Interstellar Medium & Star Formation

Workshop on Introduction to Astronomy and Astrophysics

IIT, Tirupati

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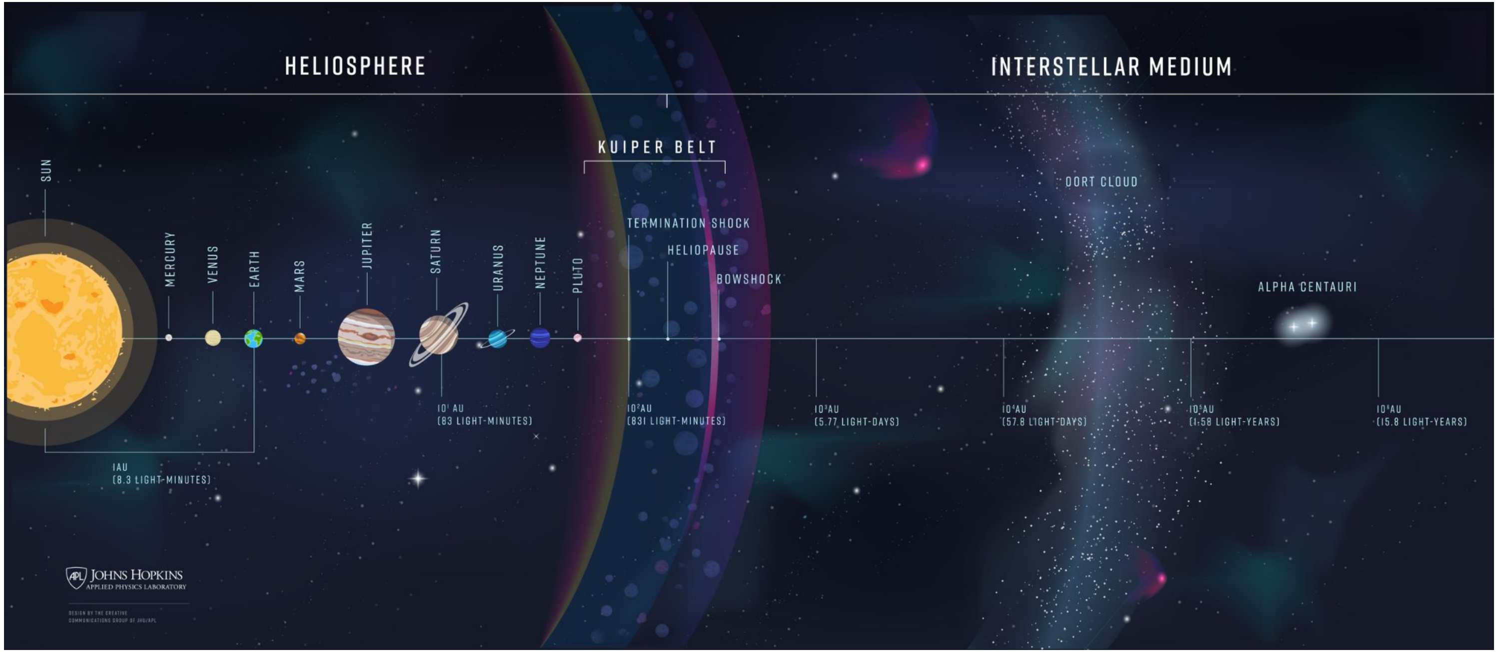
Rajeshwari Dutta
IUCAA

Reference Books

1) Physics of the Interstellar and Intergalactic Medium - *Bruce T. Draine*
2) The Physics of the Interstellar Medium - *John E. Dyson & David Williams*
3) The Interstellar Medium - *James Lequeux*
4) The Physics and Chemistry of the Interstellar Medium - *A. G. G. M. Tielens*
5) Interstellar and Intergalactic Medium - *Barbara Ryden & Richard W. Pogge*
6) Astrophysics Of Gaseous Nebulae And Active Galactic Nuclei - *Donald E. Osterbrock & Gary J. Ferland*

What is the Interstellar Medium (ISM)?

- Matter and radiation between stars in galaxies
- Dominates volume of galaxy (>99%)
- Average density ~1 atom cm^{-3} (~10^{19} molecules cm^{-3} in Earth's atmosphere)
- Interplay of matter and energy between ISM and stars determines galaxy's life cycle



What is the ISM made of?

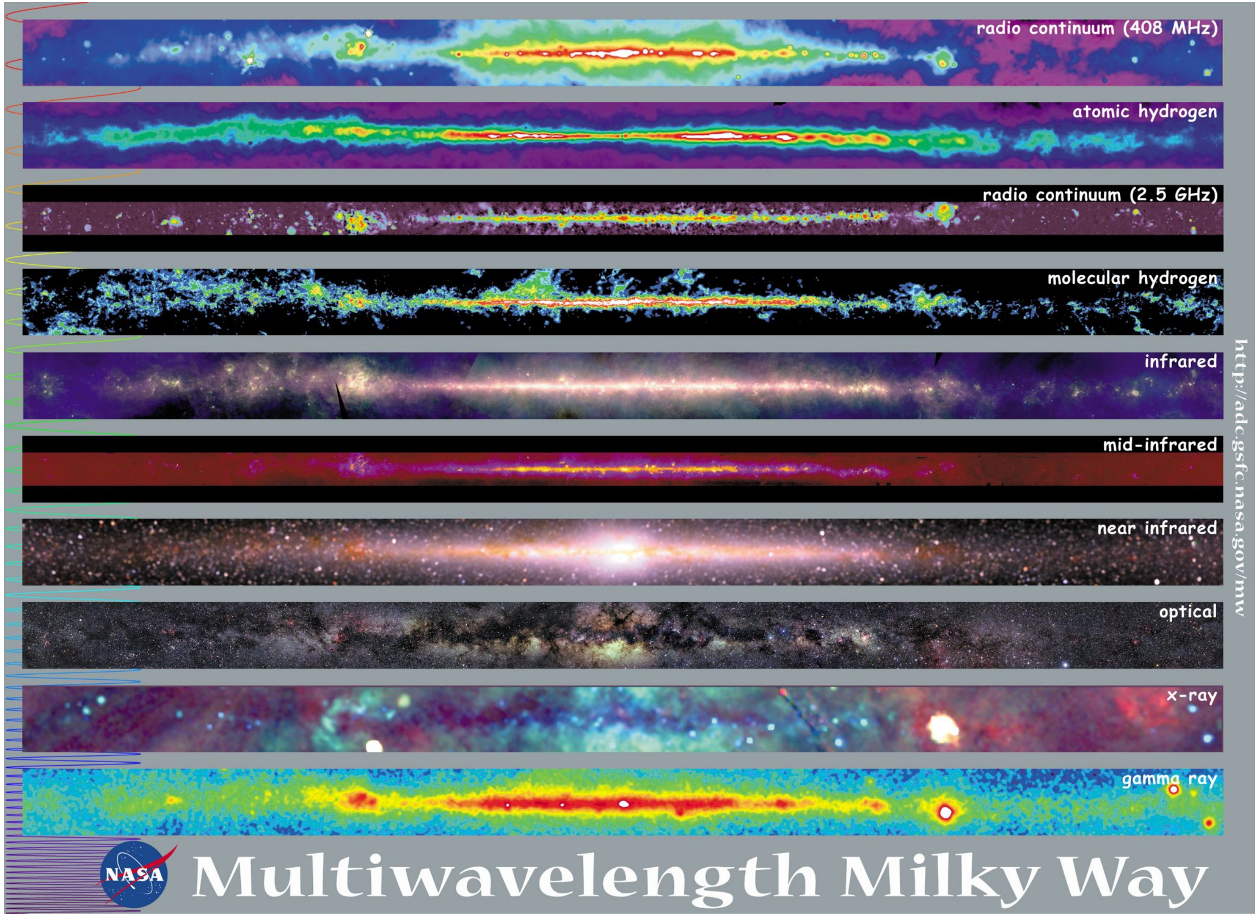
- About 99% gas by mass (~70% Hydrogen, ~28% Helium, ~1% heavier elements or metals)
- About 1% dust (solid material) by mass
- Cosmic rays, radiation, magnetic fields
- Different objects: HII regions, Reflection Nebulae, Dark Nebulae/Molecular Clouds, Photodissociation regions, Planetary Nebulae, Supernova remnants
- Different gas phases: ionized, atomic, molecular

ISM gas phases

	Phase	T (K)	n_H (cm^{-3})	f_V -	P/k_B (K/cm^3)	Comments
H II 23%	Hot ionized medium (HIM)	$10^{5.7}$	0.004	0.5	4400	Collisionally ionized, shock-heated by supernovae and stellar winds
	H II regions	10000	$0.1\text{-}10^4$	0.01	varies	Photo-ionized nebulae around stars; density and pressure vary across these bubbles
	Warm ionized medium (WIM)	8000	0.2	0.1	4400	Diffuse photo-ionized gas, large scatter in temperature and density
H I 60%	Warm neutral medium (WNM)	8000	0.5	0.4	4400	About 60% of HI by mass; in pressure equilibrium witn CNM
	Cool neutral medium (CNM)	100	40	0.01	4400	Significant fraction of the mass despite small volume filling fraction
H_2 17%	Diffuse molecular gas	50	150	0.001	4400	Self-shielded against dissociation, but not dense enough to form stars
	Molecular clouds	10-50	$10^3\text{-}10^6$	0.0001	>10000	The site of star formation; more or less gravitationally bound

credit: Benedikt Diemer

Multiwavelength observations of ISM



Relativistic particles

Cool atomic gas

Warm ionized gas

Cold molecular gas

Dust

PAH

Cool Stars

Stars & Dust

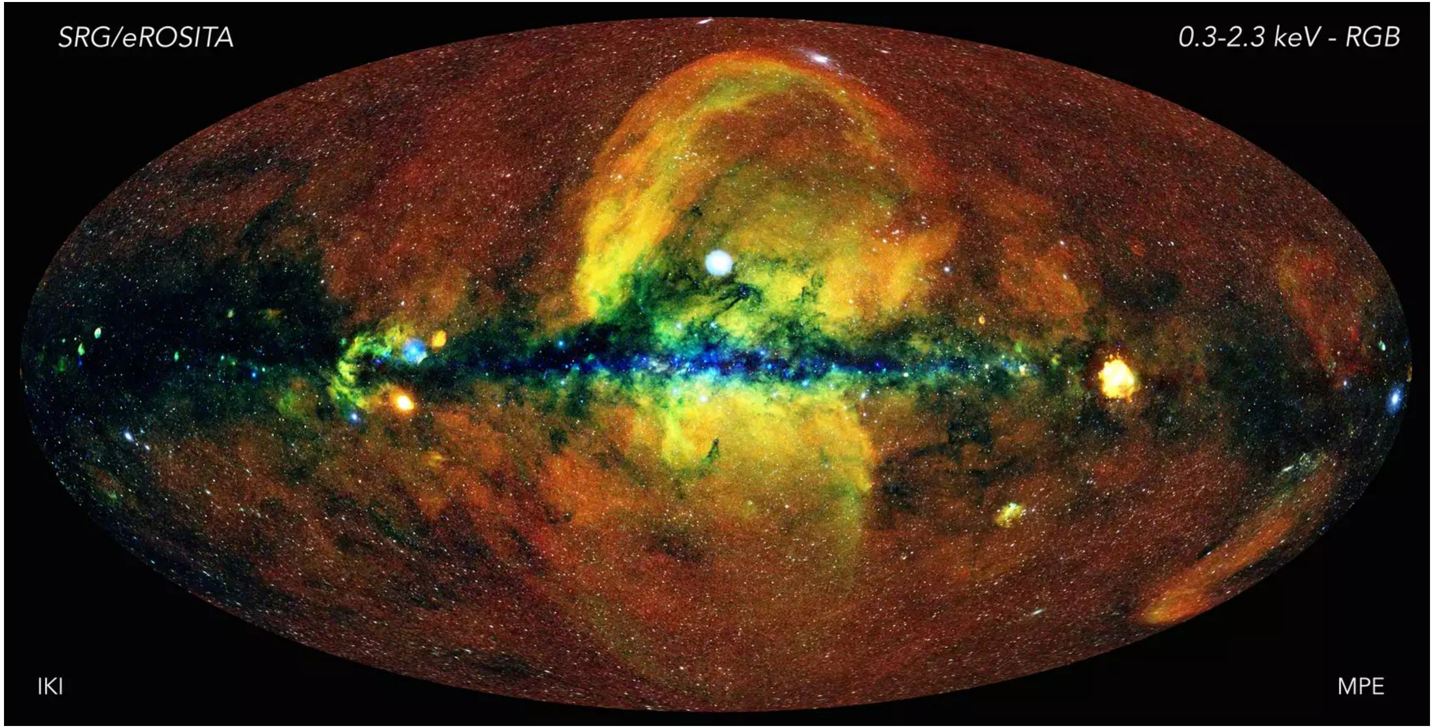
Hot ionized gas

Cosmic rays

Multiwavelength observations of ISM

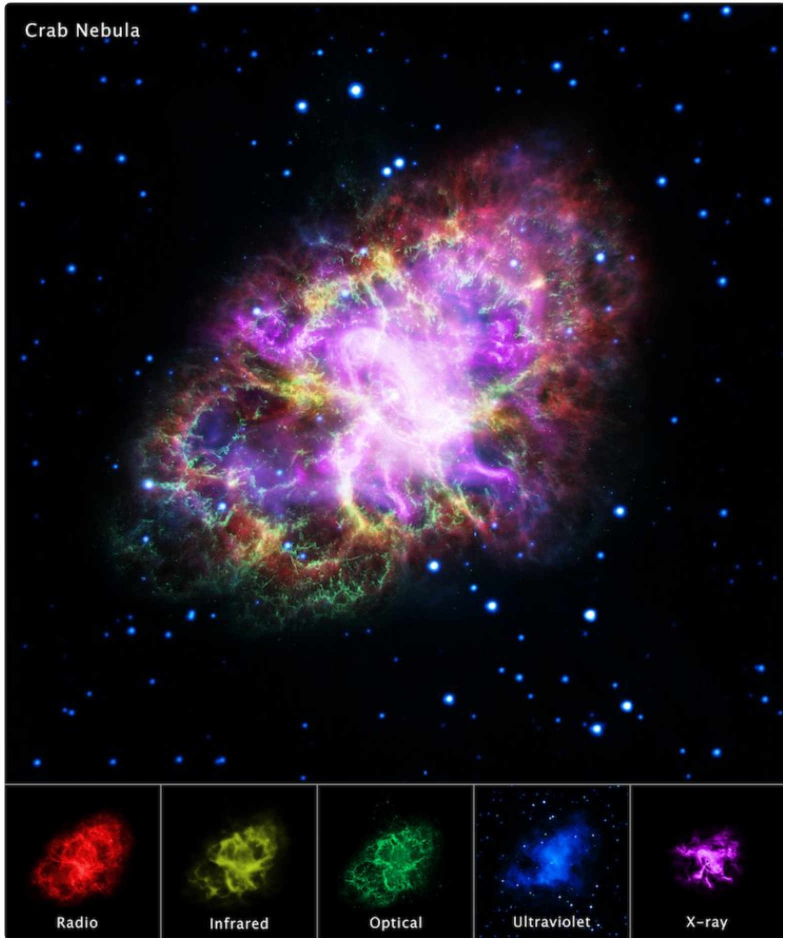
ecuip.lib.uchicago.edu

Hot ionized gas phase



- Most volume filling phase of ISM
- Collisionally ionized gas
- Heated by supernovae shocks and stellar winds
- Traced by X-ray emission, FUV (e.g. OVI) absorption against stars or quasars, radio synchrotron emission

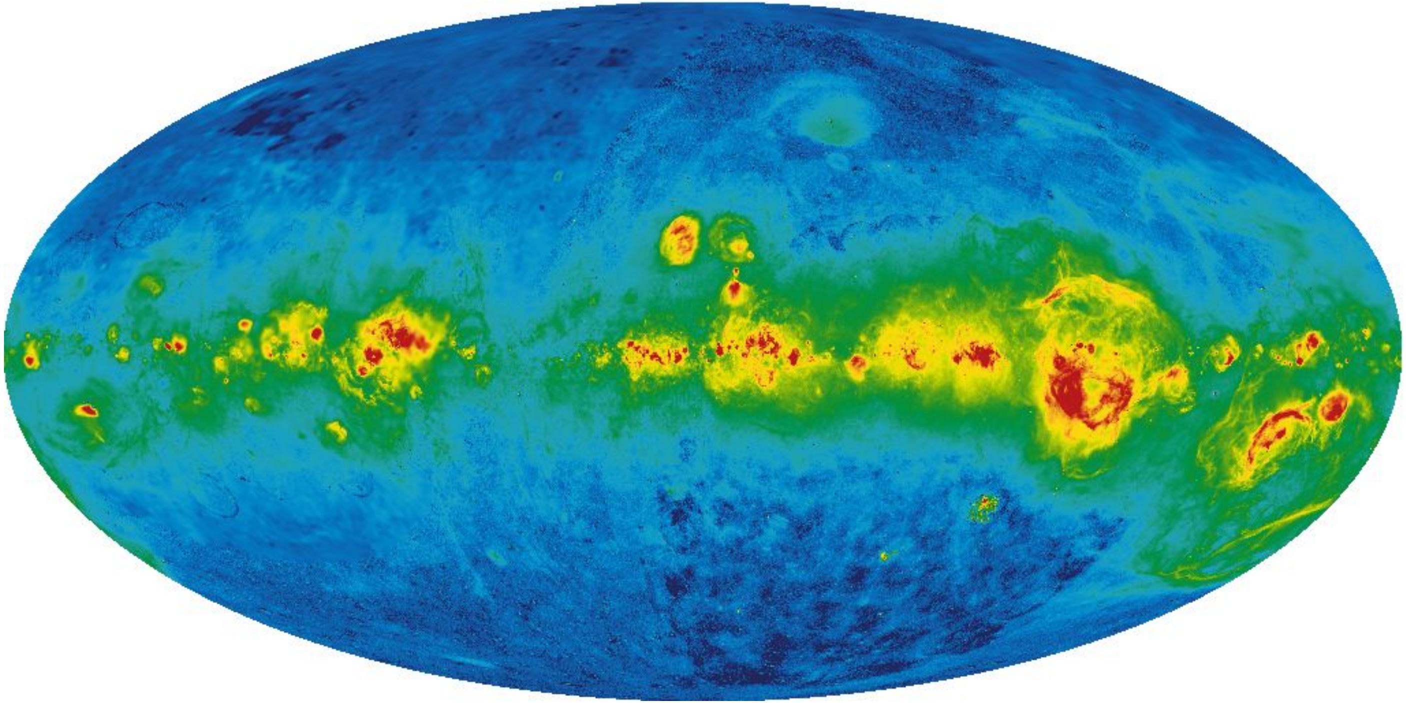
Supernova Remnants



VLA (radio); Spitzer (infrared); HST (optical); XMM-Newton (UV); Chandra (X-ray)

- Nebulae resulting from explosion of stars in supernovae
- Bound by shock waves
- Major source of heating of ISM gas
- Main source of elements heavier than Oxygen
- Major source of cosmic rays
- Around 300 known in Milky Way
- Strong synchrotron radiation
- Emits across wavelengths: radio, infrared, optical, UV, X-rays, gamma rays

Warm ionized gas phase

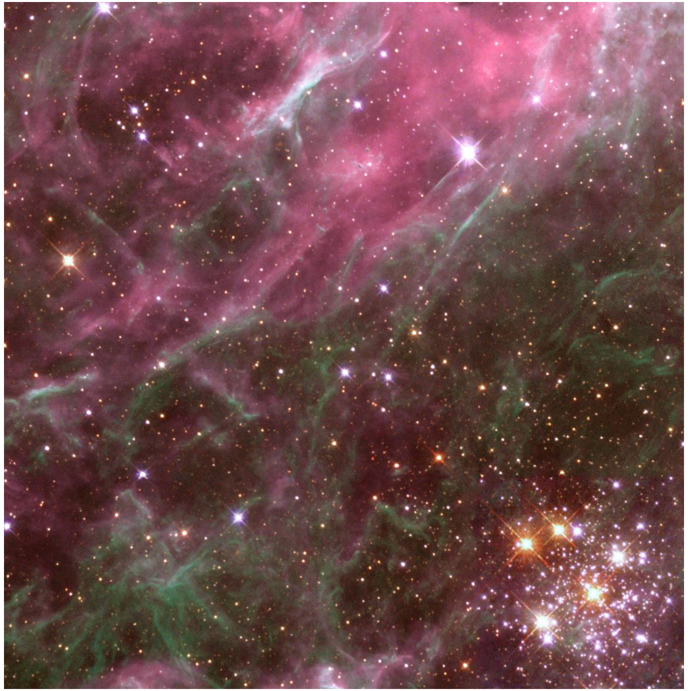


Hα emission (Finkbeiner 2003)

- Photoionized gas
- Consists of compact HII regions and diffuse ionized gas
- Traced by Hα emission, pulsar dispersion measure, free-free radio emission

HII regions

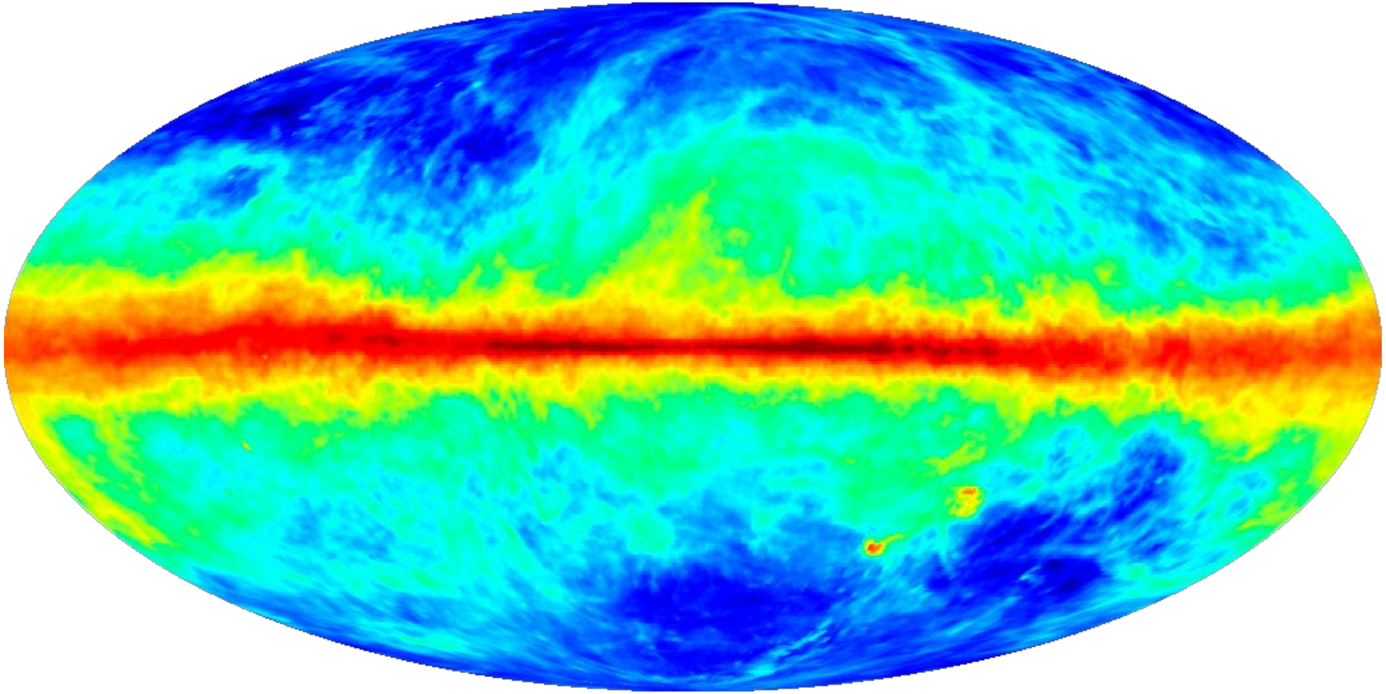
Orion Nebula (NASA)



Tarantula Nebula (NASA)

- Photoionized hydrogen gas clouds around massive, young O/B stars (Stromgren spheres)
- Temperature ~10^4 K
- Density ~$0.1\text{-}10^4$ cm^{-3}
- Strong Hα emission line

Atomic gas phase

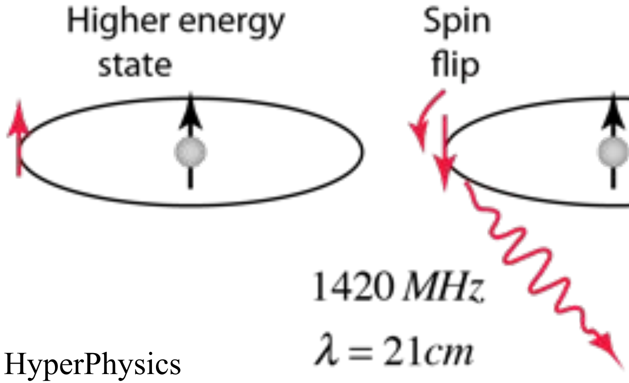


HI 1.4 GHz LAB survey (Kalberla+2005)

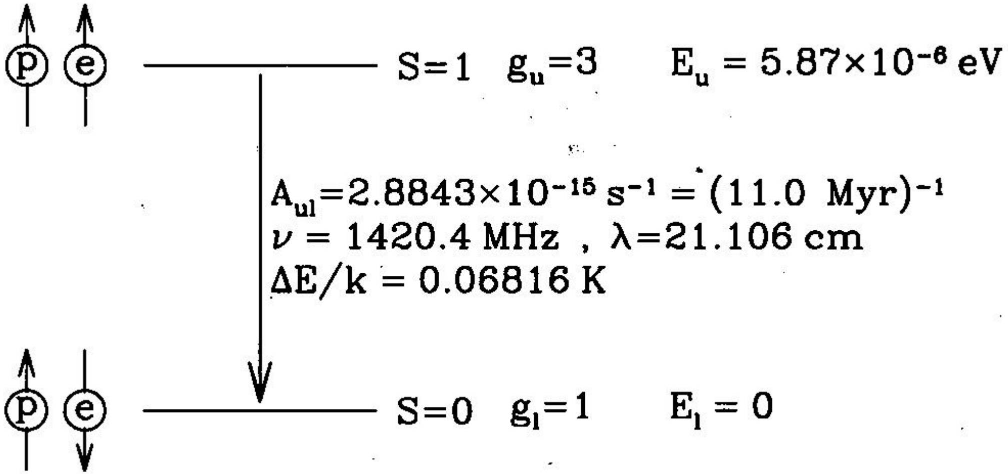
- Majority (60%) of ISM gas mass is atomic or HI
- Consists of Cold Neutral Medium (CNM) and Warm Neutral Medium (WNM) in pressure equilibrium
- Traced typically by HI 21-cm emission & absorption, optical/UV absorption lines

HI 21-cm line

Electron-proton spin-flip transition between hyperfine levels of ground state of hydrogen atom

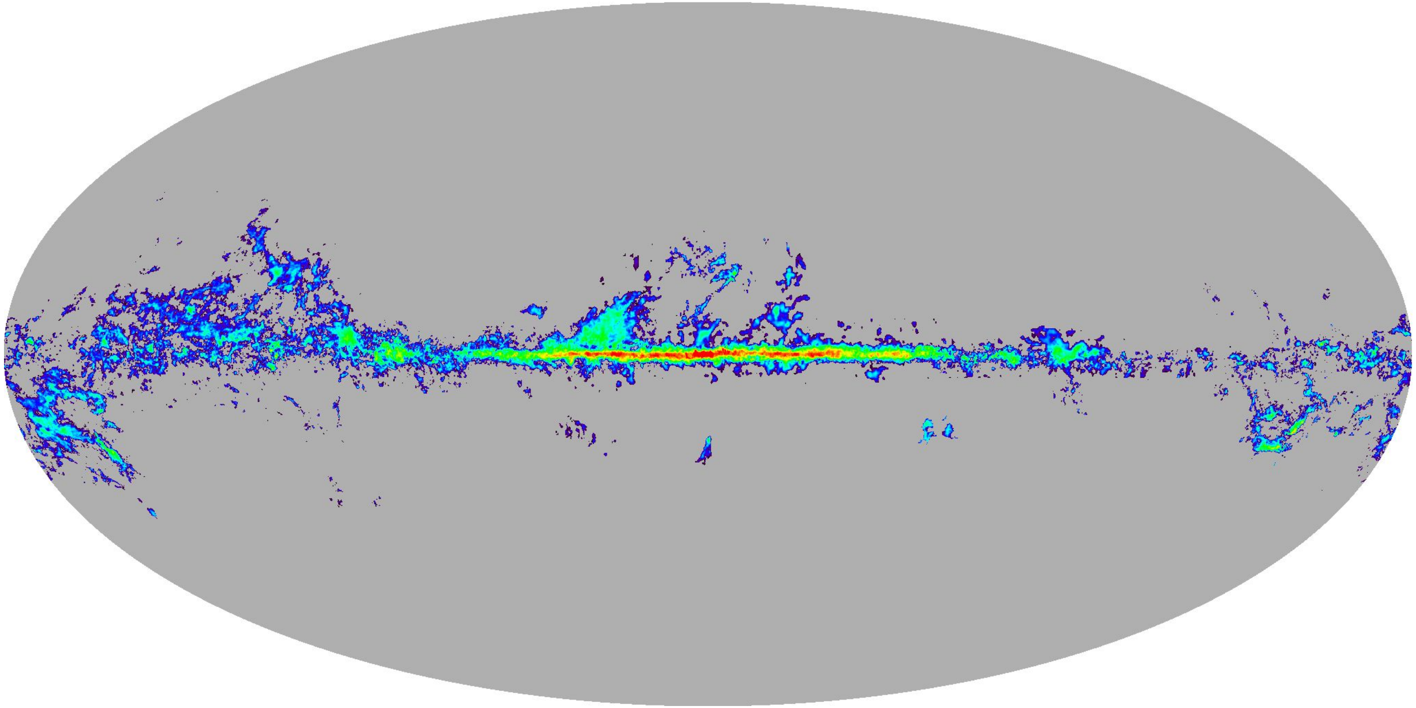


HyperPhysics



Bruce Drain's Physics of the Interstellar and Intergalactic Medium

Molecular gas phase

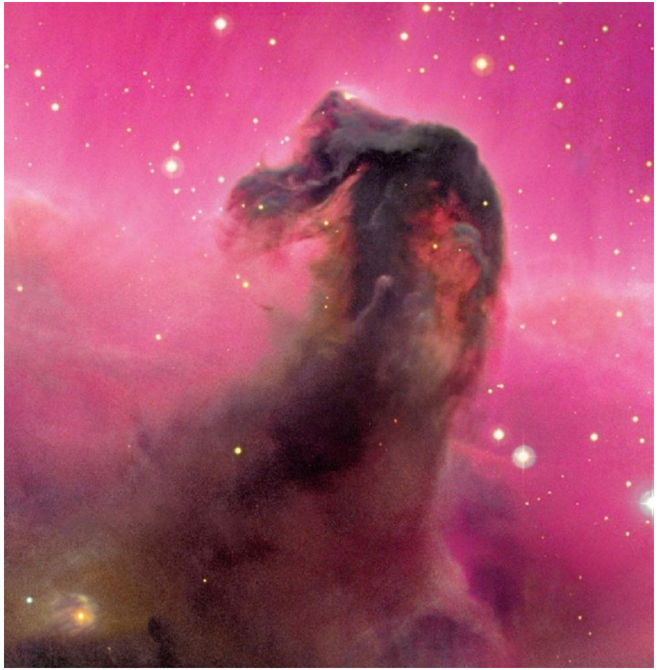


CO(1-0) 115 GHz (Dame+2011)

- Consists of mostly H_2
- Consists of dense clouds and diffuse gas
- H_2 difficult to detect
- CO mm lines typically used as tracers

Molecular Clouds

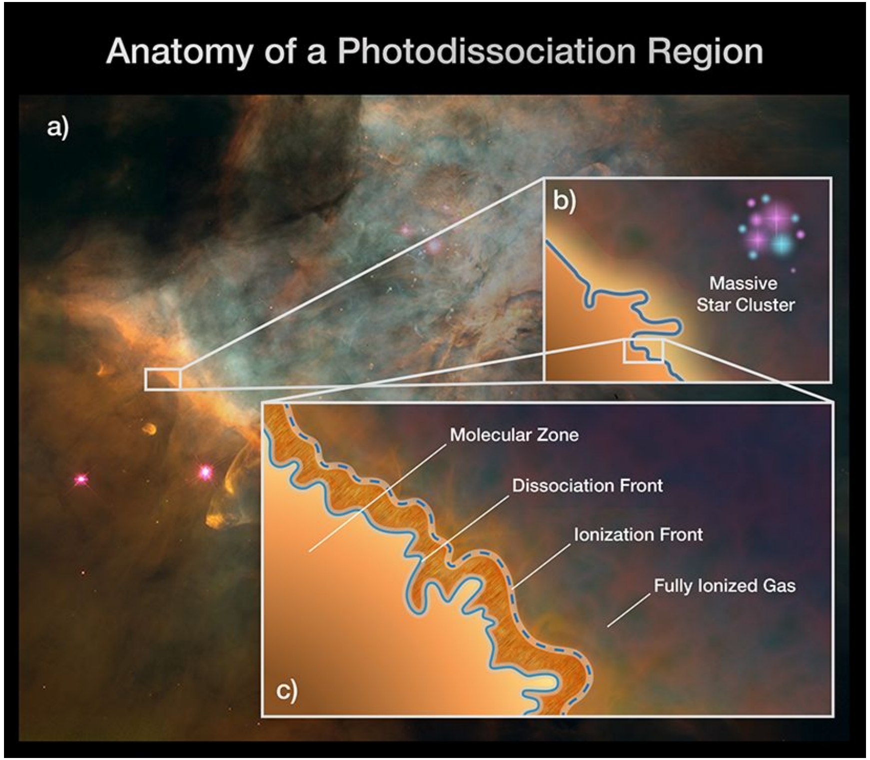
Barnard 68 (ESO)



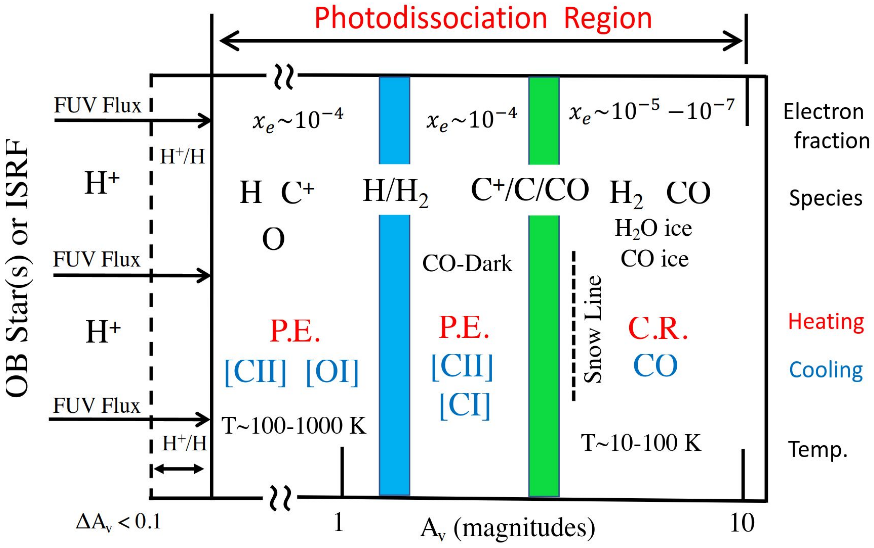
Horsehead Nebula (CFHT)

- Dense dust and molecular clouds
- Obscures optical light
- Temperature ~10-100 K
- Bright in FIR
- Range from small clumps to Giant Molecular Clouds
- Formation sites of stars and planetary systems

Photodissociation region (PDR)



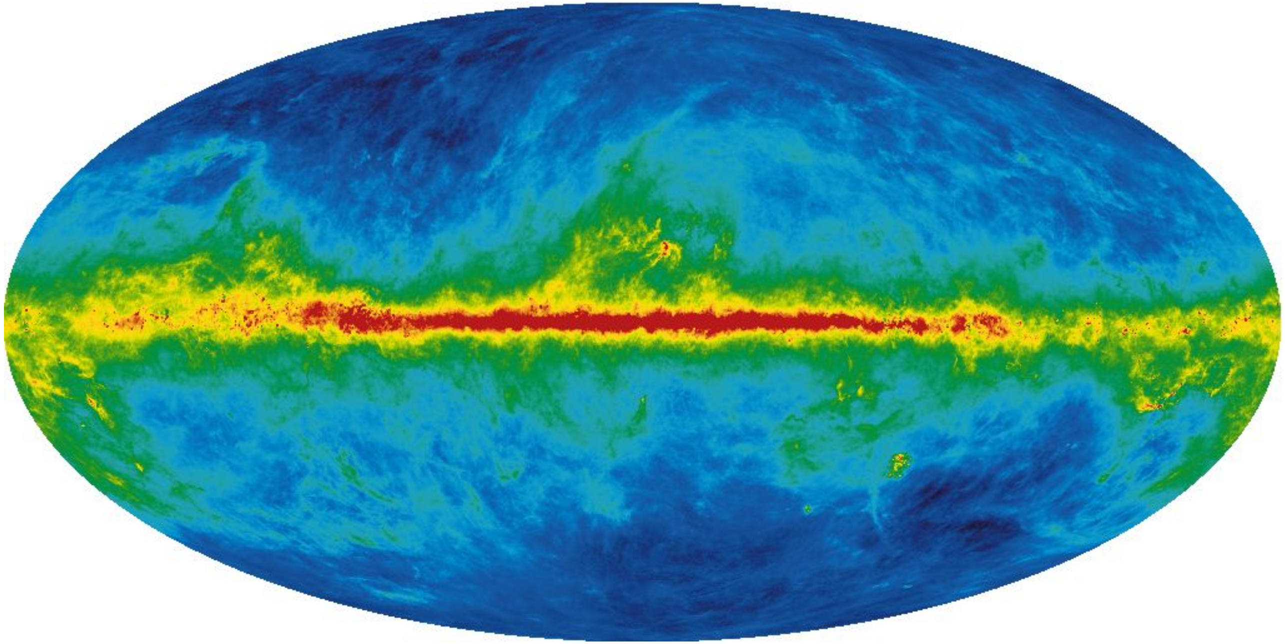
Orion Bar (JWST)



Wolfire et al. 2022

- Transition region between molecular gas and ionized gas around massive stars
- Transition of H to H_2 and C^+ to CO
- Heating and chemistry regulated by FUV photons
- Strong fine structure emission lines (e.g., [CII]), strong molecular emission lines (e.g., CO), infrared continuum emission from dust

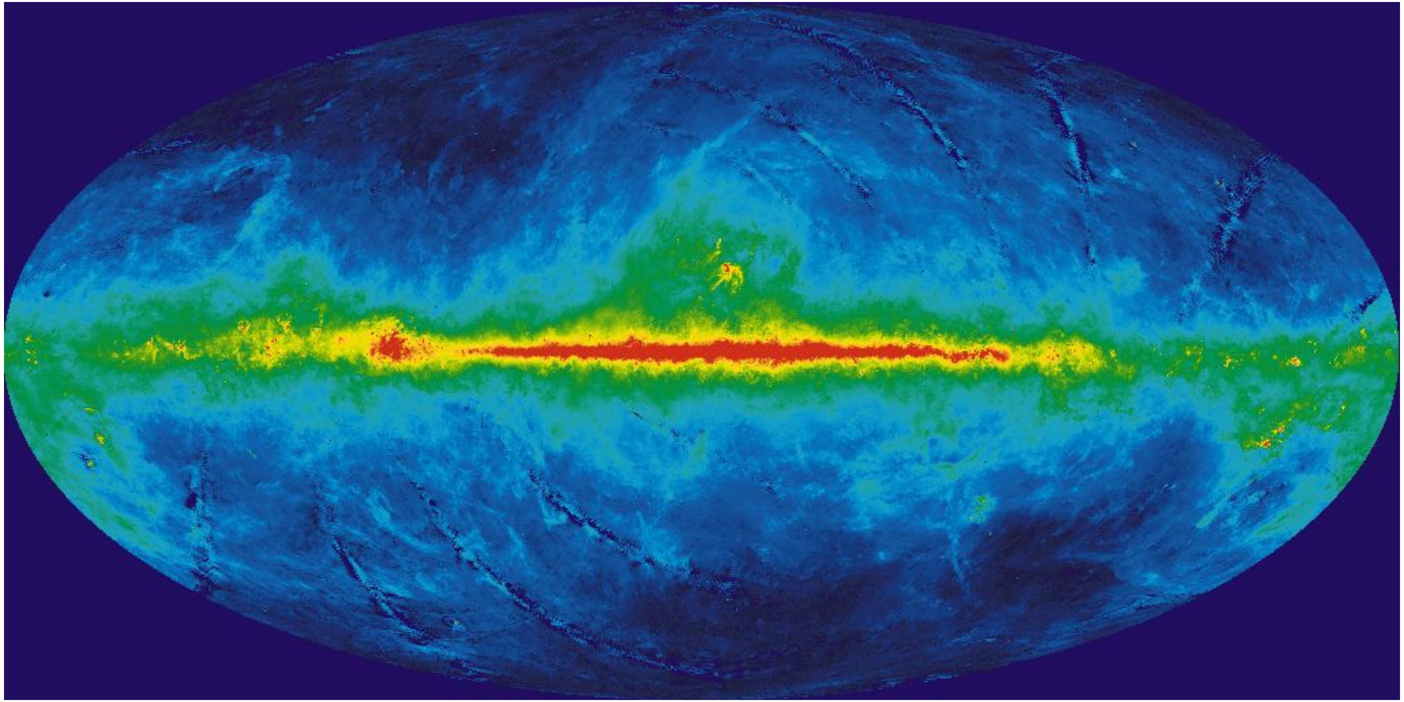
Dust



COBE & IRAS 94 GHz dust emission (Finkbeiner, Davis & Schlegel 1999)

- Dust:gas ~1:100 in MW
- Formed in atmospheres of AGB and Red Giant stars, planetary nebulae, supernovae
- Composed of refractory elements: C, O, Mg, Si, Fe
- Causes extinction of optical light
- Primary site for molecule formation
- Photoelectric heating by dust grains major source of heating in ISM
- Traced by infrared emission

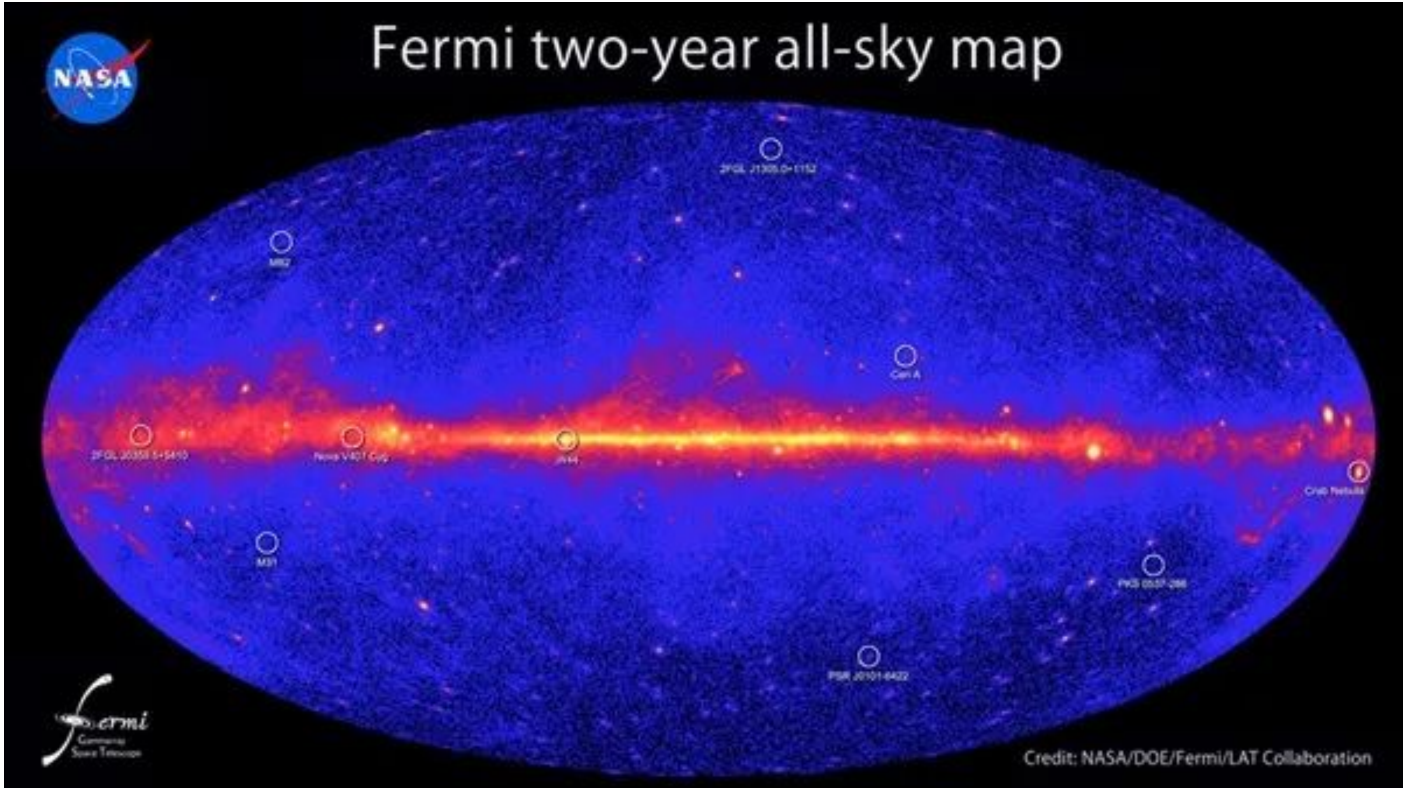
Polycyclic Aromatic Hydrocarbon (PAH)



WISE 12 micron dust emission (Meisner and Finkbeiner 2014)

- Large organic molecules
- Contains ~10% of Milky Way's Carbon
- Mid-IR (5-15 micron) emission features due to vibrational excitation

Cosmic Rays



- High-energy (~1-10 GeV) relativistic particles (mostly protons)
- Produced in supernovae and other high energy events
- Important source of heating in molecular clouds
- Traced by Gamma-ray emission

Heating in ISM

- **Photoelectric effect:** UV photons from stars knock electrons out of dust grains and PAHs, transferring kinetic energy to gas; dominant heating mechanism in neutral gas phase
- **Photoionization:** UV photons from stars ionize species, where kinetic energy of ejected electron is difference between energy of photon and ionization potential of species; C ionization (~11.26 – 13.60 eV) important in neutral gas
- **X-rays:** Photoionization of species by X-ray photons
- **Cosmic rays:** Lower energy cosmic rays (protons) ionize hydrogen atoms via collisions, with mean kinetic energy of ejected electron ~35 eV; dominant heating mechanism in molecular clouds
- **Gas dynamics:** shock waves, turbulence; shock heating by supernova explosions or stellar winds dominant in hot ionized medium

Cooling in ISM

- **Radiative cooling by collisionally excited metal lines:** In CNM, cooling is dominated by excitation of C^+ by collisions with thermal electrons followed by radiative de-excitation and emission of FIR fine-structure line, [CII] 158 μm; other FIR cooling lines: [OI] 63 μm, [SiII] 35 μm

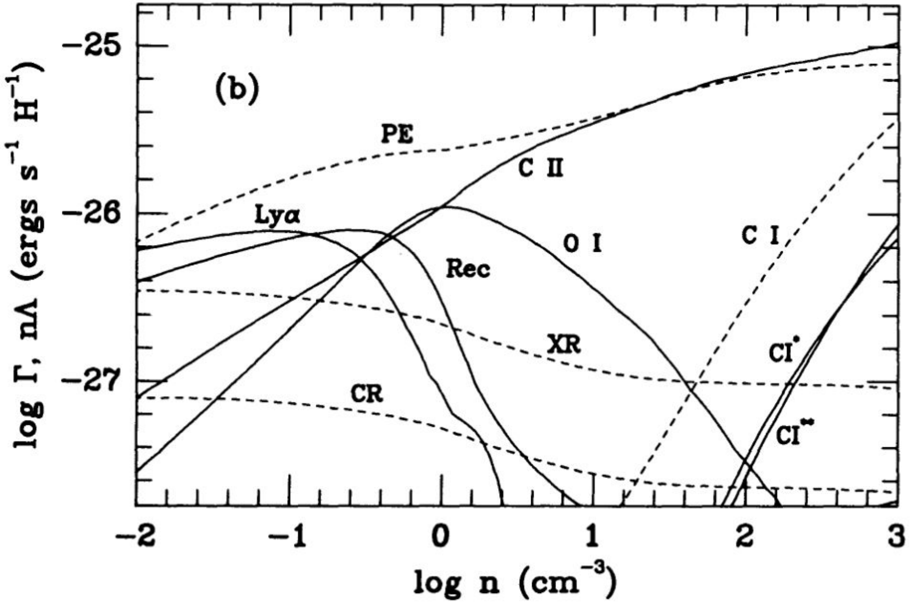
- **H Lyα radiative cooling:** Collisional excitation of hydrogen atom from ground to first excited state followed by radiative de-excitation with emission of Lyα photon; dominates in WNM ($\sim 10^4$ K)

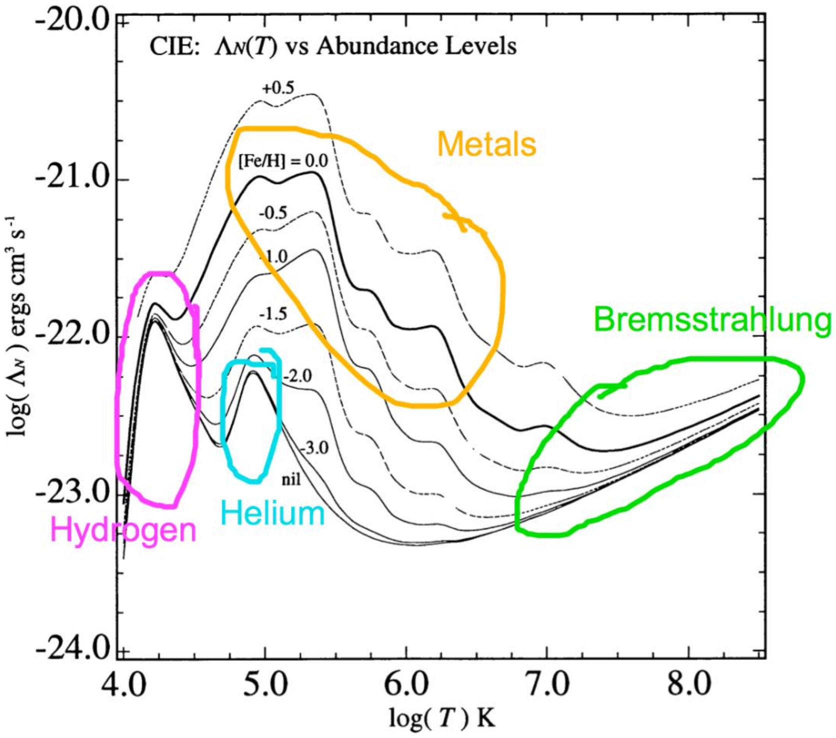
- **Thermal Bremsstrahlung (Free-Free) radiation**: Free electron de-accelerated by close encounter with free proton or ion, emitting photon that carries away its kinetic energy; dominant at $T > 10^6$ K; cooling rate $\propto T^{1/2}$

- **Recombination cooling:** Free electron undergoes radiative recombination with proton to form neutral hydrogen, decreasing total thermal energy of region by its kinetic energy

- **Dust emission:** Dust grains absorb higher energy radiation from stars and re-emit it as thermal radiation in infrared

Heating & Cooling in ISM

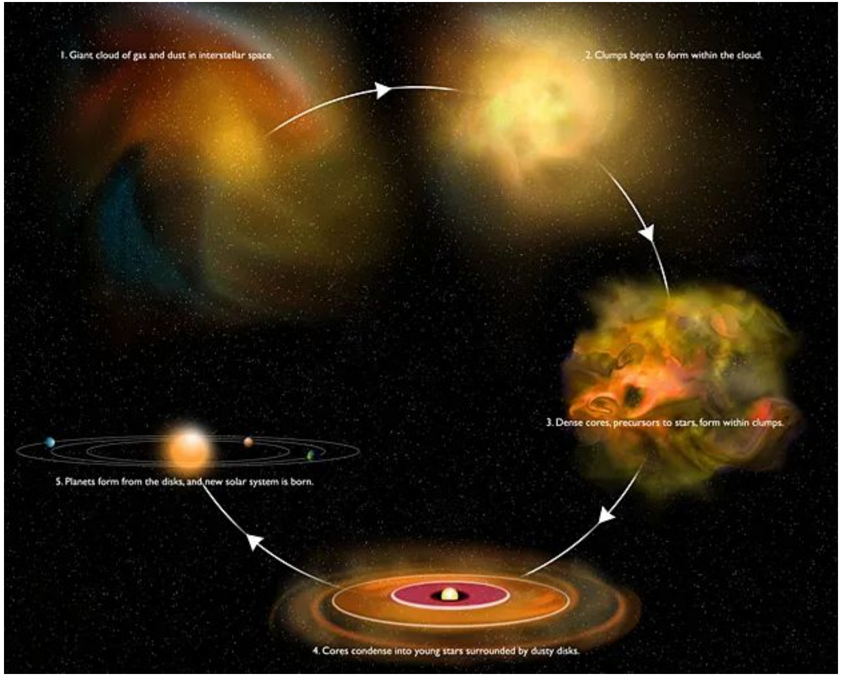


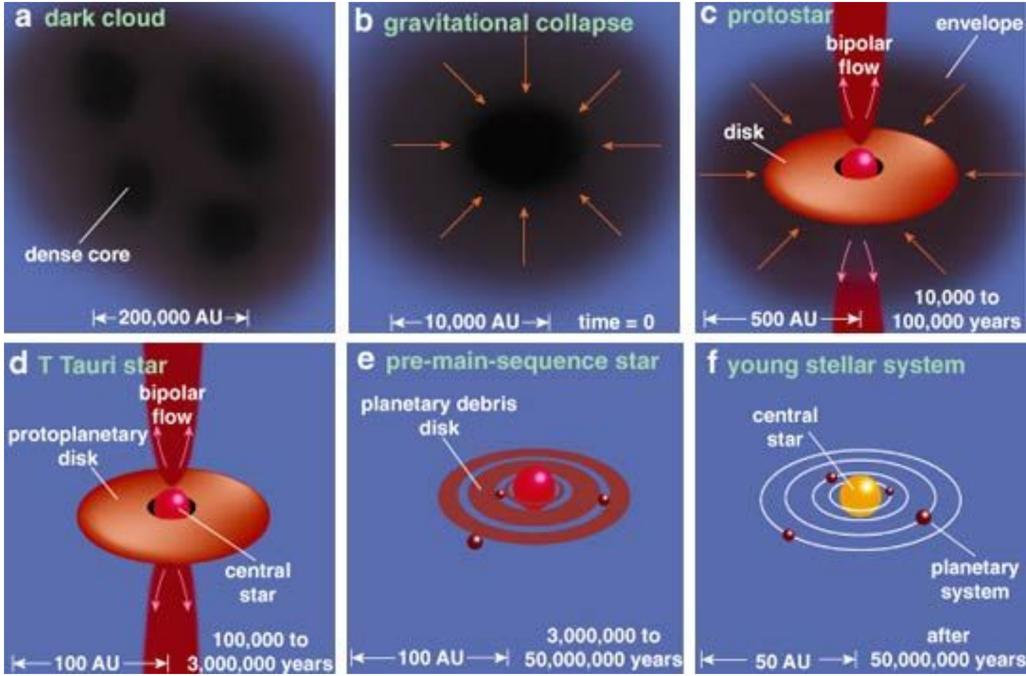


Wolfire et al. 1995

Sutherland & Dopita. 1993

How do stars form?





Jeans Criterion

- Equilibrium condition of stable, gravitationally bound system → virial theorem: $2K = -U$
- Gravitational potential energy of spherical cloud:

$$U \simeq -\frac{3}{5}\frac{GM_c^2}{R_c}$$

- Total internal kinetic energy of cloud:

$$K = \frac{3}{2}\mathcal{N}kT$$

- Total number of particles N in terms of mean molecular weight (μ): $\mathcal{N} = \frac{M_c}{\mu m_H}$
- Condition for gravitational collapse: $2K < |U|$

$$\frac{3M_c kT}{\mu m_H} < \frac{3}{5}\frac{GM_c^2}{R_c}$$

- Radius in terms of initial density (assume constant) of cloud: $R_c = \left(\frac{3}{4}\frac{M_c}{\pi\rho_0}\right)^{1/3}$

Jeans Criterion

- Jeans mass: $$M_J \simeq \left(\frac{5kT}{G\mu m_H}\right)^{3/2} \left(\frac{3}{4\pi\rho_0}\right)^{1/2}$$
- Jeans length: $$R_J \simeq \left(\frac{15kT}{4\pi G\mu m_H \rho_0}\right)^{1/2}$$
- If mass (radius) of cloud exceeds Jeans mass (length), cloud will be unstable against gravitational collapse
- Lower the temperature and higher the density, smaller the cloud mass which is unstable against gravitational collapse for a given chemical composition (μ)
- Neglected external pressure on cloud, rotation, internal macroscopic velocity gradients, magnetic fields

Jeans Criterion

$$M_J \simeq \left(\frac{5kT}{G\mu m_H}\right)^{3/2} \left(\frac{3}{4\pi\rho_0}\right)^{1/2}$$

- Diffuse HI cloud: $T \sim 100$ K, $\mu = 1$, $n_{HI} \sim 1$ cm^{-3}, $\varrho \sim n_{HI} m_H$
  $M_J \sim 10^4$ $M_\odot$ →higher than typical mass of diffuse HI clouds (stable against gravitational collapse)

- Giant Molecular Cloud (GMC): $T \sim 10$ K, $\mu = 2$, $n_{H2} \sim 10^4$ cm^{-3}, $\varrho \sim 2n_{H2} m_H$
  $M_J \sim 8$ $M_\odot$ →lower than typical mass of GMCs (unstable to gravitational collapse)

Star Formation Rate (SFR)

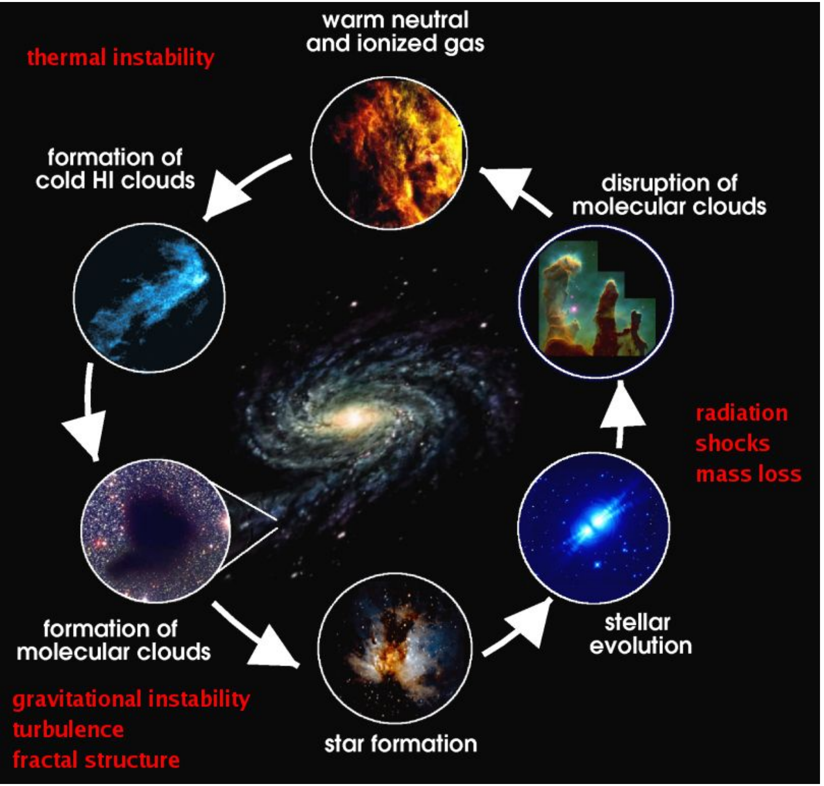
1. **Nebular emission lines** (e.g., Hα, [OII]): traces ionizing radiation from massive stars; probes SFR on shorter timescales ~4 – 10 Myr

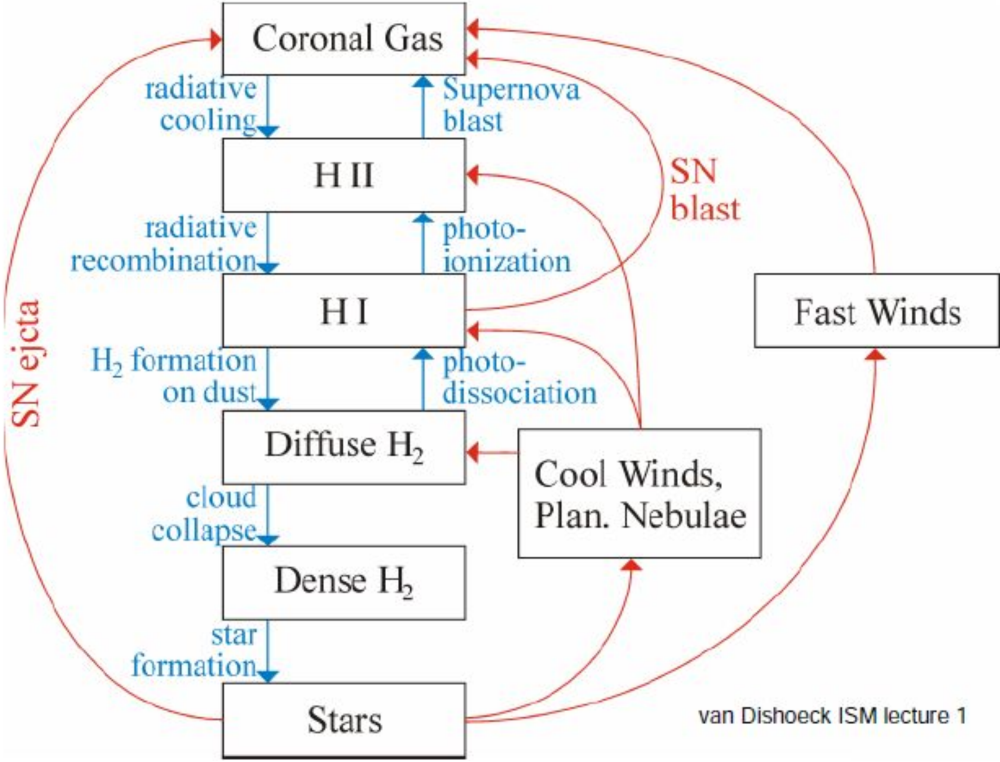
2. **UV continuum** (~1500 − 2800 Å): traces emission from short-lived massive stars M > ~5 $M_\odot$; probes SFR on intermediate timescale ~30 − 70 Myr

3. **FIR continuum** (~8 – 1000 μm): traces stellar radiation re-emitted by dust; probes SFR on longer timescales ~100 Myr

4. **Radio continuum** (e.g., 1.4 GHz): traces synchrotron emission from supernova remnants; probes SFR on longer timescales ~200 − 300 Myr

ISM: Cycle of Gas and Stars





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