The Progenitor of SN 1987A

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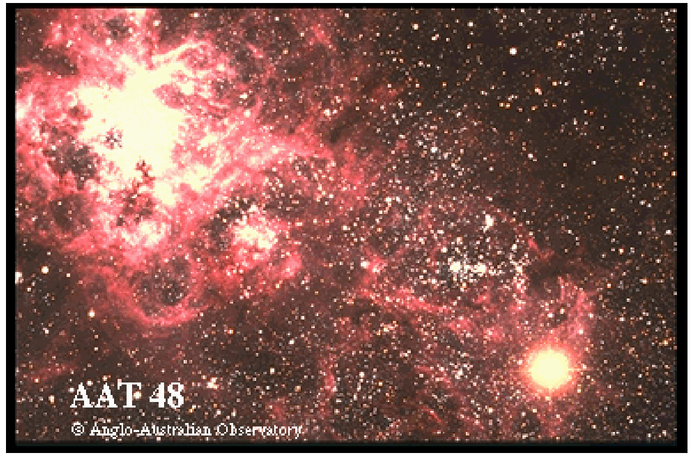
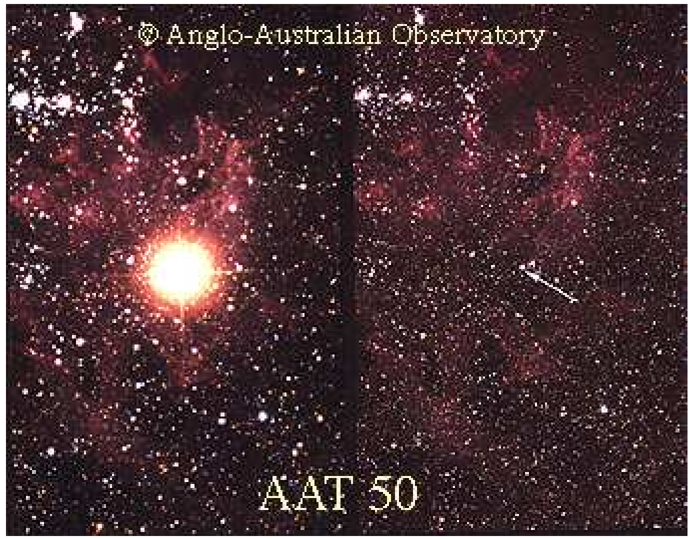


SN 1987A: an anomalous supernova

- progenitor (SK $-69^{\circ}202$): blue supergiant with recent red-supergiant phase (10^4 yr)
- chemical anomalies:
  - ▷ helium-rich (He/H$\sim$ 0.25, N/C$\sim$ 5, N/O$\sim$ 1)
  - ▷ CNO-processed material, helium dredge-up
  - ▷ barium anomaly ($5-10$ solar)
- the triple-ring nebula

→ axi-symmetric, but highly non-spherical

→ signature of rapid rotation



Early Progenitor Models

Single Models

- **low-metallicity models (Arnett, Hillebrandt, Truran)**
- **extreme-mass-loss models (Maeder, Wood)**
- **restricted-convection model (Woosley, Langer)**
- **helium-enrichment model (Saio)**
- **rapid-rotation models (Weiss, Langer)**

Binary Models

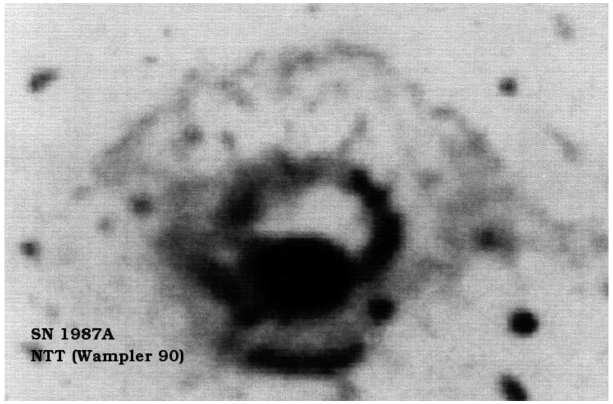
- **companion models (Fabian, Joss)**
- **accretion models (Podsiadlowski, Barkat, Vanbeveren, Rathansree, Braun)**

General problems

- **properties of stars in the LMC (red supergiants!)**
- **extreme fine-tuning to get blue-red-blue evolution**
- **physical justification of helium dredge-up**
- **triple-ring nebula**

The Triple-Ring Nebula

- discovered with NTT (Wampler et al. 1990)



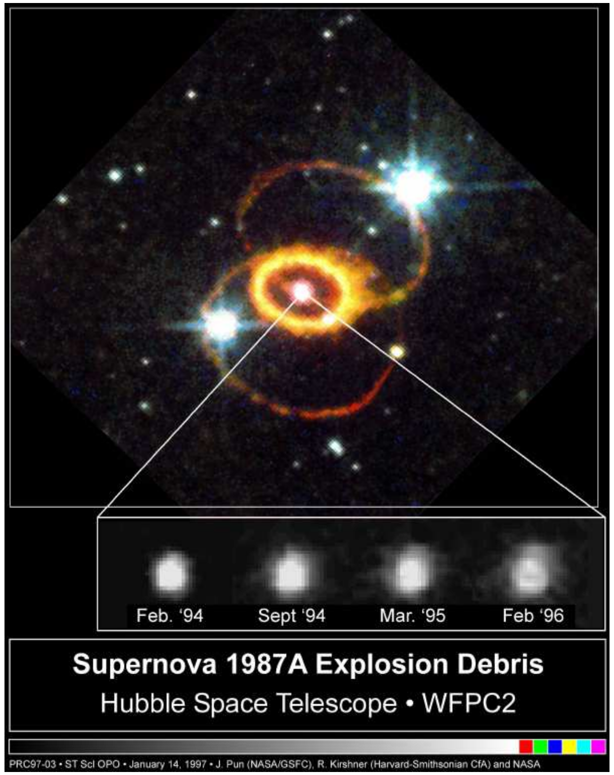
- HST image (Burrows et al. 1995)
- not a limb-brightened hourglass, but physically distinct rings
- axi-symmetric, but highly non-spherical

  $\longrightarrow$ signature of rapid rotation?

  ▷ not possible in simple single-star models (angular-momentum conservation!)

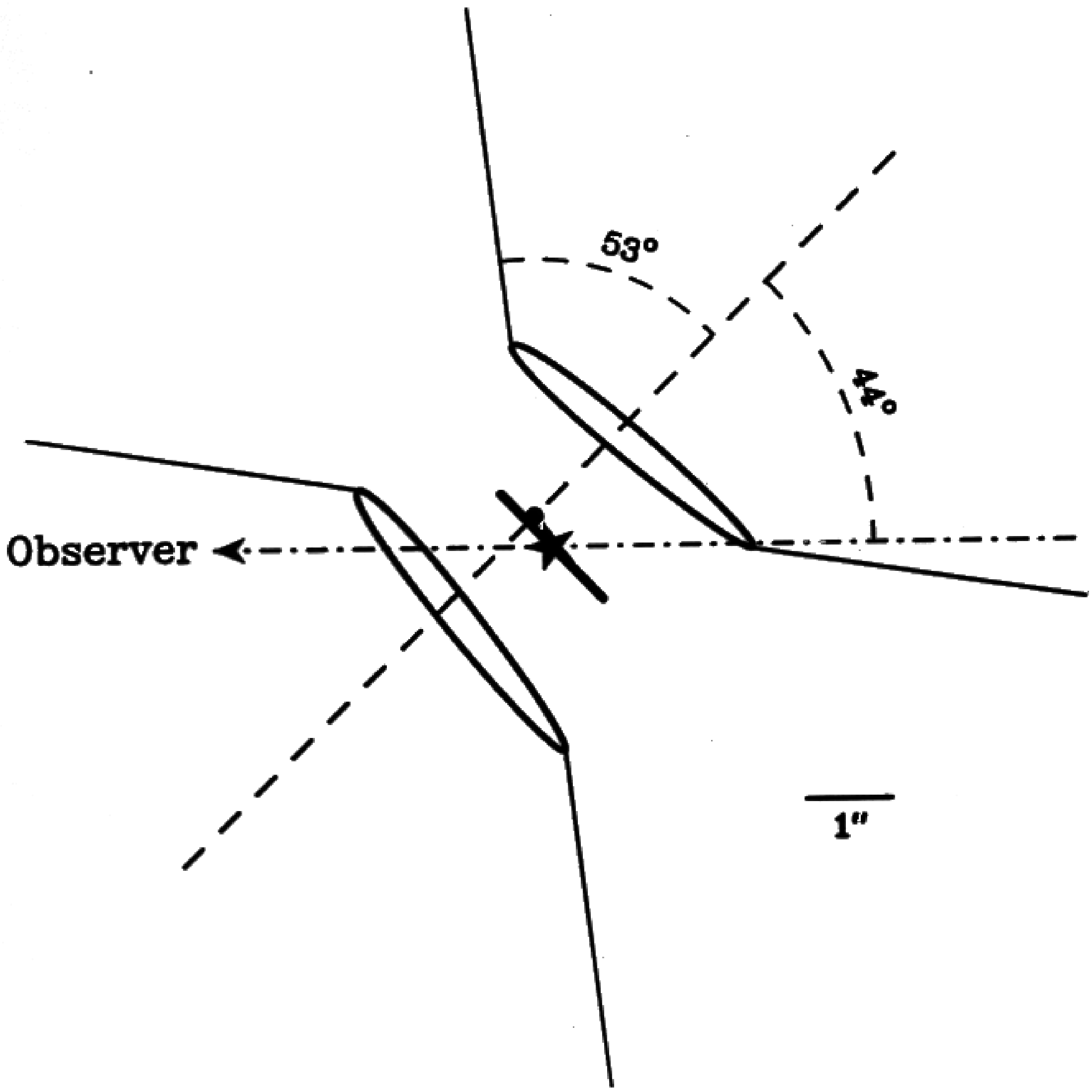
  ▷ supernova is at the centre, but outer rings are slightly displaced

  ▷ dynamical age: $\sim 20,000\,\mathrm{yr}$



all anomalies linked to a single event a few 10^4 yr ago, most likely the merger of two massive stars

Figure 2



Merger Models

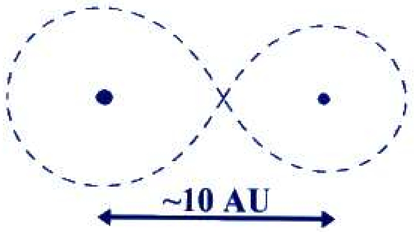
- **first merger suggestion:** to explain inferred **asymmetric envelope** expansion (Chevalier & Soker 1989)
- to explain **red-blue transition** and chemical anomalies by **helium dredge-up** (Hillebrandt & Meyer 1989; Podsiadlowski, Joss & Rappaport 1990; Podsiadlowski 1992; Chen & Colgate 1995; also Saio, Kato & Nomoto 1988)
  - ▷ motivated by ill-fated sub-ms pulsar with planet-mass companion
- to explain **triple-ring nebula** (Podsiadlowski et al. 1991; Soker 1999)

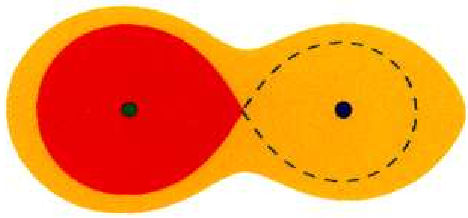
Note: $\sim 10\,\%$ of all massive stars are expected to merge with a companion star during their evolution.

Other candidates: FK Comae, V Hyd, B[e] supergiants [R4], Sher 25, HD168625, ηCar, V838 Mon.

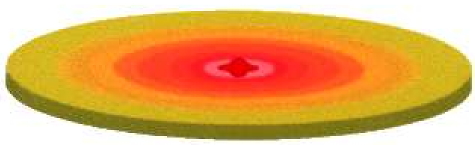
THE MODEL
(Podsiadlowski 1992)

- abundances from Russell and Bessell (1989); Russell and Dopita (1990): $Z = 0.01$ (but C abundance?)
- updated opacities (Rogers and Iglesias 1992; Alexander 1994), small amount of convective overshooting
- typical binary: $M_1 \sim 20\, M_\odot$, $M_2 \sim 5\, M_\odot$, $P_{orb} \sim 10$ yr
- dynamical mass transfer and merging after helium core burning (second dredge-up, s-processing)





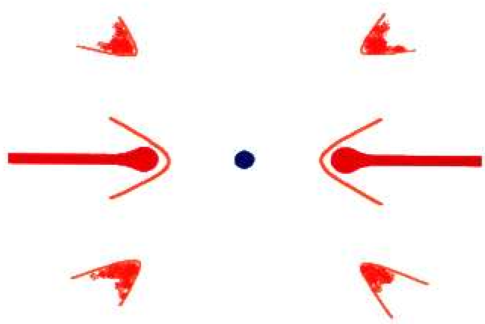
- rotationally forced disk-like outflow



- blue supergiant phase: swept-up structures

→ triple-ring nebula

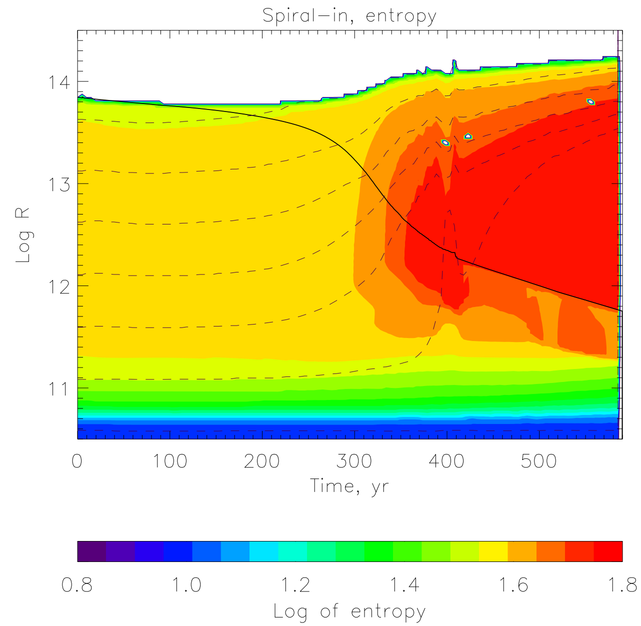
(Podsiadlowski et al. 1991; Lloyd et al. 1995)



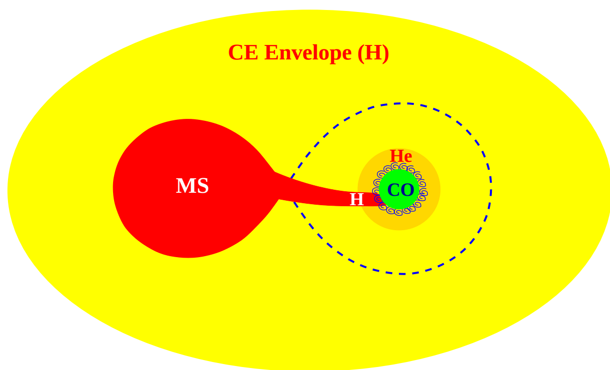
Simulations of Slow Mergers

(Ivanova, Podsiadlowski, Spruit)

- simulate the spiral-in of a $5\,M_\odot$ star in the envelope of a red supergiant ($\sim 20\,M_\odot$)
- rapid initial spiral-in until envelope envelope has expanded sufficiently
- slow self-regulated phase: frictional energy radiated away at the surface (Meyer & Meyer-Hofmeister 1979)



- spiral-in phase ends when the embedded secondary fills its Roche lobe inside the supergiant envelope ($a \sim 10\,R_\odot$)

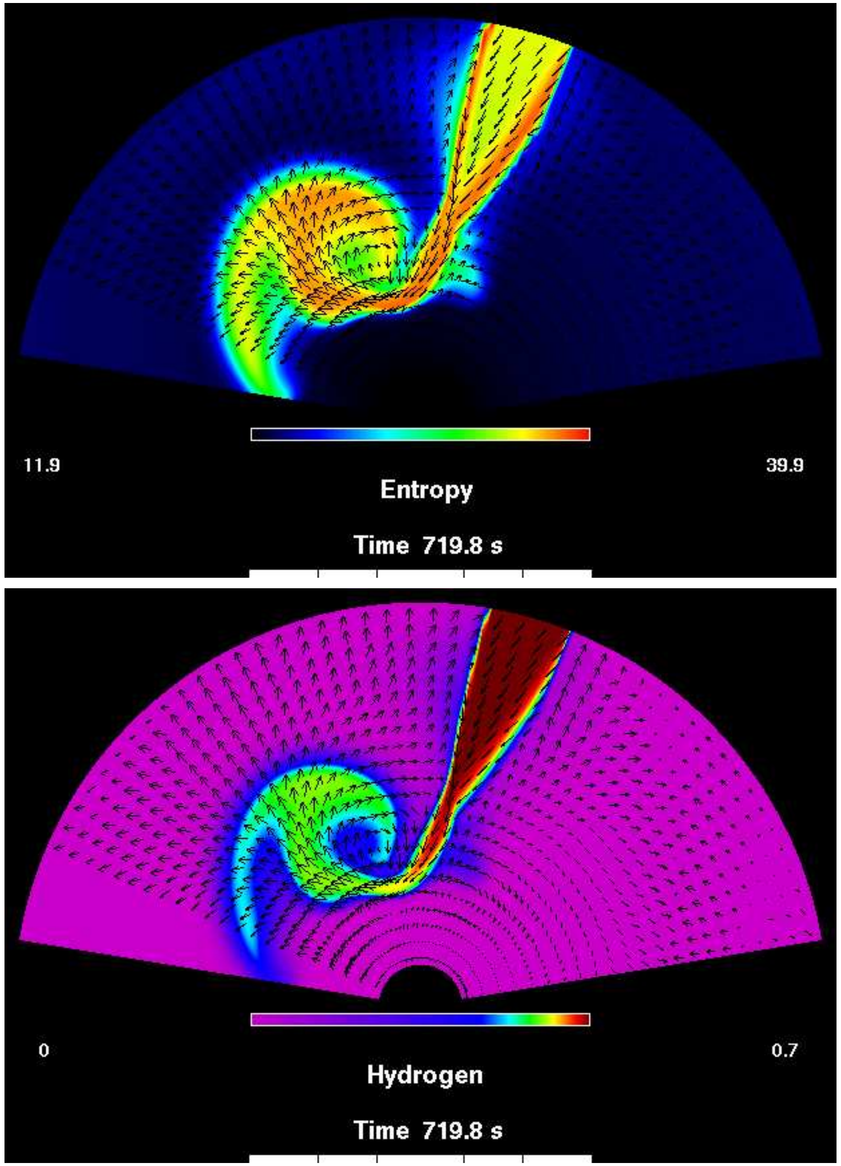


The Merger Phase

- mass transfer in opaque (low-density) envelope, driven by friction with envelope
- timescale for destruction of secondary: $\sim 100\,\mathrm{yr}$
- stream impacts with helium core $\rightarrow$ core penetration ($\sim 10^{10}\,\mathrm{cm}$) $\rightarrow$ dredge-up of helium
- temperature in mixing region: $10^{8}\,\mathrm{K}$ (s-processing possible)
- merger ends with dynamical disruption of secondary core (flat-entropy core)

Modelling:

- stream-core impact with PROMETHEUS code
- nucleosynthesis in mixing region (similar to T$\dot{\mathrm{Z}}$O code of R. Cannon)



Formation of the Triple-Ring Nebula

(Morris and Podsiadlowski 2007)

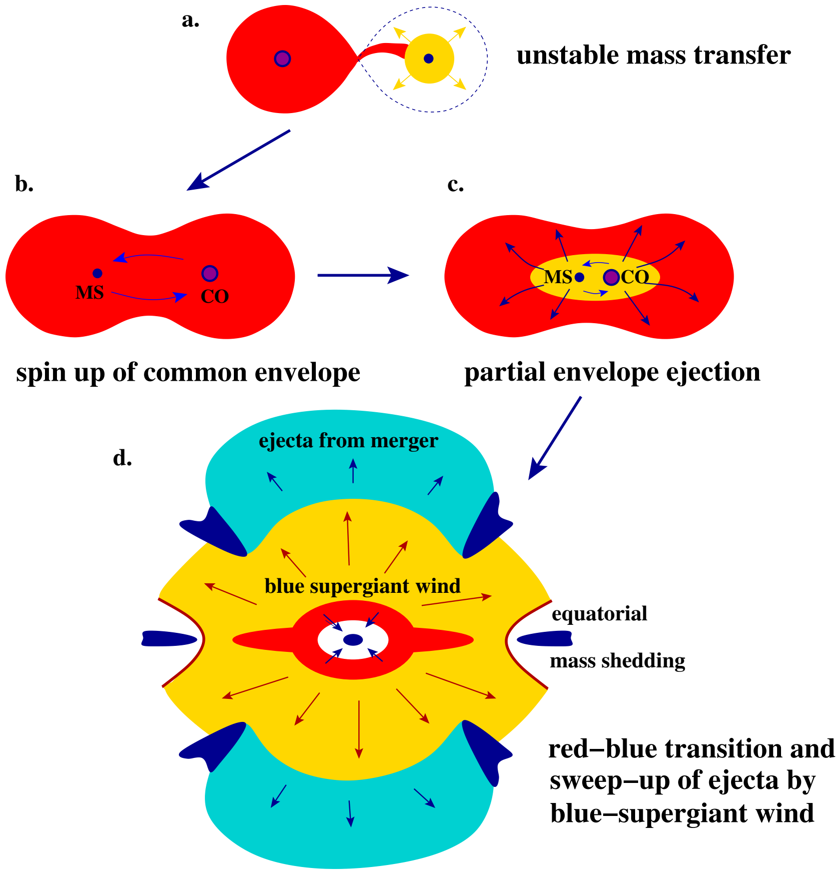
- 3-dim SPH simulations (GADGET; Springel)
- simulate mass ejection during merger and subsequent blue-supergiant phase
- angular momentum of orbit → spin-up of envelope

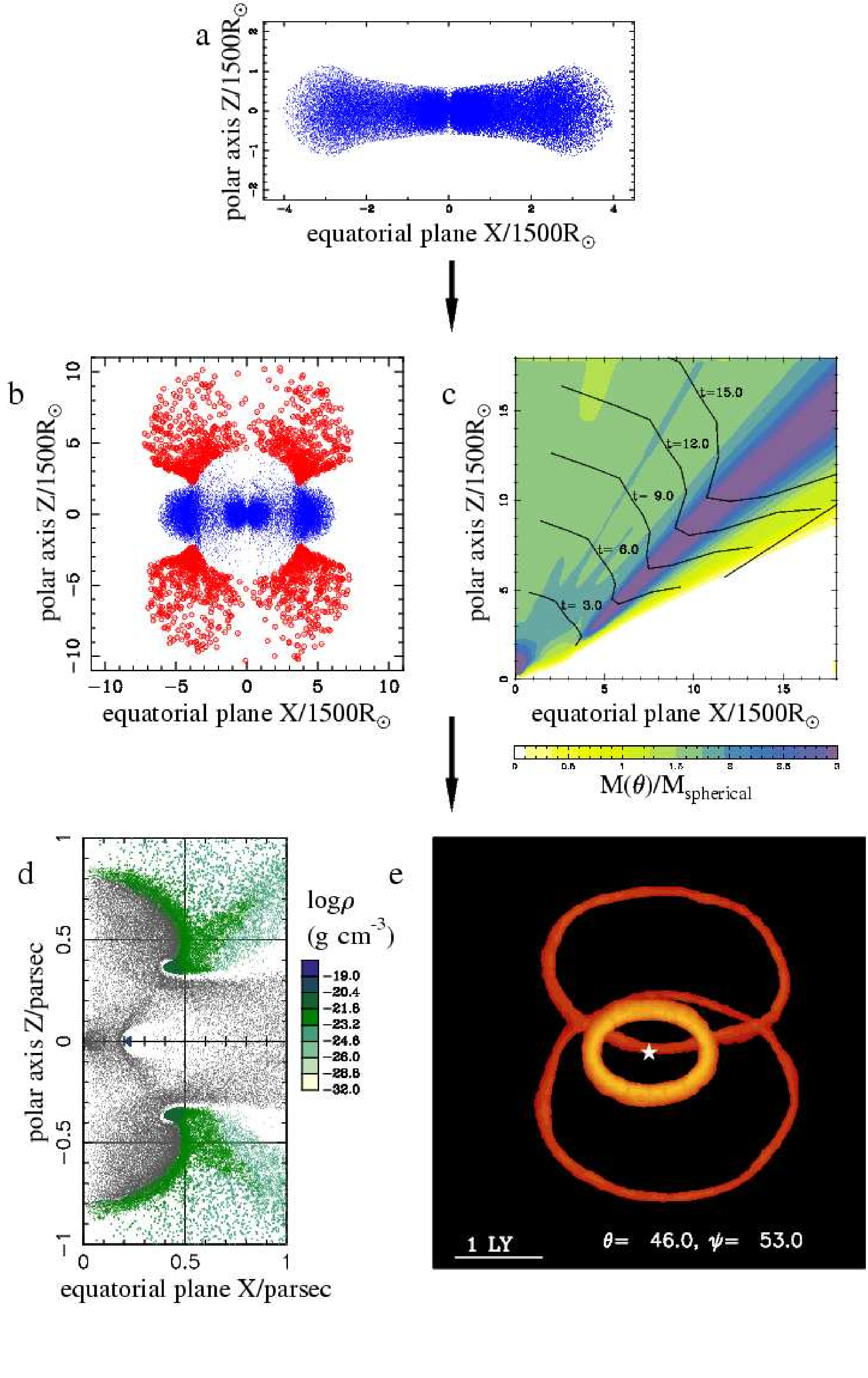
→ flattened, disk-like envelope

- energy deposition in rapid spiral-in phase ($\lesssim 1/3 E_{\rm bind}$)

→ partial envelope ejection → outer rings, bipolar lobes

- equatorial mass shedding during red-blue transition → inner ring





a
polar axis Z/1500R$_\odot$
equatorial plane X/1500R$_\odot$
b
polar axis Z/1500R$_\odot$
equatorial plane X/1500R$_\odot$
c
t=15.0
t=12.0
t= 9.0
t= 6.0
t= 3.0
polar axis Z/1500R$_\odot$
equatorial plane X/1500R$_\odot$
M(θ)/M$_{spherical}$
d
logρ
(g cm^{-3})
−19.0
−20.4
−21.8
−23.2
−24.6
−26.0
−28.8
−32.0
polar axis Z/parsec
equatorial plane X/parsec
e
1 LY
θ= 46.0, ψ= 53.0

The Present Status

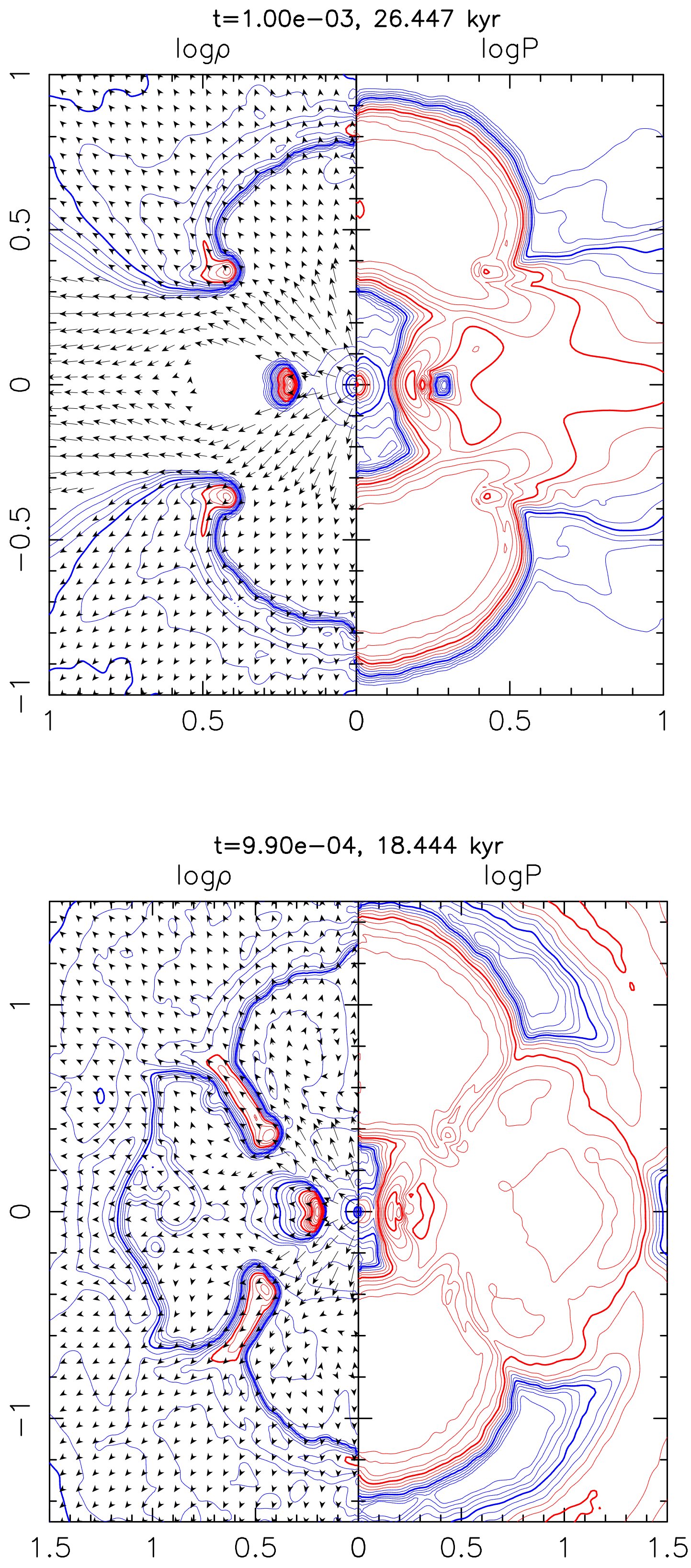
- the merger model provides a physical model for all the major properties and does not require any ad hoc assumptions
  - ▷ the blue supergiant, timing of the red-blue transition:
  - ▷ the chemical anomalies: He overabundance, CNO elements
  - ▷ the triple-ring nebula: generic outcome of the merger event
- it does not (yet) explain
  - ▷ the barium anomaly: not compatible with CNO elements (3-d effects?)
  - ▷ other structures observed in the nebula: e.g. Napoleon's hat
  - ▷ model did not include red-supergiant wind, pre-merger mass-transfer phase ($\rightarrow$ bipolar ejection; Soker)

Prediction: rapidly rotating core after the merger $\rightarrow$ asymmetric, jet-like explosion? Mystery spot? Remnant?

The Main Lesson from SN 1987A

Supernova Diversity

- there is more to supernovae than just two types due to
- binary interactions
  - ▷ affect envelope masses/structure (II-P→ II-L IIb→ Ib → Ic, SN 87A)
  - ▷ core evolution, explosion types (iron core collapse, electron capture, collapsar, prompt/fallback black-hole formation)
- metallicity effects (pair instability?)
- rotation effects
- different circum-supernova media (radio supernovae, IIn)


t=1.00e−03, 26.447 kyr
logρ
logP
t=9.90e−04, 18.444 kyr
logρ
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