There are mysterious spiral nebulae around some massive stars... Read all about it in my new paper titled:

Draft version August 20, 2025
Typeset using LaTeX twocolumn style in AASTeX7.0.1

The Serpent Eating Its Own Tail: Dust Destruction in the Apep Colliding-Wind Nebula

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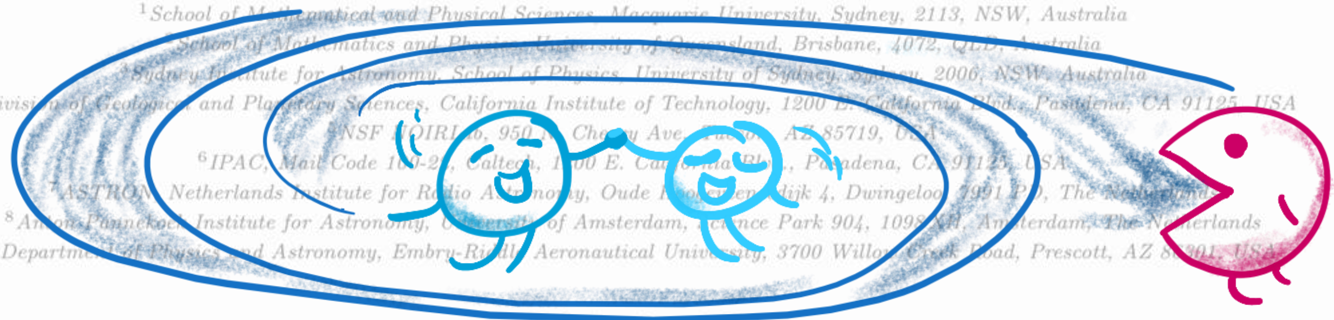


Submitted to ApJ

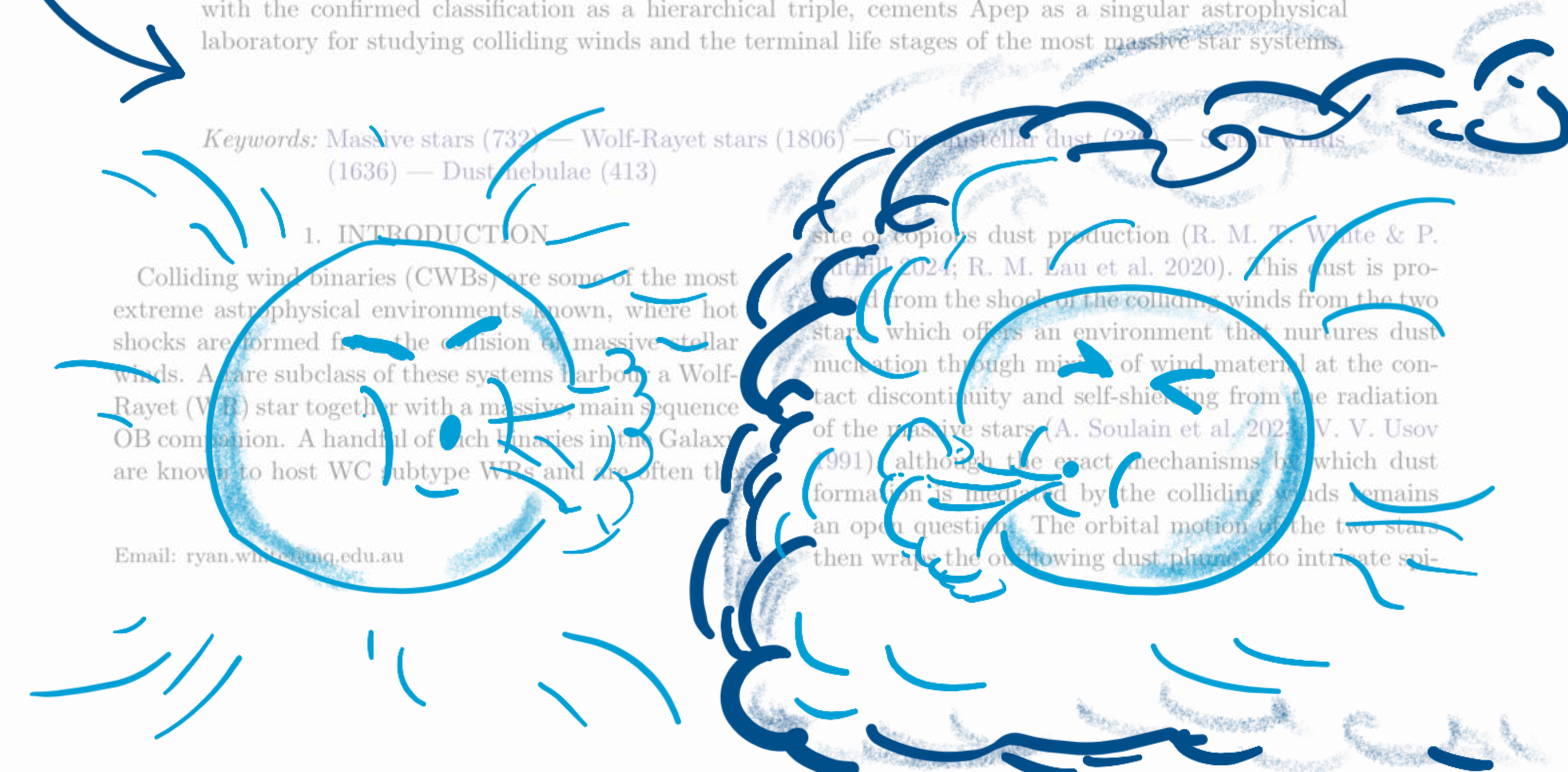
Give it to me straight, doc:

Lots of massive stars, those much heavier than our Sun, come in pairs. These stars have 'winds', and since they are so close, their two winds smash together! This makes a hell of a lot of carbon soot which we can then image with our fancy telescopes. We use the (very fancy) James Webb Space Telescope to look at one such system – the Apep System, named after the Egyptian god of chaos – and we use this soot to figure out (almost) everything that's going on. Turns out that there's not just two, but three stars and it's all very complicated!

ABSTRACT

Much of the carbonaceous dust observed in the early universe may originate from colliding wind ... the stellar winds there exists a suitable environment for dust grain formation, and the orbital motion of the stars wraps this dust into richly structured spiral geometries. The Apep system is the most ... slow expansion has been linked to a gamma-ray burst progenitor. It has been unclear whether the O-type supergiant 0.7'' distant from the WR+WR binary is physically associated with the system, ... that this northern companion star routinely carves a cavity in the dust nebula – the first time such an ... to the Apep system. These observations are used together with a new geometric model to infer the cavity geometry and the orbit of the WR+WR binary, yielding the first strong constraints on wind ... an order of magnitude longer than the next longest period dust-producing WR-CWB. This, together with the confirmed classification as a hierarchical triple, cements Apep as a singular astrophysical laboratory for studying colliding winds and the terminal life stages of the most massive star systems.

Keywords: Massive stars (732) — Wolf-Rayet stars (1806) — Circumstellar dust (236) — Stellar winds (1636) — Dust nebulae (413)



1. INTRODUCTION

Colliding wind binaries (CWBs) are some of the most extreme astrophysical environments known, where hot shocks are formed from the collision of massive stellar winds. A rare subclass of these systems harbor a Wolf-Rayet (WR) star together with a massive, main sequence OB companion. A handful of such binaries in the Galaxy are known to host WC subtype WRs and are often the site of copious dust production (R. M. T. White & P. Tuthill 2024; R. M. Lau et al. 2020). This dust is produced from the shock of the colliding winds from the two stars, which offers an environment that nurtures dust nucleation through mixing of wind material at the contact discontinuity and self-shielding from the radiation of the massive stars (A. Soulain et al. 2023; V. V. Usov 1991), although the exact mechanisms by which dust formation is mediated by the colliding winds remains an open question. The orbital motion of the two stars then wraps the outflowing dust plume into intricate spi-

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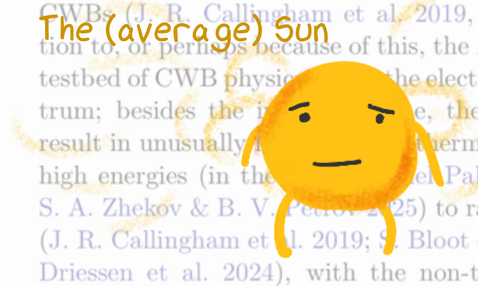
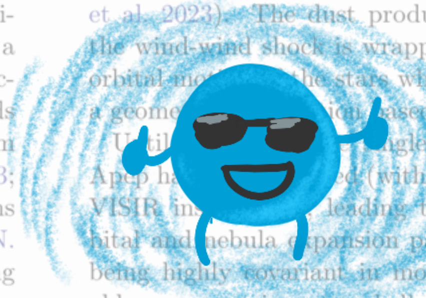
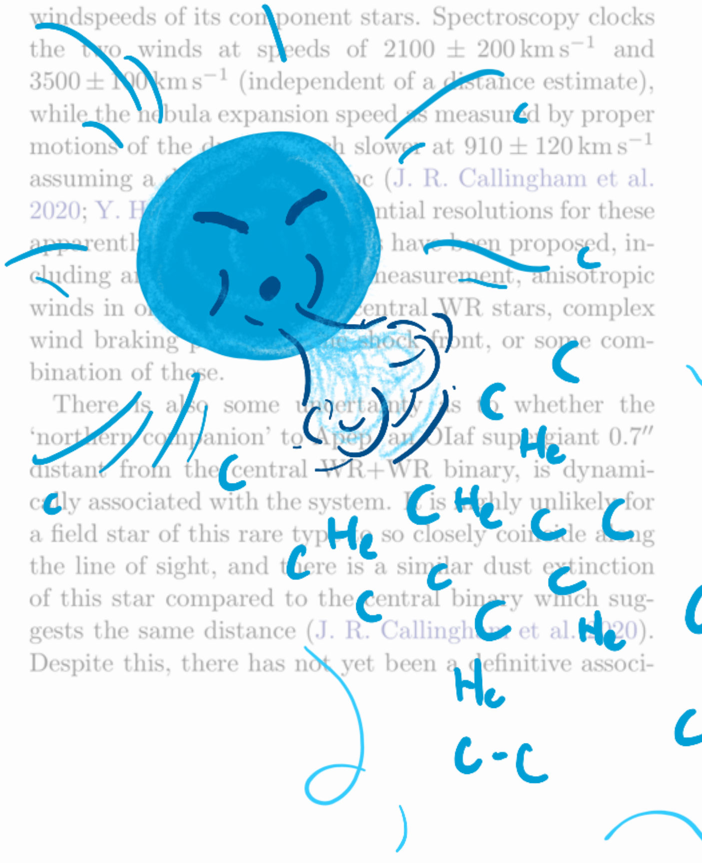
Okay, what are these systems and why do we care?

You're probably familiar with the Sun. It's a fairly average star. Most stars are a lot lighter than the Sun, and there are also many that are a *lot* heavier – some can be up to 100 times more massive. Those that are initially ~30 times or more as massive as our Sun will eventually get rid of most of their hydrogen, leaving behind a core of helium, carbon, and nitrogen. These cores are called 'Wolf-Rayet' stars – after the two French dudes who discovered them – and they are exceptionally bright stars, with unusually strong winds.

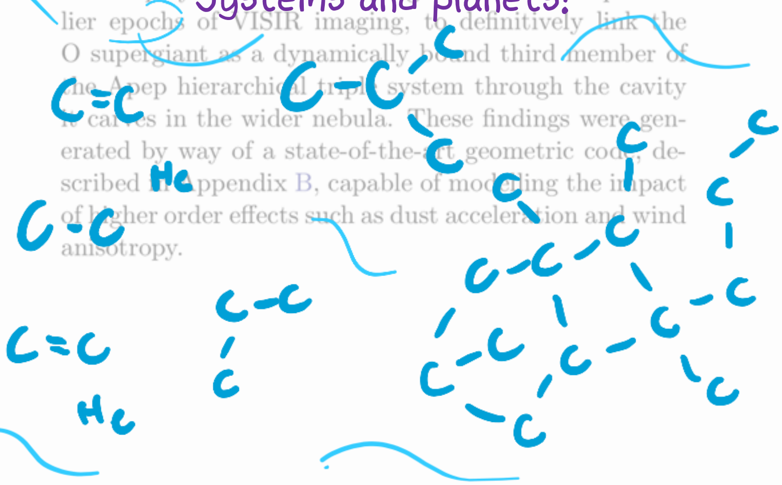




It might be strange to think of stars having winds, but our Sun does too! This is why we have aurorae on Earth: the solar wind interacting with our atmosphere. A Wolf-Rayet star's wind is about a trillion times more powerful than that of our Sun. Almost 10 years ago, our team found a system with *two* of these Wolf-Rayet stars and they named it Apep. More about Apep soon...



Because Wolf-Rayet stars have no hydrogen, their winds are made up entirely of helium and carbon*. This means that they can be very efficient factories of carbon dust – jumbled together grains of carbon molecules. This dust goes on to form new Solar Systems and planets!



Double trouble?

2. METHODS

2.1. *Apep Direct Images*

Most of these Wolf-Rayet stars, like our Apep system, are in binary or higher order systems – systems where two or more stars orbit a common centre of mass. Each of these massive stars have their own wind, and so somewhere between the stars their winds collide which 'shocks' the wind, compressing it and mixing it together.

The Apep system was observed with JWST MIRI as part of the JWST GO Program 5842 on July 24, 2024 [illegible] F1500W [illegible] 2550W filters. We show a false-colour composite image using these filters in Figure 1 following the reduction process of [illegible] (submitted) [illegible].

In addition to the multi-wavelength JWST images taken, Apep was imaged with the VLT VISIR instrument in June 2024, bringing the total number of VISIR-Apep epochs to 4 spanning the years 2016 to 2024. All VISIR images used in this study were taken in the J8.9 band which is centred at 8.7 μm. The data reduction for the VLT images is described in more detail in Y. Han et al. (submitted).

Our Wolf-Rayet star with the strong wind

2.2. [illegible]ric Model

We have develop[illegible]nd fast colliding wind nebula geometric model, [illegible]orph (R. M. T. White 2025) – which is motivated by the new VLT and JWST imagery of Apep – that can be applied to any CWB with resolved dust spirals. The basic principle is similar to previous geometric codes, e.g. that in Y. Han et al. (2022), although our new code is ~ 100 times more performant due to our using the JAX framework for Python (J. Bradbury et al. 2018), as well as featuring more physical parameters, being more user friendly, and better [illegible]ce code is available at github.com/ryanwhite1/xenomorph. We describe the physical features of the code and their motivation in Ap[illegible] be how we have used the software in the context of our Apep imagery.

The stronger wind overpowers the weaker one, creating this bow shock

2.2.1. *Parameter Estimation with the Geometric Model*

Geometric models are a key tool in learning about the orbital parameters of the binary stars at the heart [illegible] orbital and wind parameters involves forwards modelling the nebula, changing parameters until the ridge geometry best aligns with th[illegible]bserved; because of this, we need not consider the precise dust properties (as described in the companion paper, Y. Han et al. submitted), only its density structure. That is, the simulated images reproduce the projected (and normalised) column density of dust in the nebula, and not its luminosity, temperature, or other quantities which require deeper modelling.

The dust forms in this turbulent, post-shock mixture, once it's had enough time to cool down

The xenomorph code was designed with Bayesian parameter inference in mind, such as Markov Chain Monte Carlo (MCMC) or Hamiltonian Monte Carlo (HMC). However, there are too many parameters to fit for in using a conventional MCMC algorithm (which struggle or fail with high dimensionality; D. Huijser et al. 2015), which leaves gradient-based methods like HMC as the [illegible] in the model via autodifferentiation with JAX, the gradients are unstable and are not suitable for such a method. In addition to this it is difficult to describe an informative goodness of fit function for the fitting, given that the geometric model does not account for the radiative transfer and thermal emission of the nebula (where doing so would make the computational cost intractable for fitting). With this in mind, we manually fit for the parameters using the difference imaging within the graphical user interface (GUI) built into the xenomorph model to best align the nebula structure. We describe below the parameter-specific choices we made in this fitting process.

Orbital and system parameters: We begin fitting for the imprint of the WR+WR binary orbit on the nebula using the previous best values in the literature (most notably those in Y. Han et al. 2020). We treat the orbital eccentricity, inclination, longitude of ascending node, argument of periastron, and orbital phase as free parameters. We adopt the orbital period of Y. Han et al. (submitted) which was found via a proper motion analysis of dust ridge expansion. The orbital semi-major axis and stellar masses are unconstrained by geometric modelling of the nebula at this spatial scale and so cannot be fit for. We [illegible] distance of 2.4 kpc (J. R. Callingham et al. [illegible] et al. 2020) to the system which sets th[illegible]ansion speed as a fixed parameter when co[illegible] the adopted orbital period (due to the trigonometry of the nebula expanding in the plane of the sky).

Our other star with the weaker wind

Wind and dust parameters: We treat the shock cone open angle (describing the momentum ratio of the two WR stellar winds), true anomaly of dust turn on/off, and azimuthal dust variation as free parameters in fitting. We fixed the amplitude of azimuthal variation to $A_{az} = 0.5$ which appeared to best match the data. The orbital modulation and gradual turn on/off in dust production was not included in the fit in this study after initial tests with it did not appear to match the observations.

Tertiary cavity: As described in Section 3, we have found strong evidence of a cavity in the north-eastern region of the Apep nebula. In constraining the geometry of this cavity (and hence the parameters of the tertiary star), we allowed the cavity open angle and the polar and azimuthal positions of the cavity to be free. The destruction constant was fixed to $A_{tert} = 1.75$ although more negative values can just as suitably fit the

The orbital motion of the stars wraps this dust into a perfect spiral!

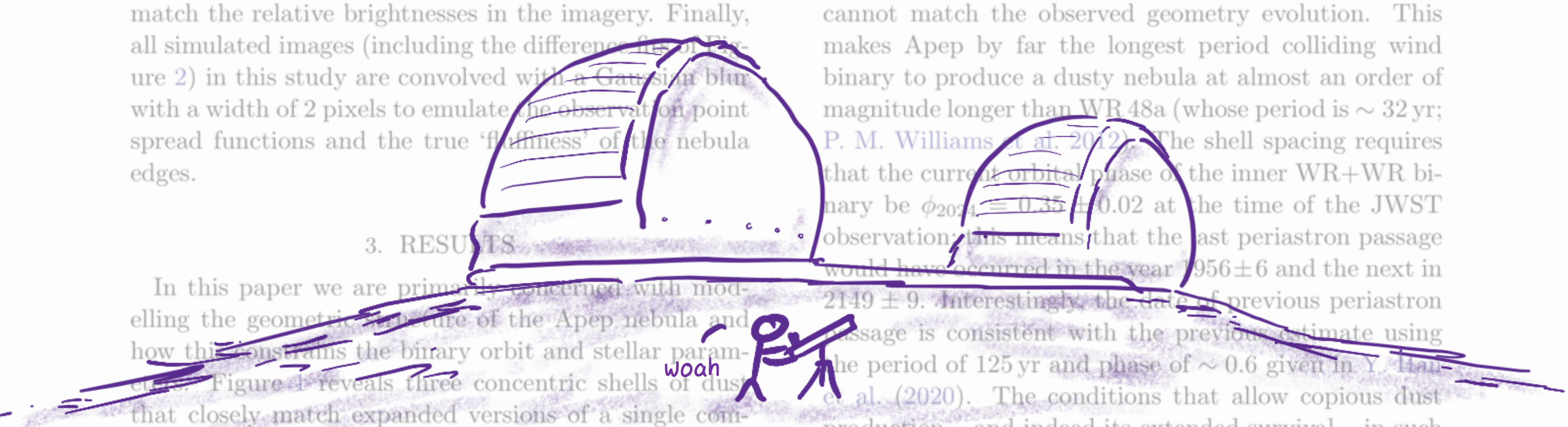
The exact shape of the dust spiral we see can tell us just about everything about the stars' orbits, just from a single image. On this page, and the one before, we briefly describe the model we've made from scratch that can very quickly simulate the geometry of these nebulae. We go into much more detail in the last several pages, so stay tuned!

observat[illegible] lar sprites, we also allowed the distance of the tertiary star from the inner binary to be a free parameter. Our proposed phenomenology for the cavity is that it is a result of sculpting from the tertiary companion in Apep, however in fitting for the position of the cavity we only considered the nebular geometry itself and not the position of the tertiary star in the imagery.

Miscellaneous parameters: The nucleation distance of the dust with respect to the shock front is only constrained by high angular resolution observations of the inner core of colliding wind binaries. Given that our observations are over very large spatial scales, there is no way to constrain the nucleation distance from such direct images; regardless, the nucleation distance is only relevant in the geometric model at small spatial scales ([illegible] of the semi-major axis) as it dictates the distance at which dust first appears. Hence, we have fixed the nucleation distance to 0 au and note that this has no effect [illegible] producer and at an orbital phase far from periastron passage. Additionally, the brightness and width of the Gaussian profiles of the stars in the image were treated as free parameters, and were scaled until they appeared to roughly match the relative brightnesses in the imagery. Finally, all simulated images (including the difference [illegible] of Figure 2) in this study are convolved with a Gaussian blur with a width of 2 pixels to emulate the observation point spread functions and the true 'fluffiness' of the nebula edges.

The first real image of this type of system was published by our co-author Peter Tuthill in 1999. The system's name is WR 104, and it looked something like this

3. RESULTS



In this paper we are primarily concerned with modelling the geometric structure of the Apep nebula and how this constrains the binary orbit and stellar parameters. Figure 1 reveals three concentric shells of dust that closely match expanded versions of a single common structure, although with evidence for some degree of geometric evolution between them. The innermost shell cannot be mapped by a pure inflation to perfectly match the the older (outer) shells since the projected geometry evolves slightly over time as the three-dimensional structure expands (see the linked animation in the Figure [illegible] caption). Each shell is [illegible] production coinciding with a periastron passage, so this image contains nearly a minimum of dynamical information about the Apep system.

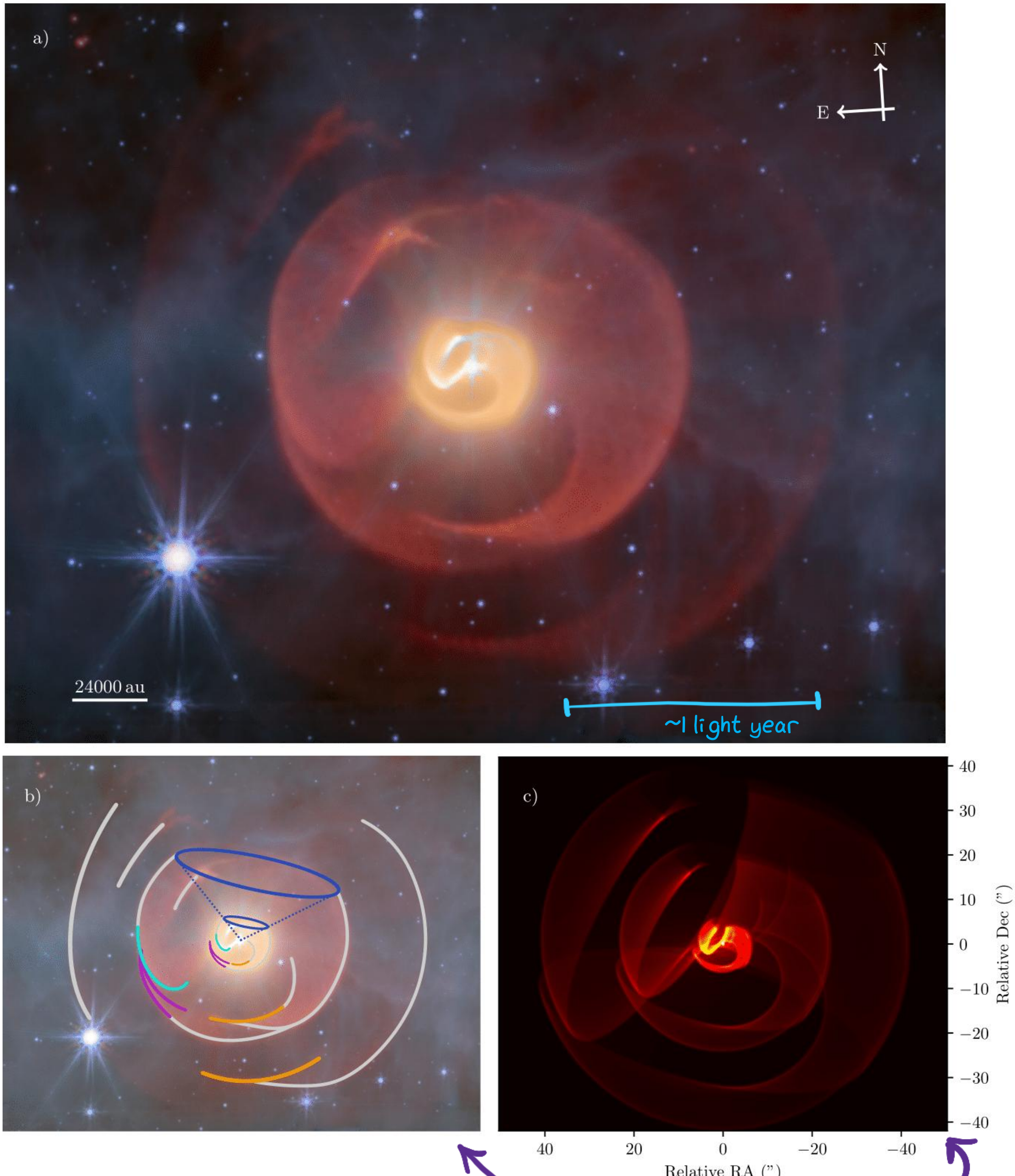
To analyse the structure of the Apep nebula, we de[illegible] that reproduces the dust morphology given orbital and stellar parameters (see Section 2.2). By fitting simulated structures to the images, we determined the sys-

[illegible] Table 1 [illegible] to the images shown in Figure 2. The fitting was aided by multiple epochs of Apep imagery spanning 8 years from the VLT, and the VLT images together with the JWST image allowed us to break any degeneracies between orbital phase, orbital period, and [illegible] expansion speed. When fitting with only a single epoch and a single shell, the ridge geometry can be suitably fitted by a range of degenerate orbital periods, expansion speeds and phases; more epochs of imaging and more visible shells thus greatly constrain the parameter space. The most surprising result of the fitting (and the proper motion analysis in Y. Han et al. submitted) given by the separation between successive shells now revealed by JWST, is that the central WR+WR binary in the centre of the Apep system must have an orbital period of 193 ± 11 yr – [illegible] thought based on anal[illegible]. We note that this period [illegible] as it only relies on [illegible] expansion speed – although [illegible] the period is covariant with expansion speed; simultaneously fitting the VISIR epochs + th[illegible] lower bound of 170 yr for the orbital period, [illegible] periods below this cannot match the observed geometry evolution. This makes Apep by far the longest period colliding wind binary to produce a dusty nebula at almost an order of magnitude longer than WR 48a (whose period is ~ 32 yr; P. M. Williams et al. 2012). The shell spacing requires that the current orbital phase of the inner WR+WR binary be $\phi_{2024} = 0.35 \pm 0.02$ at the time of the JWST observation; this means that the last periastron passage would have occurred in the year 1956 ± 6 and the next in 2149 ± 9. Interestingly, the date of previous periastron passage is consistent with the previous estimate using the period of 125 yr and phase of ~ 0.6 given in Y. Han et al. (2020). The conditions that allow copious dust production – and indeed its extended survival – in such a widely separated long period system are not well understood, but the unique configuration of a double WR star at the heart of Apep is likely a pivotal factor.

With successive outer dust shells now visible thanks to the sensitivity of JWST MIRI, we are able to better understand how the dust geometry changes over time. Comparing the innermost (first) shell to the second shell, we can see that the relative spacing between the south-east ridge and south-east tail is re[illegible] with the significantly earlier orbital phase estimate at 2024 ϕ_{2024}, means that the WR+WR binary must be on a[illegible] separation by such a degree over 193 years. We have found that

WR 104 was observed with the Keck telescope on top of Mauna Kea in Hawaii. These spiral nebulae are brightest in the mid-infrared where we can see the warm thermal emission from the carbon dust, but the atmosphere blocks and distorts a lot of this light which dims and blurs the image. Ideally, we would want to use a very powerful infrared telescope that lives in space: the James Webb Space Telescope. We used exactly this to view the Apep system...

This is our *real* image!



This is our best model recreation of the nebula!

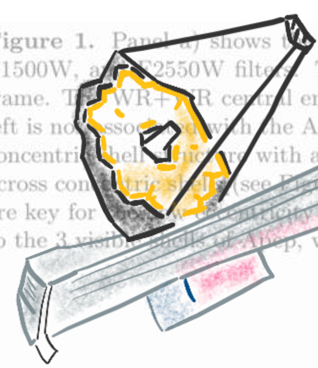


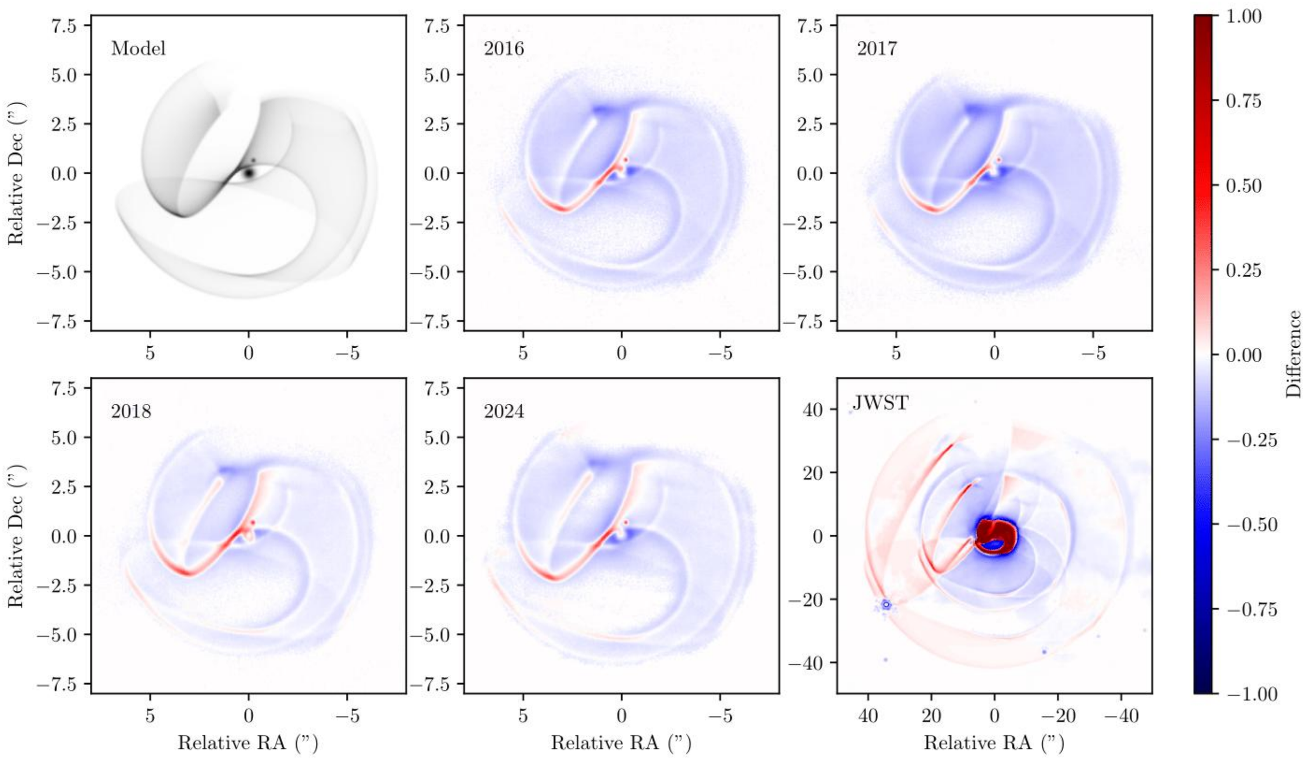
Figure 1. Panel a) shows the false colour composite image of the Apep nebula made by combining data from the F770W, F1500W, and F2550W filters. Three concentric shells of dust are clearly seen, with faint evidence of a fourth at the edge of frame. The WR+WR central engine and the tertiary O supergiant lie in the centre of frame, while the bright star in the lower left is not associated with the Apep system. The processing procedure is described in Section A.1. In panel b) we highlight the concentric shell structure with a grey skeleton, where the coloured ridges indicate regions of interest: the position of the cavity across concentric shells (see Figure 3), the relative positions of the south-east ridge coinciding with the south-east tail over time are key for the low eccentricity value, and the southern bar aids in the period determination. Panel c) shows the best geometric model fit to the 3 visible shells of Apep, where the alignment of the modelled to the observed shells is shown in Figure 2.

These are the features of the nebula that help us make the model

By modelling the 3D geometry of the nebula, we learn some pretty precise estimates of the orbits of the stars and what their winds are like. This helps us figure out what the lives of the stars have been like so far, and where they'll end up.

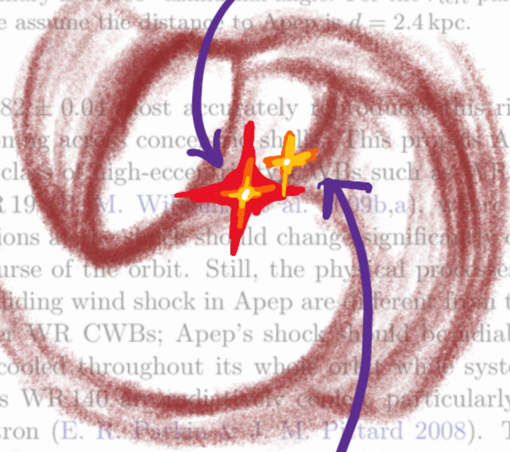
One of the main results we find is that the two Wolf-Rayet stars have an orbital period of almost 200 years – almost 10 times as long as the next longest-period system that makes these nebulae. Apep is truly special!

To really make sure we have the right model, we compared our simulations with 5 different epochs of imagery, 4 images of the innermost shell taken by a ground-based telescope, and our beautiful JWST image.



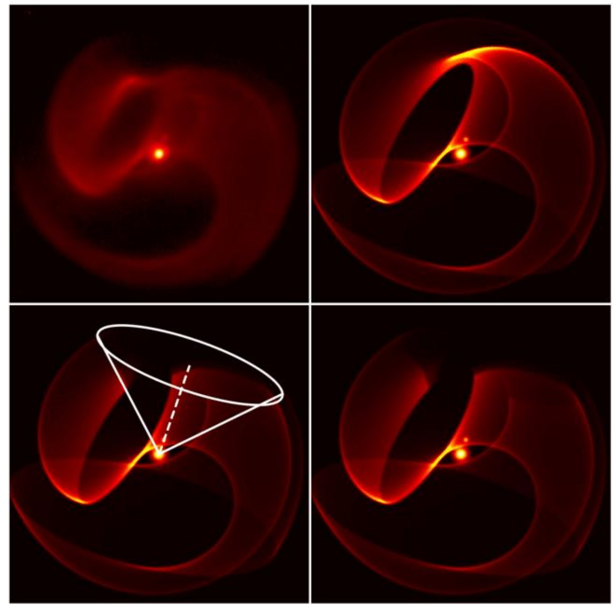
In this plot we compare our simulations and our 8 years of data. Where the colour is blue, the data is 'brighter', and where the colour is red, the simulation is 'brighter'. You can see that it doesn't match up in colour perfectly, but the *outline* of our simulations matches the data exactly; this is good, because we learn our parameters from the outline of the match, not the intensity.

When Apep was discovered, astronomers saw not just two but *three* stars near the centre of the nebula:



We weren't sure whether or not this third star was a part of the system or just a chance alignment of the stars in the sky, but I think I've found a way to tell!

The spiral dust nebula is created by the two WR stars at the centre of the nebula independent of any third star. But... if a third star is a part of the system, should we expect it to have some influence on the nebula?



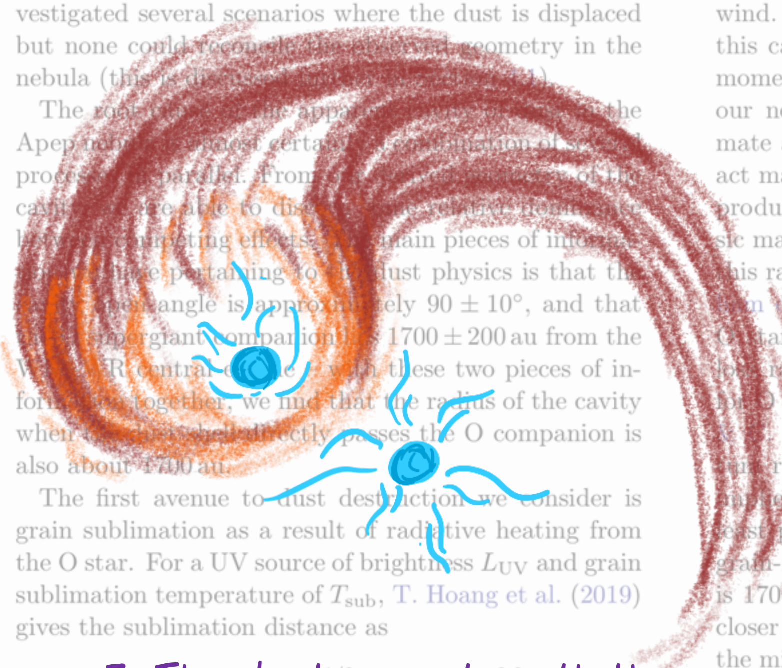
In this figure above, I show evidence that the third star *does* actually have some geometric impact on the nebula!

The top left panel shows a real picture of the Apep nebula. We compare that to the top right panel which is our model of the nebula assuming that there are just two stars in the system.

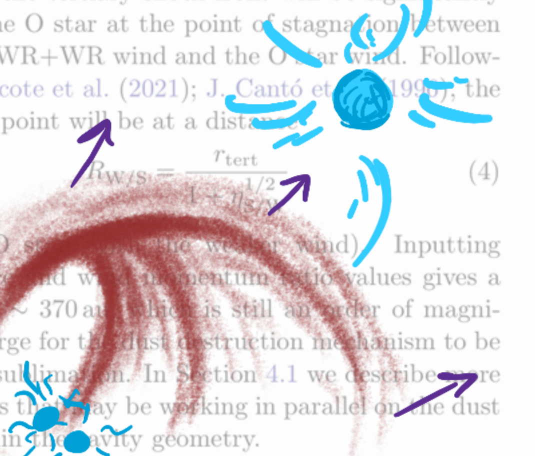
If there are *three* stars, we would expect this third star to carve a hole in the nebula. In the bottom left panel we show the geometry of the hole we cut out, and in the bottom right panel we show our model of the nebula including this cavity (which seems to match better!)

So what exactly is happening?

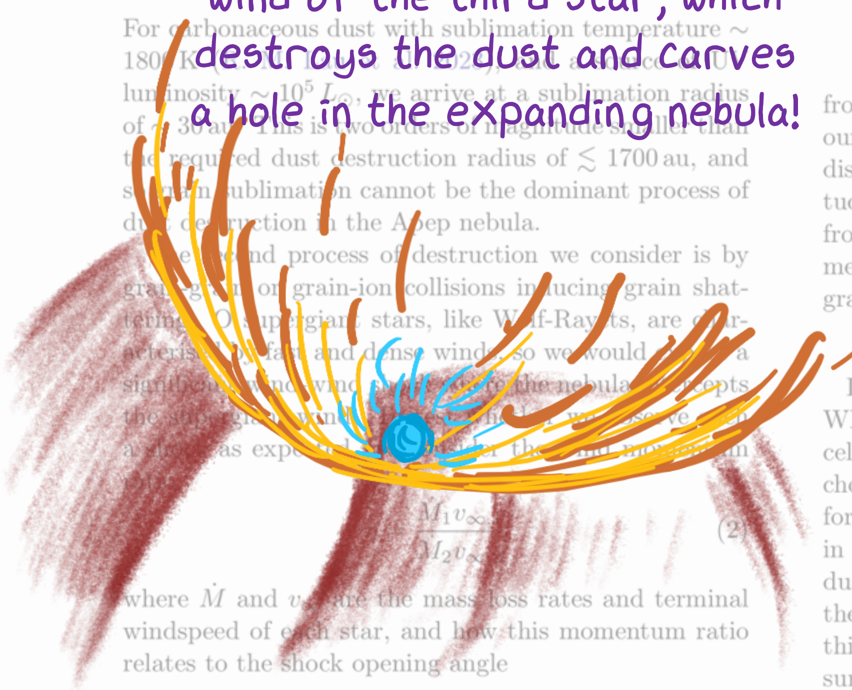
1. The dust nebula is formed from the colliding winds of the inner two Wolf-Rayet stars.



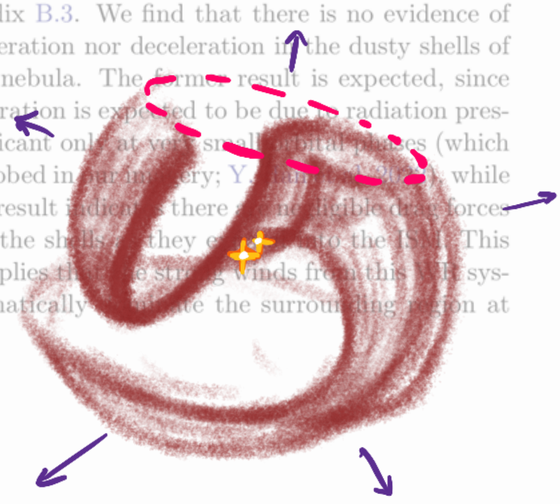
2. This dust nebula then expands out away from the binary stars and towards the third star



3. The dust impacts with the wind of the third star, which destroys the dust and carves a hole in the expanding nebula!



4. With the northern dust being destroyed in a ring, the nebula keeps expanding into the Milky Way



least to the limits of the shells we see. Our imagery also indicates that the dust from the Apep nebula is capable of surviving for at least [illegible] while subjected to the harsh ISM environment.

This is a pretty convincing argument, but we still aren't entirely sure of the *physics* of why this third stellar wind is carving a hole in the nebula.

Since the discovery paper of the Apep nebula, there has been a puzzling contradiction between the measured nebular expansion and the spectroscopic wind speeds of the central WR stars (J. R. Callingham et al. 2019). Our fitted expansion speed of $1020 \pm 100\,\mathrm{km\,s^{-1}}$ (at an assumed distance of [illegible] kpc; [illegible] 2020, submitted) confirms this discrepancy. A proposed resolution to this is that at least one of the WR stars in the system has a slow and dense equatorial wind with a fast polar wind, such that the observed slower uniform expansion of the shells and fast winds may coexist. To investigate this we inc[illegible] a phenomenological anisotropic wind into t[illegible]tric model that [illegible] the expansion speed a[illegible] angle of some [illegible] of the simulated sh[illegible]mulate orbital phase-dependent wind conditions at different latitudes of the WR stellar surface contribute to the wind-wind shock (Appendix B.4). Such a model cannot rule out or confirm anisotropic winds where the stellar rotation is aligned with orbital motion. However, using this we have found that it is unlikely for the (would-be) anisotropic star to have its rotation significantly misaligned with the orbital plane as we do not find any geometric signatures of this in the nebula. If the slow-wind region extends to high stellar latitudes, we would also not be able to detect such a shell deformation. This is consistent with previous spectroscopic observations of a [illegible] in the plane of the sky (inclination of $24 \pm 3°$). Investigating [illegible] will be essential to determine if Apep really does harbour a critically rotating star that may be a long gamma-ray burst (LGRB) progenitor.

Despite that, we can still put some constraints on what's happening to narrow it down.

4.[illegible] Effect on Dust Grains in the Cavity

This will help out future scientists who want to do some simulations to try to get to the bottom of it (which would warrant a whole new paper!).

Our tertiary cone modelling does not exactly produce the observed structure and one of the last remaining mysteries in the Apep [illegible] geometry is the origin of the horizontal ridge outlining the cavity on its southern border. [illegible] that the O star may deflect some proportion of the dust onto this outer ridge, but modelling this has proven difficult. We considered and implemented several models of deflection in an attempt to explain this ridge, where the O star deflects dust particles: into a ring along the entire cavity edge; onto the cavity edge on those angular coordinates co-located with the dust; or onto a central angular position along the cavity boundary with some azimuthal spread, but all three mode[illegible] unsuccessful in reproducing the geometry. T[illegible] two ideas significantly over-predict ridges at [illegible] that are not seen in the observations, a[illegible] can produce a ridge in the correct location [illegible] but at an angle which does not match the observed ridge. Given that this is a persistent feature across the shells, we do not think that this is an anomalous dust feature (created by e.g. [illegible] our picture of the tertiary [illegible] dust grains but rather destroys them. Estimates on the dust grain properties within and around the cavity are difficult to discern without spectra, however, but constraints can be inferred based on the environmental conditions.

The disruption of dust grains via radiative torques (radiative torque disrupti[illegible] RATD) has recent[illegible] studied in the context [illegible] colliding wind binaries (R. M. Lau et [illegible]; T. Hoang et al. [illegible]). This occurs due to h[illegible] photon absorption inducing rotation in asy[illegible], thereby inducing a centrifugal stress which [illegible] the grains (T. Hoang et al. 2019). At a given distance r_* [illegible] from a central point source of luminosity L_* (units of [illegible]) with mean wavelength $\bar{\lambda}_{0.5}$ (in units of $0.5\,\mu$m), the maximum size of dust grains with tensile strength S_9 (units of $10^9\,\mathrm{erg\,cm^{-3}}$) surviving this mechanism is given by T. Hoang et al. (2019) as

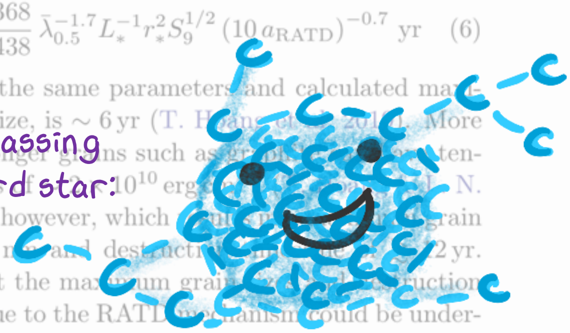
$$a_{\mathrm{RATD}} \simeq 0.003197 \left(\bar{\lambda}_{0.5}^{-1.7} L_*^{-1/3} r_*^{2/3} S_9^{1/2}\right)^{1/2.7} \quad \mu\mathrm{m} \quad (5)$$

For example, if any little grains of dust do survive their trip past the third star, we can be pretty sure that they'll be a fraction of their former self.

Using [illegible] distance of 1700 au, a mean wavelength given by a blackbody distribution of 30 kK, a luminosity of [illegible] $L_\odot$ (typical of O8 Iaf supergiants), and a grain maximum tensile strength of [illegible] $\mathrm{erg\,cm^{-3}}$ (for disordered grains, T. Hoang & L. N. Tram 2019), we obtain a maximum surviving dust grain size of ~ 4 nm. The timescale on which this destruction takes place is

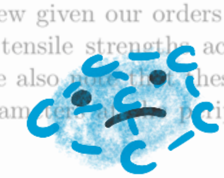
$$\tau_{\mathrm{RATD}} \simeq \frac{368}{438} \bar{\lambda}_{0.5}^{-1.7} L_*^{-1} r_*^2 S_9^{1/2} \left(10\, a_{\mathrm{RATD}}\right)^{-0.7} \ \mathrm{yr} \quad (6)$$

Before passing by the third star:



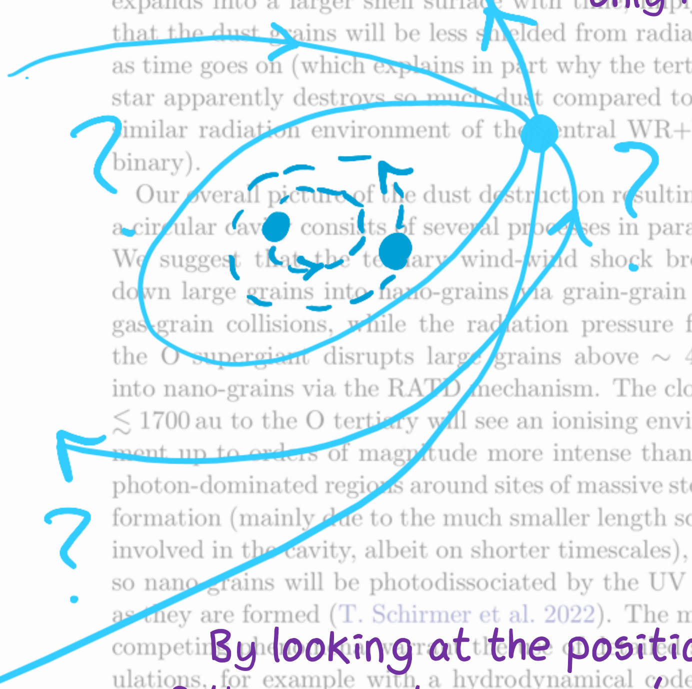
which, with the same parameters and calculated maximum grain size, is ~ 6 yr (T. H[illegible]). More ordered, stronger grains such as [illegible] tensile strengths of [illegible] 10^{10} erg [illegible] N. Tram 2019), however, which [illegible] grain size of ~ 13 n[illegible] and destruct[illegible] 2 yr. We note that the max[illegible]um grai[illegible]uction timescales due to the RATD mechanism could be underestimated by factors of a few given our orders of magnitude uncertainty in the tensile strengths across the true grain distribution. We also [illegible] these calculations are done given param[illegible] periphery of

...and after:



We know the orbit of the Wolf-Rayet + Wolf-Rayet binary strikingly well now, and our models of the nebula give us the precise 3D location of the third star with respect to the inner binary. With that said, we don't yet know the orbit of the third star because we only have it's location at one point in time.

the dust cavity; in reality, we might expect a gradient of dust conditions across the cavity 'surface'. These calculations assume that the environmental conditions are constant across the destruction timescale, when this is not the case: the dust shell produced from the colliding wind of the WR+WR binary, is moving radially outwards [illegible] out of it. In parallel the dust is becoming less dense as it expands into a larger shell surface with time, implying that the dust grains will be less shielded from radiation as time goes on (which explains in part why the tertiary star apparently destroys so much dust compared to the similar radiation environment of the central WR+WR binary).



Our overall picture of the dust destruction resulting in a circular cavity consists of several processes in parallel. We suggest that the tertiary wind-wind shock breaks down large grains into nano-grains via grain-grain and gas-grain collisions, while the radiation pressure from the O supergiant disrupts large grains above ~ 4 nm into nano-grains via the RATD mechanism. The closest $\lesssim 1700$ au to the O tertiary will see an ionising environment up to orders of magnitude more intense than the photon-dominated regions around sites of massive stellar formation (mainly due to the much smaller length scales involved in the cavity, albeit on shorter timescales), and so nano-grains will be photodissociated by the UV flux as they are formed (T. Schirmer et al. 2022). The many competing [illegible] ulations, for example with a hydrodynamical code, to model the observed geometry in Apep in future studies.

By looking at the positions of those cavity rings, we're effectively looking back in time. The ring positions tell us the position of the third star 500 yr ago, 300 yr ago, and 100 yr ago

4.2. *Orbit of the Tertiary Star*

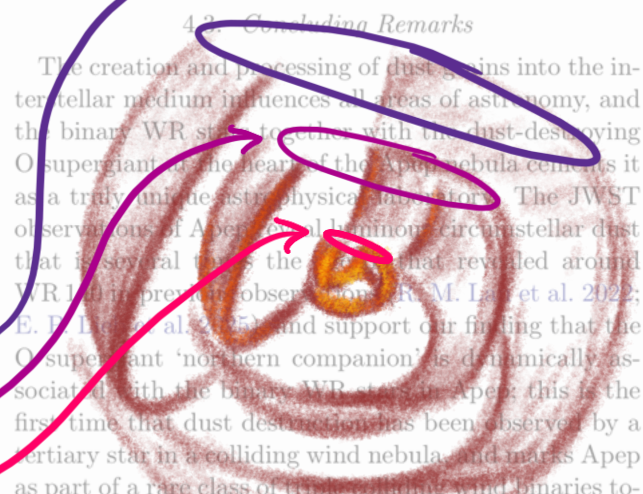
If we take the distance to the Apep system to be 2.4 kpc (J. R. Callingham et al. 2019; Y. Han et al. 2020), the tertiary star must be presently 1700 ± 200 au from the WR+WR binary centre of mass. Given the positioning of the dust cavity, the O star is approximately $34 \pm 10^\circ$ above the plane of the WR+WR orbit. If the tertiary star is in a circular orbit at such a distance, with a total system mass of [illegible] $M_\odot$, the orbital period should be of order $P_{\rm tert} \sim 8 \times 10^3$ yr. If this is the case, we would expect the tertiary star – and by extension its associated cavity in the dust plume – to move $\sim 28^\circ$ in its orbit around the common CoM over the 3 visible dust shells and $3P_{\rm orb} \simeq 600$ yr of visible dust in the JWST imagery. This extent of cavity displacement is not supported by our fits which is constrained to $< 10^\circ$ of movement. Imaging of even older shells – which would be [illegible] with the Atacama Large Millimetre Array (ALMA) may unambiguously reveal the [illegible]

Similarly, detection of molecular lines, and their subsequent radial velocity profile, in the Apep nebula with ALMA would yield an unambiguous expansion velocity (and corresponding orbital period) of the nebula.

The low movement of the cavity can be explained if the O star companion is on an eccentric orbit, where it is presently [illegible] analogous circular orbit. This is a plausible explanation, since often in hierarchical triples the companion star is on a highly elliptical, distant orbit (S. Toonen et al. 2016; J. M. O. Antognini & T. A. Thompson 2016). In such a case, the tertiary star will [illegible] perturbative influence on the dynamics of the inner binary. Even with a modest eccentricity of [illegible], the Kozai-Lidov timescale of this configuration would be of order $P_{\rm KL} \sim 10^5$ yr (S. Naoz 2016; J. M. O. Antognini 2015). Massive stars – which eventually evolve into WR stars – have lifetimes of a few million years, and so the Apep system will have experienced several Kozai-Lidov timescales at minimum; since this mechanism can in principle pump the eccentricity of the inner binary up to values of $e \gtrsim 0.95$, the companion star must be accounted for in any binary evolution studies of the Apep system in order to discern past epochs of close passages and/or mass transfer.

But we know that there is a cavity in the nebula centred on the location of the third star! Could we look to see if there's a shift in the cavity location across the four shells?

4.3. *Concluding Remarks*



The creation and processing of dust grains into the interstellar medium influences all areas of astronomy, and the binary WR stars together with the dust-destroying O supergiant at the heart of the Apep nebula cements it as a truly unique astrophysical laboratory. The JWST observations of Apep reveal luminous circumstellar dust that is several times the [illegible] that revealed around WR 140 in previous observations (R. M. Lau et al. 2022; E. P. Lieb et al. 2025) and support our finding that the O supergiant 'northern companion' is dynamically associated with the binary WR stars in Apep: this is the first time that dust destruction has been observed by a tertiary star in a colliding wind nebula, and marks Apep as part of a rare class of triple colliding wind binaries together with WR 147 (L. F. Rodríguez et al. 2020). Our work motivates more detailed simulations of the dust destruction in such a system, for example with a hydrodynamic code, and the modelling of dynamical effects of a tertiary star on the binary evolution in Wolf-Rayet colliding wind binaries.

5. DATA AVAILABILITY

The JWST data used in this study were obtained from the Mikulski Archive for Space Telescopes (MAST; https://archive.stsci.edu/missions-and-data/jwst) at the Space Telescope Science Institute,

We find that... the cavity doesn't move very much. Less than we'd expect given the current position of the third star! This means that it is probably in a very slow and elliptical orbit, but we certainly need more data to figure that out for sure.

The take-home:

under JWST GO program ID 5842. The JWST data used in this paper can be found in MAST: doi:10.17909/mf14-ga19.

We made a brand new code to model the nebulae created by the colliding winds of binary stars. Using shiny new JWST imagery and this new code, we learned more than ever about the most unique stellar system: Apep. Not only does Apep have the longest orbital period of any system of this type, we found that it's got a far-off third friend! This just makes us even more confused about how this system came to be, and we are left with more questions than answers.

6. CODE AVAILABILITY

The geometric model code, xenomorph (R. M. T. White 2025) is open source on GitHub and available at github.com/ryanwhite1/xenomorph with a documentation site online at ryanwhite1.github.io/xenomorph/. We encourage community contributions to the code [illegible] on the state of documentation. The code makes use of Jax (J. Bradbury et al. 2018), Numpy (C. R. Harris et al. 2020), Matplotlib (J. D. Hunter 2007), SciPy (P. Virtanen et al. 2020), and Astropy (Astropy Collaboration et al. 2013, 2018, 2022). The version of the code current to the date of publication is available on Zenodo and can be accessed via doi:10.5281/zenodo.15875502.

This work is based on observations made with the NASA/ESA/CSA *James Webb Space Telescope*. The data were obtained from the Mikulski Archive for Space Telescopes at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-03127 for JWST. These observations are associated with program #5842. Support for program #5842 was provided by NASA through a grant from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-03127.

We acknowledge and pay respect to the traditional owners of the land on which the University of Queensland is situated, upon whose unceded, sovereign, ancestral lands we work. We acknowledge the traditional custodians of the Macquarie University land, the Wallumattagal clan of the Dharug nation, whose cultures and customs have nurtured and continue to nurture this land since the Dreamtime. We acknowledge the tradition of custodianship and law of the Country on which the University of Sydney campuses stand. We pay our respects to those who have cared and continue to care for Country.

ACKNOWLEDGMENTS

We are grateful to Peredur Williams, Orsola De Marco, and Katelyn Smith for valuable discussions during the analysis and writing of this work. We thank the University of Sydney and University of Queensland 'FOCI' group for helpful discussions and feedback throughout the project. RMTW acknowledges the financial support of the Andy Thomas Space Foundation. SD and BJSP were funded by the Australian Government through the Australian Research Council DECRA fellowship DE210101639. NDR is grateful for support from the Cottrell Scholar Award #CS-CSA-2023-143 sponsored by the Research Corporation for Science Advancement.

And now for thanks!

We are very grateful to a lot of researchers (of whom we asked *many* silly questions during the science and write up), as well as a bunch of funding agencies which pay for our computers and salaries.

AUTHOR CONTRIBUTIONS

RMTW developed the geometric wind model, conducted all data analysis, and led the writing of the manuscript. YH led the telescope proposals and contributed to discussions and analysis. BJSP and PGT supervised the project and provided comments on the manuscript. SD and BJSP reduced and processed MIRI imagery for both scientific and aesthetic purposes. All authors contributed to the text of the final manuscript.

Facilities: JWST(MIRI), VLT(VISIR)

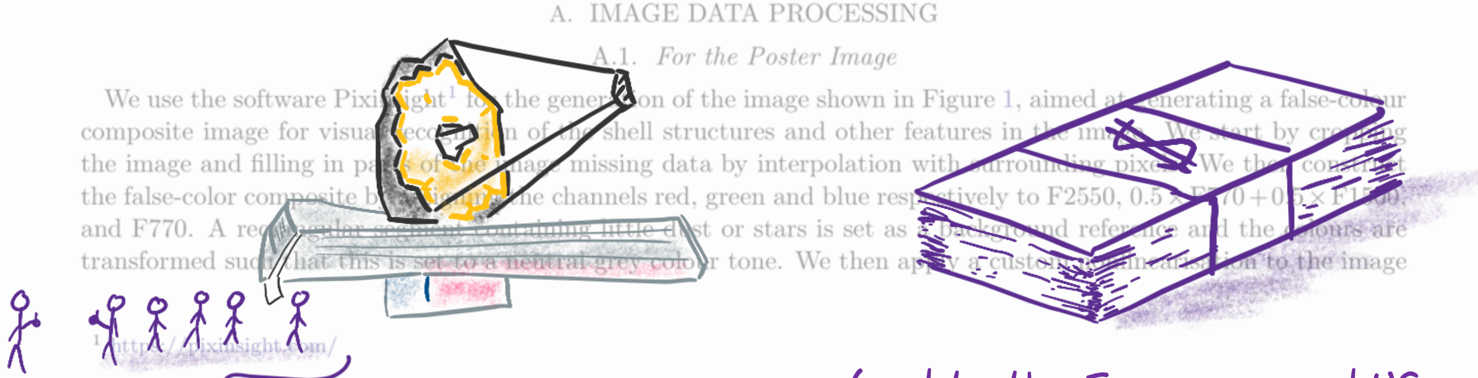
And, of course, we are tremendously grateful to everyone at NASA/ESA who worked on and maintain the James Webb Space Telescope!

APPENDIX

A. IMAGE DATA PROCESSING

A.1. *For the Poster Image*

We use the software PixInsight[1] for the generation of the image shown in Figure 1, aimed at generating a false-colour composite image for visual [illegible] of the shell structures and other features in the image. We start by cropping the image and filling in parts of the image missing data by interpolation with surrounding pixels. We then construct the false-color composite by assigning the channels red, green and blue respectively to F2550, $0.5 \times$ F1130 $+ 0.5 \times$ F1500, and F770. A rectangular segment containing little dust or stars is set as a background reference and the colours are transformed such that this is set to a neutral grey colour tone. We then apply a custom [illegible] to the image



[1] https://pixinsight.com/

(and to the European and US taxpayers who funded this mission)

(JWST is worth 16x its weight in US $100 bills) are exceedingly rare with only a handful in the Galaxy. Hierarchical triple variants of these, especially those whose tertiary companion is close enough to sculpt surviving and bright dust, are rarer still. At present, there appear to be only two other confirmed hierarchical triple CWBs hosting WR stars: WR 104 (D. J. Wallace et al. 2002; A. Soulain et al. 2018) and WR 147 (L. F. Rodríguez et al. 2020). For the former, the tertiary star seems too distant to affect the spiral dust plume, and radio imagery of the latter implies that the tertiary shock does not affect the spiral nebula. Still, this cavity prescription may be useful in later studies should similar nebular morphology be observed in other systems.

Before we do *any* science, we have to familiarise ourselves with the literature – what other people are doing and where there's room for improvement. It's a lot of reading (trust me), but it's worth it to really understand the problem you're tackling.

I read a *lot* of papers when doing this project, and it's an honour to be able to add another layer to our understanding of the Universe.

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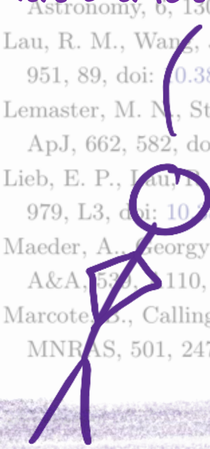

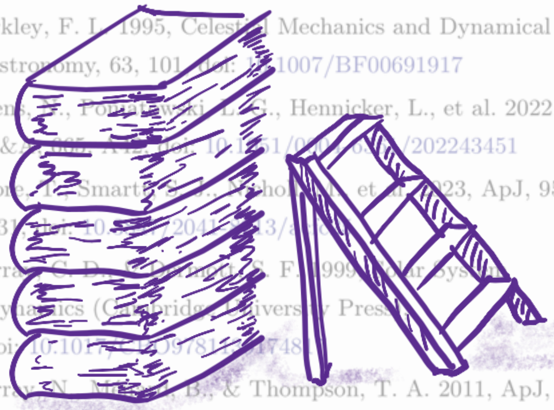

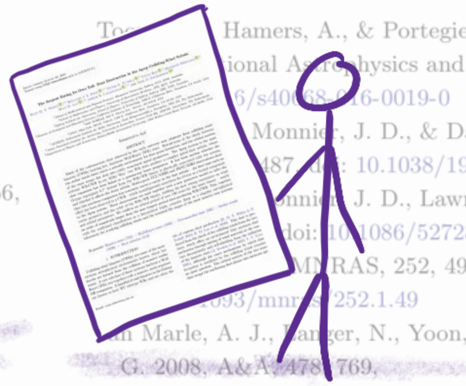

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Congratulations on making it to the end! I put a lot of effort into trying to make our jargon-filled paper accessible. Feel free to reach out to me at ryan.white.astro@gmail.com if you have any questions!

This annotated paper was inspired by the work of Claire Lamman, and you should definitely check out her research and annotated papers! Since you probably don't want to see my handwriting, I've also used the xkcd font for my annotated paper.

If you've come across this annotated paper independently of my website, you should check that out to here: ryanwhite1.github.io
You can also read more about this Wolf-Rayet work here and take a look at our companion paper (another paper of our team about Apep!) at this link!

Thank you again for reaching the end. I hope you enjoyed it!

(Ryan White, me!)