  | 12.91          |                   |
| 2MASS $K_s$   | 2159.666            | .0117    |                   |                   |                   | 0.78           | 12.392  | 12.72          |                   |
| WISE W1       | 3353.310            | .0061    | 12.845           | 12.523            | 12.201            | 0.644          | 12.84   |                |                   |
| WISE W2       | 4603.172            | .0047    | 12.805           | 12.444            | 12.084            | 0.722          | 12.80   |                |                   |

$m_{\text{phot}} = m_{\text{Gaia RP}} + k_\lambda(BP - RP) + ZP$.

While the $\text{rms}$ of the $ZP$ for the stars $m_{\text{Gaia RP}} < 17$ was better than $0.02$ only minor systematic variations of the order of $0.08$ were found between the better covered central region and the extreme field corners (Fig. B.1). The color term $k_\lambda = 0.35 \pm 0.11$ was derived. To derive a flux calibration of the emission line, the stellar flux $f$ had to be integrated over the response curve $I$ of the 3 nm wide filter.

$$I_\star = \int_{\lambda_{\text{eff}}}^{\lambda_{\text{max}}} f(\lambda)I(\lambda) d\lambda.$$  

As the colors of the field stars show that the sample is dominated by stars later than G5 one can assume that the $H\alpha$ absorption lines do not dominate the flux variation in that region and the stars in a statistical average and we thus can take out the $f(\lambda)$ from the integral in this small wavelength region. The response curve $R(\lambda)$ of the Astrodon filters published by the vendor was integrated numerically giving a value of $2.95$ nm. The monochromatic flux in the Vega system was obtained again from the SVO filter service (Rodrigo et al. 2013) from various published 3 nm $H\alpha$ filters from ING, ESO and TNG. They vary by less that 4%. We adopted thus for $m_{\text{phot}} = 0.0$ the mean value of $f(\lambda) = 1.65 \times 10^{-9}$ erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$. Using this calibration we obtain a zero point for the surface brightness of $2.8 \times 10^{-17}$ erg cm$^{-2}$ s$^{-1}$ arcsec$^{-1}$ for the mosaic.

### Appendix C: Model grid

Figure C.1 shows a fraction of the whole grid of models. The effects of the most critical parameters for the modeling, namely the system inclination $i$ and the fraction of the donor star radius in units of the Roche lobe radius $R_{\text{Roche}}$ are demonstrated for the solution fulfilling the best match to the amplitude for this pair of parameters.
Fig. C.1. A section of the model grid for lowest mass of the grid ($M_{WD} = 0.4 M_\odot$). The deviation of the TESS data intensity $I_{\text{data}}$ to the model $I_{\text{model}}$ as function of the phase is shown. The columns are for constant radius of the donor star from left to right 1.000, 0.955, 0.910, 0.865, 0.820 times of the Roche lobe radius $R_{\text{Roche}}$. Along the rows the system inclination $i$ varies from 28° to 52° in steps of 4°. The compact companion luminosity was varied each time to fit the system amplitude (see Sect. 3).
Appendix D: Possible Historical Link

Finally, although a bit speculative, we briefly discuss a possible link of YY Hya and its nebula with an apparent "guest star" sighting in Hydra reported in August and September 1065 AD by Korean and Chinese astronomers (Hsi 1957; Ho 1962; Kronk 1999). Although the secondary is not Roche Lobe filling and thus is not feeding accretion yet, fullback from the very slowly ejected CE envelope may cause possibly similar accretion at slower scales on the WD. Taking into account the rotation of the equinox, we find YY Hya to lie at $a = 08^h43^m26^s, \delta = -18^\circ25'54''$ in 1065 AD. Assuming an observational site in China where the location of YY Hya was visible above the horizon, then YY Hya would be visible about 1.5 hours before sunrise and reached a position about 14° above horizon at the end of the night. It would appear just above the constellation called the celestial temple in the medieval Chinese constellation map by Su Song dated 1092 (Needham 1959). Using this position and constellations as input to Stellarium\(^{18}\), we find that the YY Hya is near to the constellation Tian Miao (天疆 – also

http://stellarium.org

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Table B.1. Observed Emission Lines in YY Hya at Phase 0.5. The listed line strengths are relative to C iv 4650 = 100.

| Obs. $\lambda$ | Rel. Flux | FWHM [A] | Line ID | Lab $\lambda$ [A] |
|---------------|-----------|-----------|---------|------------------|
| 3996.4        | 3         | 3.5       | N ii    | 3995.0           |
| 4010.8        | 7         | 3.9       | He i    | 4009.3           |
| 4027.6        | 41        | 4.5       | He i    | 4026.2           |
| 4044.1        | 12        | 7.1       | N ii    | 4041.3, 4043.53  |
| 4071.6        | 28        | 4.7       | C iii   | 4070.3           |
| 4076.8        | 24        | 6.0       | C i, C ii| 4073.3, 4075-76  |
| 4103.1        | 271       | 7.7       | H i     | 4101.8           |
| 4121.7        | 17        | 4.2       | He i    | 4120.8           |
| 4132.1        | 8         | 4.7       | N iii   | 4133.8, 4134.9   |
| 4145.1        | 18        | 4.6       | N i, N ii| 4143.4, 4145.8   |
| 4242.1        | 20        | 15.7      | C i, C iii| 4223-28, 4247-52 |
| 4268.3        | 41        | 3.9       | C ii    | 4267.2           |
| 4277.4        | 5         | 3.5       | O ii    | 4276.6           |
| 4318.9        | 9         | 5.0       | C ii    | 4317.4           |
| 4341.7        | 227       | 7.5       | H i     | 4340.5           |
| 4359.3        | 15        | 5.7       | O ii    | 4357-59          |
| 4379.9        | 6         | 3.3       | C iii   | 4379.5           |
| 4389.0        | 28        | 4.8       | C iii   | 4388.0, 4390.5   |
| 4416.6        | 22        | 5.5       | O ii    | 4414.9, 4417.0   |
| 4448.8        | 2         | 2.8       | N ii    | 4447.0           |
| 4472.2        | 40        | 5.0       | He i    | 4471.7           |
| 4482.1        | 13        | 3.8       | Mg ii   | 4481.3           |
| 4514.7        | 10        | 11.5      | N iii   | 4510.9, 4514.9   |
| 4532.0        | 2         | 4.9       | N iii   | 4530.9, 4534.6   |
| 4542.5        | 4         | 4.1       | O iii, N iii| 4540.4, 4544.8 |
| 4553.3        | 6         | 5.3       | N iii, Si iii| 4551.4, 4553-54 |
| 4568.8        | 2         | 3.1       | Si iii  | 4567.8           |
| 4591.9        | 4         | 3.2       | O ii    | 4591.0           |
| 4610.2        | 5         | 4.7       | N ii, N iii| 4607.2, 4610.7   |
| 4634.2        | 21        | 7.0       | N ii    | 4630.5, 4634.1   |
| 4641.9        | 35        | 3.6       | N iii   | 4640.6           |
| 4649.9        | 100       | 5.8       | C iii   | 4647.4, 4650.3   |
| 4662.4        | 4         | 3.3       | O ii    | 4661.6           |
| 4677.1        | 4         | 2.7       | C i     | 4676.7           |
| 4686.5        | 52        | 3.4       | He ii   | 4685.7           |
| 4700.0        | 2         | 2.8       | O ii    | 4699.1           |
| 4705.9        | 3         | 2.7       | O ii    | 4705.3           |

Fig. D.1. The visibility of the region of YY Hya in the morning hours of September, 11th 1065 from Beijing, China using the medieval Chinese constellations. The circle marks the position of YY Hya. The plot was generated by Stellarium 0.19.1.
called Thiên Miào, Tiānmiào, Thien-miao and T’ien-Miao) containing 14 stars. The precession-corrected position of YY Hya is indicated as well (Fig. D.1). That is what (Hsi 1957) mentions for the vicinity of the 1065 event. Furthermore, it corresponds to the maps in the investigation about ancient comets in Williams (1871) and independently in the framework of the tail of the comet of 1385 in Hind (1845). They appoint this region mostly covered nowadays by Pyxis (or Pixis Nautica).

The position of YY Hya is just on the border to this modern constellation definition\(^{19}\). Moreover, the crude positional estimate of \(\alpha = 10^h 20^m, \delta = -30^\circ\) in B1950 (\(\alpha = 09^h 49^m, \delta = -25^\circ 30^\prime\) in 1065) given by Hsi (1957), which is in fact near to the \(m_V = 4\pm 25\) star \(\alpha\) Ant, was too much south and not observable in nighttime from China at that time. We thus have not to further consider this result. In view of these positional agreements, we propose that the link of the 1065 AD transient event with YY Hya is at least possible.

Assuming a typical absolute visual magnitude of a Nova with \(M_V \approx -8^{m} 0\), it should have been at \(m_V \approx +0^{m} 2\). As there are no stars brighter than \(m_V < +4^{m} 0\) in roughly 13.5 from the position, and the nearest planet was Saturn at a distance of over 25 degrees away in late August and September 1065 AD, it would seem the 1065 AD guest star may have been fairly noticeable given this nearly empty bright star region of the sky. However, with an angular size of 36\(\prime\) (\(\equiv 4.8\) pc @ \(D_{\text{Gaia}} = 456\) pc) and an age of about 1000 years, YY Hya’s main nebula would require an average expansion of slightly above 2200 km s\(^{-1}\) if it was created in a single event. The outer lobes lying at a distance of 11.5 pc would lead to jets with even higher velocities, around 11 200 km s\(^{-1}\). Something we do not observe. Also the mass estimate of the shell is by orders of magnitudes too large for a single Nova event. This, excludes that the nebulae around YY Hya was generated during that event about 1000 years ago.

\(^{19}\) https://www.iau.org/public/themes/constellations/