Interstellar Medium 2020

Lecture 12: Shocks and the 3-phase ISM

Sterrewacht Leiden

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Course Contents

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2. Physical conditions and radiative processes
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8. Molecular clouds
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11. Molecular clouds and their properties
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Today's lecture

- Shock waves: principles
- Shocks in molecular clouds
- Supernova remnants
- 3-phase Interstellar Medium

Corresponding textbook material: Draine, Ch. 35, 36 & 39

Shock waves

- A shock wave is a pressure-driven compressive disturbance propagating faster than “signal speed”: a hydrodynamic surprise.

- Shock waves produce an irreversible change in the state of the gas (or fluid).

Sound speed and Mach number

- Sound speed: $c_s^2 = \frac{dP}{d\rho}$
- $c_s \approx \sqrt{\frac{kT}{m}} \approx 1\ \mathrm{km\ s^{-1}}$ for T ~ 100 K
- Mach number: M ≡ ratio of velocity w.r.t. sound speed:
  $M \equiv v/c_s$
- When speaking of a "strong" shock, this refers to the velocity of the disturbance: a strong shock is a fast shock.

“Signal speed” in the Interstellar Medium

- In the absence of magnetic fields, information travels with sound speed:
  - $M < 1$ subsonic
  - $M > 1$ supersonic $\Rightarrow$ shocks

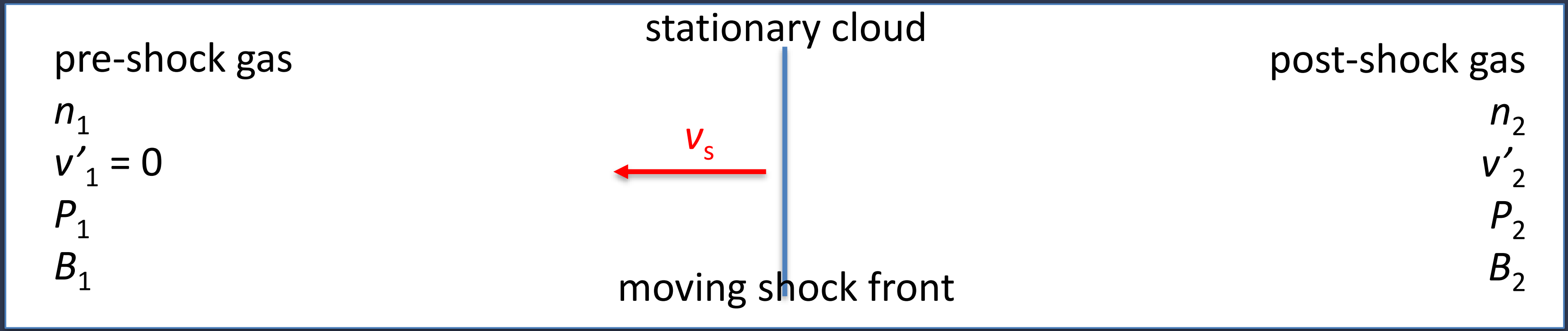
- If magnetic field is present, disturbances will travel along B at Alfvén speed v_A: $v_A^2 = \frac{B^2}{4\pi\rho}$

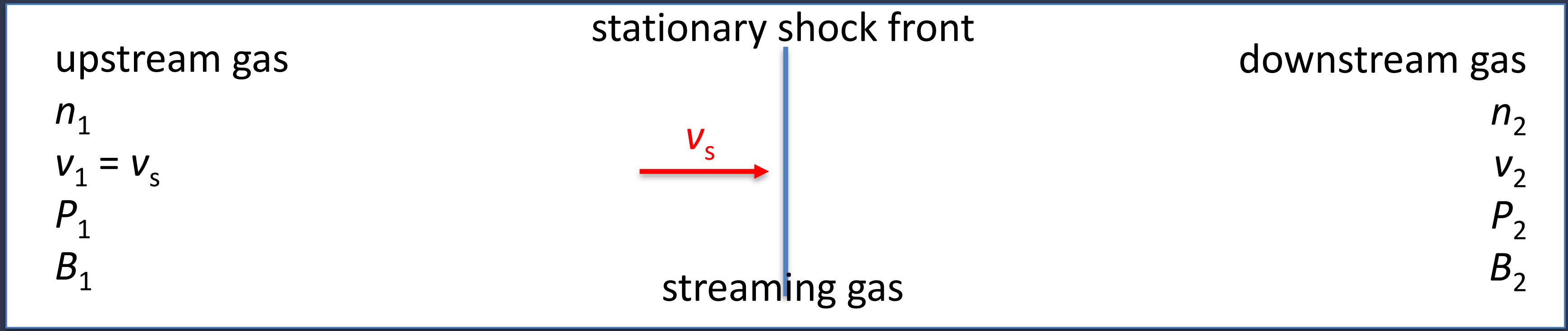
- Interstellar magnetic field (empirical): $B = 1\ \mu G \cdot \sqrt{n_H}$ for $10 < n_H < 10^6\ cm^{-3}$

Shock waves in the ISM occur in…

- cloud-cloud collisions
- expansion of HII regions
- fast stellar winds (“interstellar bubbles”)
- supernova blast waves
- accretion and outflows during star formation
- spiral shocks in Galactic disks
- supersonic turbulence

Cloud frame and shock frame

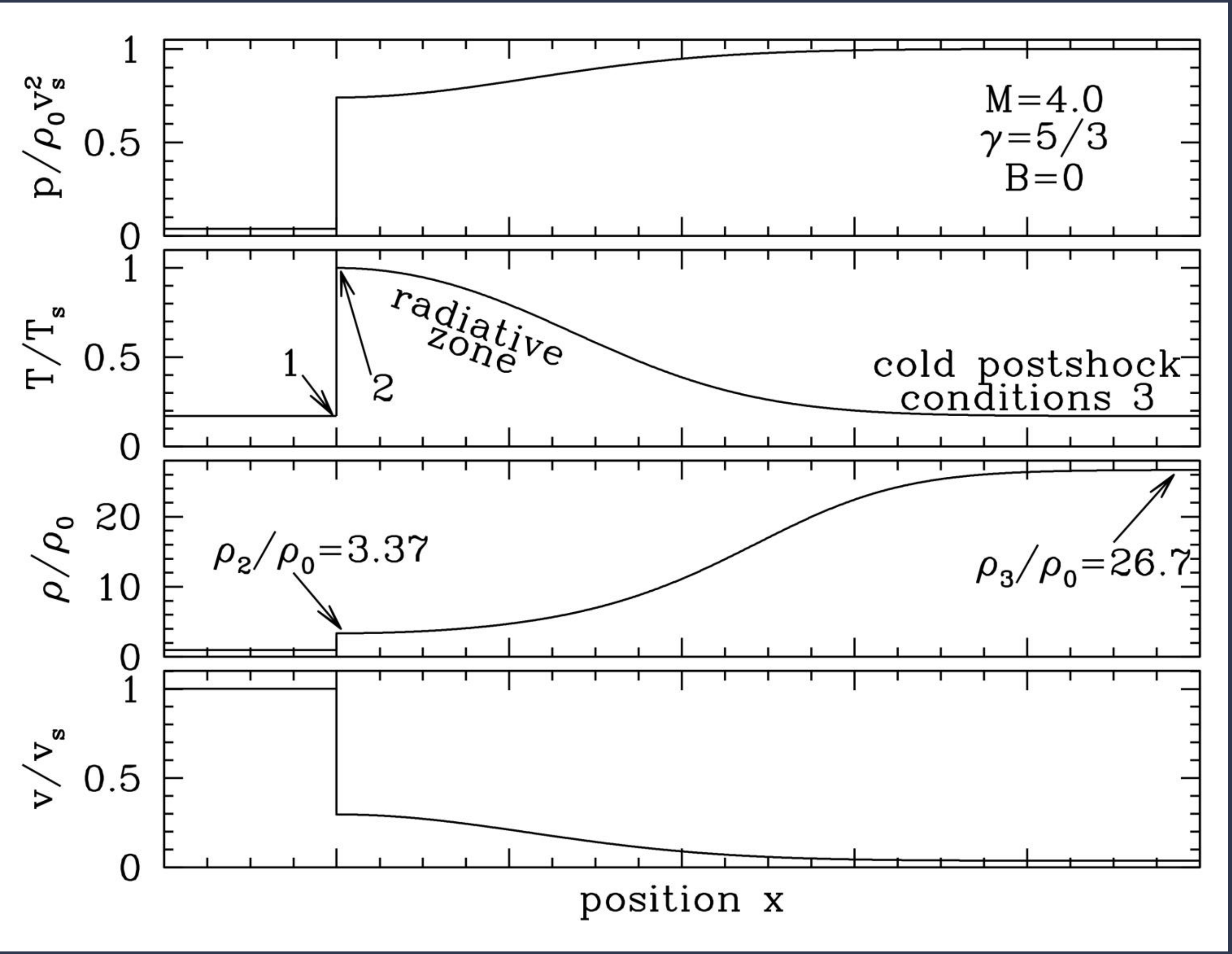




Shock jump conditions

- Adopt frame in which shock is stationary
- Consider plane-parallel shock: gas properties depend only on distance from shock front
- In shock transition zone: transform part of the bulk kinetic energy into heat $\Rightarrow$ irreversible change (entropy increases)
- Immediately pre-shock and post-shock conditions are connected by the (Rankine-Hugoniot) jump conditions

Structure of a radiative shock



(Draine, Fig. 36.1)

Rankine-Hugoniot jump conditions

Following Draine, write *u* for velocity and subscripts 1 and 2 for pre-shock and post-shock conditions (and $u_1 = v_s$)

- Mass conservation: $\rho_1 u_1 = \rho_2 u_2$
- Momentum conservation: $\rho_1 u_1^2 + p_1 + \frac{B_1^2}{8\pi} = \rho_2 u_2^2 + p_2 + \frac{B_2^2}{8\pi}$
- Energy conservation:

$$\frac{1}{2}\rho_1 u_1^3 + \frac{\gamma}{\gamma - 1} u_1 p_1 + \frac{u_1 B_1^2}{8\pi} = \frac{1}{2}\rho_2 u_2^3 + \frac{\gamma}{\gamma - 1} u_2 p_2 + \frac{u_2 B_2^2}{8\pi}$$

- Magnetic flux conservation: $u_1 B_1 = u_2 B_2$
- NB: also must adopt a magnetic field configuration (here assumed parallel to shock front)

Solving the R-H jump conditions

- 4 equations with 4 unknowns (u_2, n_2, p_2, B_2)
- Solution $u_1 = u_2$, $n_1 = n_2$, etc. always exists. What is the requirement for the existence of a second solution?
- This requirement can be shown to be (see Draine, Sect. 36.2.5)

$$v_s > V_{\mathrm{ms}} = \sqrt{c_s^2 + v_{\mathrm{A}}^2}$$

where V_{ms} is the magnetosonic speed

- This is the requirement for the existence of a shock.

Key results for strong shocks (*M*>>1)

- Immediately post-shock, the maximum compression (density increase) is only a factor 4 (no cooling ⇒ post-shock pressure is high)

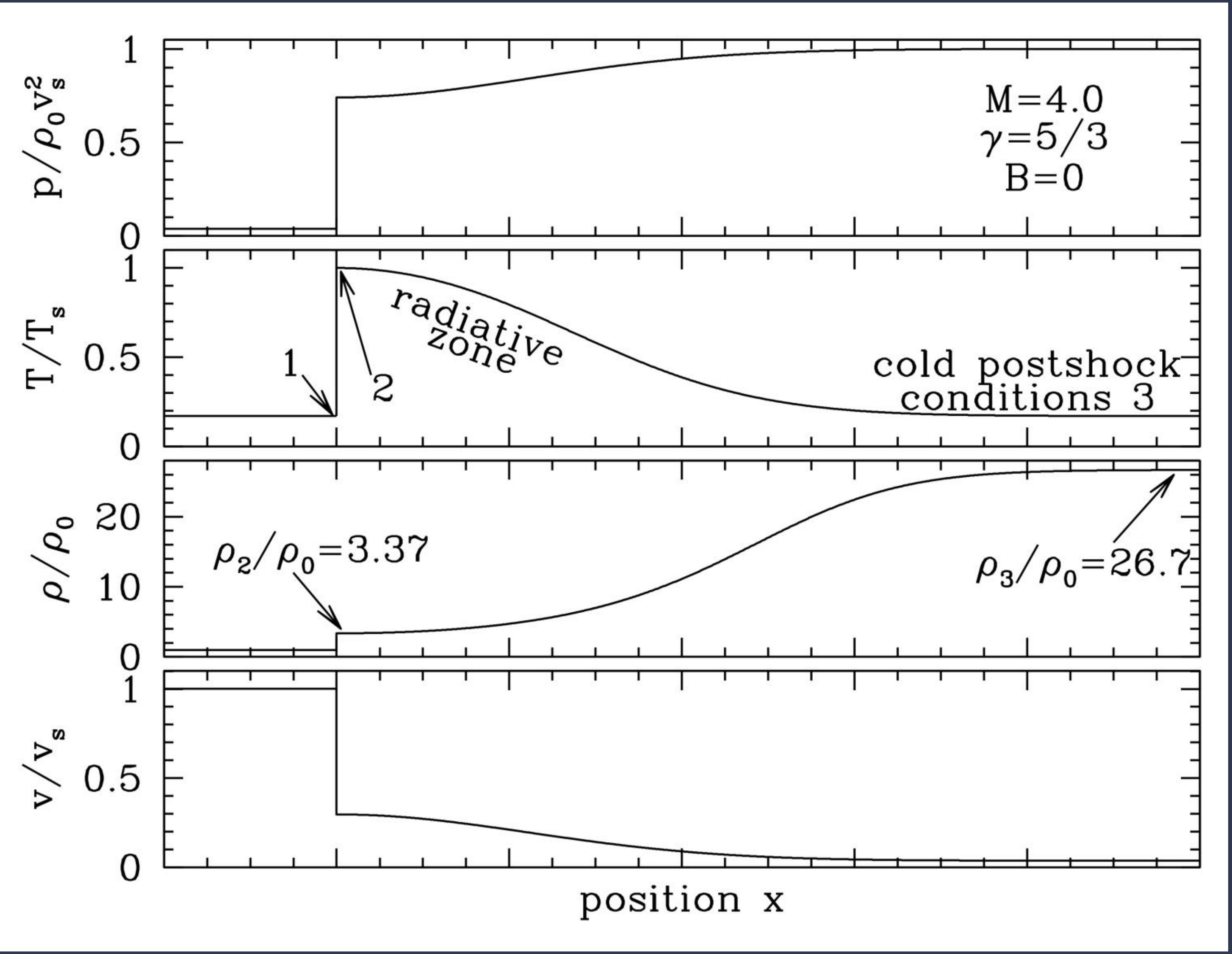
- Immediately post-shock: $T_2 = \frac{3}{16}\mu v_s^2$ (μ is average particle mass)

  so $T_2 = 2890\ K\ \frac{\mu}{1.273\ m_{\mathrm{H}}}\left(\frac{v_s}{10\ \mathrm{km\ s^{-1}}}\right)^2$ (neutral atomic gas)

  $T_2 = 1.38 \cdot 10^7\ K\ \frac{\mu}{0.609\ m_{\mathrm{H}}}\left(\frac{v_s}{1000\ \mathrm{km\ s^{-1}}}\right)^2$ (ionized gas)

- After cooling, much higher compression possible

Structure of a radiative shock



(Draine, Fig. 36.1)

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Shocks in molecular clouds

So far we considered only single-fluid shocks; normally interstellar gas consists of 2 fluids:

- neutral particles
- ions and electrons

These fluids are not 100% coupled, and will respond differently to the presence of a magnetic field.

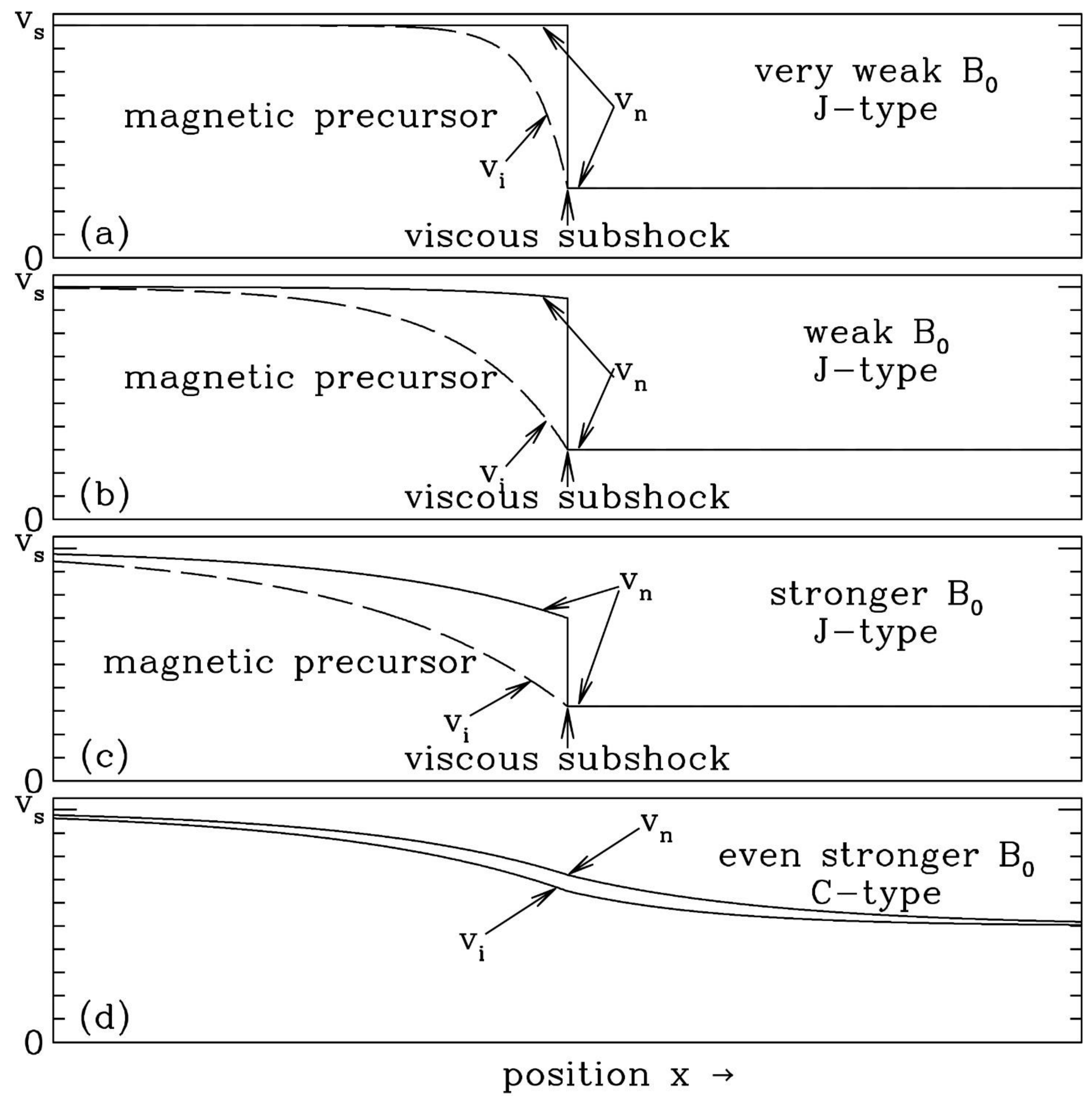
For $B \neq 0$, disturbances travel by MHD waves; perpendicular to B the propagation speed is the magnetosonic speed: $V_{\mathrm{ms}} = \sqrt{c_s^2 + v_{\mathrm{A}}^2}$

Normally $v_{\mathrm{A}} \gg c_s$, so $V_{\mathrm{MS}} \approx v_{\mathrm{A}}$

C-type and J-type shocks

- In many cases: $c_s < v_s < v_A$
- In this case, the ion-electron fluid is not actually shocked but subject to a submagnetosonic disturbance (not a jump but continuous)
- This sends information ahead of the shock front to “inform” pre-shock gas that compression is coming: magnetic precursor
- Resulting transition can be smooth and continuous $\Rightarrow$ C-type shock
- In case of jump: J-type shock

Schematic structure of J- and C-shocks



(Draine, Fig. 36.3)

J-shocks *vs*. C-shocks

J ("jump")-shocks: $v_s \geq 50$ km/s; fractional ionization high

1. Shock abrupt
2. Neutrals and ions tied into single fluid
3. *T* high: $T \approx 20\,(v_s\,/\,\mathrm{km\,s^{-1}})^2$
4. Molecules destroyed (but reform in cooling post-shock gas)

C ("continuous")-shocks: $v_s \leq 50$ km/s; fractional ionization low

1. Gas variables (T, ρ, v) change continuously
2. Ions ahead of neutrals; drag modifies neutral flow
3. $T_i \neq T_n$; both much lower than in J-shocks
4. Gas heated but molecules (mostly) not destroyed
5. Can be important gas heating mechanism (dissipation of supersonic turbulence)

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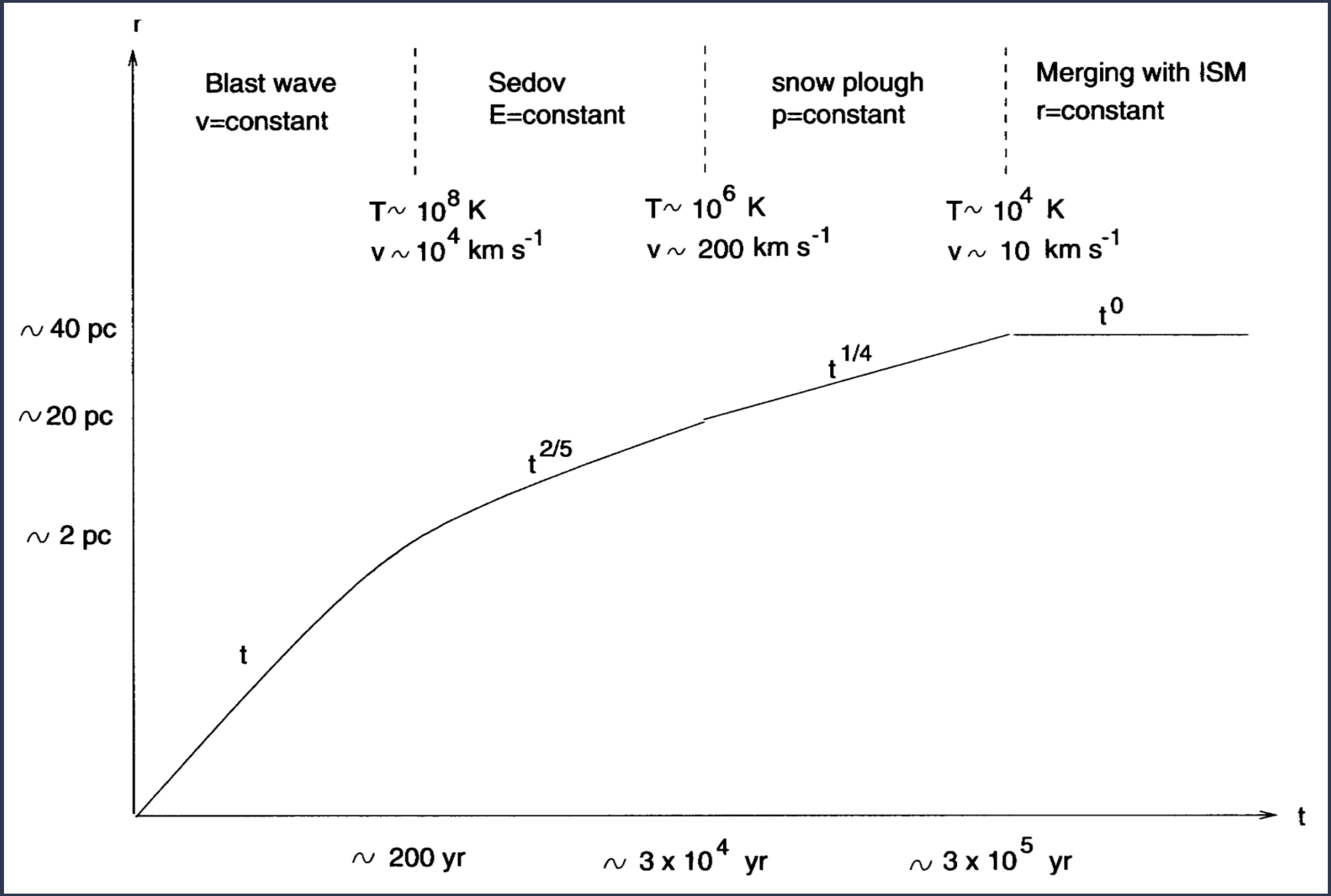
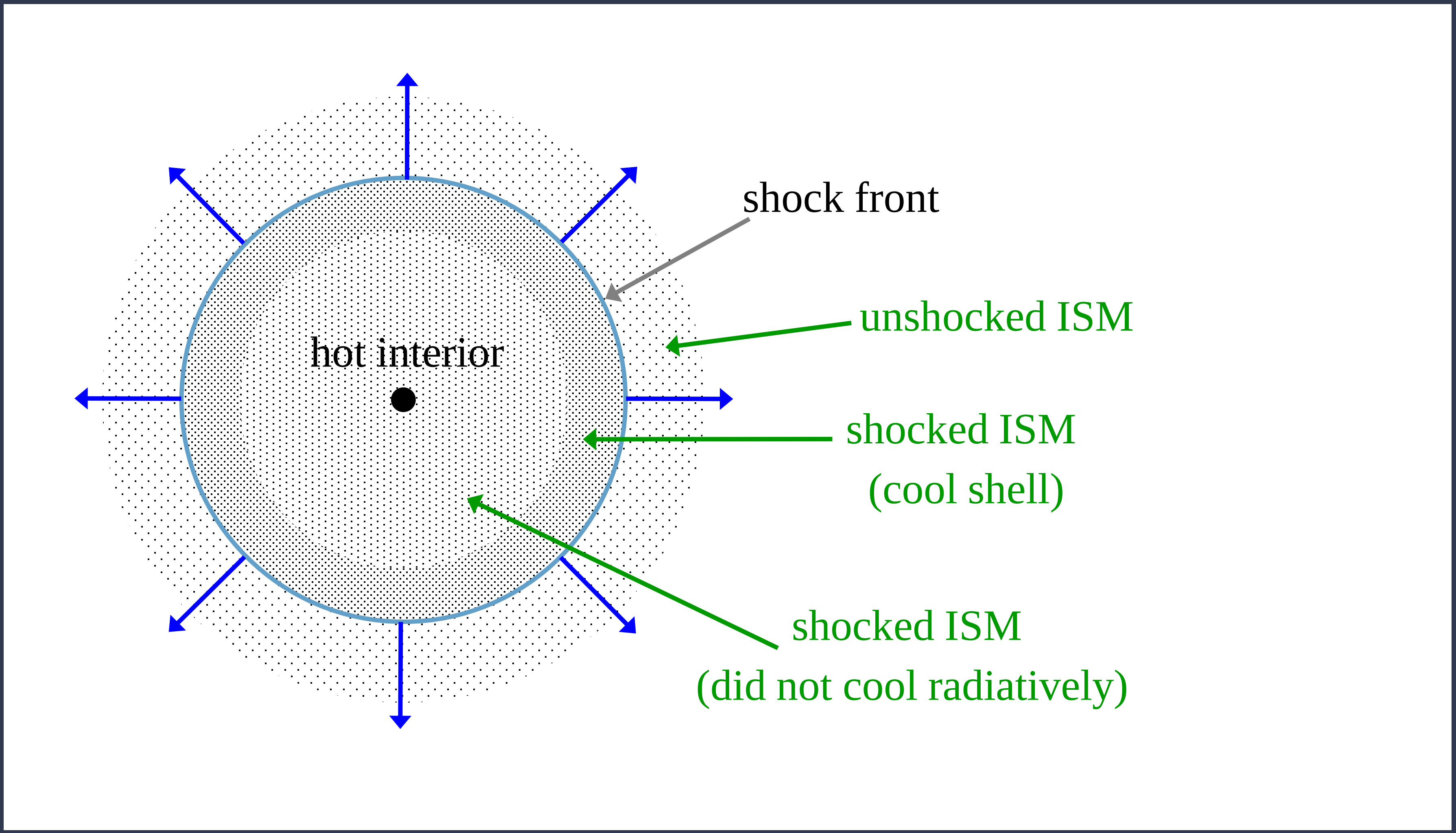
Supernova remnant evolution and shocks

- Early phase ($M_{\text{swept-up}} < M_{\text{ejecta}}$): free expansion, $R_s = v_s$ t
- Sedov-Taylor phase ($M_{\text{swept-up}} > M_{\text{ejecta}}$ and $t < t_{\text{cool}}$): non-radiative shock, slower expansion
- "Snowplow" phase ($t > t_{\text{cool}}$): radiative shock, even slower expansion
- Merging phase: v_s drops below velocity dispersion of ambient ISM

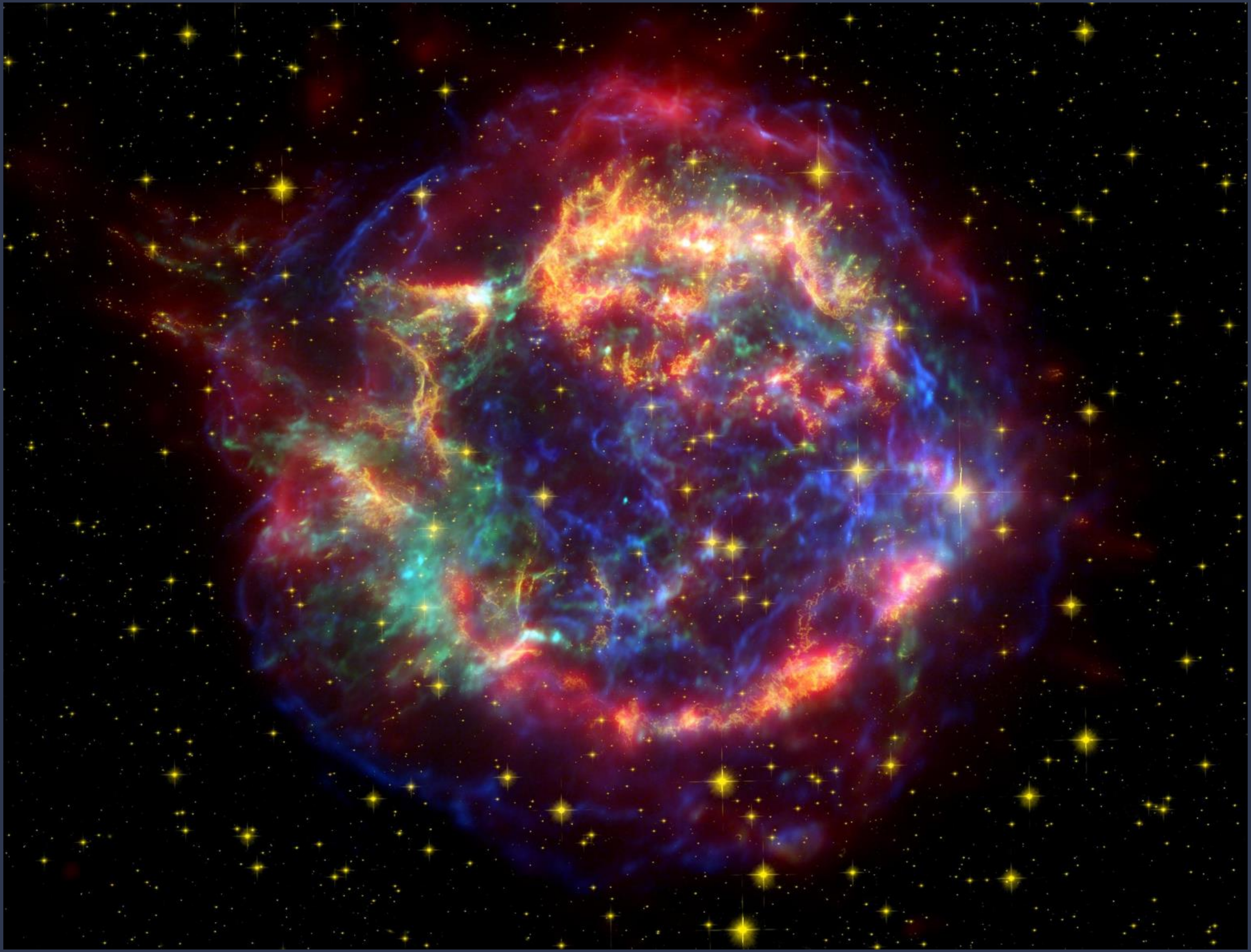
Supernova Remnant evolution



Supernova Remnant structure



Young supernova remnant



Cas A, ~1680:

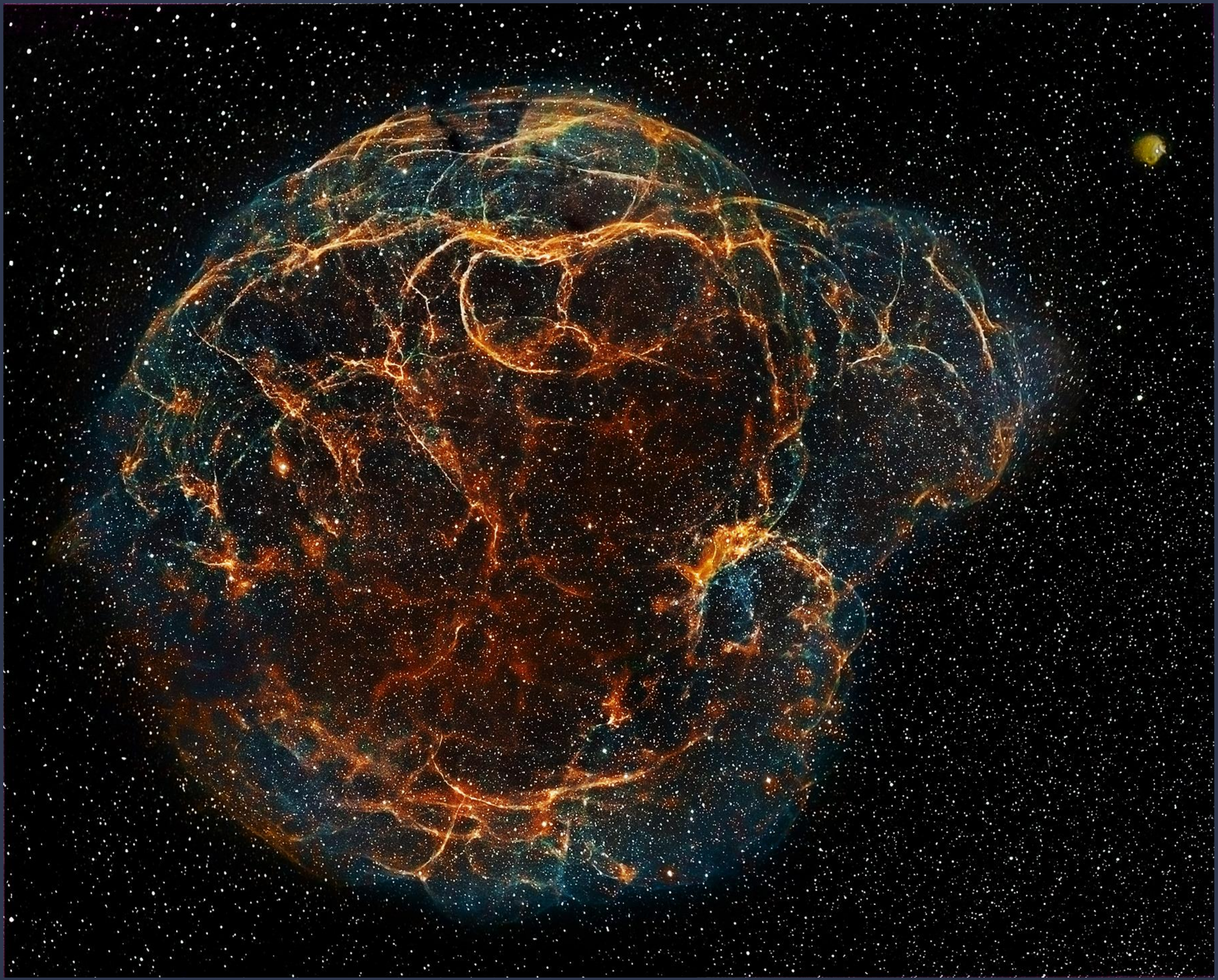
in Sedov-taylor phase

red: infrared

yellow: optical

Blue: X-rays

Old supernova remnant



Simeis 147: at end of Snowplough phase

red: [SII]
yellow: Hα
blue: [OIII]
(credit: Emil Ivanov}

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Need for a 3-phase ISM model

- 2-phase model accounts for only WNM & CNM (parts of which can become ionized or molecular); how do we account for the HIM?
- With Milky Way Supernova rate, lifetimes and sizes, neutral medium will be destroyed on timescales < 10^6 yr.
- Vertical scale height of CNM/WNM can only be explained if the medium is turbulent, ~7 km s^{-1} ➞ something must be stirring up the ISM continuously

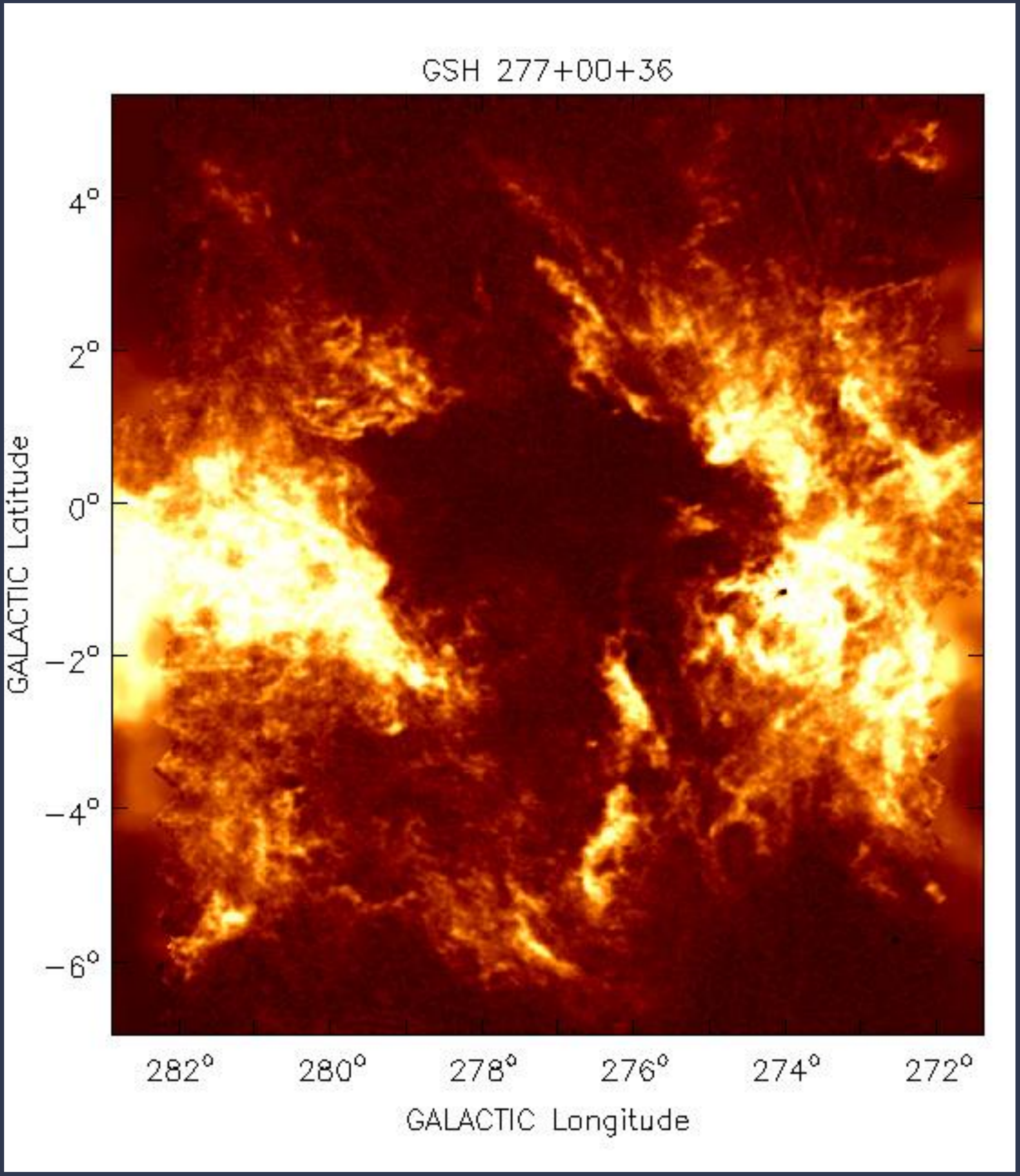
All three point to a role for supernova remmants.

SNRs in the 3-phase model

- Overlapping SNRs create a “tunnel” system of hot ionized gas threading the HI clouds, much like the “holes”in a “swiss cheese”: the HIM.

- SNR evolves in isolation until it intersects a tunnel and connects to the HIM; then pressure drops suddenly as SNR “vents” to tunnel system and contributes to pressure of the HIM.

Supershells in HI 21cm – bubbles blown by SNRs



Physical principles of the 3-phase model

McKee & Ostriker 1977

1. Pressure balance

- Pressure is from supersonic turbulence, maintained by SNRs
- Can be used to determine P_{ISM} giving the correct result within factor of 2!

2. Mass balance

- Balanced mass exchange between phases

3. Energy balance

- most SN energy leaves system as radiation. This is satisfied if SNRs enter radiative phase before they overlap (which they do)
- A small fraction of SN energy remains as kinetic energy of shells at time of SNR overlap. This energy maintains random motions of clouds.

The 3-phase model: successes

- Predicts pressure of the ISM correctly “ab initio”
- Observed soft X-ray background in rough agreement with $T \approx 5\times10^5$ K expected for cooling SNR gas = HIM
- Predicted cloud velocity dispersion ≈ 7 km s^{-1} agrees with observations

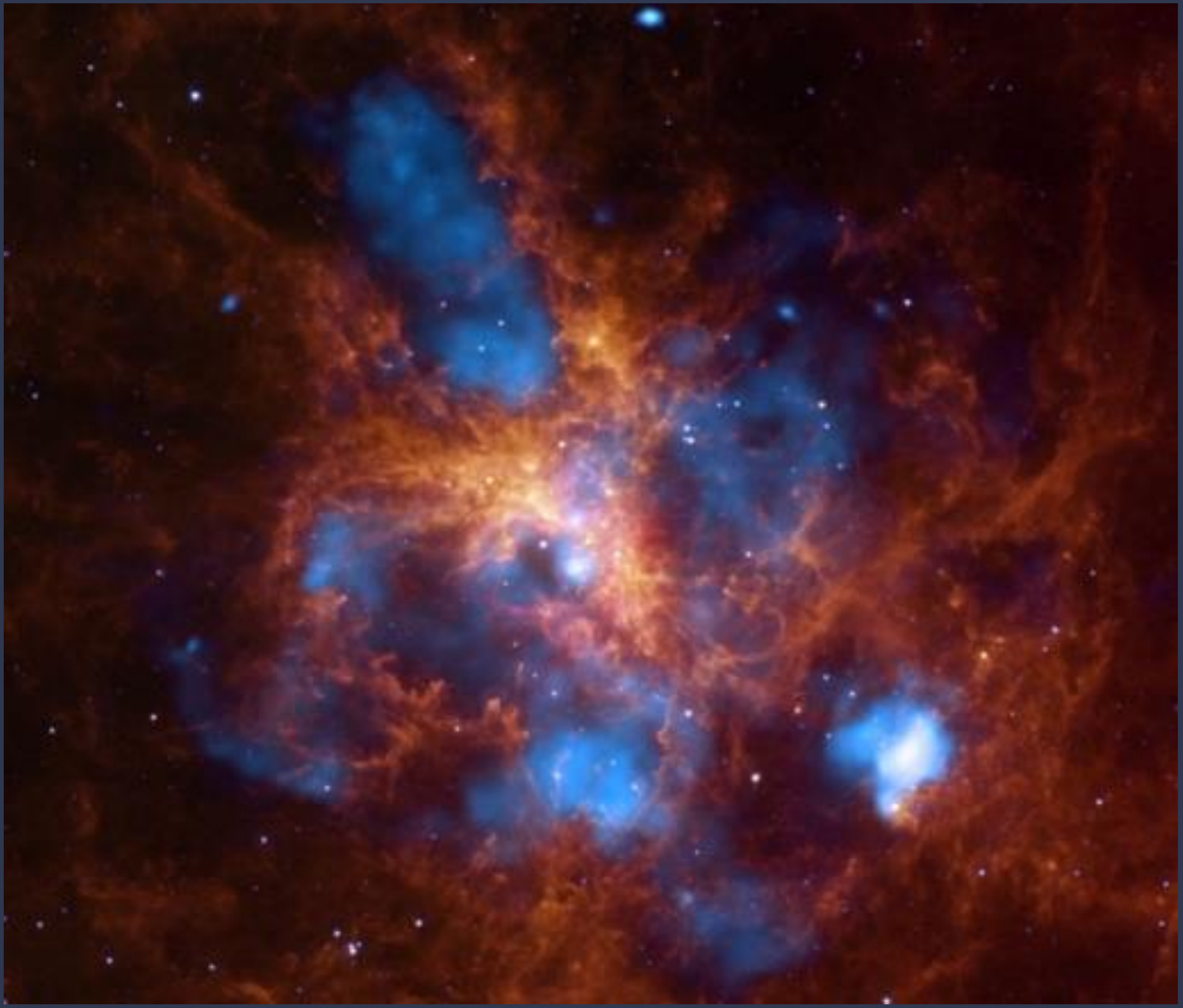
The classical 3-phase model: problems

- Does not predict enough WNM
- Required porosity is larger than observed

But additional effects to be considered:

- Clustering of supernovae
- Blowout into the halo
- Inhomogeneous ISM
- Magnetic field

Multiphase structure in the Large Magellanic Cloud

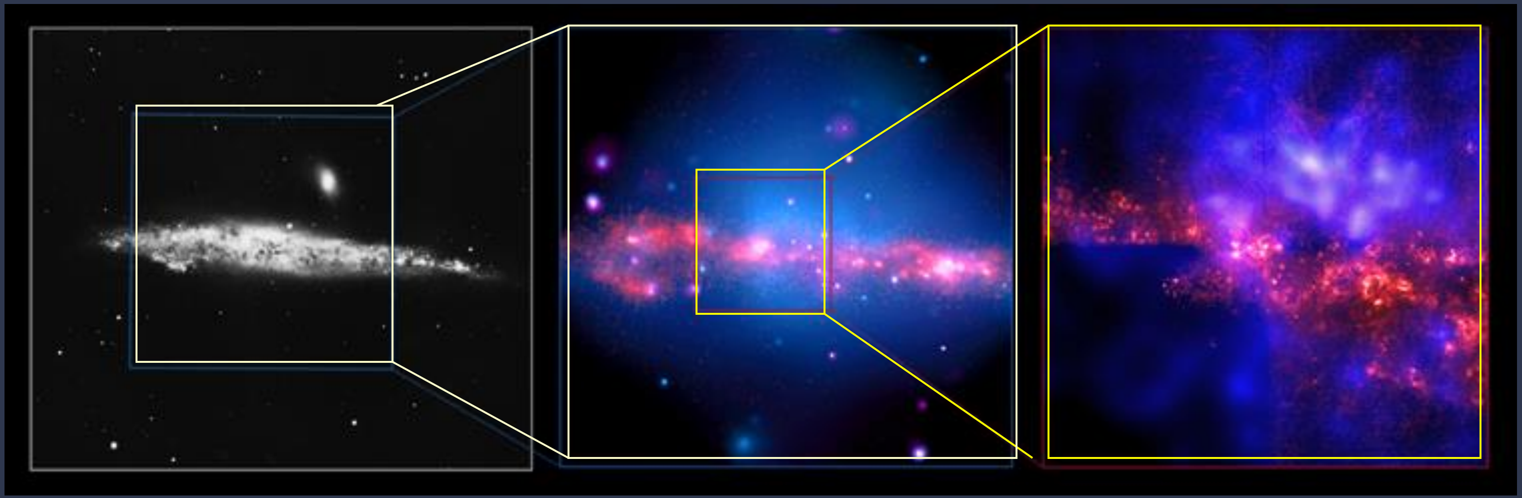


Blue: X-rays (HIM)

Orange: dust emission (mostly CNM)

Blowout into the halo (“superwind”)

NGC4631



optical

red = Hα

blue: X-ray

Outlook, hot topics, further study…

- Star (and planet) formation
- Origin (and universality) of the Initial Mass Function
- Role of ISM regulating star formation on Galaxy-wide scales
- ISM in ultraluminous galaxies
- ISM and Active Galactic Nuclei
- ISM in high-z galaxies (where 50% of baryonic mass is gas)
- ISM in low-metallicity galaxies (including at very high z)
- Formation of the first stars
- etc, etc, etc…