On the Origin of Long GRB Afterglow Variety

Ashley Chrimes

Radboud Excellence Initiative Fellow

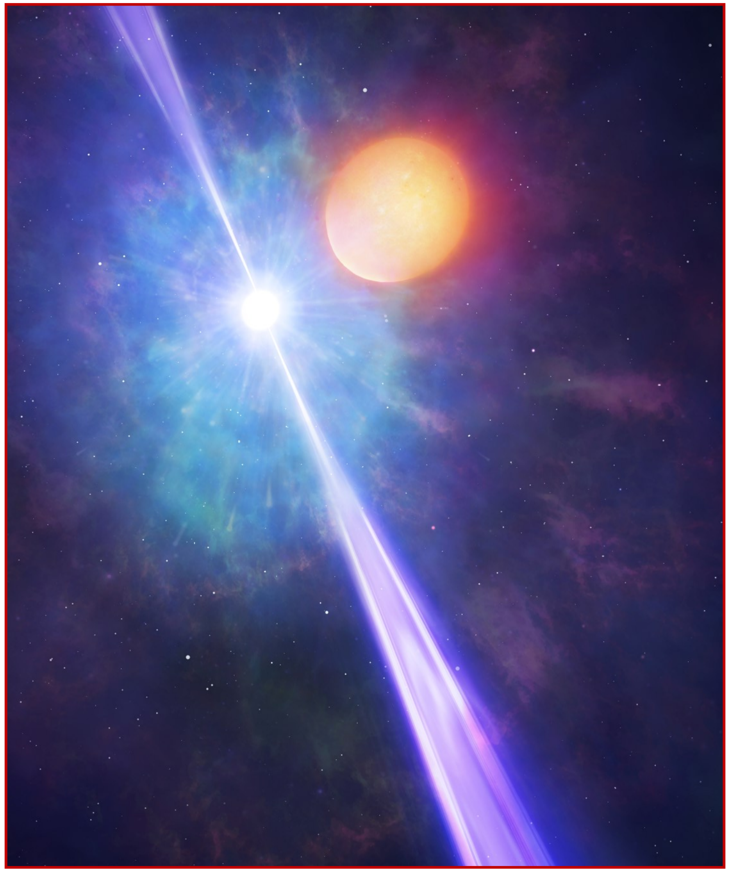
Department of Astrophysics/IMAPP, Radboud University, Nijmegen, the Netherlands

Email: a.chrimes@astro.ru.nl | Website: ashtronomy.com | Twitter: @astroash42

1. LONG GAMMA-RAY BURSTS (GRBs)

Long GRBs (>2s) are powerful, relativistically beamed explosions. They are caused by the collapse of massive, fast spinning stars which have had their outer layers removed, when a jet is launched by accretion onto a newborn compact object. The prompt γ-ray emission is observable if Earth lies inside the jet opening angle. The jet decelerates as it collides with the circumstellar medium (CSM). The peak synchrotron frequency drops, and we observe a fading **afterglow** which can be seen in X-rays through to radio waves.

Right: Image credit - University of Warwick/Mark Garlick



2. TWO CLASSES OF CSM

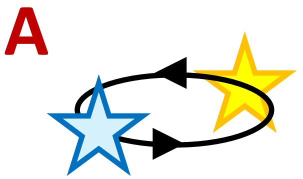
The density profile of the CSM can be inferred from afterglow observations. It is typically be classified as **constant density** (like the interstellar medium, ISM) or **wind-like,** with an r^{-2} density profile (e.g. **Chevalier et al. 2004**, **Li et al. 2015**).

3. THE PROBLEM

Simulations of GRB progenitor winds have struggled to produce **constant-density environments close to the progenitor**, the **variety** of wind and ISM densities observed, and predictions for the **distributions** of these parameters (**Eldridge et al. 2006**, **van Marle et al. 2006**).

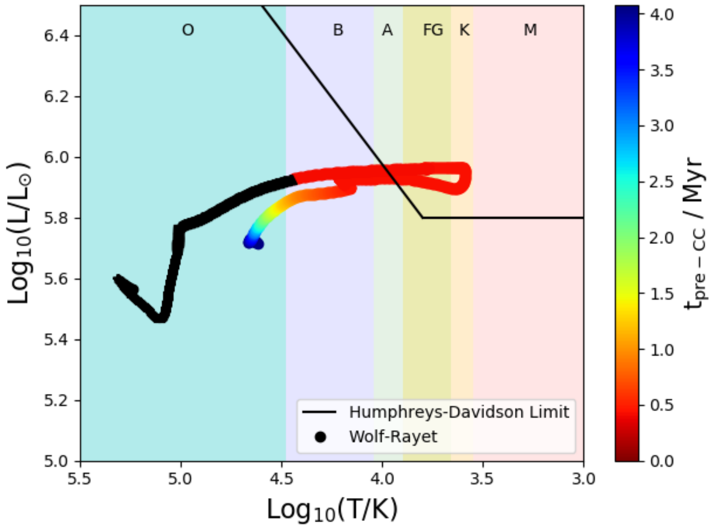
Long GRB Progenitor Models

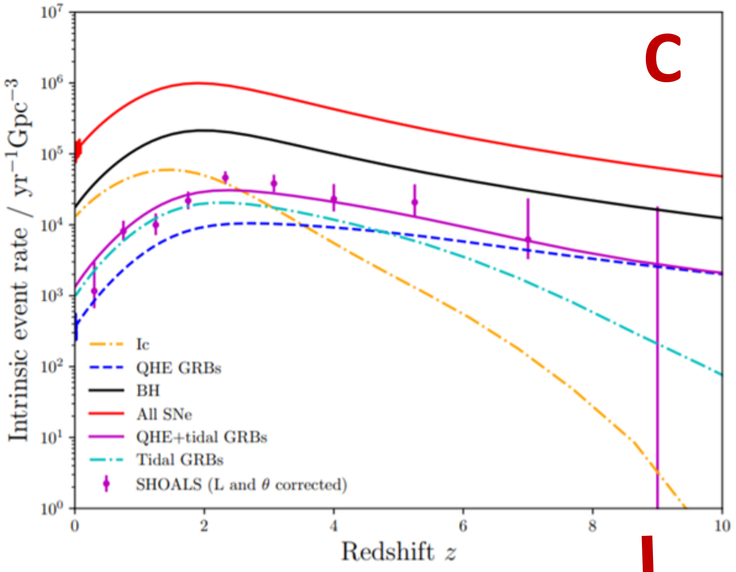
Chrimes et al. (2020), MNRAS, 491, 3479



4. BPASS

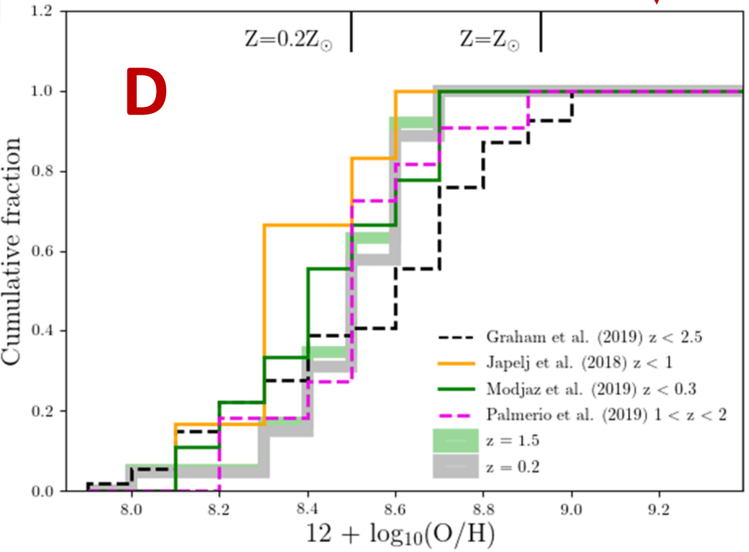
To model GRB progenitor winds, we need **stellar evolution models**. We use the **BPASS** models (**Eldridge et al. 2017**), which incorporate binary interactions and cover the full breadth of binary parameter space. An example evolutionary track is shown below (for a 60$M_\odot$, $Z_\odot$ star). The model outputs include **mass loss rate**, but not **wind speed**. We employ the wind speeds of **Lamers et al. (1995)** for O to AF stars (revised down for high *T* based on recent work, e.g. **Vink et al. 2018**), and Wolf-Rayet wind speeds from **Lamers & Nugis (2000)**.





5. GRB PROGENITOR MODELS

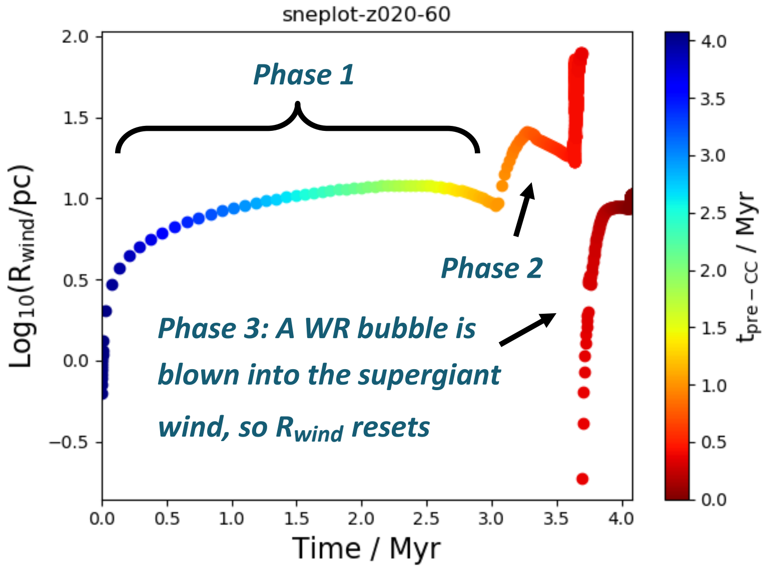
Selecting models that satisfy GRB requirements, and determining how often these occur in populations (A, B above), we can compare to the observed rate (C) and obtain other distributions such as metallicity *Z* (D). **Chrimes et al. (2020)** showed that a **two-pathway** model of **tidally—spun** fast rotators, and accretion—spun quasi-homogenously evolving (**QHE**) stars, could fit the rates and *Z* distribution. These models are used for our wind study.



Wind Modelling: Analytical vs Numerical Methods

6. ANALYTICAL SOLUTIONS

There are three key parameters of interest in—the **termination shock radius R_{wind}**, the **wind 'density' $A_\star$** if the afterglow is wind-like, and the **constant-density** equivalent, ***n***. We calculate R_{wind} analytically for every BPASS GRB model, using the **three-wind model** of **Garcia-Segura & Mac Low (1995)**. The phases are main sequence, supergiant, and Wolf-Rayet (see right).



The 3-wind model ,and formula for R_{wind} in the fast, dense (Wolf-Rayet) phase:

Fast, diffuse → Slow, dense → Fast, dense

$$R_{wind} = \left(\frac{\dot{M}V_{wind}}{4\pi r_0^2\rho_0}\right)^{\frac{1}{2}} t$$

$$r_0^2\rho_0 = \frac{\dot{M}_{RSG}}{4\pi V_{RSG}}$$

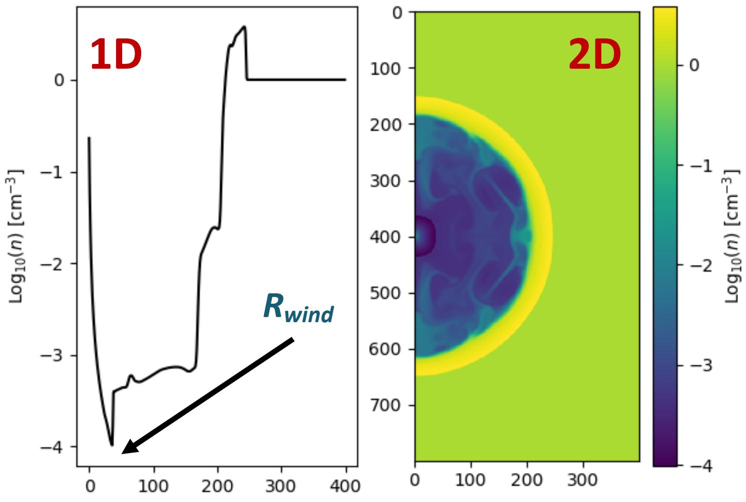
8. VERIFICATION

We first ran a set of trial runs to confirm that PLUTO produces the same results as the analytic approach when the assumptions of the analytic approach are met. *Left:* an analytic run for a $60M_\odot$, $Z_\odot$ star in an $n=1\mathrm{cm}^{-3}$ ISM. *Right:* the hydrosimulation equivalent (at t=1.5Myr) with a cold ISM and no cooling. The x axis is in cell units, in physical units this is 100pc. R_{wind} ~ 10pc in each case.

$$A_* = \left(\frac{\dot{M}}{10^{-5}\,\mathrm{M_\odot\,yr^{-1}}}\right)\left(\frac{1000\,\mathrm{km\,s^{-1}}}{v_{\rm wind}}\right)$$

7. HYDRODYNAMICAL SIMULATIONS

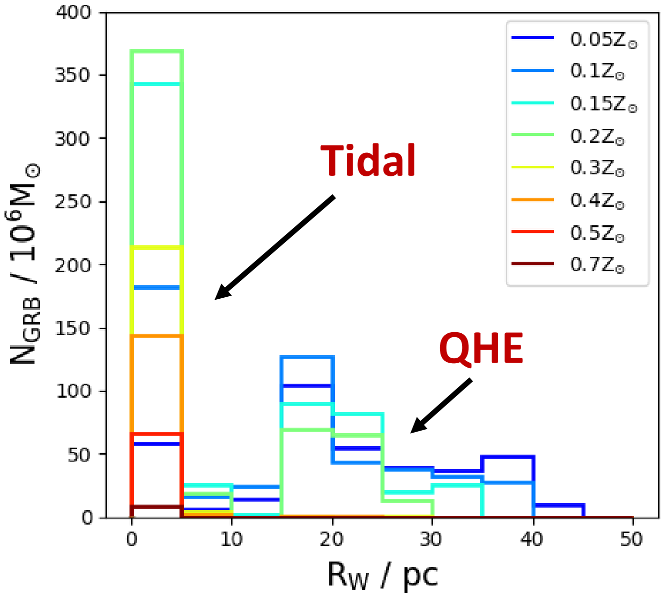
The analytic solutions are only valid for the case of a supersonic shock and cold ISM with negligible thermal pressure (**Weaver et al. 1977**). **Hydrodynamical simulations** are too computationally expensive to run for every model, but incorporate physics such as an ISM thermal pressure, radiative cooling and instabilities. For a subset of models, we calculate R_{wind} using the **PLUTO** hydro code (**Mignone et al. 2014**), allowing us to quantify the uncertainties in the analytic approach. The stellar wind is initialised with $A_\star$ as defined above.



Circumstellar Medium Pop Synth & Comparison Data

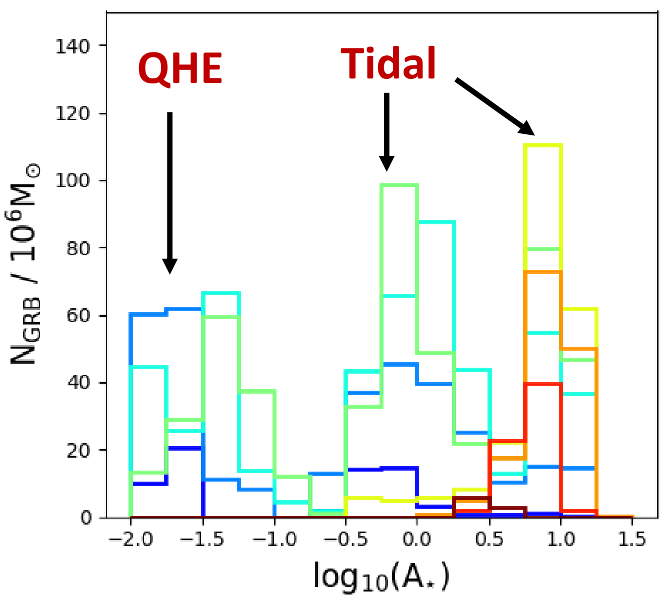
9. WIND PARAMETER UNCERTAINTIES

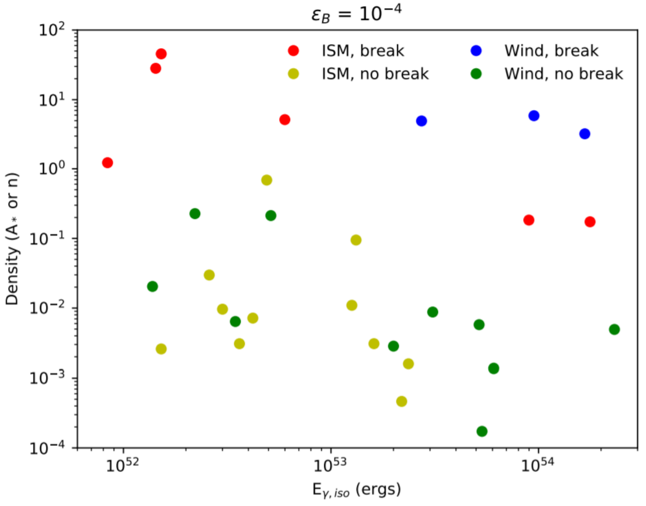
The analytic calculations have been applied to every BPASS GRB model, and the results of this are shown below. The bimodality in R_{wind} corresponds to QHE models (which are **low *Z*** with **weak winds** and overall **longer lifetimes**) and tidal models which can occur at **higher *Z***, with **stronger winds**. The tidal peak resolves into two in the $\log_{10}(A_\star)$ distribution, corresponding to different spectral types of progenitor.



10. THE AFTERGLOW SAMPLE

Collaborator **Ben Gompertz** is re-analysing and expanding the sample of afterglows in **Gompertz et al. (2018)**, building on over 10 years of *Fermi* GRB observations. *Right*: from **Gompertz et al. (2018)**, there is a wide range in $A_\star$ and *n*. This spread is expected to reduce when the afterglows are fit with larger datasets, as more parameters will be constrained (in particular, the the magnetic field energy, ε_B).





11. FURTHER WORK

This includes finishing a **grid of hydrosimulations** to determine **uncertainties** on the analytically-derived distributions (left), and completing the analysis of the **afterglow sample**. Our implementation of winds can also be updated (**Sander & Vink, 2020**). We can then ask: can the complex **shock structure** seen in hydrosimulations explain the **range** of ISM-like densities seen, or is a large variety of **environmental** densities required? And what **further insights** can be gained into GRB progenitors and environments?