Modeling Type-IIn Interacting Supernovae

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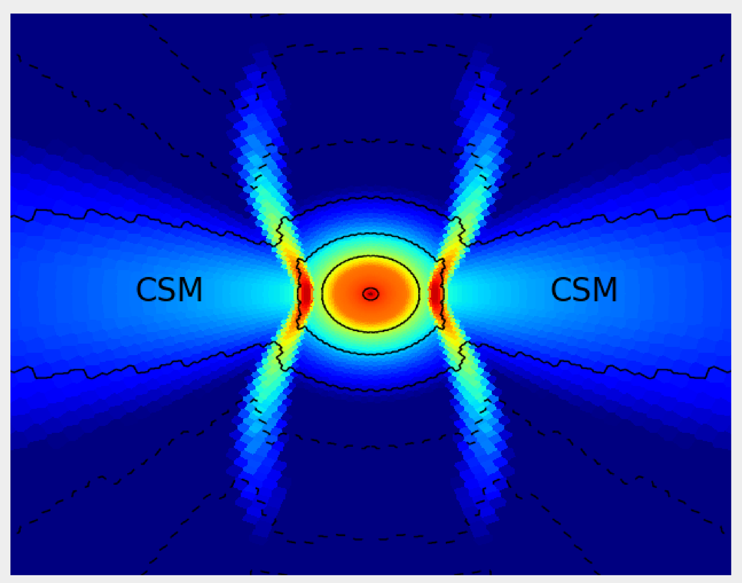
Introduction

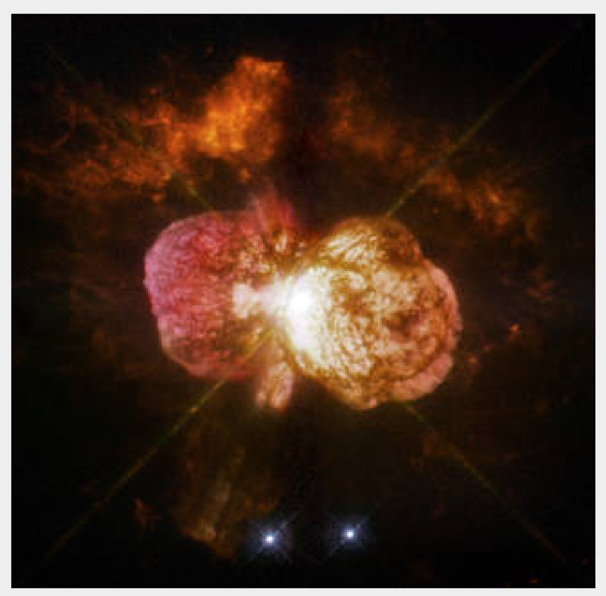
Type-IIn supernovae (SNe) are characterized by narrow Hydrogen lines in their spectra. These lines are created as the radiation produced by heat generated during the interaction escapes through the slow-moving CSM. During the collision, a significant fraction of kinetic energy from the ejecta is converted into radiation and can produce luminosities ~10x greater than that of Type-Ia SNe.

The CSM around these massive stars comes from mass loss via line-driven winds or episodic eruptions. Observations of objects such as eta-Carinae and spectropolarimetry of SN2009ip during its 2012 explosion have shown that the CSM may often be asymmetric.

We perform 2-D hydrodynamic simulations to study the interaction between SN ejecta and the CSM. We study the propagation of shock waves through the CSM and compare our results with the expected Chevalier and Sedov-Taylor scalings. Bolometric light curves and unshocked CSM mass are calculated to understand the efficiency of energy conversion and the appearance of narrow spectral lines. By varying the density and geometry of the CSM, we study how observable features depend on these properties.



Explosion created using JET code. Colors show regions of high pressure, while contour lines depict log of density



Asymmetric circumstellar medium in Eta-Carinae (nasa.gov)

Numerical Methods

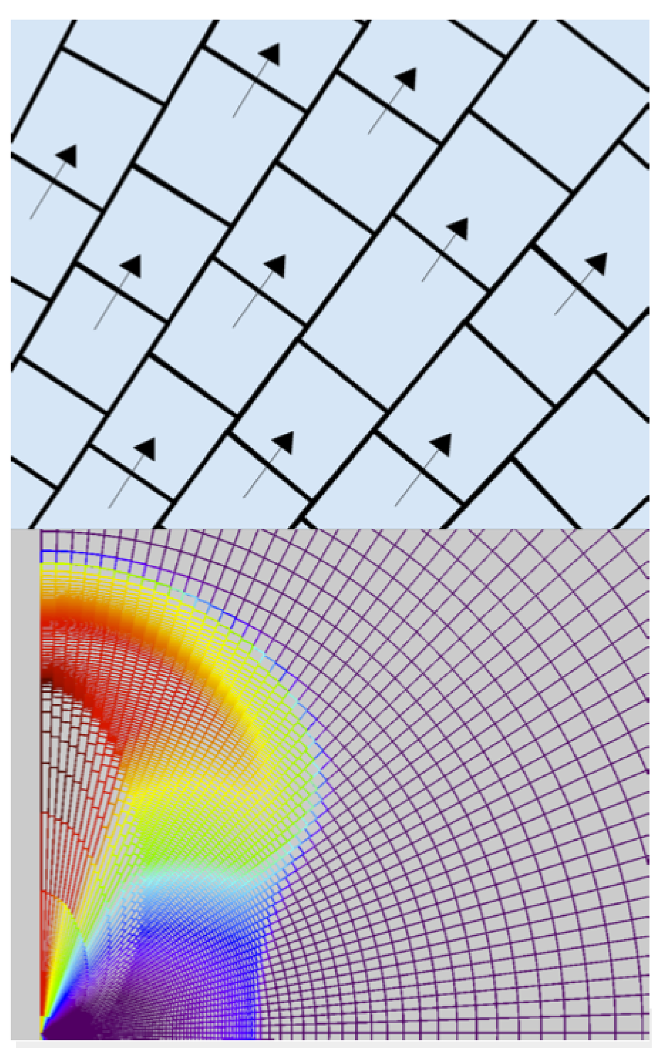
- Numerical calculations integrate the two-dimensional axisymmetric hydro equations to track evolution of density, pressure, and velocity
- Calculations are performed using the JET code, a moving mesh code that is effectively Lagrangian due to radial motion of computational zones
- Ejecta density scales with a broken power law

$$\rho_{\rm ej}(r,\theta,t) \sim \begin{cases} r^{-d} & r < v_T t \\ r^{-n} & r > v_T t \\ 0 & r > 10 * v_T t \end{cases}$$

- For our study we consider the cases where n=10 and d=1

$$\rho_{\rm disk}(r,\theta,t) \sim \left(\frac{r}{R_{\rm disk}}\right)^{-2} e^{-(r/R_{\rm disk})^4}$$

- Disk density scales as a power law in radius which cuts off at r=R_{disk}~10^{15} cm



JET's radially moving mesh (duffell.org)

Shock Dynamics

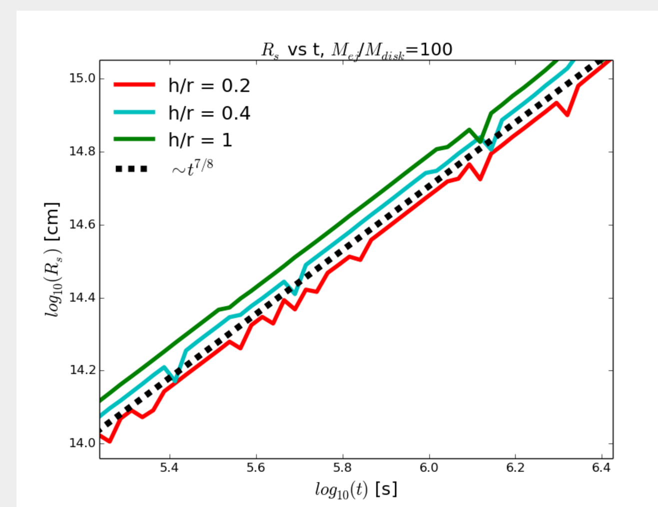
- When the mass of the CSM is much smaller than that of the ejecta, the position of the shock as a function of time should have the same scaling as the one-dimensional Chevalier solution (s=2). The overall constant depends on properties of the ejecta and CSM but includes a power of h/r that accounts for the CSM asymmetry.

$$R_s(t) \sim A\,(h/r)^{1/(n-s)}\, t^{(n-3)/(n-s)}$$

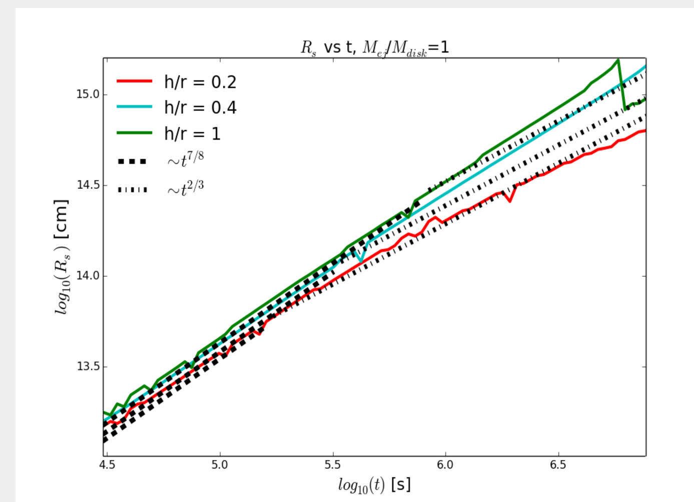
- In the regime where the CSM mass is comparable to the ejecta mass, the shock position follows a Sedov-Taylor scaling with time. This regime also results in a different power of h/r

$$R_s(t) \sim B\,(h/r)^{1/(5-s)}\, t^{2/(5-s)}$$

- The remainder of the analysis is done for the case where the CSM mass is small compared to the ejecta mass



Shock position as a function of time for a CSM mass much smaller than ejecta mass. Solid lines show numerically calculated shock position. Dashed lines shows Chevalier scaling with overall constant matched to h/r=0.4, however, all lines have a slope of ~7/8



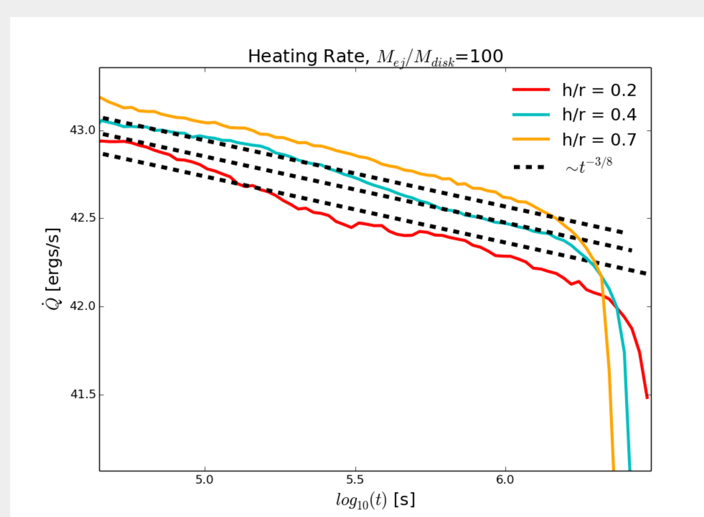
Shock position vs. time for CSM mass equal to ejecta mass. Solid lines show numerically calculated shock position. Dashed lines show Chevalier scaling, dot-dashed lines show Sedov-Taylor scaling. Transition between scalings happens when mass swept up by the shock is comparable to ejecta mass that intercepts the CSM.

Shocked CSM Properties

Shock Heating Rate:

- The shock wave heats the CSM as it travels though the disk.
- By evolving entropy as a passive scalar, the shock heating can be calculated numerically
- Shock heating can be estimated analytically

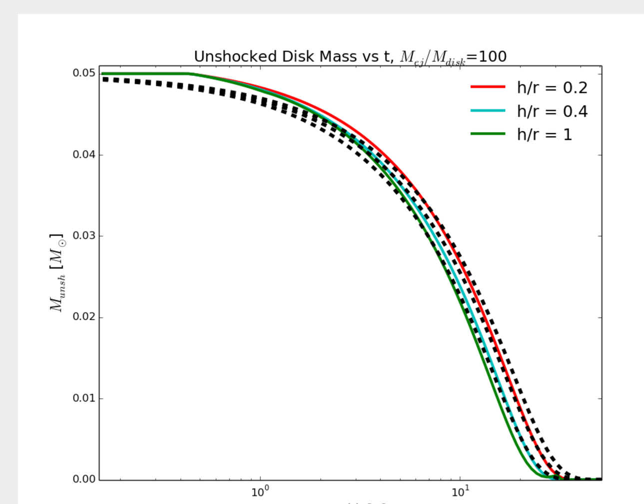
$$\dot{Q} \sim (h/r)^{3/(n-s)}\, t^{\frac{(5-s)(n-3)}{n-s}-3}$$



Solid lines show numerically calculated heating rate. Dashed lines show a -3/8 scaling with time and are scaled to different values of h/r. CSM is heated until sufficiently accelerated by the shock

Unshocked Disk Mass:

- Slow-moving CSM is accelerated as the shock moves through the disk
- CSM mass is considered 'shocked' when its velocity is comparable to the ejecta mass
- Integrating the CSM density profile from the shock position to infinity gives an analytic solution



Solid lines show unshocked disk mass calculated numerically. Dashed lines show analytic solutions. All curves agree reasonably well as to when the CSM is completely shocked

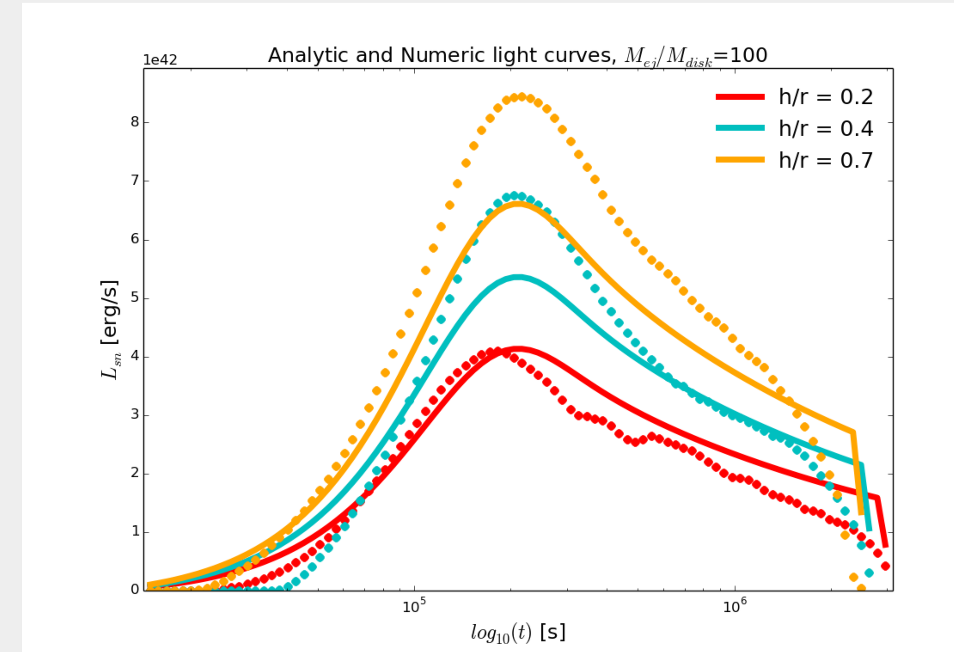
Observables

- The opacity drops as the shocked material expands, and eventually the energy deposited by the shock can escape as radiation
- We estimate that the shocked CSM becomes translucent at a time given by

$$t_{sn} \approx 14.5 \left(\frac{M_{ej}}{M_\odot}\right)^{3/4} \left(\frac{E_{ej}}{10^{51} ergs}\right)^{-1/4} days$$

- Through the use of energy conservation and the radiation diffusion approximation, the luminosity can be estimated by the integral

$$L(t) = e^{-(t/2t_{sn})^2} \int_0^t \dot{Q} e^{(t'/2t_{sn})^2} (t'/t_{sn}) dt'$$



To the left is a plot of light curves calculated using the above integral. Dotted lines depict light curves found using a numerically calculated heating rate. Solid lines show light curves found using the analytic formula discussed previously. At late times both analytic and numerically calculated curves follow a ~$t^{-3/8}$ scaling

Conclusions

- We find that the shock position, and thus heating rate and unshocked disk mass, can be estimated analytically and are generally in agreement with calculated quantities. Discrepancies may be explained by the ejecta's ability to circumvent the CSM by flowing around the disk.
- Timescale for the CSM to be swept up by the shock can be found analytically and predicted quantities are similar to numerically calculated values. After the sweep up time, one does not expect to see narrow Hydrogen lines and evidence of an interaction is lost.
- Geometry of the CSM and supernova ejecta may also obscure narrow Hydrogen line features.
- Light curves found using the analytic or numerical heating rate peak at similar orders of magnitude and have approximately the same scaling with time after peak magnitude.
- Certain CSM geometries and densities in addition to higher explosion energies may produce light curves that resemble those of Superluminous Supernovae.

Acknowledgements

Much thanks goes out to Dr. Paul Duffell and Professor Daniel Kasen for their time and effort in facilitating this project. I would also like to thank Research IT at UC Berkeley for providing the High Performance Computing service. Also, thanks to my mom for her ongoing support of my goals, regardless of their orthodoxy.

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