# Shockwave Propagation Through Wind Driven Bubbles

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The unique structures of the Crab Nebula have engendered a lot of speculation We will attempt to provide a model for their formation by simulating a supernova shockwave propagating through a wind driven bubble that formed around a progenitor star, eventually overtaking the bubble and starting into the cold interstellar medium.

## The Crab Nebula

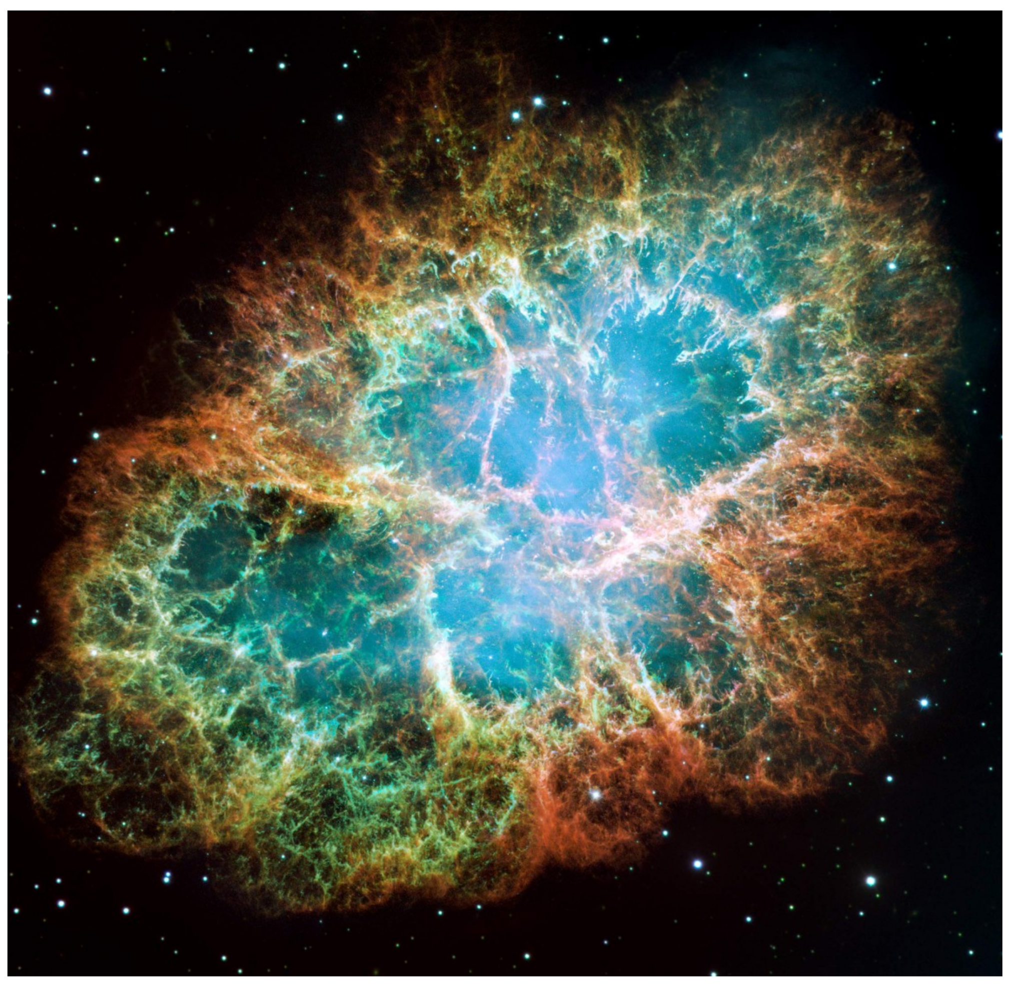


Fig 1.: Composite image of the Crab Nebula, taken from the Hubble Space Telescope. The syncotron nebula is show in blue in the center of the nebula.

The Crab Nebula is perhaps the most studied supernova remnant. It is the remains of a core-collapse supernova described by Chinese astronomers in 1054 AD, and is the first item described by Messier in his catalogue of 'comet-like objects' in 1774. 'Core-collapse' indicates that there is a neutron star left behind, in this case the Crab Pulsar. Pulsars are neutron stars (the collapsed remains of the progenitor star's core) which spin incredible fast (for the Crab Pulsar, about once every 33 milliseconds). This periodic signal was once considered possible evidence of other civilizations until it was understood that it is an entirely natural phenomenon. Fig 2. is an X-ray image of the nebula with the pulsar clearly visible in the center as well as showing the synchotron nebula which results from the strong magnetic field the pulsar emits.

Fig 2.: X-Ray image of the Crab Nebula taken from the Chandra X-Ray Observatory.

One reason it receives so much scrutiny is that it doesn't seem to fit into what we currently think a core-collapse supernova remnant should look like- it is far too light and not nearly energetic enough. Current models predict a lower bound of 8 solar masses for a star to die in a core-collapse supernova, while the visible mass in the Crab Nebula adds up to about 4.6 solar masses, ±1.8 solar masses. One current theory to explain this discrepancy calls for a diffuse shell of high-energy hydrogen that was ejected before the rest of the mass and surrounds the nebula (Hester, 2008)- which could also explain the sharp, defined edges seen there as this outer shell would constrain the later ejecta This hypothesis has received a lot of attention including several attempts to find this shell, but so far no one has any observational evidence that it's there. Another explanation, which we will explore, states that a lower mass star than predicted did, indeed, explode and the structure we see is the result of the supernova induced shockwave propagating through a bubble of hot gas put out by the progenitor star during its lifetime. The shockwave eventually overtook the thin outer shell of this bubble, accounting for some of the feature of the nebula that we observe today.

## Wind Driven Bubbles

Wind driven bubbles are the huge bubbles of hot gas that form around stars during their lifetime. They are created by stellar winds that are a part of any star above a certain mass. The Sun has a wind that puts out about $10^{-14}$ solar masses each year, while some stars (known as Wolf-Rayet) can put out as much as $10^{-5}$ solar masses each year. The mass lost in this way forms a bubble of gas around the star, pushing the interstellar medium out of the way.

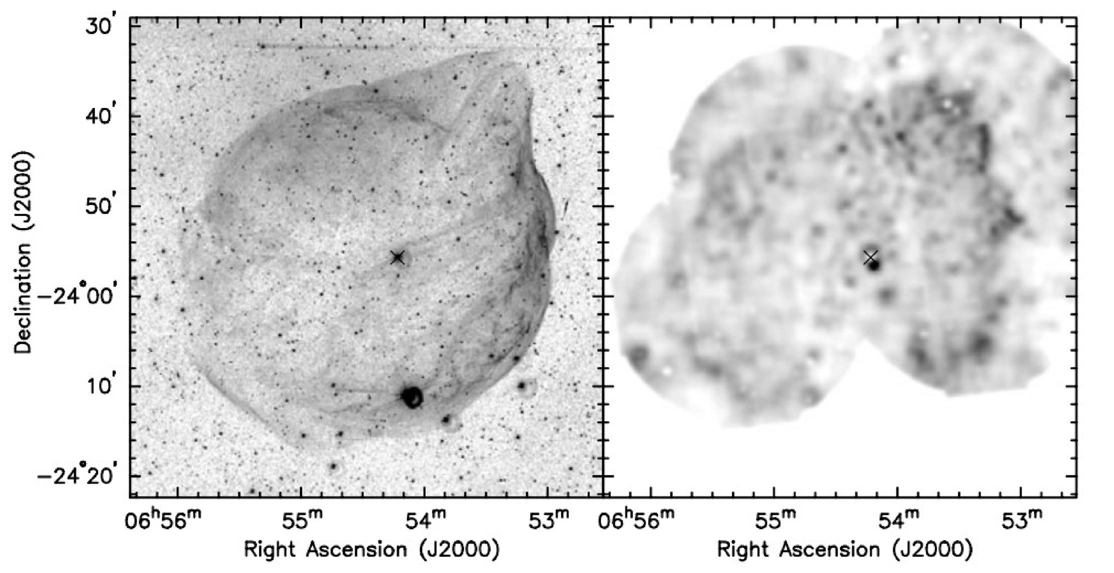
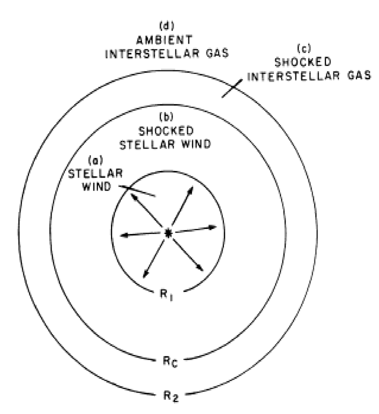
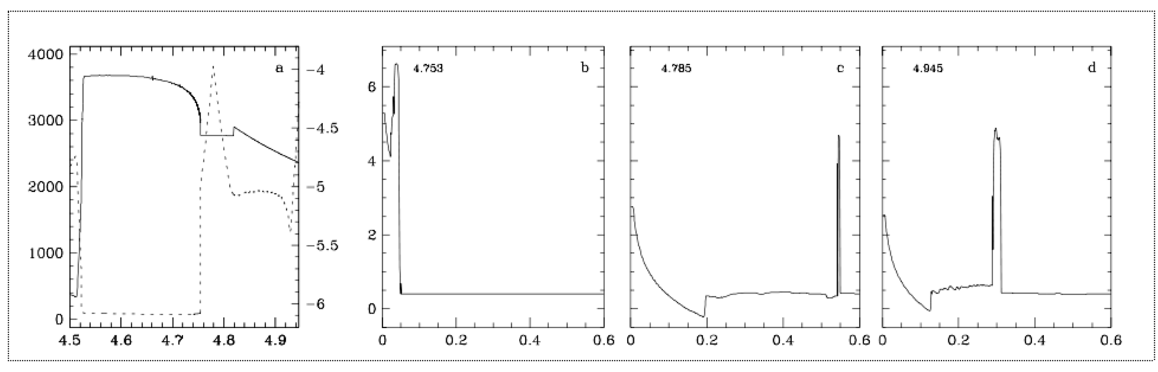



**Figure 3.** Left - [O III] λ5007 image of S 308. Right - *XMM-Newton* EPIC-pn X-ray image of S 308 in 0.3-1 keV band. Obvious point sources have been excised and adaptive smoothing has been applied. Diffuse X-ray emission inside S 308 shows a limb-brightened morphology. The central WN star HD 50896 is marked with a "×".

Shown below is an example of the structure of a bubble formed over the lifetime of a 15 solar mass star. The basic structure consists of an inner, high temperature gas with an outward velocity and a thin outer shell where the gases pile up against the pressure of the cold gas of the interstellar medium. This example is slightly different than the one that will be used in this simulation, as it is generated from a much more massive star and is expanding into a denser interstellar medium than we suppose exists around the Crab Nebula.



*Evolution of a wind-driven bubble in a high pressure medium. (a) Evolution of a stellar wind from a 35 M⊙ star. Left scale: terminal wind velocity (km s−1 ); right scale: mass loss rate (M⊙ yr−1 ); horizontal scale: time (millions of yr). (b)-(d): Evolution of the wind-driven bubble. The gas density (cm−3 ) is plotted in a logarithmic scale against the radial distance (pc). Evolutionary times (shown in the upper-left corner of each panel) are given in million years.*

## Supernova Remnants

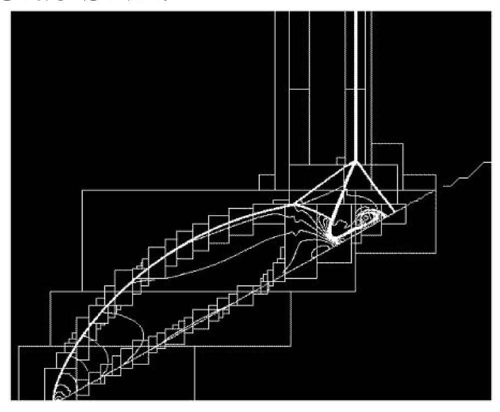
Supernova remnants tend to evolve in three main phases. During the first, known as free expansion, the front of the expansion is formed from the shock wave interacting with the ambient interstellar medium. This phase has constant temperature within the SNR and constant expansion velocity of the shell. In the second phase, known as the Sedov or adiabatic phase, the SNR material slowly begins to decelerate and cool. The main shell of the SNR experiences Rayleigh-Taylor instability, which causes the SNR's ejecta to become mixed with the gas that was just shocked by the initial shock wave and causes the complicated structures visible in remnants like the Crab Nebula. The third phase, known as the snowplow phase, begins after the shell has cooled to about $10^6$ K, when the shell can more efficiently radiate energy. It cools faster, making it shrink and become more dense, which cools it faster still. Because of the snowplow effect, the SNR quickly develops a thin shell and radiates away most of its energy as optical light. Outward expansion stops and, after millions of years, the remnant is absorbed into the ISM

## Tools

### FLASH

This simulation will use a modified FLASH code, which is a simulation package maintained by the University of Chicago. It comes with a number of example problems that span the range of its abilities and allows for a preconfigured starting point for many problems. For current problem, we will modify boundary conditions to impose time-dependent hydrodynamic state corresponding to a supersonic stellar wind. After evolution reaches a supernova explosion stage, the central portion of computational domain will be overwritten with the supernova ejecta. The following evolution will be continued for several hundred years essentially up to the current age of Crab SNR.

### AMR



Adaptive Mesh Refinement is a discretization strategy used by many modern simulation tools as a way to reduce computational cost. In the AMR framework, mesh resolution is constantly adapted to follow critical flow structures. That is, computational effort is focused only on select regions. Overall strategy offers greatest savings for problem with discontinuities, e.g. shock or material interfaces.

### Sensitivity Study

The varying density of the bubble interior means that the supernova shock will move at different speeds, causing several types of hydrodynamic instabilities (for instance, Rayleigh-Taylor at the inner face of the WDB shell, Richtmeyer-Meshkov at the same location after the passage of the SN shock, and Kelvin-Helmholtz instability developing on small scales at later times). One of our goals is to determine how sensitive the final structure of SNR is on key parameters of this system: the stellar wind, the bubble morphology, the density of the interstellar medium that surrounds the bubble. We will determine which of these variables are the most important in the evolution of the SNR, ultimately allowing us to estimate more accurately the age of the remnant, the energy of the explosion, and the probable nature of the progenitor star. Due to relatively high cost of the model, one possible method for the proposed sensitivity analysis is the One at a Time (OAT) strategy. In OAT, a sequence of models is obtained with the initial conditions between models modified in such a way that only the value of one of the critical system parameters is changed.

## Computational Strategy

**I. Wind-Driven Bubble.** The bubble is created by the supersonic stellar wind of the progenitor. The wind parameters are obtained from A. Heger (private communication) for a number of low-mass supernova progenitors. As time progresses, the inflow conditions (which represent the stellar wind from the star) change. In this phase of computation, an AMR mesh will be adapted to resolve the leading WDB shock, the dense shell, and the terminal shock of the stellar wind.

**II. Supernova Remnant.** Once the end of the stellar lifetime is reached a point-like strong explosion representing supernova will be initiated in the central region of the grid. At this time, supernova ejecta will have to be carefully resolved until homologous expansion is established. As we mentioned before, the following evolution will include several strong flow interactions. The first of those interactions will be between the SNR shock and the terminal shock of the wind, leading to a pair of transmitted/reflected shocks and the contact discontinuity. The transmitted shock, or the supernova shock, will next overrun the shocked stellar wind and run into the dense WDB shell. The most technically challenging phase of the evolution is associated with the shock leaving the dense shell when the gas density is abruptly changing by 2-3 orders of magnitude. This causes rapid acceleration of the shock and severely constrains the time step.

**III. Analytic considerations.** The above computational scenario can be examined by means of a (simplified) analytic model of a wind driven bubble and a model of a supernova explosion in a constant density medium. The radius of a wind-driven bubble is (Weaver et al. 1978):

$$R_{WBD}(t) = \alpha(L_w t3/\rho_0)^{1/5}$$

The supernova remnant radius is given by (Chevalier et al, 1974) :

$$R_{SNR} = (2.02E_0/\rho_0)^{1/5}t^{2/5}$$

We can use these formulas to estimate time when the supernova shock radius becomes larger than the radius of a wind driven bubble, and compare to the fully nonlinear simulation results.

## References

Weaver et al., *Interstellar Bubbles II*, 1977
Hester et al., *The Crab Nebula, An Astrophysical Chimera*, 2008
Franco, J., et al., *The State of Gas Around Young Stellar Groups*, 1996
Chevalier, R. et al., *The Evolution of Supernova Remnants*, 1974