Supernova Remnant Explorer: a softare tool to calculate SNR evolution

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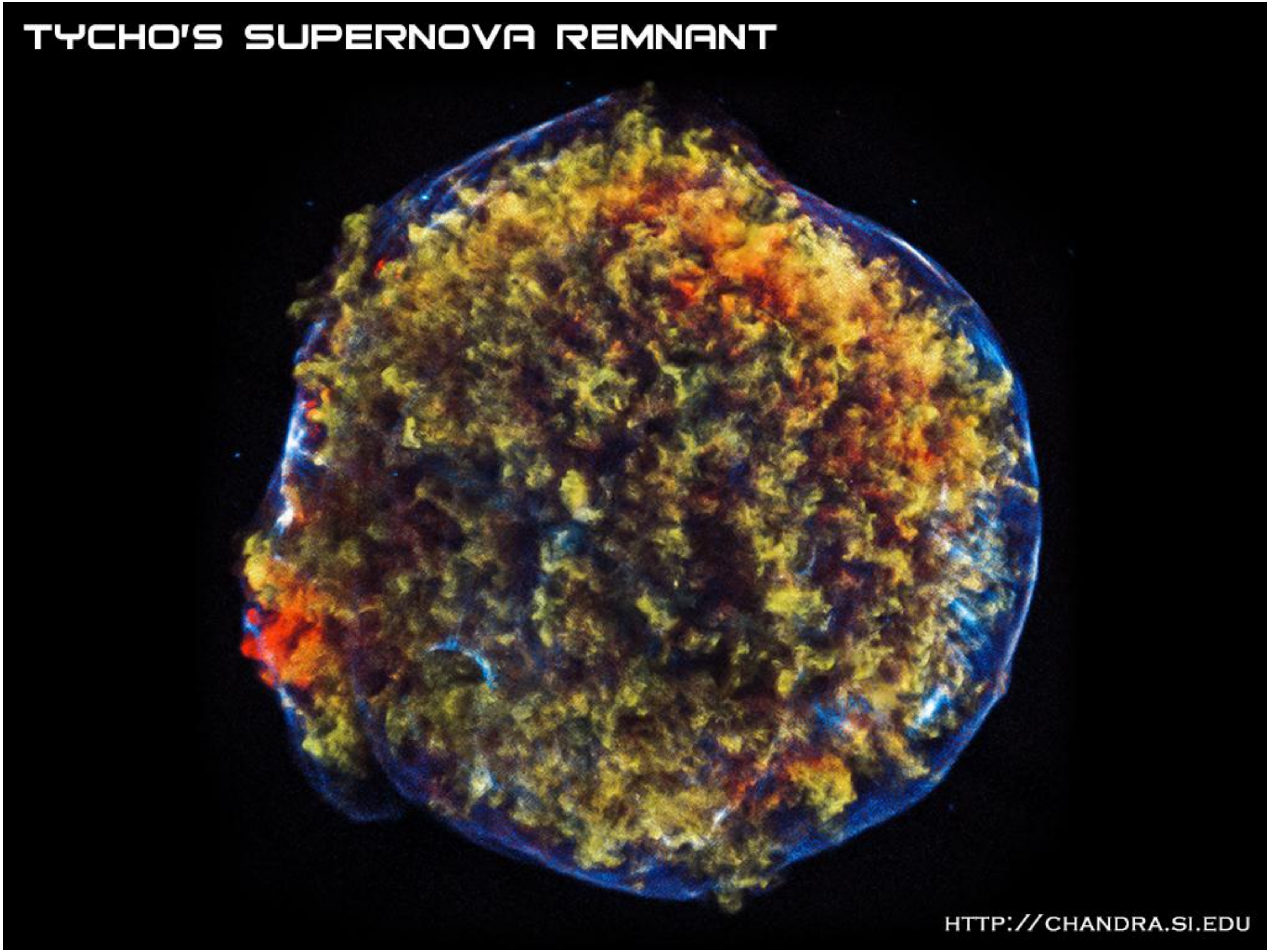
TYCHO'S SUPERNOVA REMNANT
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Supernova remnants (SNR)

- SNR=the result of a supernova (SN) explosion in interstellar space
- A SN gradually turns into a SNR
- SN: kinetic energy of ~10^{51}erg (10 billion yr. worth of 1 solar luminosity)
- 1-5 solar masses of elements ejected at speeds of 5000-10000 km/s (the “ejecta”)
- Ejecta hits the surrounding gas and heats it to ~100 million K (10 keV)
- The hot gas expands with a shock wave, reaching a radius of a few light years within ~100 yr.
- The shock wave gradually slows, reaching 100 km/s after ~40000 yr.

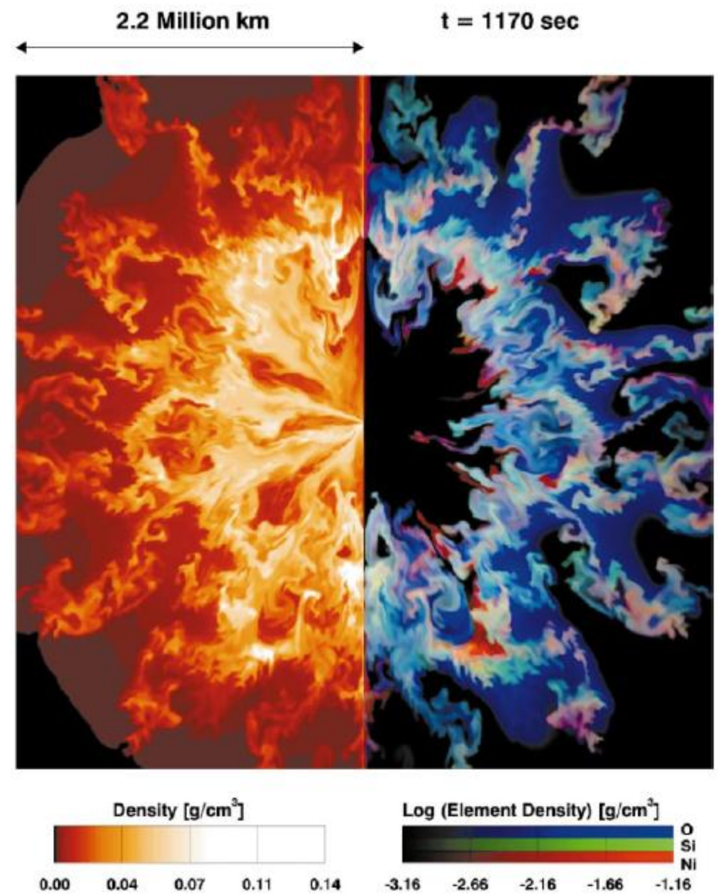


FIG. 24. Mixing in the explosion of a 15$M_\odot$ red supergiant. From Kifonidis *et al.*, 2000 [Color].

SNR evolution phases

- **Free expansion of the ejecta**, until it sweeps up their own mass in circumstellar or interstellar medium. (last tens to a few hundred years)
- Shocked circumstellar/interstellar gas or **Sedov-Taylor phase**, which can be approximated by a self-similar analytic solution. Strong X-ray emission traces the strong shock waves and hot shocked gas.
- Cooling of the shocked shell, to form a thin (< 1 pc), dense shell surrounding the hot (few million K) interior. Also called the **pressure-driven snowplow phase**. The shell can be seen in optical emission from recombining hydrogen and heavier (e.g. oxygen) atoms.
- **Momentum-driven phase**: cooling of the interior. The dense shell continues to expand from its own momentum.
- **Merging** with the surrounding interstellar medium. When the supernova remnant shell slows to the speed of the random velocities in the surrounding medium (after roughly a million years) it will merge into the general turbulent flow, contributing its remaining kinetic energy to the turbulence.

Ejecta dominated (ED) and Sedov-Taylor (ST) phases

- Assume spherically symmetric SN and circumstellar medium.
- The blast wave during ST phase (Sedov, 1946, Taylor 1950) and the early part of the ED phase (Taylor 1946) has self-similar solutions.
- The existence of a reverse shock was realized by McKee (1974). Chevalier (1982) and Nadyozhin (1985) found self-similar solutions for the early ED phase including the reverse shock.
- Most of the ED phase is not self-similar and one usually uses numerical simulations to obtain the evolution.
- However fairly accurate analytic approximations were obtained by Truelove & McKee (1999, hereafter TM99), valid in the case that radiative cooling and magnetic fields are not important.
- The TM99 solutions are scalable so can be applied to a wide variety of initial SN and ISM conditions.
- The characteristic scale lengths are

$$\boxed{\begin{aligned} R_{\rm ch} &\equiv M_{\rm ej}^{1/3}\rho_0^{-1/3} , \\ t_{\rm ch} &\equiv E^{-1/2}M_{\rm ej}^{5/6}\rho_0^{-1/3} , \\ M_{\rm ch} &\equiv M_{\rm ej} . \end{aligned}}$$

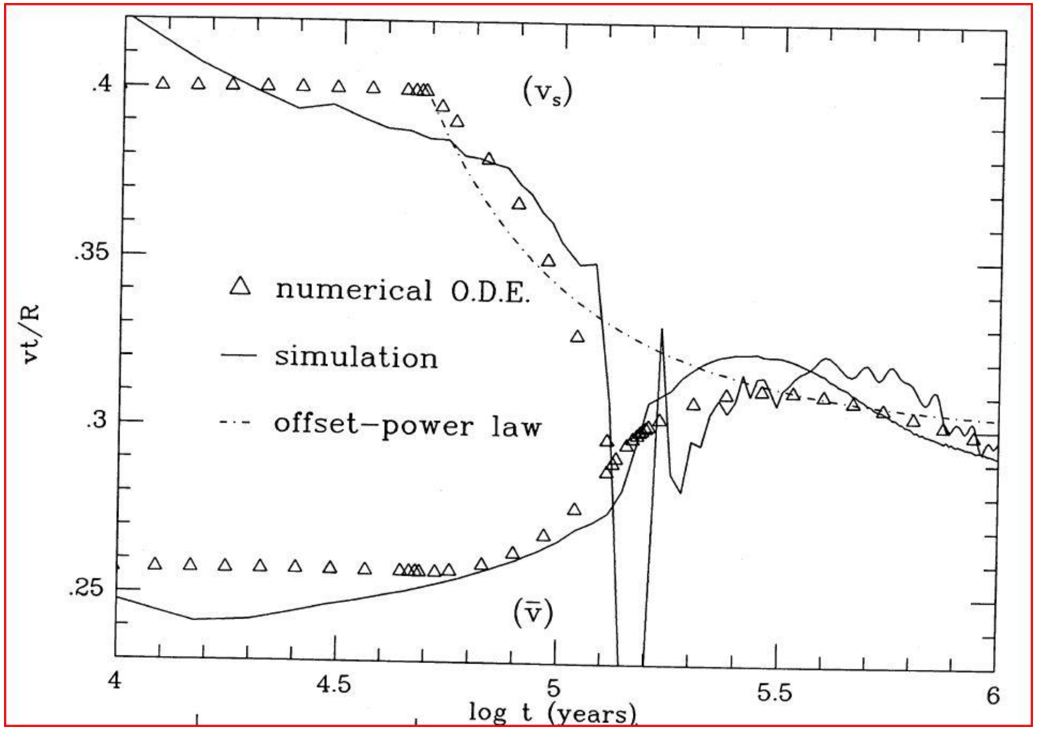
$$\boxed{v_{\rm ch} \equiv R_{\rm ch}/t_{\rm ch}}$$

$$\boxed{T_{\rm ch} \equiv \frac{3}{16}\frac{\mu}{k}v_{\rm ch}^2}$$

Pressure driven snowplow(PDS) and Momentum conserving shell (MCS) phases

- When radiative losses from post-shock gas becomes important the pressure driving the expansion decreases and slows the shock.
- The inclusion of radiative losses is calculated in numerical simulations for the SNR evolution.
- An approximate ODE for the blast wave motion can be derived and solved.

Reasonably accurate analytic formulae can be fitted to the numerical simulations and the ODE solution (e.g. Cioffi, McKee, Bertschinger 1988, hereafter CMB88).



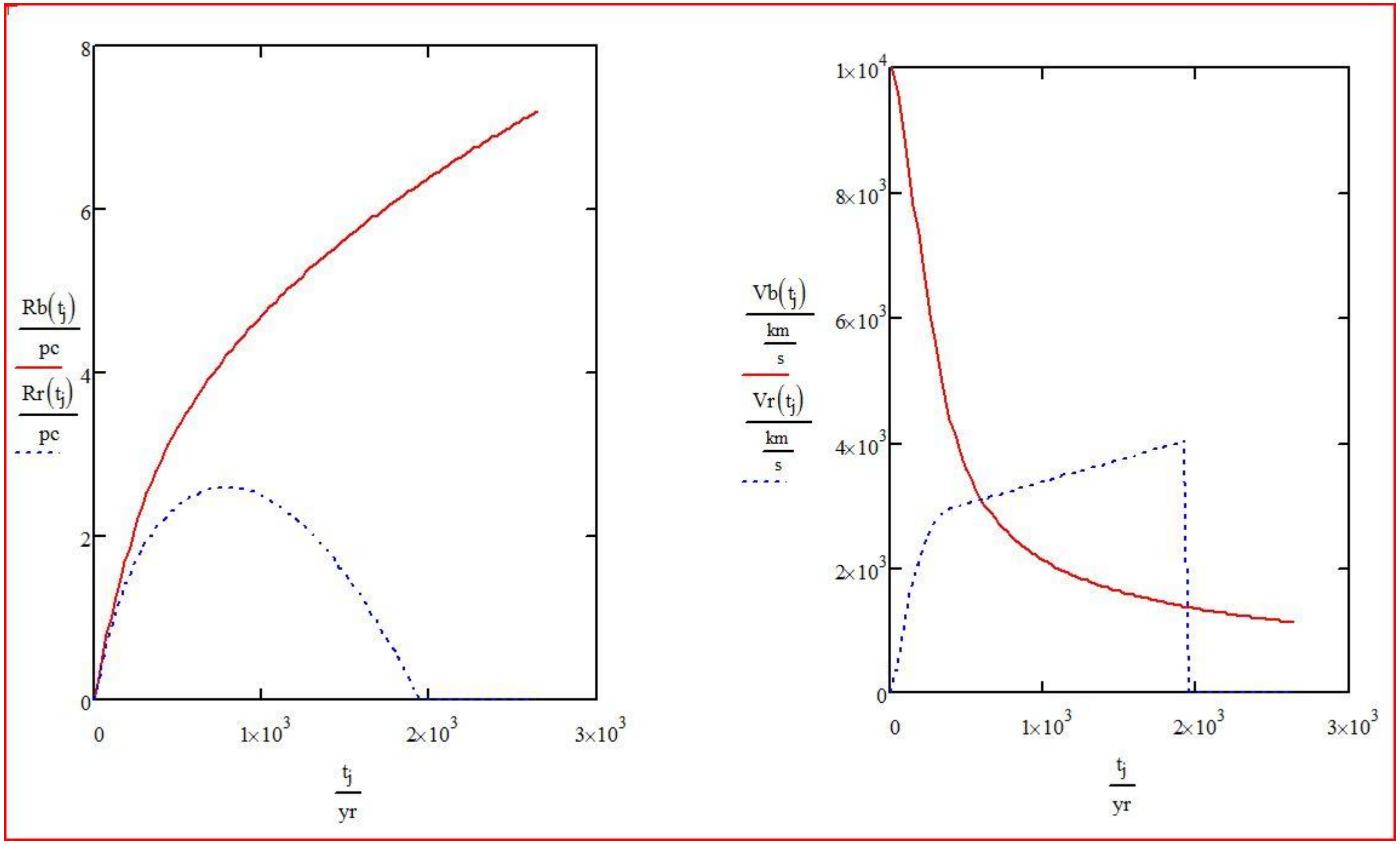
The current work: SNR explorer structure

- Includes all phases of SNR evolution in spherically symmetric circumstellar medium (CSM).
- Phases are Ejecta Dominated phase including reverse shock, Sedov-Taylor (or adiabatic) phase, radiative phases (both PDS and MCS).
- Alternative late phase models are incorporated (Tang & Wang, 2005; Liang & Keilty, 2000)
- The calculation ends with merger of SNR with the ISM.
- Input explosion parameters are ejecta mass, explosion energy, power-law density profile of the ejecta (choices n=0, 2, 4, 6, 7, 8, 9, 10, 12 or 14)
- Input CSM parameters: power-law density profile (s=0 or 2), temperature, density (s=0) or wind velocity and mass loss rate (s=2), mean molecular weight, metallicity (for the radiative cooling efficiency)
- Input time since explosion.

The software calculates determines the appropriate evolution stage, calculates output quantities and also produces evolution plots for the forward and reverse shock radii and their velocities.

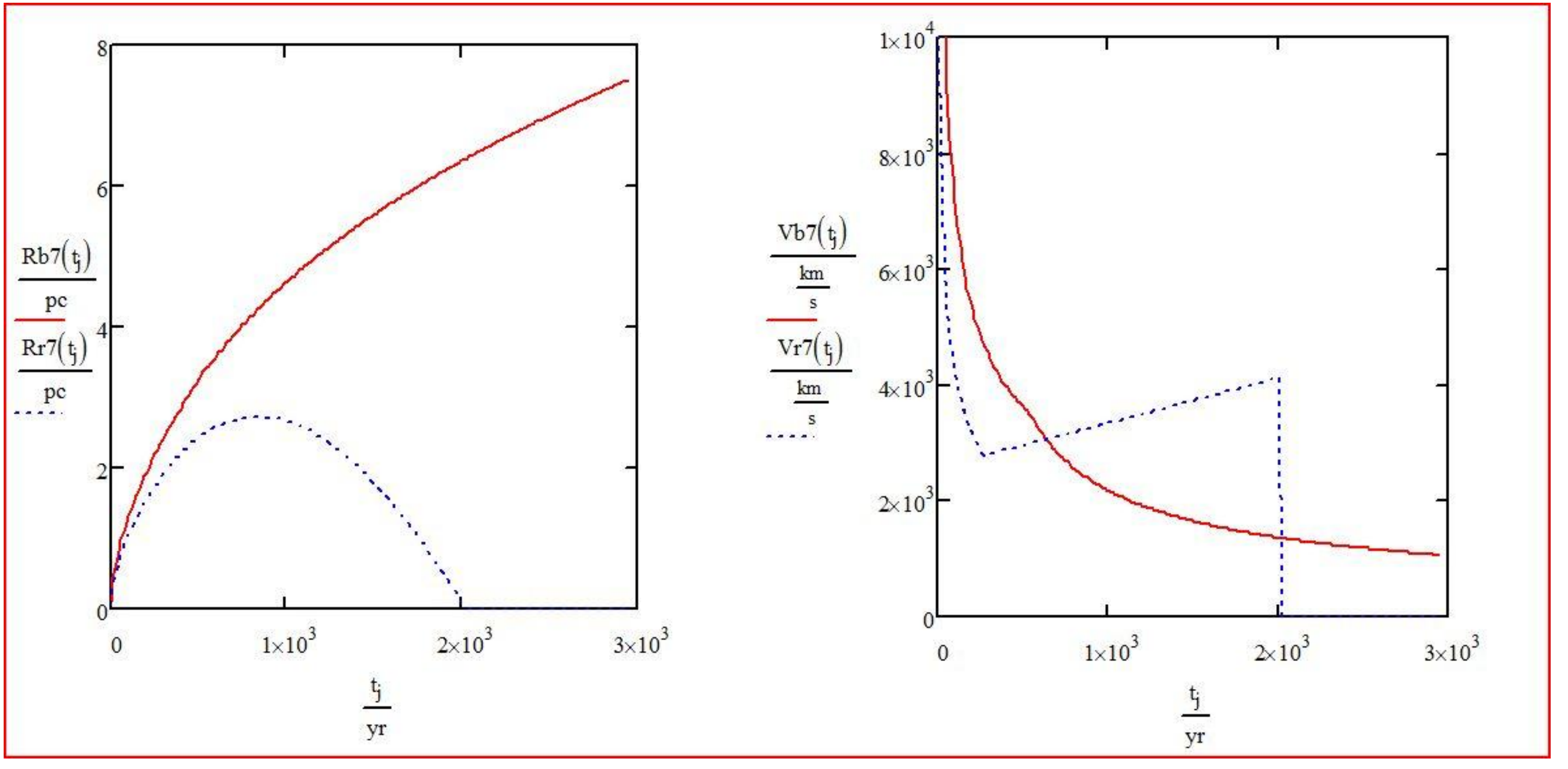
SNR explorer sample output

- Uniform ISM n0=1, E51=1, Mej=2, Tism=100K, n=0
- Ejecta Dominated and Sedov-Taylor phases
- Transition to PDS phase is at 13,300 yr, R=14pc
- Transition to MCS phase is at 9.9 Myr, R=111pc, similar to merger time (depends strongly on sound speed/turbulence of ISM)



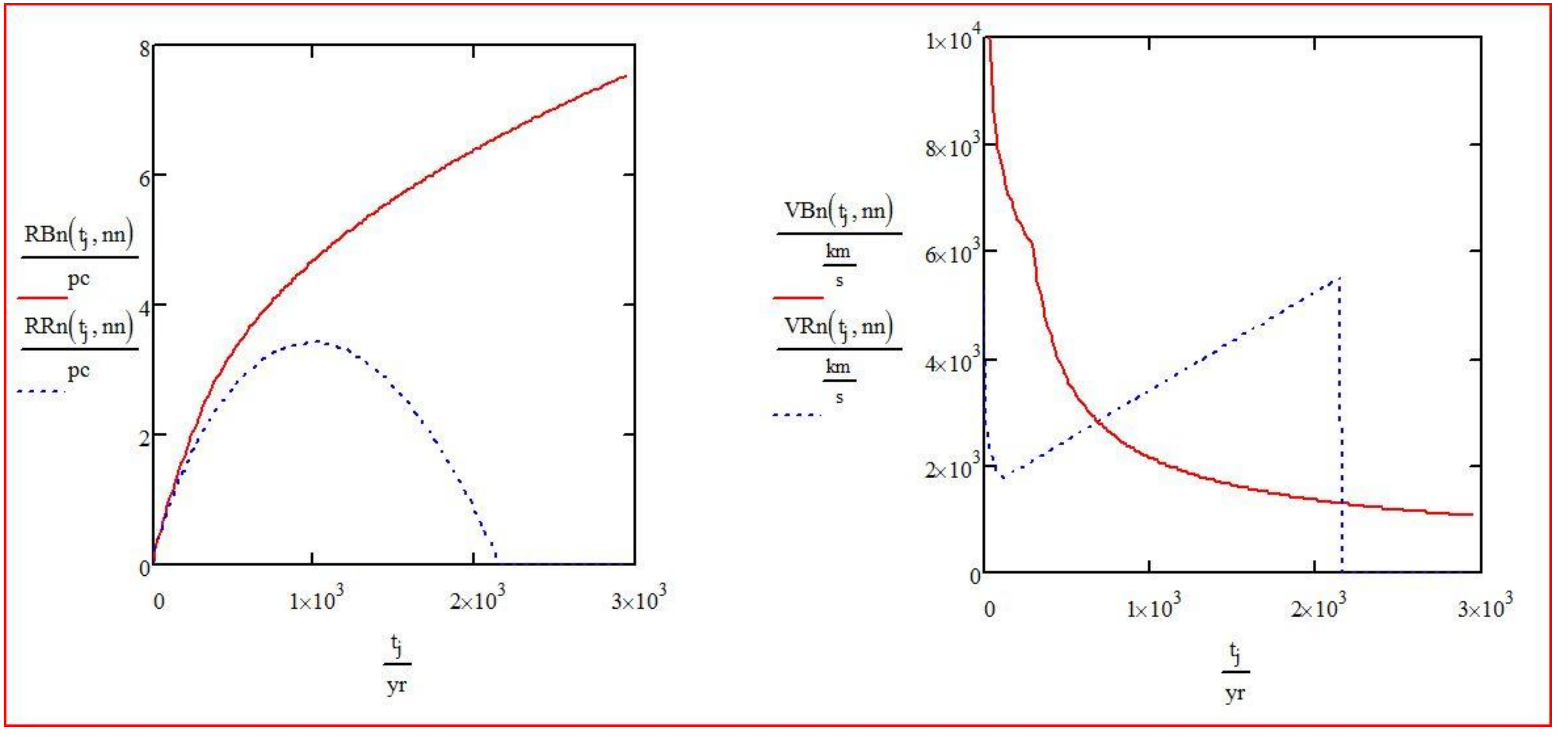
SNR explorer sample output

- Uniform ISM n0=1, E51=1, Mej=2, Tism=100K, n=7
- Reverse shock decelerates in steep envelope of the ejecta then accelerates when it encounters the core of the ejecta
- Ejecta Dominated and Sedov-Taylor phases



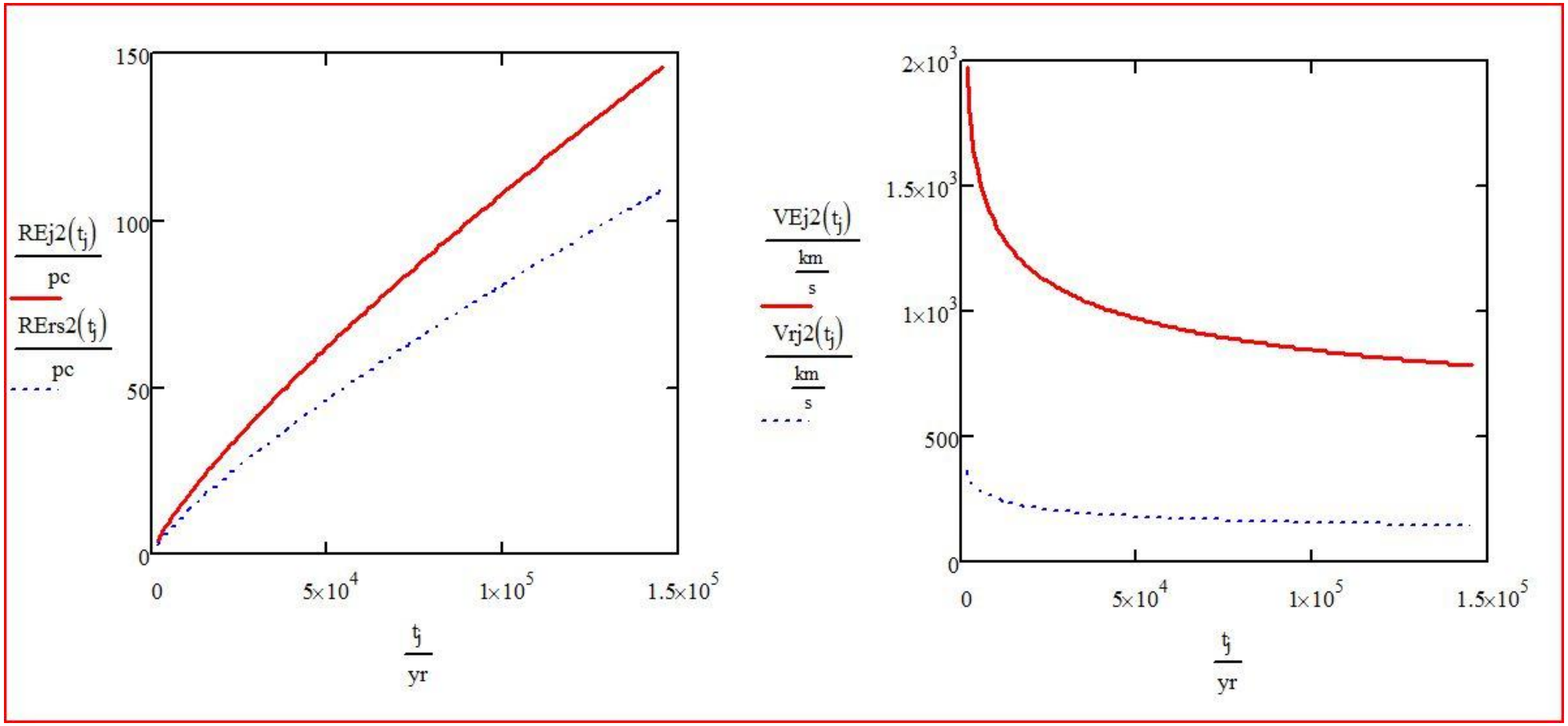
SNR explorer sample output

- Uniform ISM n0=1, E51=1, Mej=2, Tism=100K, n=14
- Ejecta Dominated and Sedov-Taylor phases



SNR explorer sample output

- Stellar wind CSM: vwind=30 km/s, Mdot=10^{-6} Msun/yr,
- E51=1, Mej=2, Tism=100K, n=7
- Ejecta Dominated phase (transition to ST is at t=1.5 Myr, R=770 pc)
- s=2 case CSM is currently of infinite extent.



SNR explorer: summary

- Note on accuracy of the analytic approximations for ED/ST phases. The results have been tested against numerical calculations.
- The error depends on the values of s and n.
- s=0,n=0 maximum error for Rb is <5%, for Rr <10%, for Vb<10%, for Vr<6% (b=blast wave, r-reverse shock).
- Other cases of s,n have similar maximum errors. Typical errors are 2-4%.
- Current working version is written in MathCad. The creation of a Python tool with the same functionality is mostly complete.
- A public version of the python software tool will be released this summer.

Please contact Denis Leahy (leahy@ucalgary.ca) if you would like to obtain and test the software or have suggestions for how it can be improved.