Interfacial instabilities in supernovae and supernova remnants

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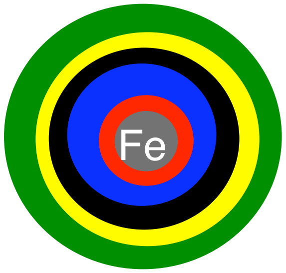
Outline

- Simplified supernova taxonomy
- Hydro instabilities in core-collapse supernova explosions
- Hydro instabilities in thermonuclear supernova explosions
- Linking the supernova explosion and remnant stages
- Hydro instabilities in supernova remnants
- Summary of forefront issues
- Opportunities for significant progress

Simplified supernova (SN) taxonomy

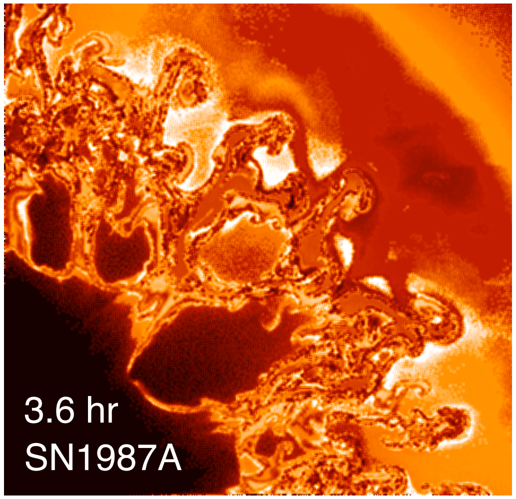
Progenitor **Explosion stage** **Remnant stage**

Core collapse (Type II)



Massive star

+ Binding energy/ nucleon curve =>



Muller, Fryxell, and Arnett, Astron. Astrophys. 251 (1991)

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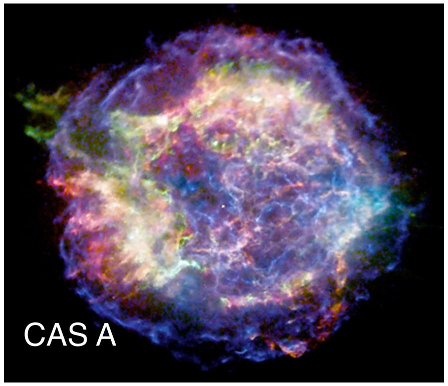
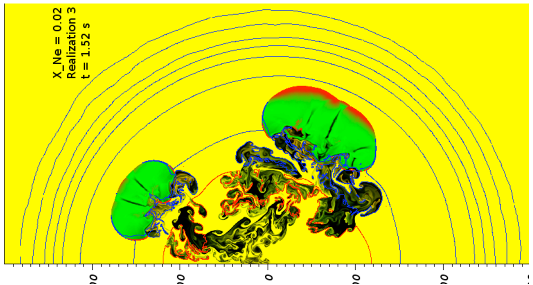


NASA/CXC/MIT/UMass Amherst/ M.D.Stage et al.

Thermo-nuclear (Type Ia)

+ $\left[\left(\frac{dM}{dt}\right) > 0\right]$ =>

Accretion



D.M. Townsley et al., ApJ 701,1582(2009)

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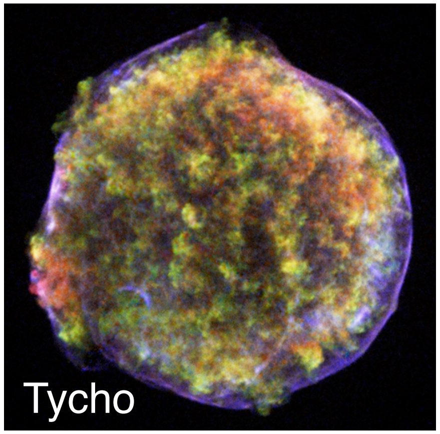


http://chandra.harvard.edu/photo/ 2005/tycho/index.html

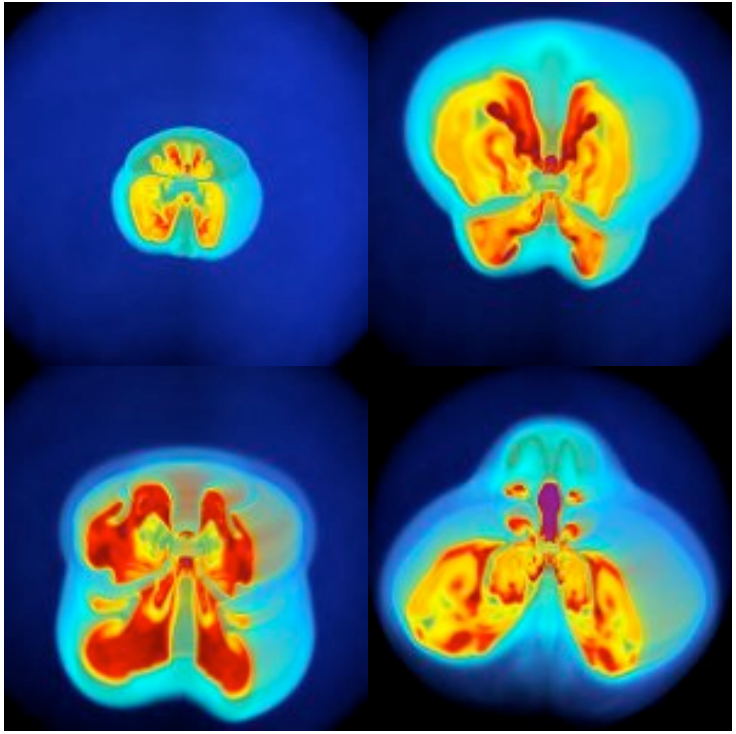
Core-collapse SNe: Standing Accretion Shock Instability (SASI)

- Successful explosion requires shock revival following bounce and stall

- Standing accretion shock instability has been observed in numerical simulations

- One interpretation is an acoustic-advective cycle:
  - Perturbed SAS generates vorticity that is advected inward
  - Deceleration of vorticity generates acoustic waves that propagate back out to the shock
  - Shock perturbations are reinforced

Sub-second after collapse



A. Marek & H. Th. Janka, http://www.mpa-garching.mpg.de/mpa/institute/news_archives/news0902_thomas/news0902_thomas-en.html

Onset of supernova explosion of a 15 solar mass star at 0.53-0.7 s after collapse.

Shock revival & successful explosion might depend on an instability that is poorly understood and has never been directly observed

Core-collapse SNe: Steep density gradients at composition interfaces are driven unstable by the blast wave

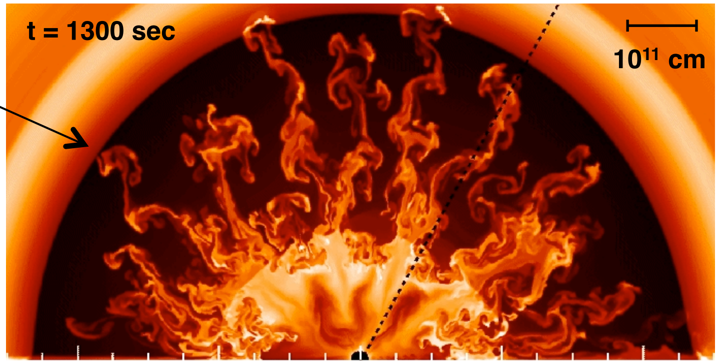
Observe very fast mixing of core material into the outer layers of the star - Not typically seen in 2D simulations

- Large-amplitude low-modes can give high velocities early enough via Richtmyer-Meshkov instability
  - Convection yields perturbed shocks as well as interfaces
  - How are the initial perturbations affected by differential rotation?

- Interaction of multiple mixing zones

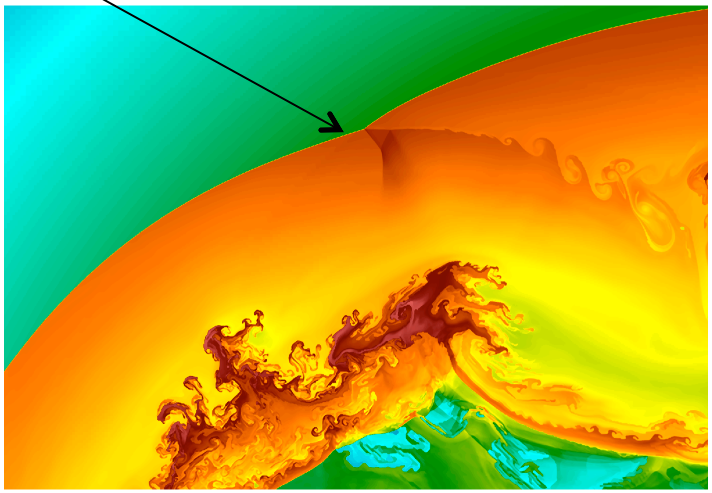
- Transition to inherently 3D turbulent mixing zone following growth to large amplitudes: Numerical simulations limited in attainable effective Reynolds number

Minutes to hours



Kifonidis et al., Astron. Astrophys. **408**, 621 (2003).

Seconds to minutes



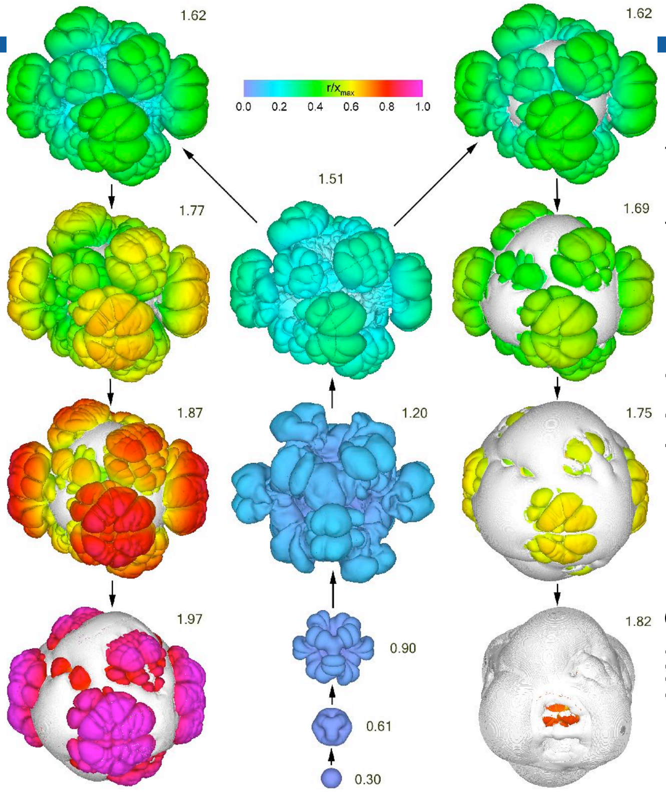
http://people.sc.fsu.edu/~tomek/SNII/index.html12

Thermonuclear SNe: How do intrinsic instabilities of wave fronts affect their global dynamics?

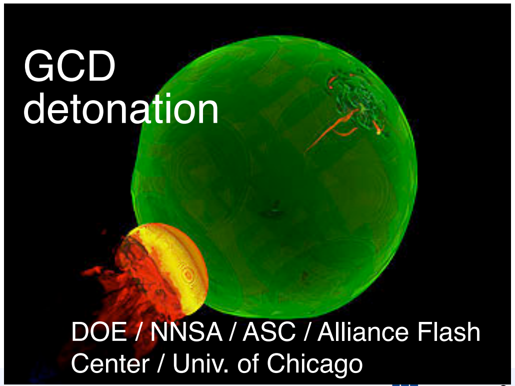
- Observations favor explosion models with transition from an initial subsonic deflagration phase to a supersonic detonation phase (DDT)

- Deflagration phase
    - Carbon “cooking” yields rising ash bubbles that are unstable to buoyancy-driven instabilities
    - Bubble boundaries are unstable deflagration fronts that become corrugated and turbulent, and propagate much faster than the laminar flame speed
    - Turbulent flame propagation speeds are not known from first principles

- Detonation-deflagration mechanism is unknown (several are proposed) and often proscribed ad-hoc in calculations



V.N. Gamezo et al, ApJ 623, 337 (2005)



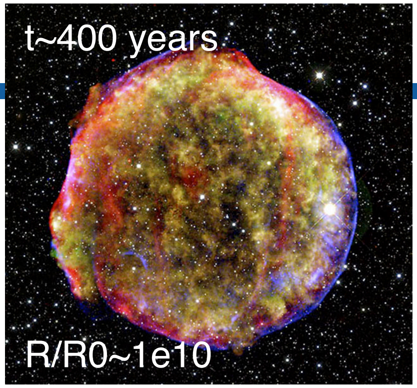
DOE / NNSA / ASC / Alliance Flash Center / Univ. of Chicago

Linking the supernova explosion and remnant stages: Are there connections between their instability structure?

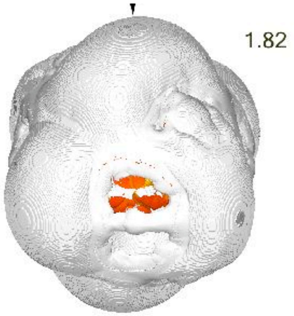
- Core-collapse: Bipolar jet explosion models (Khokhlov et al) would likely produce correspondingly-asymmetric remnants

- Thermonuclear: Can explosion-phase instabilities explain why the perturbed interface in Tycho is “too close” to the forward blast wave shock
  - Large-scale ash bubbles can perturb the outgoing detonation wave after delayed detonation
  - Large-amplitude low-mode perturbed shock should drive RM instability growth at the outer surface of the star
  - Signature of the instability might survive into the remnant stage and perturb the forward shock out to scaled Tycho time
  - SNR calculations are initiated with spherical explosion profiles from models or simulations

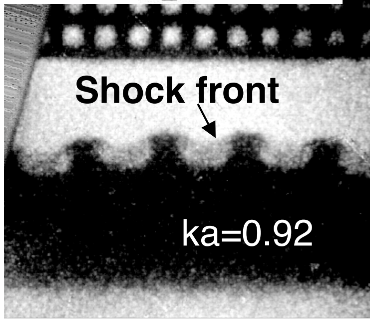
Is the implicit assumption that SNR instabilities are independent of the explosion initial conditions valid?



Observed spectral peak @ mode 6



V.N. Gamezo et al, ApJ 623, 337 (2005)



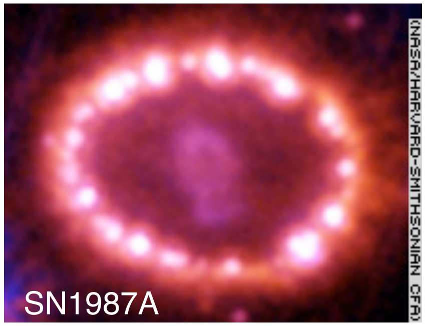
S.,G. Glendinning et al

OMEGA RM experiment, Glendinning et al

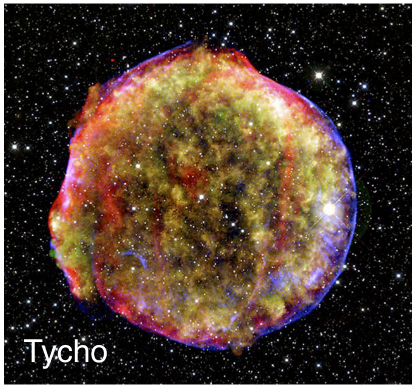
Interfacial instabilities in supernova remnants (SNR)

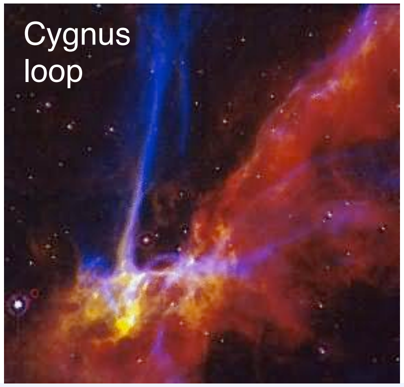
- Deceleration of expanding layers by circumstellar medium drives RT instabilities that develop against spatially nonuniform backgrounds
    - SN1987A ring interaction: Supernova blast wave collides with ring of material ejected earlier in the progenitor's evolution
    - Can ISM clumps explain proximity of mixing zone to forward shock in Tycho?

- Radiative blast wave fronts are susceptible to thin-shell (Vishniac) instabilities (see C. Kuranz talk)
    - What is the connection to the complex structure observed in supernova remnants?
    - Computationally intensive due to huge range of scales



(NASA/HARVARD-SMITHSONIAN CFA)





J.J. Hester (Arizona State University), and NASA.

Summary of forefront issues by common theme

- Newly-discovered instabilities that have never been directly observed
    - Standing accretion shock instability

- Initial conditions and RM/RT interplay
    - Differential rotation of SN progenitors

- Instabilities of interfaces in complex fluids (Beyond classical gravitational RT)
    - Multiple interfaces in core collapse SNe
    - Interfacial instabilities in spatially nonuniform fluids
    - Interfacial instabilities in reacting fluids
    - Interfacial instabilities developing in a fluid with a pre-existing turbulent field

- Problems spanning a wide range of scales
    - Transition and turbulence
    - SN-SNR connections
    - Radiative shock-front instabilities
    - Flame physics

Opportunities for significant progress

- Standing Accretion Shock Instability (SASI): Observe, characterize, and explain experimentally as well as numerically

- Fast outward mixing of core material in core-collapse SNe
    - Initial conditions for the instabilities
    - Interplay of Richtmyer-Meshkov and Rayleigh-Taylor instabilities
    - Both computational and experimental aspects

- Turbulent flame propagation and deflagration-detonation transition

- Establish connections between instability structure created during the rapid explosion and the structure observed much later in the remnant

- Enablers of near-term progress potential
    - New HEDP facilities (NIF, ZR) and massively parallel computers offer larger range of temporal and spatial scales
    - Reynolds numbers are ~10,000 in direct numerical simulations, and sub-grid scale models are implemented in many codes (Classical RT remains a good first use of the newest, biggest machine)
    - New 3D astrophysics codes enable multi-physics numerical study of relevant complex flows