Master of Research Project Plan

Radiative and Hydrodynamical Modelling of Colliding Wind Binaries
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1 Background and Aims

The lives and deaths of massive stars (those $\gtrsim 8\,M_\odot$) are some of the dominant forces in shaping the Galaxy and indeed our stellar neighbourhood. As such, our knowledge of massive stars and their evolution is foundational to how we understand many other areas of astrophysics. The final evolutionary stage of the most massive stars – immediately preceding their supernova explosion – is the Wolf-Rayet (WR) stage, characterised by extreme winds that can seed a spiral 'colliding wind nebula' when the star has a massive companion. **Replicating this nebula structure with geometric and hydrodynamic simulations reveals many otherwise elusive orbital and wind parameters of these stars**; in the process we form a more complete picture of the role of massive stars in enriching the interstellar medium and seeding the next generation of stars.

Stars form from the collapse of dense molecular clouds, where massive stars will preferentially form in binary or multiple systems [Sana and Evans, 2011]. The stars in these multiple systems will evolve together over their lifetime, potentially interacting through mass transfer and via chaotic gravitational perturbations. How we see these systems in their present state can then give us vital clues as to their evolutionary history both backwards and forwards in time. In particular, the colliding wind binaries (CWBs) – systems where the stellar wind of each star collide to form a bow shock – allow an unparalleled view into the dynamics and chemistry of the massive stars at their centre. There are a subset of CWBs – ones hosting WR stars at their centre – that are surrounded by an intricate circumstellar dust structure formed from this bow shock. This WR star catalyses copious dust formation in the turbulent mixed wind further downstream to the bow shock, which is then bright in the infrared [White and Tuthill, 2024].

Infrared imaging of these systems was first done in [Tuthill et al., 1999], revealing a 'pinwheel' structure of an Archimedean spiral. The spiral shape occurs as a result of the orbital motion of the binary stars – as they move in their orbit, the location of the wind-wind shock correspondingly traces the orbital motion. This basic orbital motion allows us to analytically model the resulting nebula when we treat the dust production as being in a ring along the surface of the conical shock at equally spaced timesteps; this method underpins my code `xenomorph` which was the topic of my completed Honours project. One of the immediate aims of my MRes project is to expand the `xenomorph` code to better model the three-dimensional velocity structure of the colliding wind nebulae which will have direct applications to data being taken with the Atacama Large Millimetre Array (ALMA).

We had demonstrated in previous research that our `xenomorph` code is capable of roughly modelling the infrared light curves of colliding wind binary systems. This was achieved despite not having a radiative transfer code in the light curve pipeline. As a result, our modelled light curves could not accurately account for the dust properties in the circumstellar shell (and hence cannot be accurately matched to observations), nor the spectral energy distributions of the central stars. One of our goals in the MRes project is therefore to include a radiative transfer code as a post-processing step on our `xenomorph` models so that we may match our simulated light curves to real systems' data, allowing us to infer the geometry of CWBs much too distant and unresolved to directly image.

Several colliding wind nebulae have now been directly imaged with ground based and space telescopes in the time since the first observed pinwheel nebula. Perhaps the most striking of these is the hierarchical triple system Apep, featuring two classical WR stars at its centre as well as an evolved O supergiant many times further out than the inner binary separation Callingham et al. [2019]. After some historical ambiguity, we used Very Large Telescope + James Webb Space Telescope imagery to definitively associate this tertiary O star with the WR+WR binary on account of a coincident dust cavity it carves into the surrounding dust nebula. Apep's nebula is the first time such a phenomenon has been observed in this kind of environment, and so the second immediate aim of this MRes project is to determine the mechanism by which the O star destroys the circumstellar dust. How we determine this will be multifaceted: we aim to use analytic dust destruction formulae together with the stellar parameters (a phenomenological focus), as well as hydrodynamical modelling to better understand the physics at play (a mechanistic focus). The latter method will be additionally useful in understanding why Apep – the only WC+WN classification system known in the Galaxy, with an orbital period ~ 8 times that of the next longest period dusty colliding wind binary – has a circumstellar dust nebula to begin with.

One of the longest standing mysteries in the Apep system is the windspeed discrepancy between its spectrum and nebular expansion speed: the spectrum reveals two central WR stars with windspeeds of $2100 \pm 200\,\mathrm{km\,s^{-1}}$ and $3500 \pm 100\,\mathrm{km\,s^{-1}}$ Callingham et al. [2020], while our fitted nebula expansion speed is $860 \pm 100\,\mathrm{km\,s^{-1}}$. The proposed resolution to these contradictory speeds is that through the spectrum we are observing the fast polar wind of the WR stars, while one or both of the stars has a slow and dense equatorial wind that explains the dust expansion. A slow equatorial wind is indicative of near-critical rotation of the star, suggesting that the dominant WR star in Apep is a Long Gamma Ray Burst (LGRB) progenitor. These anisotropic winds offer a convenient explanation for the observations, but it is not clear how a velocity and density gradient (with latitude) should affect the visible dust plume. While we model the Apep system with a hydrodynamic code to determine the dust destruction physics, we will simultaneously investigate the effect of an anisotropic wind on the dust nebula. This will give vital insight into Apep's role as an LGRB progenitor in an epoch of the Milky Way where we expect these events to now be exceedingly rare.

2 Methodology

Radiative Modelling and `xenomorph` Development
Our progress so far with the `xenomorph` geometric modelling code allows us to efficiently estimate the infrared light curves of Wolf-Rayet colliding wind binaries. As previously mentioned, this neglects the complex radiative physics that is involved in the true astrophysical systems and so one main goal of my project is to include these physics. We will do this with the 3D radiative transfer code `MCFOST` [Pinte et al., 2022]. While originally designed to model protoplanetary discs and young stellar objects, `MCFOST` has also been used to describe the spectral energy distributions, dust properties and radiative environments around post main-sequence systems. We intend to use `xenomorph` to generate the circumstellar nebulae around our WR-CWBs which we will then feed into `MCFOST` to determine the dust properties that best match observations. In the process, this will give us the dust mass and composition for these nebulae where it is otherwise difficult to infer from direct imaging.

In parallel with our use of a radiative transfer code post-processing step, I will further develop the `xenomorph` code in anticipation of ALMA CWB datasets. ALMA data will give us not only the spatial information of bright gas in the colliding wind nebula, but its radial velocity profile too. The `xenomorph` implementation generates a point cloud of particles that defines the three dimensional nebula geometry, each particle having an associated position and radial velocity although the latter is not accessible to the user. We will expand the code so that ALMA data may be readily compared to our generated nebulae, through, for example, velocity sliced nebula bins and three dimensional velocity maps. Comparing our model to the data in this way is essential to break parameter degeneracies in model fitting, since nebula radial velocity information determines windspeed and, when combined with other observables, can yield a unique distance to the system. This has applications to the Apep system in particular whose distance is ambiguous, stoking the windspeed discrepancy debate.

Analytic and Hydrodynamic Dust Analysis
We are approaching the Apep dust analysis in two ways. For the phenomenological approach, we are using the geometrical and stellar constraints from our previous work together with analytic dust destruction formulae to better understand the conditions that lead to the observed dust cavity. Research on Photon-Dominated Regions (PDRs), – regions of high ultraviolet flux that are observed around sites of massive stellar formation [Schirmer et al., 2022] – yields some clues as to the dust processes involved around Apep, albeit on a much larger scale. The first part of the project will be dedicated to seeing how relevant these dust destruction mechanisms, such as radiative torque disruption [Hoang et al., 2019], are to the Apep system and what they describe about the circumstellar dust properties.

The geometric code provides a uniquely efficient way to model colliding wind nebulae, although at a cost of detailed gas and dust physics. Therefore for the mechanistic approach, we will model the Apep system using the smoothed particle hydrodynamics code `Phantom` [Price et al., 2018]. In doing so we will better understand the small-scale and detailed physics that results in dust formation and subsequent destruction. The orbit of the inner WR+WR binary as well as the current position of the tertiary supergiant are extremely well constrained from our geometric code which provides a suitable starting point for the dynamics in the simulation. Some properties of each stellar wind, such as their terminal velocity along the line of sight, are known through spectra of the system, but other properties like the mass loss rates are not as well constrained; where some wind parameters are unknown, we may begin our simulations with typical values of that stellar class.

Anisotropic stellar winds are defined by varying mass loss rates and wind velocity as a function of latitude. There are recently published formalisms for how these parameters vary as a function of latitude (e.g.Hastings et al. [2023] for mass loss rates, and gravity darkening prescriptions for radiation driven windspeed variation), and we aim to implement these in `Phantom` together with external collaborators. We expect to run multiple simulations with this prescription while varying the axial tilt of the dominant WC star in Apep; this will give insight into how the plume geometry changes in the presence of an anisotropic wind, if at all, and give sorely needed constraints on the LGRB hypothesis attached to Apep.

The timeline of the project and expected duration of each component is outlined below (Table 1).

Task	Project Week														
	0	3	6	9	12	15	18	21	24	27	30	33	36	39	42
Literature Review (reading)															
Tertiary Dust Analysis															
`xenomorph` Development															
Project Plan					x										
Hydrodynamic Modelling with `Phantom`															
Radiative Modelling with `MCFOST`															
Literature Review (Report)										x					
Fit other WR Binaries (time permitting)															
Poster Presentation (incl. Prep)											x				
Thesis Preparation															x

Table 1: Estimated Project Timeline and Milestones. Crosses indicate a rough due date (±1 week) of that assessment piece.

References

J. R. Callingham, P. G. Tuthill, B. J. S. Pope, P. M. Williams, P. A. Crowther, M. Edwards, B. Norris, and L. Kedziora-Chudczer. Anisotropic winds in a Wolf-Rayet binary identify a potential gamma-ray burst progenitor. *Nature Astronomy*, 3:82–87, Mar. 2019. doi: 10.1038/s41550-018-0617-7.

J. R. Callingham, P. A. Crowther, P. M. Williams, P. G. Tuthill, Y. Han, B. J. S. Pope, and B. Marcote. Two Wolf-Rayet stars at the heart of colliding-wind binary Apep. *MNRAS*, 495(3):3323–3331, Jan. 2020. doi: 10.1093/mnras/staa1244.

B. Hastings, N. Langer, and J. Puls. A model of anisotropic winds from rotating stars for evolutionary calculations. *Astronomy & Astrophysics*, 672:A60, Apr. 2023. doi: 10.1051/0004-6361/202245281.

T. Hoang, L. N. Tram, H. Lee, and S.-H. Ahn. Rotational disruption of dust grains by radiative torques in strong radiation fields. *Nature Astronomy*, 3:766–775, May 2019. doi: 10.1038/s41550-019-0763-6.

C. Pinte, F. Ménard, G. Duchêne, P. Bastien, T. J. Harries, M. Min, A. M. Watson, C. P. Dullemond, P. Woitke, and M. C. Durán-Rojas. MCFOST: Radiative transfer code. Astrophysics Source Code Library, record ascl:2207.023, July 2022.

D. J. Price, J. Wurster, T. S. Tricco, C. Nixon, S. Toupin, A. Pettitt, C. Chan, D. Mentiplay, G. Laibe, S. Glover, C. Dobbs, R. Nealon, D. Liptai, H. Worpel, C. Bonnerot, G. Dipierro, G. Ballabio, E. Ragusa, C. Federrath, R. Iaconi, T. Reichardt, D. Forgan, M. Hutchison, T. Constantino, B. Ayliffe, K. Hirsh, and G. Lodato. Phantom: A Smoothed Particle Hydrodynamics and Magnetohydrodynamics Code for Astrophysics. *PASA*, 35:e031, Sept. 2018. doi: 10.1017/pasa.2018.25.

H. Sana and C. J. Evans. The multiplicity of massive stars. In C. Neiner, G. Wade, G. Meynet, and G. Peters, editors, *Active OB Stars: Structure, Evolution, Mass Loss, and Critical Limits*, volume 272 of *IAU Symposium*, pages 474–485, July 2011. doi: 10.1017/S1743921311011124.

T. Schirmer, N. Ysard, E. Habart, A. P. Jones, A. Abergel, and L. Verstraete. Nano-grain depletion in photon-dominated regions. *Astronomy & Astrophysics*, 666:A49, Oct. 2022. doi: 10.1051/0004-6361/202243635.

P. G. Tuthill, J. D. Monnier, and W. C. Danchi. A dusty pinwheel nebula around the massive star WR104. *Nature*, 398 (6727):487–489, Apr. 1999. doi: 10.1038/19033.

R. M. T. White and P. Tuthill. Wolf-Rayet Colliding Wind Binaries. *arXiv e-prints*, art. arXiv:2412.12534, Dec. 2024. doi: 10.48550/arXiv.2412.12534.