Interstellar Medium

Dr. Laurence Sabin

46th International School for Young Astronomers ISYA 2025 - Ecuador

Quick Presentation

JWST

HST

- PhD in Astronomy and Astrophysics (Jodrell Bank Center for Astrophysics, University of Manchester, UK).
- Associate Professor at the Institute of Astronomy of Universidad Nacional Autónoma de México, sede Ensenada, México.
- Field of study: Evolved Intermediate mass stars (Detection, analysis and Magnetism).

Before starting

- ➢ **The ISM in 7.5h !**
- ➢ **Conceptual course … very few equations !**
- ➢ **Help from AI Tools : Perplexity !**

perplexity

Bibliography

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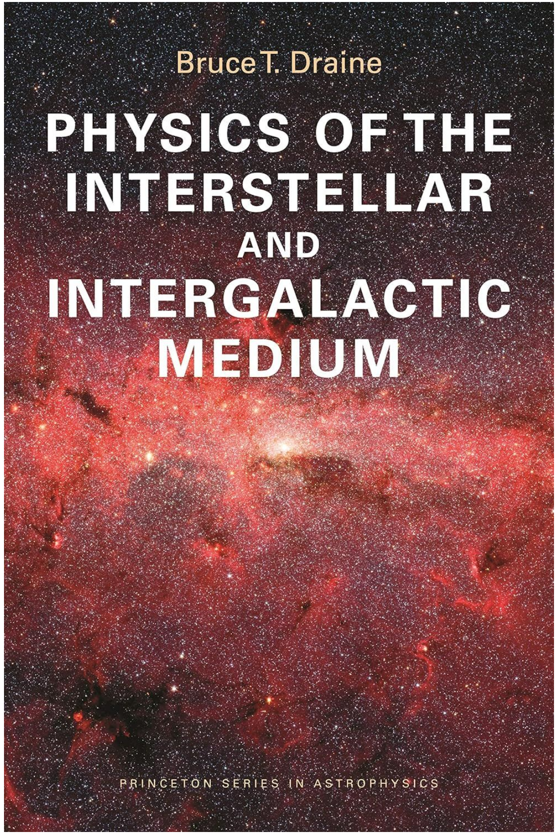
Overview

1. Components of the ISM
2. Dust
3. Heating & Cooling processes
4. Observational diagnostics
5. Dynamics



1- Components of the ISM

Physical Conditions, Gas Phases, Dust, Magnetic Fields, and Cosmic Rays

The Trifid Nebula and the Lagoon Nebula © HANDOUT / NSF-DOE Vera C. Rubin Observatory/AFP (23/06/25)

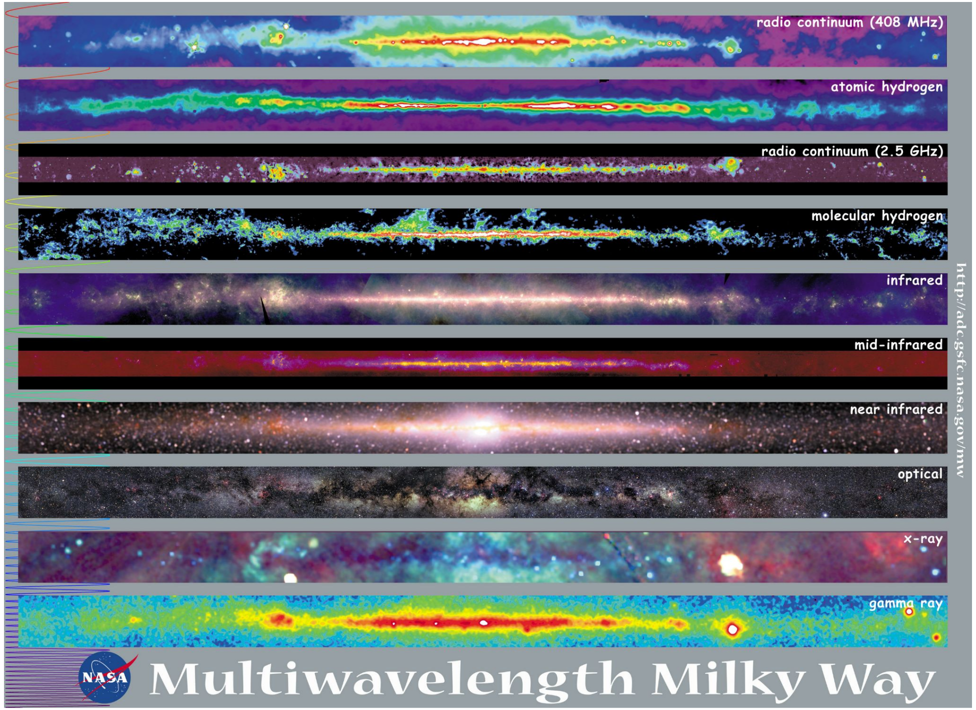
What is the ISM ?

NASA/JWST

What is the ISM ?

- The ISM is the matter that exists in the space between stars within a galaxy.
- Composed primarily of hydrogen and helium, along with heavier elements, dust, cosmic rays, and magnetic fields.
- Serves as the raw material for star formation and plays a crucial role in the life cycle of galaxies.
- Mass of ISM in Milky Way ~10^9 $M_\odot$; occupies ~15% of volume within the Galactic disk.

ISM Overview Diagram



NASA/JWST

https://asd.gsfc.nasa.gov/archive/mwmw/mmw_images.html

Observing the ISM

- Electromagnetic spectrum overview: radio to X-ray.

- Techniques: spectroscopy (emission/absorption lines), imaging, polarimetry.

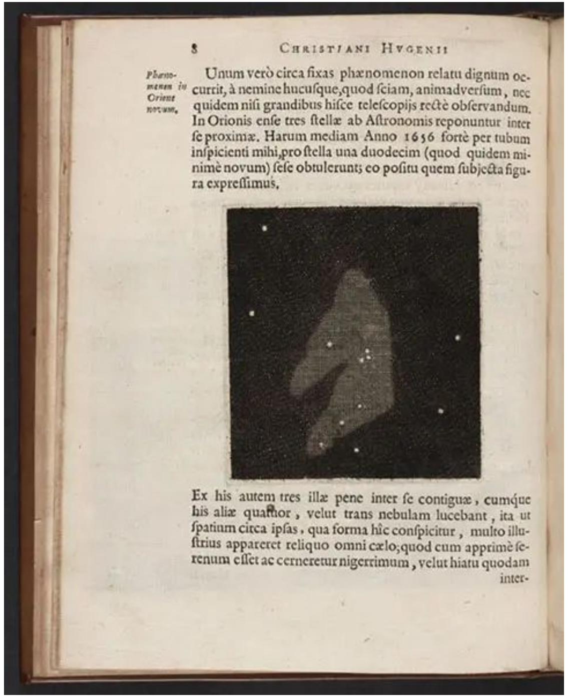
- Instruments: VLA, ALMA, HST, Herschel, Chandra, Fermi.

- Highlight wavelength-phase correspondence: 21 cm (HI), CO (mm), Hα (optical), X-rays (HIM).

eROSITA: Screenshot taken from Roscosmos Space Corporation's Twitter

ESO/ALMA

From the 17th century to now...



8 CHRISTIANI HVGENII

Phænomenon in Oriente novum.

Unum verò circa fixas phænomenon relatu dignum occurrit, à nemine hucusque, quod sciam, animadversum, nec quidem nisi grandibus hisce telescopijs rectè observandum. In Orionis ense tres stellæ ab Astronomis reponuntur inter se proximæ. Harum mediam Anno 1656 fortè per tubum inspicienti mihi, pro stella una duodecim (quod quidem minimè novum) sese obtulerunt; eo positu quem subjecta figura expressimus.

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Christiaan Huygens, *Systema saturnium*, 1659

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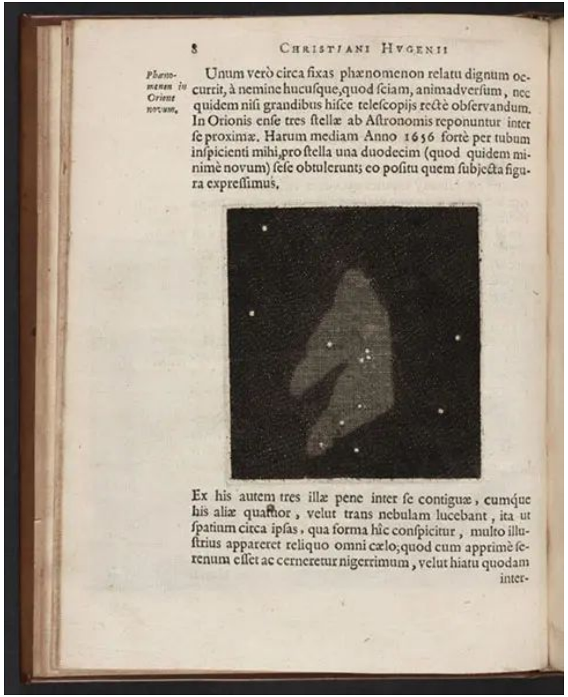

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Christiaan Huygens, *Systema saturnium*, 1659

HST/NASA

Phases of the ISM

Hot Ionized Medium - Coronal (HIM)

- Temperature: $>10^6$ K; Density: $\sim10^{-3}$ cm^{-3}

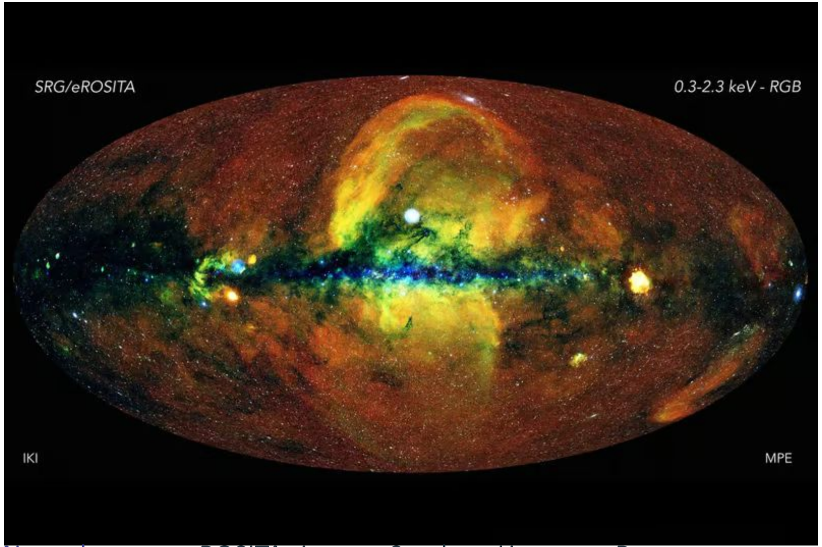
- Originates from supernova explosions and stellar winds.

- Structure: fills cavities and forms superbubbles and chimneys.

- Observations: soft X-ray emission, thermal bremsstrahlung, high-ionization lines (e.g., O VII, O VIII).

- Volume filling factor: ~50%

- Tracers: Chandra, XMM-Newton, ROSAT. - Example: Local Bubble (~200 pc, density ~0.005 cm^{-3}).



Newatlas.com. eROSITA: Jeremy Sanders, Hermann Brunner, Andrea Merloni and the eSASS team (MPE); Eugene Churazov, Marat Gilfanov (on behalf of IKI)

Warm Ionized Medium (WIM)

- Temperature: ~8000 K; Density: ~0.1 cm^{-3}

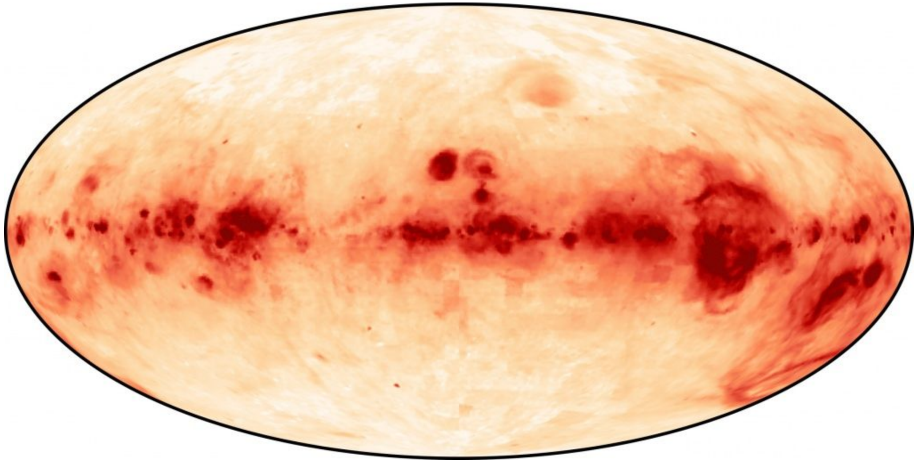
- Ionized by UV photons from O and B stars.

- Extended above the Galactic plane (scale height ~1 kpc).

- Observations: Hα emission (e.g., WHAM), radio continuum, free-free emission.

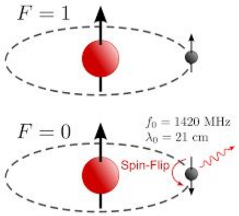
- Contributes significantly to ISM ionization and dispersion measures.

- Often associated with diffuse HII regions.



A survey image of ionized hydrogen gas in the Milky Way.. WHAM Collaboration, UW–Madison, Space Science Institute & National Science Foundation

Warm Neutral Medium (WNM)



- Temperature: ~6000–10000 K; Density: ~0.2–0.5 cm^{-3}

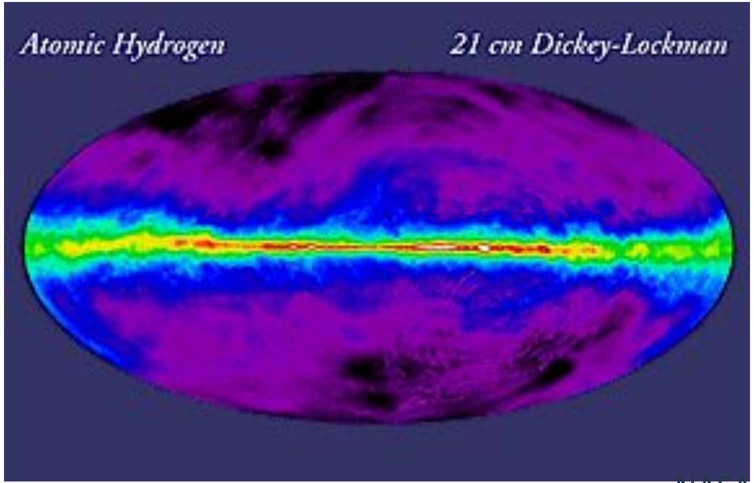
- Composed mainly of neutral hydrogen.

- Observed through 21 cm emission line (hyperfine HI transition).

- Moderately turbulent; line widths ~10 km/s.

- Coexists with CNM in pressure equilibrium.

- Found in interarm regions and outer Galactic disk.



NASA

[Animation]

Cold Neutral Medium

- Temperature: ~50–100 K; Density: ~30–100 cm^{-3}

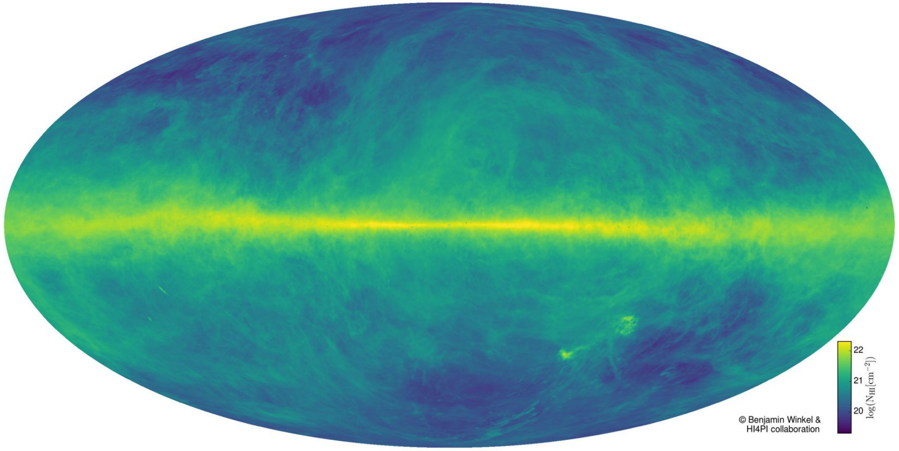
- Denser, cooler atomic hydrogen phase.

- Traced by HI absorption.

- Narrow line widths ~1–2 km/s indicate low temperatures.

- Often found as sheets or filaments, precursors to molecular clouds.

- Associated with regions of molecule formation.



HI4PI: A full-sky H I survey

Molecular Gas

- Temperature: ~10–30 K; Density: $>10^3$ cm^{-3}

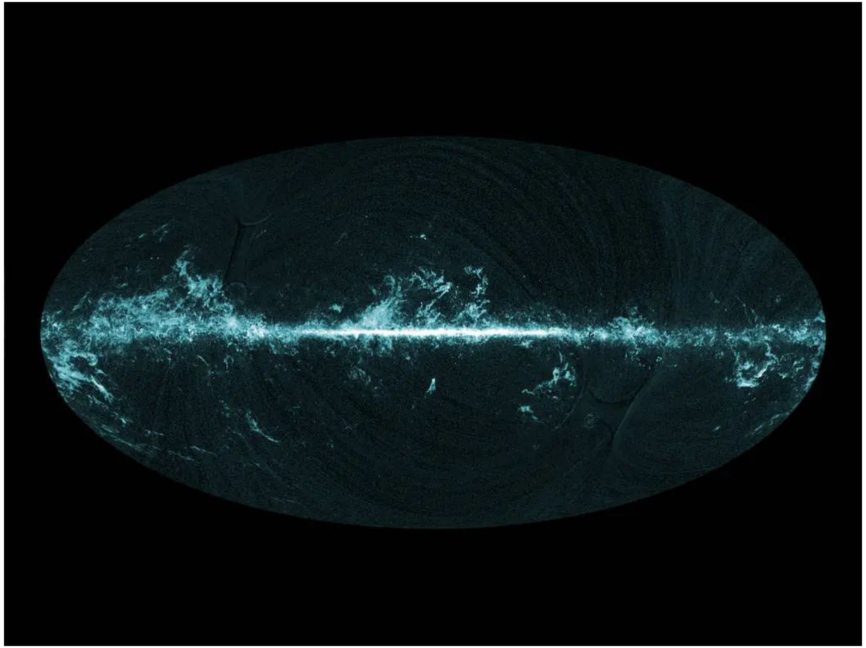
- Dominated by H_2 (not directly observable in cold conditions).

- Traced using molecules like CO, HCN, HCO^+.

- Dense, cold regions where star formation occurs.

- Observed with millimeter and sub-mm telescopes (e.g., ALMA, IRAM).

- Shielded from UV radiation; high Av (>1 mag).



This all-sky image shows the distribution of carbon monoxide (CO) seen by NASA/Planck.

Phase Comparison Table

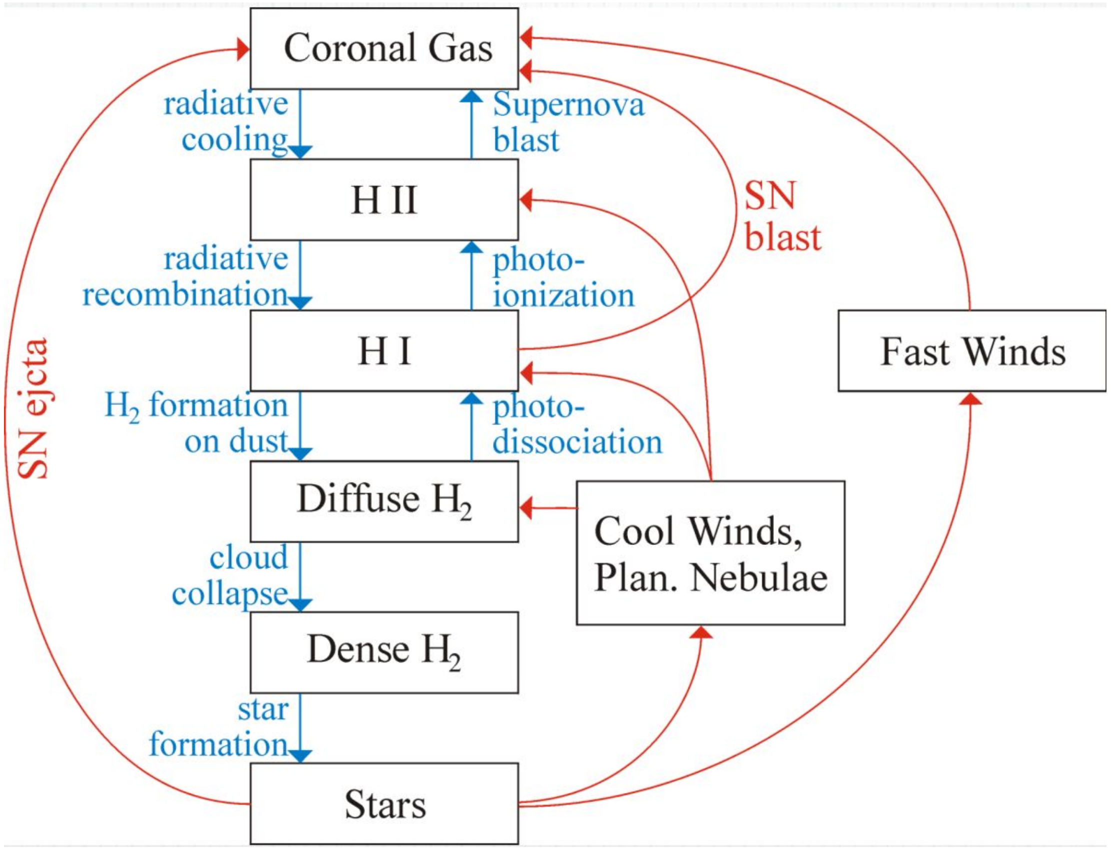
Component	Fractional volume	Scale height (pc)	Temperature (K)	Density (particles/cm^3)	State of hydrogen	Primary observational techniques
Molecular clouds	< 1%	80	10–20	10^2–10^6	molecular	Radio and infrared molecular emission and absorption lines
Cold neutral medium (CNM)	1–5%	100–300	50–100	20–50	neutral atomic	H I 21 cm line absorption
Warm neutral medium (WNM)	10–20%	300–400	6000–10000	0.2–0.5	neutral atomic	H I 21 cm line emission
Warm ionized medium (WIM)	20–50%	1000	8000	0.2–0.5	ionized	Hα emission and pulsar dispersion
H II regions	< 1%	70	8000	10^2–10^4	ionized	Hα emission, pulsar dispersion, and radio recombination lines
Coronal gas Hot ionized medium (HIM)	30–70%	1000–3000	10^6–10^7	10^{-4}–10^{-2}	ionized (metals also highly ionized)	X-ray emission; absorption lines of highly ionized metals, primarily in the ultraviolet

Adapted from Ferriere 2001, wikipedia

ISM Cycle

The phases are not isolated !

Conservation & Transformation



Credit: Paul van der Werf

Objects of the ISM

HII Regions: Ionized Gas around Massive Stars

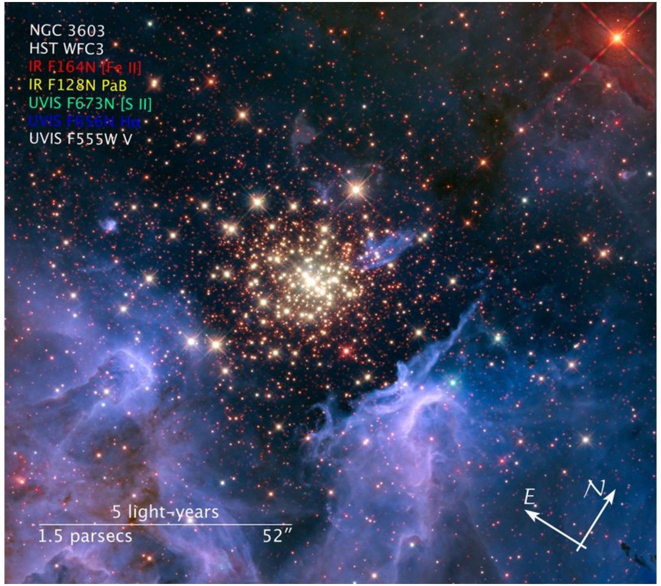
Definition: Regions of ionized hydrogen (H^+) formed around hot, young O and B stars.

Ionization Source: Lyman continuum photons ($E > 13.6$ eV) from massive stars.

Physical Conditions: Temperature: ~7,000 – 10,000 K, Electron density: $10 - 10^4$ cm^{-3}

Diagnostics: Optical/IR spectroscopy, Radio free-free emission, Line ratios → temperature, density

Examples: Orion Nebula (M42), NGC 3603



Strömgren sphere

Concept

- A Strömgren sphere is a theoretical region of **ionized hydrogen (H II)** surrounding a hot O/B-type star, formed by the star's intense UV radiation ionizing neutral hydrogen (H I) in the ISM.
- Proposed by Bengt Strömgren (1937) to model the sharp transition between ionized and neutral gas around massive stars
- Transition from H II (interior) to H I (exterior) occurs over a narrow layer (≪RS≪RS), creating a well-defined boundary

Ionization Mechanism:

UV photons (E>13.6 eV) from the central star eject electrons from H I atoms, creating H II plasma .

Recombination Limit:

Recombination emits lower-energy photons incapable of further ionization, confining the ionized region

Equilibrium Condition:

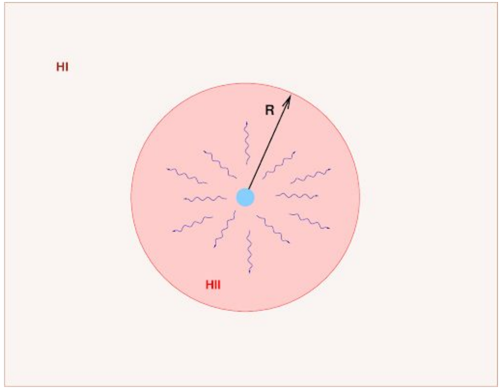
Ionization rate balances recombination rate:

Ionizing photons=$(4\pi/3)R_S^3\ n_e\ n_p\ \alpha_B$, where α_B is the Case B recombination coefficient

Strömgren Radius (R□)

$$R_S = \left(\frac{3}{4\pi} \frac{Q}{n_H^2 \alpha_B} \right)^{1/3}$$

- Q: Ionizing photon luminosity (s^{-1}) of the star.
- n_H: Hydrogen number density (cm^{-3}).
- α_B: Temperature-dependent recombination coefficient



http://spiff.rit.edu/richmond/asras/stromgren/stromgren.html

Rosette Nebula, HST/NASA

Nowadays models include: Radiation-hydrodynamic simulations incorporate turbulence, metallicity, and multiple stars

Reflection Nebulae: Scattering of Starlight by Dust

Definition: Nebulae where dust grains scatter the light of nearby stars, rather than emit or absorb strongly.

Illumination Source: Typically early-type (B-type) stars not hot enough to ionize gas.

Spectral Signature: Starlight scattered by dust grains, Blue appearance due to Rayleigh-like scattering (λ^{-4} dependence)

Physical Conditions: Low temperatures (~20 K for dust), No significant ionization

Diagnostics: Imaging polarimetry → dust grain alignment, Spectral energy distribution (SED)

Examples: Pleiades reflection nebula

NASA/HST

Dark Clouds: Cold, Dense Molecular Gas and Dust

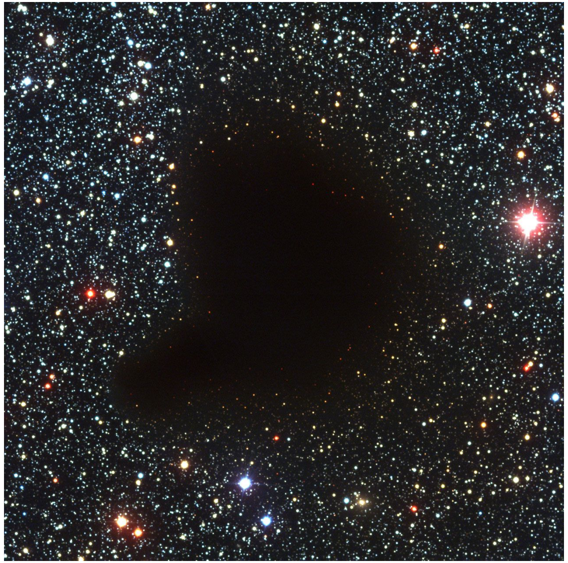
Definition: Dense interstellar clouds opaque to optical light, seen in silhouette against background starlight.

Physical Conditions:Temperature: 10–20 K, Density: $10^3 - 10^6$ cm^{-3}, High extinction: Av > 1–10 mag

Tracers:H_2 , CO, NH_3, CS, dust grains .

Diagnostics: Millimeter/sub-mm molecular line emission (e.g., CO), FIR/sub-mm dust continuum, Extinction mapping using background stars

Examples: Barnard 68, Taurus Molecular Cloud



ESO

Supernova Remnants

Origin: Explosions of massive stars (core-collapse) or white dwarfs (Type Ia)

Evolution: Free expansion → Sedov-Taylor phase → radiative cooling shell

Physical Conditions: Shock-heated gas ($T > 10^6$ K),Densities ~0.1–10 cm^{-3}, Non-thermal synchrotron radio/X-ray emission

Diagnostics: X-ray emission (thermal + synchrotron), Optical: [S II]/Hα diagnostic of shock heating, Radio: synchrotron continuum

Examples: Tycho, Cassiopeia A

NASA/Chandra

Planetary Nebulae

Origin: Ejected envelopes of low/intermediate-mass stars during post-AGB evolution.

Structure: Expanding ionized shell, Often bipolar/multipolar morphologies.

Physical Conditions: Temperature: ~10^4 K, Density: $10^3 – 10^4$ cm^{-3}.

Radiation: Strong recombination and forbidden lines (e.g., [O III], [N II]), UV from central white dwarf.

Diagnostics: Optical/UV/IR spectroscopy, Morphology from optical,IR and radio imaging

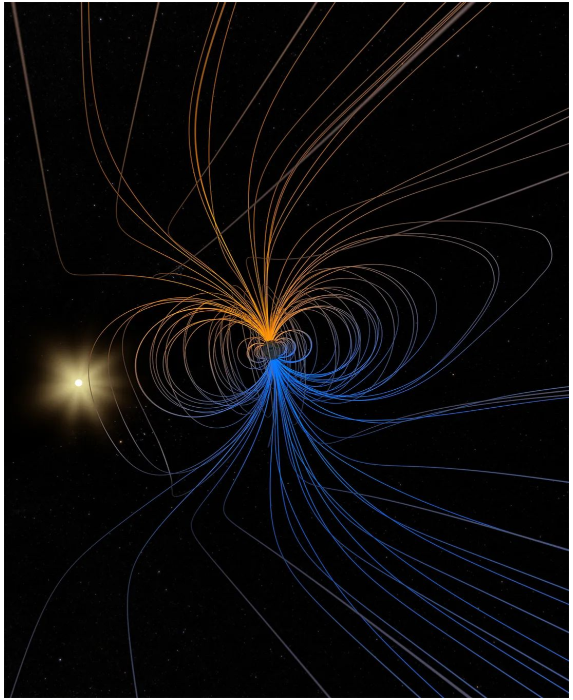
Examples:NGC 6543 (Cat's Eye), NGC 7027

NASA’s Chandra X-ray Observatory (blue) and Hubble Space Telescope (red and purple)

Energy sources of the ISM

Magnetic Fields

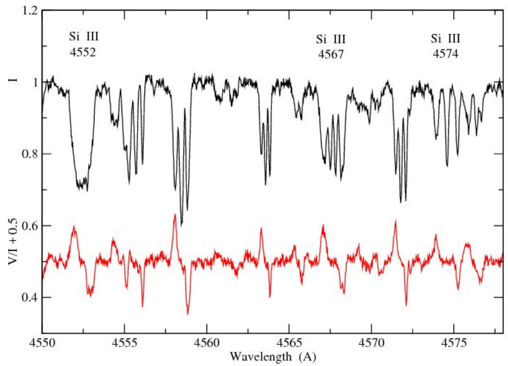
- Magnetic field strength ~few μG.
- Provide support against gravitational collapse or help ?
- Guide cosmic rays (complex) and affect shock propagation.
- Contribute to anisotropic pressure and ISM turbulence.
- Magnetic pressure: $P_B = B^2/8\pi$; often comparable to gas pressure.
- To date, it remains a non-trivial problem for observational studies !



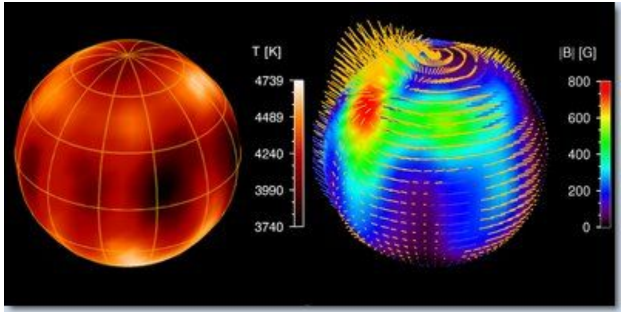
NASA

a) Zeeman splitting

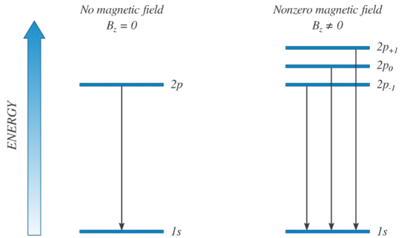
- Observes line-of-sight component of magnetic field.
- Applied to HI (21 cm), OH, and CN lines in dense clouds and atomic lines
- Yields direct B-field strengths
- Limited to regions with strong lines and narrow linewidths.



Landstreet, John. (2015). Basics of spectropolarimetry. Proceedings of the International Astronomical Union. 9. 311-320..



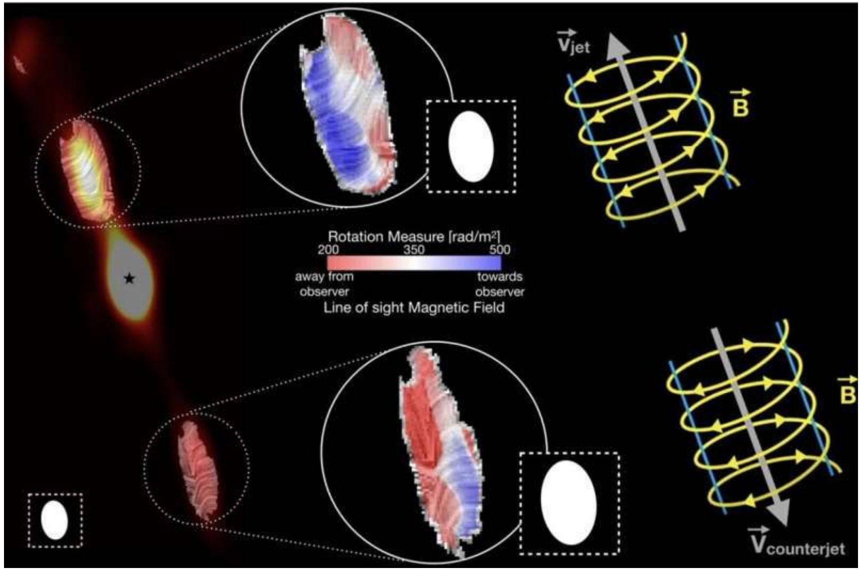
Zeeman-Doppler imaging tracing the surface magnetic field of II Pegasi. Carroll et al. 2007



https://chem.libretexts.org

b) Faraday Rotation

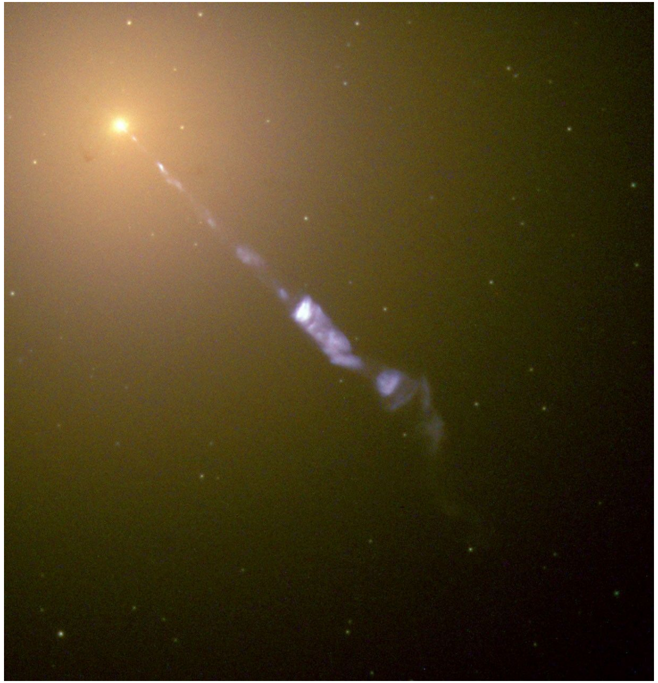
- Faraday showed in 1845 that a magnetic field can rotate the polarization of an electromagnetic wave.
- Measures rotation of plane of polarization as function of λ^2.
- Sensitive to $B_{||} \times n_{e^-}$ along line of sight.
- Used with pulsars, extragalactic radio sources, AGN…
- Provides info on magnetic field structure and strength in ionized gas.



VLA allowed astronomers to perform an unprecedentedly detailed Rotation Measure (RM) analysis of the HH 80-81 protostar jet. The RM analysis allows researchers to correct for Faraday rotation—the rotation of the polarization of light as it passes through a magnetized plasma—revealing the true orientation of the magnetic field. A. Rodríguez-Kamenetzky et al. (2025)

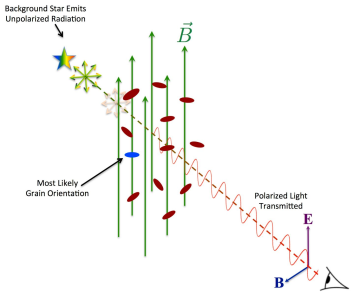
c) Synchrotron Emission

- Non-thermal radio emission from relativistic electrons spiraling in B-fields.
- Degree and angle of polarization constrain B-field direction.
- Synchrotron spectral index : negative
- Radio: LOFAR, VLA, ALMA.



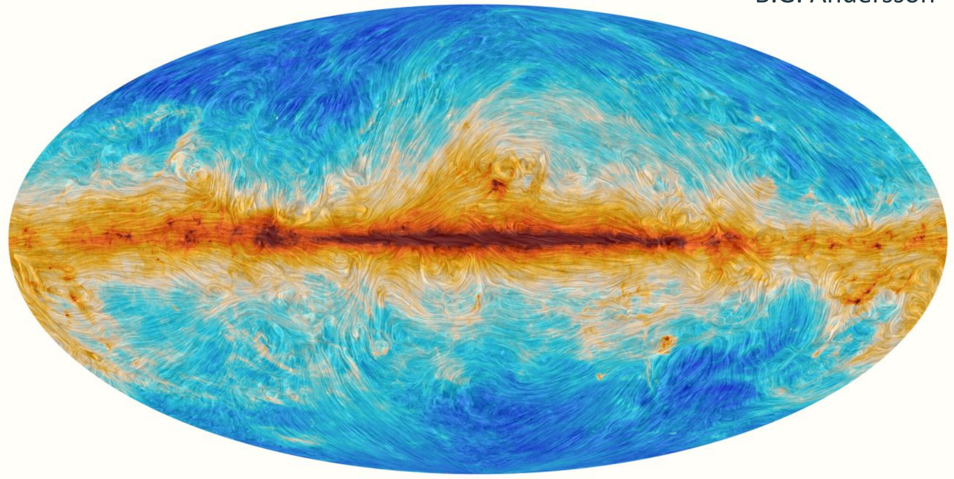
Black Hole-powered synchrotron jet launched from the center of the Galaxy M87. HST/NASA.Violet: F300W (U)Blue: F450W (B)Green: F606W (V)Red: F814W (I)

d) Dust polarization



B.G. Andersson

- Elongated dust grains align with magnetic fields (Davis-Greenstein mechanism, RAT (see Lazarian)).
- FIR/submm emission from grains is polarized perpendicular to B-field.
- Observed with Planck,ALMA.
- Traces plane-of-sky magnetic field orientation.



Bfield by Planck/NASA

Cosmic rays

Properties:

- High-energy charged particles (mostly protons, some electrons and nuclei).

- Energy range: MeV to $>10^{20}$ eV.

- Likely originate from supernova remnants (acceleration by shocks: Fermi mechanism). AGN?

- Interact with ISM via ionization, heating, and chemical reactions.

- Contribute significantly to pressure budget in ISM (comparable to magnetic pressure).

Observations:

- Direct detection: balloon and satellite experiments (e.g. Voyager).
- Indirect detection:

- Synchrotron radiation from relativistic electrons (radio continuum).

- Gamma-ray emission from pion decay (Fermi-LAT).

- Ionization rates inferred from molecular abundances (e.g., H_3^+).

Cosmic Rays

Effects on the ISM:

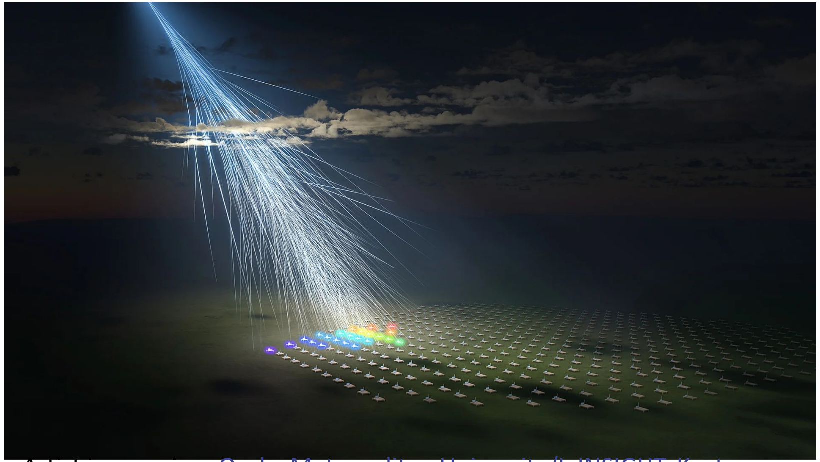
- Ionization of molecular clouds ⟶ initiates chemistry (e.g.,formation of H_3^+, CO).

- Heating of gas: especially important in dense, UV-shielded regions.

- Drive outflows/ winds in galactic environments.

- Alter charge balance, affect coupling of gas and magnetic fields.

- Affect thermal balance and star formation rates.



Artist impression, Osaka Metropolitan University/L-INSIGHT, Kyoto University/Ryuunosuke Takeshige

Sources of Energy in the ISM

Thermal energy from particle motions,

Hydrodynamic (kinetic) energy from bulk gas flows and turbulence,

Magnetic energy stored in large-scale and turbulent magnetic fields,

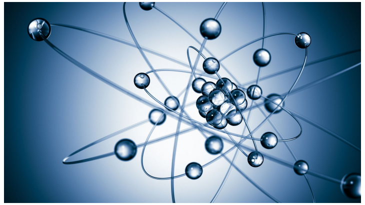
Starlight energy from the integrated radiation of stars that heats and ionizes gas and dust,

Cosmic ray energy from high-energy charged particles that permeate the Galaxy and contribute to ionization and heating, and

Cosmic microwave background energy as a relic, uniform radiation field from the early Universe that provides a low-temperature photon bath throughout space.

So, What about those Forbidden Lines ?

ISM Physical conditions



In the case of **thermodynamic equilibrium** at temperature T, the Maxwell, Boltzmann, and Planck distributions are valid.

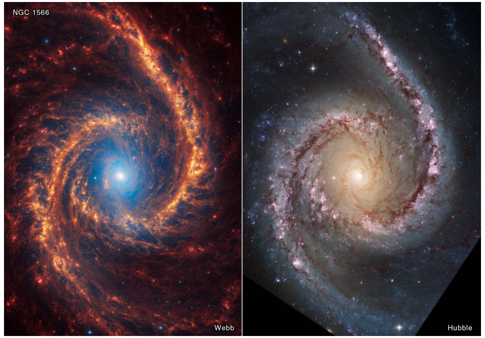
Thermal equilibrium: each process occurs as often as the inverse process

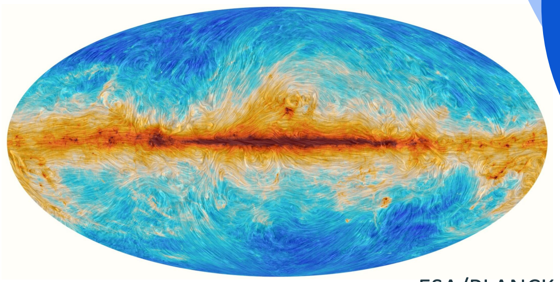
- **Global thermal equilibrium in the ISM: NO**

≠Phases with ≠physical conditions -> Coexistences via heating & Cooling processes -> Because the energy exchange between ISM phases occurs slowly (not efficient on short timescale), a uniform temperature cannot be maintained across them.

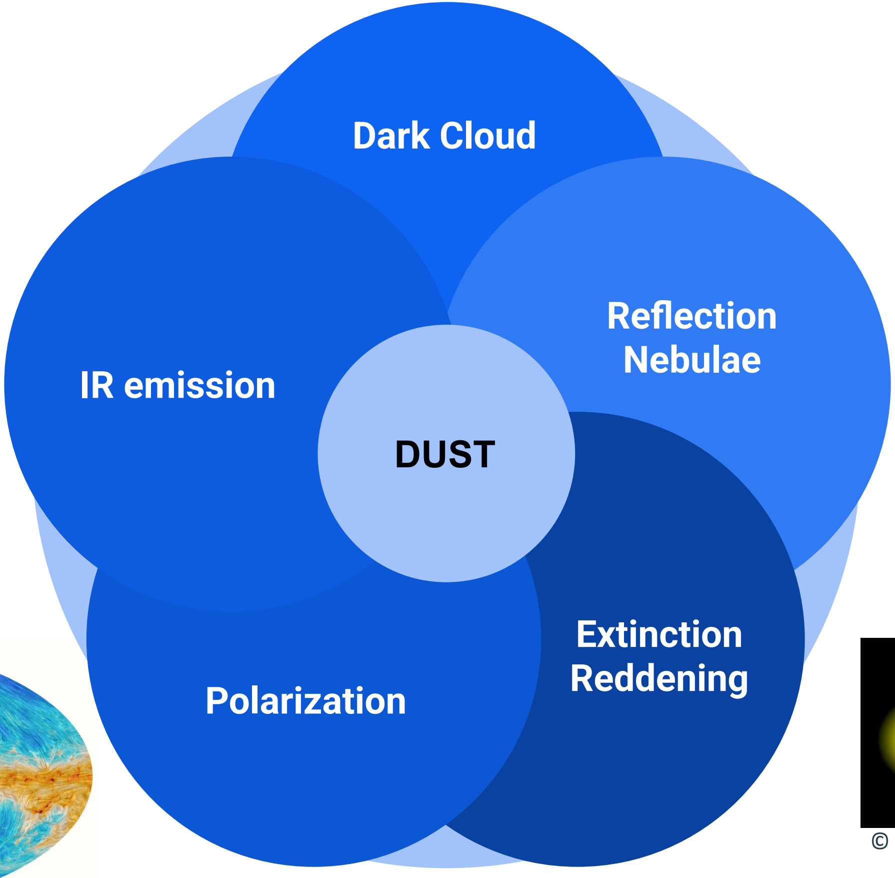
- **Local Thermal Equilibrium (LTE) in the ISM: Possible (Dense regions)**

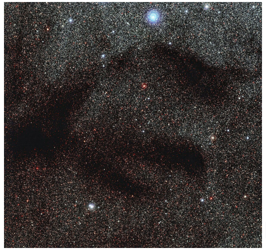
2- Dust





ESA/PLANCK





HST

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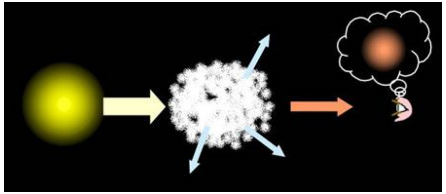
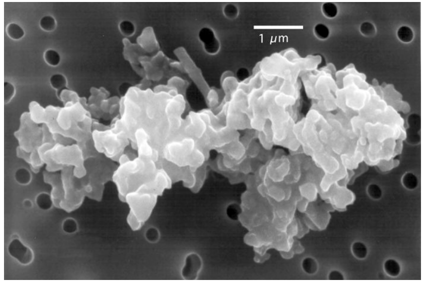


Composition

- Amorphous **silicate** grains (Mg, Si, O-dominated) ⟶ responsible for 9.7 μm and 18 μm IR absorption features .
- **Carbonaceous** material: graphite grains, polycyclic aromatic hydrocarbons (PAHs; 15–20% of interstellar carbon), and aliphatic hydrocarbons
- 90% of Mg, Si, Ca, Al locked in dust; ~40–50% of interstellar carbon in solid phase: **Depletion**
- Mass fraction: **~1% of ISM mass**, **but essential in ISM physics.**

Material	Spectral Signatures	Abundance
Amorphous Silicates	9.7 μm, 18 μm absorption	~70% Si
Graphite	2175 Å UV bump	~30% C
PAHs	3.3–11.3 μm emission bands	15–20% C
Dirty Ices	IR absorption (3.1 μm H_2O, etc.)	Mantles



Wikipedia

Additional Components:

- **Ices** (H_2O, CO, CO_2) in dense, cold regions
- **Metal compounds** (Fe, FeS, etc.) possibly included in core-mantle models

Observation

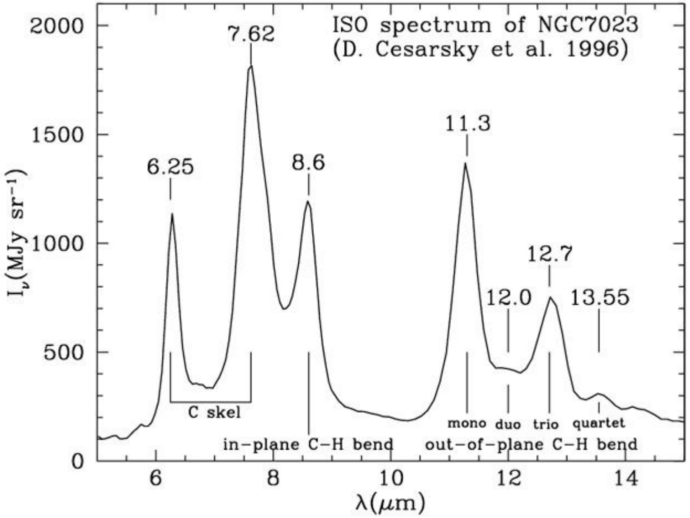
Extinction and scattering:

- Wavelength-dependent starlight attenuation
- Polarization: Reveals dust distribution via scattering and grain alignment via magnetic fields

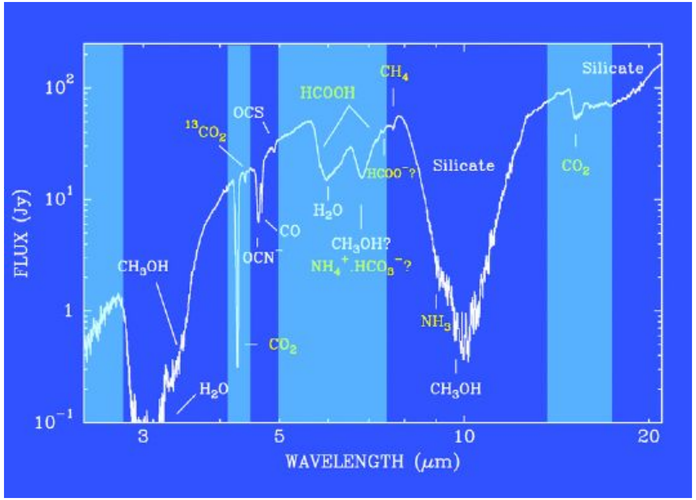
Infrared signatures:

- PAH emission bands (3.3, 6.2, 7.7, 8.6, 11.3 μm)
- Continuum emission from ~10–100 μm (thermal radiation from heated dust grains)
- Absorption features (e.g., 9.7 μm silicate band)

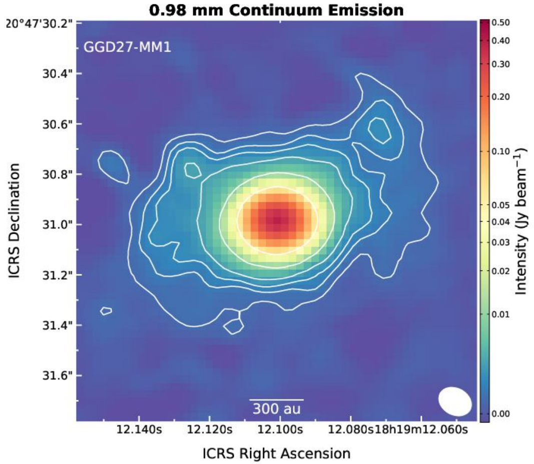
JWST/NASA



PAH (B.T. Draine)



ISO spectrum of a YSO (Credit: Gibb et al. 2000; van Dishoeck et al. 2003)



ALMA 0.98 mm dust continuum emission of the protostar GGD27-MM1 (Fernandez-Lopez et al. 2023)

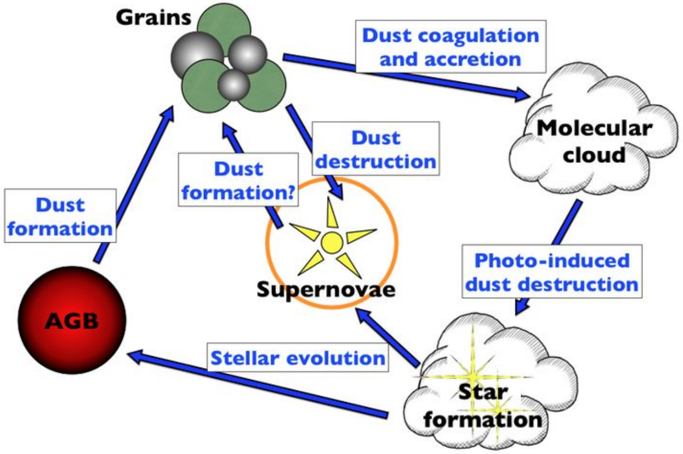
Formation and destruction

Origins:

- Stardust injection: Only ~5–10% of total dust mass (e.g., from AGB stars, supernovae)
- *In-situ* growth: ~90–95% forms in ISM via gas-phase accretion (e.g., silicate mantles on preexisting cores)

Destruction mechanisms:

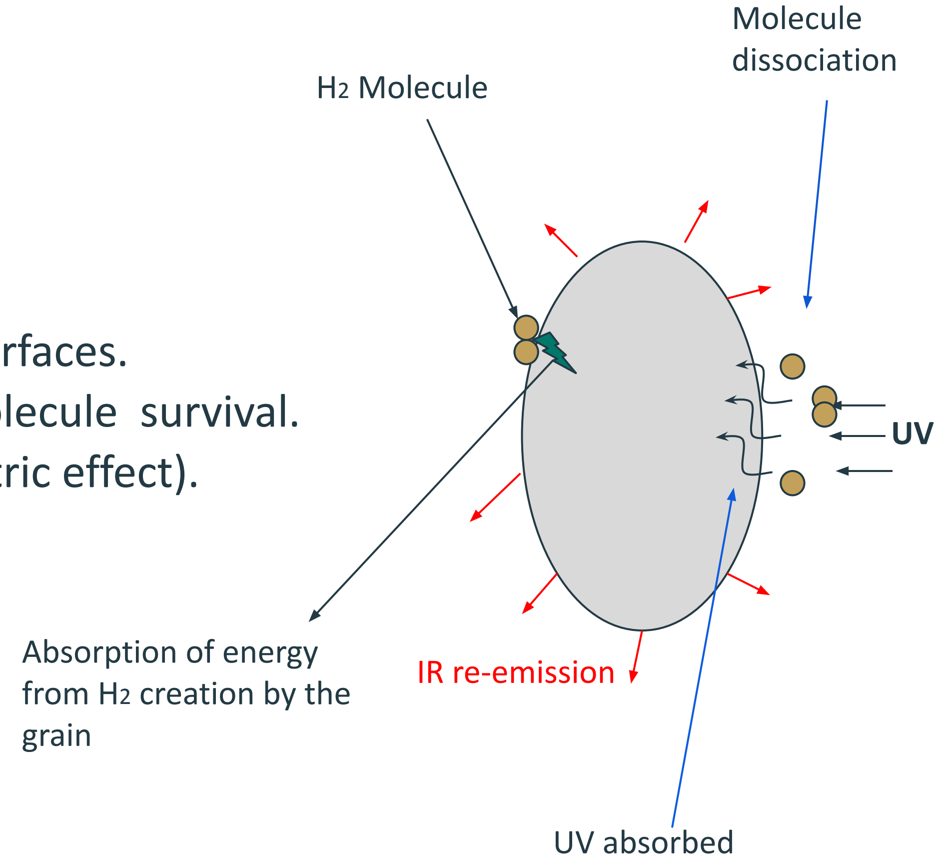
- Sputtering in supernova shocks (timescale ~4×10^{8} yr)
- Grain-grain collisions in turbulent flows



Credit: Marco Bocchio,PhD,2015

Importance

- Catalyze H_2 formation on grain surfaces.
- Shield UV radiation → enable molecule survival.
- Influence gas heating (photoelectric effect).
- Charge carriers in plasma.



Size

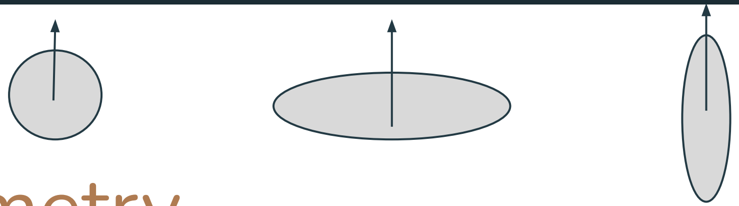
- Follows a power-law: $dn/da \propto a^{-3.5}$ for $a \lesssim 0.25$ µm, with a cutoff at larger sizes .(Mathis, Rumpl & Nordsieck 1977 – MRN model), valid for a~0.005–0.25 µm.
- Theoretical models: MRN size distribution, Draine & Li dust model (2001, 2007): reproduce IR SEDs with grain mixtures.

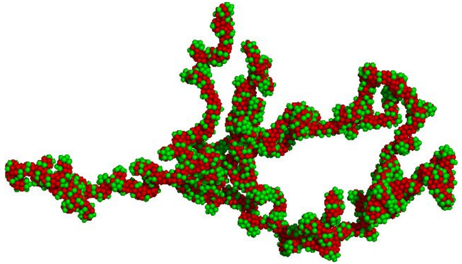
Very Small Grains:

- Grains with $a \lesssim 0.01$ µm
- Undergo **single-photon heating** → dominate **mid-IR emission**

Large Grains:

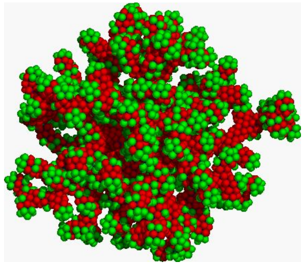
- Grains with $a \gtrsim 0.05/0.1$ µm
- Stay in **thermal equilibrium** → emit **in far-IR**





Geometry

Idealized Models: Spheres often used for simplicity, **but in reality…**



- Fractal, porous aggregates with "fluffy" structures
- Elongated/irregular shapes inferred from polarization measurements

Evidence for Non-Sphericity:

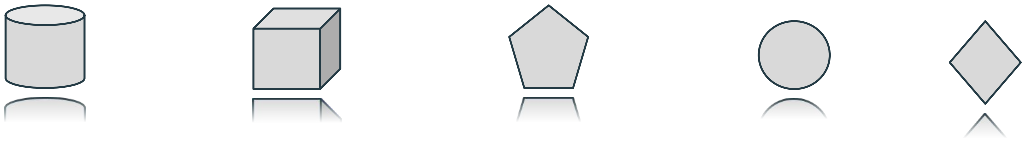
- **Interstellar polarization** implies non-spherical grains aligned with magnetic fields
- Elongated grains preferentially absorb and emit light along specific axes

Grain Shapes Considered in models (e.g. PyCloudy)

- Oblate or prolate spheroids
- Cylinders, ellipsoids, or fractal aggregates (e.g., coagulated grains)

Credits:
https://astro.ucla.edu/~wright/dust/

Geometry



Effects on Radiative Properties:

- Extinction cross sections depend on shape and orientation
- Polarized light from stars and dust emission arises from shape + alignment

Alignment Mechanisms:

- Radiative Alignment Torques (RATs) dominate for large grains
- Davis-Greenstein mechanism less effective for small grains

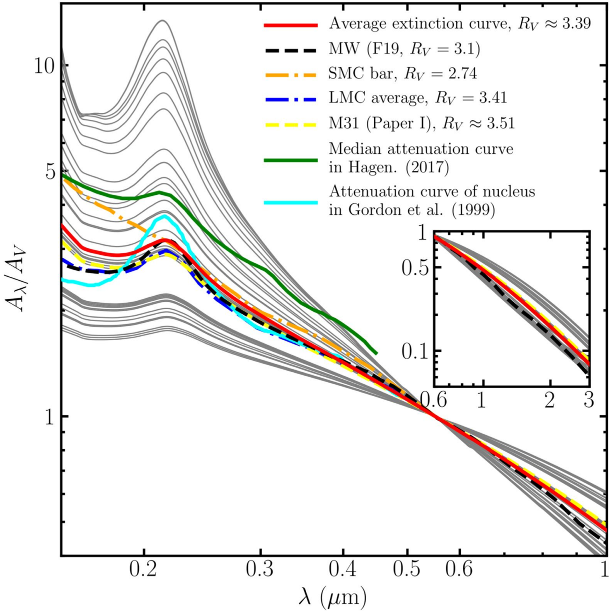
Surface complexity:

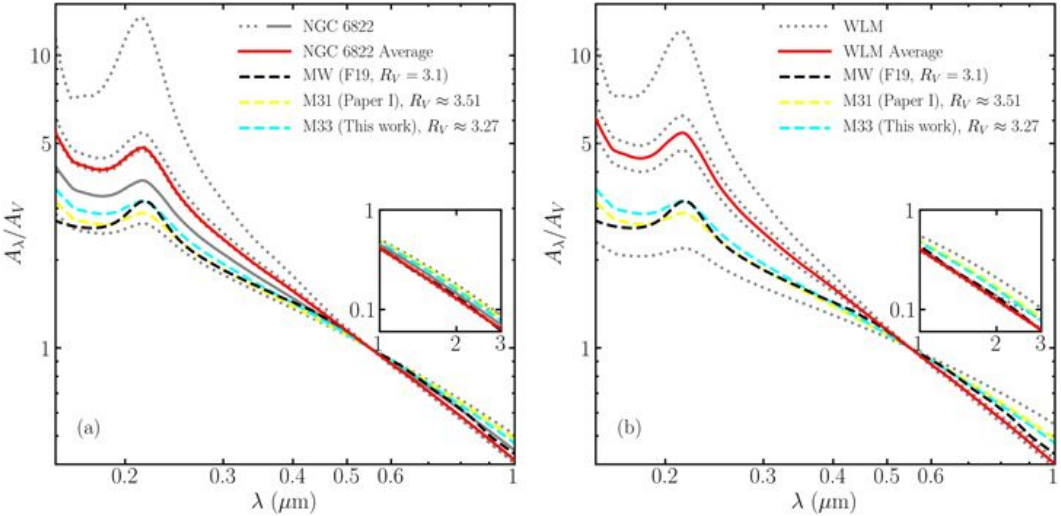
- Icy mantles (H_2O, CO, CH_4) coat cores in cold clouds
- Rough surfaces enhance catalytic reactions (e.g., H_2 formation)

Extinction

- Extinction: attenuation of starlight by dust due to scattering + absorption.
- Expressed as $A(\lambda)/A(V)$ or $E(B–V) = A(B) – A(V)$.
- Typical Galactic extinction curve: strong UV rise + 2175 Å bump + flattening in IR.
- Extinction law varies with environment:
  - $R_V = A(V)/E(B–V) = 3.1$ (diffuse ISM), higher in dense regions (e.g., $R_V \approx 5$).
  - Steeper curves (lower R_V) $\longrightarrow$ smaller grains.

- Diagnostics:
    - Broad-band photometry (UBVRIJHK), spectra (e.g., IUE, HST).
    - Compare observed stellar colors with expected (intrinsic) colors.
    - Polarized extinction traces aligned grains → magnetic fields.
- Interpretation:
    - Shape of the extinction curve reflects grain composition and size distribution.
    - 2175 Å bump likely due to carbonaceous grains (e.g., graphite or PAHs).
    - Far-UV rise due to small grains.
- Key references: Cardelli, Clayton & Mathis (1989); Fitzpatrick (1999); Draine (2003, 2011).

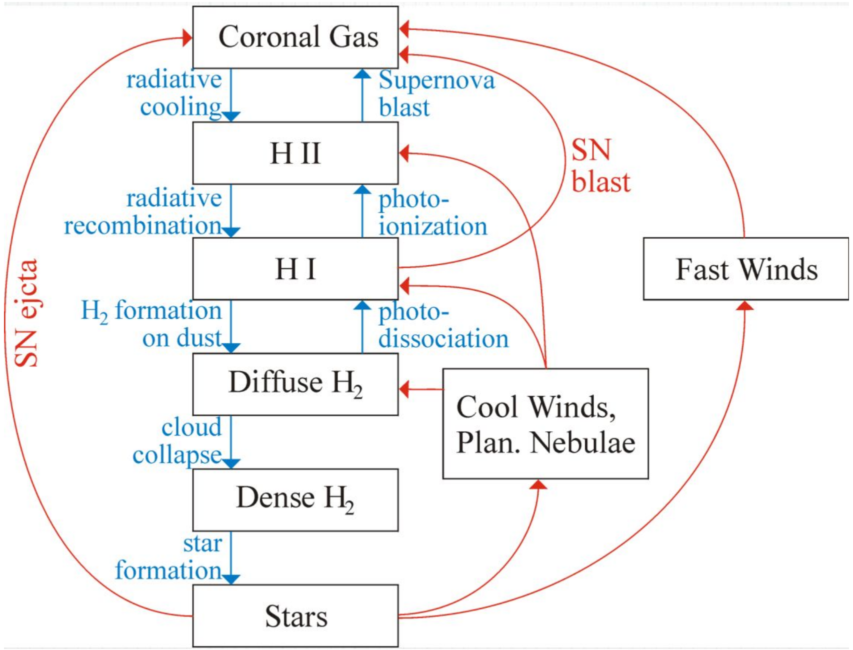




Extinction curves in different lines of sight (Yuxi Wang et al, 2022)

- New: Three-dimensional maps of the interstellar dust extinction curve within the Milky Way galaxy
  Xiangyu Zhang and Gregory M. Green (Science, 2025)

3- Heating and Cooling Processes



https://astro.uni-bonn.de/~uklein/teaching/ISM/HeatingandCooling2009.pdf

Credit: Paul van der Werf

Sources

- Stellar winds
- Shocks
- Ionizing photons

- Radiation (from X-rays to radio)

https://www-zeuthen.desy.de/~pohlmadq/teach/405-505-f05/sess13.pdf
https://www.astro.umd.edu/~richard/ASTRO620/LATTIMER_ISM_Lectures.pdf

Main Heating sources in the ISM

- **Photoelectric Effect on Dust Grains and PAHs** (dominant in diffuse neutral gas)
- **Photoionization Heating** (especially in H II regions)
- **Cosmic Ray Ionization** (dominant in dense, shielded gas)
- **X-ray and EUV Ionization** (in hot, ionized gas or near AGNs)
- **Grain-Gas Collisions & thermal exchange** (in very dense regions with warm dust)
- **Chemical Heating**
- **Hydrodynamic and magneto-hydrodynamic heating**
- **Interstellar shocks**

Photoelectric Heating

- **Process**: UV photons (6–13.6 eV) eject electrons from grain or PAH surfaces
- **Energy Transfer**: Ejected electrons heat surrounding gas through collisions
- **Heating rate**: $\Gamma pe \propto G_0\, nH\, \epsilon$

  Where: G_0: FUV field strength ; ϵ: heating efficiency (~1–5%, decreases with electron density)
- **Grains involved**: Small grains and PAHs dominate due to high surface area-to-volume ratio
- **Efficiency reduction**: Decreases with increasing electron density and grain charge
- **More:** Primary heating source in diffuse atomic/ionized regions (e.g., HI, HII)

Cosmic Rays Heating

- **Process**:

  Low-energy cosmic rays (~MeV) ionize/excite atoms, transferring energy via Coulomb interactions . Cosmic rays ionize H and H_2, generating fast electrons.
  Electrons thermalize, heating the gas (~10–20 eV per ionization).

  Region:

  Effective in shielded regions (e.g., molecular cloud cores) where UV is attenuated. Dominates in dense, UV-shielded clouds.

- **Rate**:
  $\Gamma_{CR} \approx 10^{-27}$ erg s^{-1} per H atom for standard galactic flux. (Heating rate depends on ionization rate ζ, typically ~10^{-17} s^{-1})

Photoionization & X-Ray/UV Heating

Photoionization Heating:

- Important in **H II regions,PNe…**
- Ionizing photons (E > 13.6 eV) impart excess energy to electrons

X-ray/EUV Heating:

- High-energy photons ionize deep shells → high-energy photoelectrons
- Important in hot plasma or near compact objects
- Leads to **extended warm gas regions**, esp. in galaxies and AGN environments

Grain-Gas thermal exchange

Conditions:

Dominates in dense molecular clouds ($n>10^3$ cm^{-3}) where dust-gas collisions frequent .
In **dense PDRs or protostellar disks**, warm dust can heat gas.
Efficiency depends on dust temperature and gas density.

Energy transfer:
$\Gamma = n_{gas} n_{dust} \sigma v\ \alpha\ k\ (Td - Tgas)$, with accommodation coefficient $\alpha \approx 0.35$

- σv: Geometric cross-section of a dust grain (cm^2), typically $\sigma gr = \pi a2$ for spherical grains of radius a. ; αT: Accommodation coefficient (dimensionless, ~0.35), representing fractional energy transfer per collision (Energy transfer efficiency).

Equilibrium:
Dust warmed by far-IR radiation maintains Td > Tgas in GMCs

Chemical Heating

Primary source:

Formation of molecular hydrogen (H_2) both on dust grain surfaces and in the gas phase releases energy that heats the surrounding gas .

Mechanism:

- When H atoms combine to form H_2, the binding energy (~4.5 eV per molecule) is partly converted into kinetic energy of the gas.
- On dust grains, the newly formed H_2 molecule can carry away some energy, but a significant fraction heats the gas via collisions.

Importance in dense regions:
Chemical heating is especially significant in dense molecular clouds where UV photons are attenuated and other heating mechanisms (e.g., photoelectric effect) are less effective.

Other chemical reactions:
Additional exothermic reactions involving ions and molecules (e.g., formation of CO, OH) also contribute to chemical heating but generally at lower rates compared to H_2 formation

M(HD) and shocks

Sources:

Supernovae, stellar winds,HII regions and gravitational collapse inject thermal energy via compression (modelling of the ISM)

$M = v/ v_s > 1$: supersonic = shock

Timescales:

Intermittent but powerful (e.g., SNR shocks heat gas to $T{\sim}10^6$ K)

Main Cooling sources in the ISM

Atomic and Molecular Line Emission cooling

Free-Free cooling

Recombination cooling

Dust Cooling

Line Cooling

Atomic Line Cooling *(dominant in diffuse gas)*

- Collisional excitation of atoms/ions → radiative de-excitation
- Key coolants:

  C^+ 158 µm (fine structure) – dominant in CNM and PDRs

  [O I] 63 µm, **[Si II]**, **[Fe II]** – dense neutral gas

  [O III], **[N II]**, **[S II]** – ionized gas cooling in H II regions

Fine structure line cooling

[C II] 158 µm and [O I] 63 µm dominate below 10^4 K at low densities ($n<3000\ cm^{-3}$)

Cooling rate per unit volume:

$\Lambda \propto$ ne nion q_{ul} (T) hν (q_{ul}=collisional de-excitation rate coefficient)

Line Cooling

Molecular Line Cooling *(dominant in dense, cold gas)*

- Excitation of **CO**, **H_2**, **H_2O**, **OH**, etc.
- CO rotational transitions (mm/sub-mm) efficiently cool (dense) molecular clouds ($n>10^4$ cm^{-3})
- **H_2** important in warm, low-metallicity gas

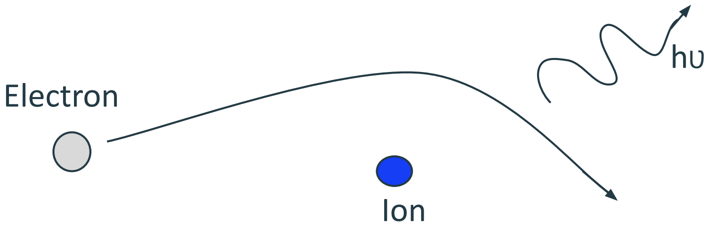
Cooling efficiency depends on:

- Collisional partners (e.g., H, H_2, e^-)
- Density and temperature
- Optical depth (can suppress cooling)

Free-Free (Bremsstrahlung) Cooling & Recombination Cooling

Emission from electrons deflected & accelerated by ions.

Dominant in **hot ionized gas (T > 10^6 K)**



Occurs when electrons recombine with ions, emitting photons

Strong in **photoionized regions** like H II regions

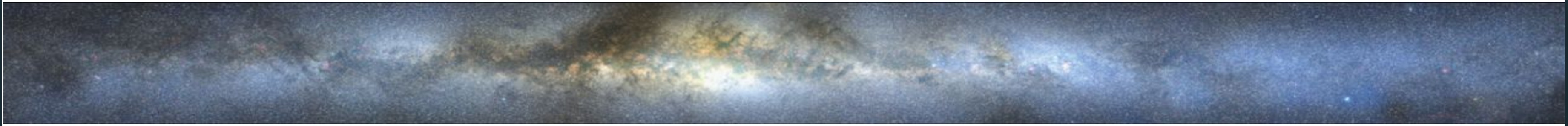
Dust Cooling

Gas-to-dust collisional cooling becomes important in **dense, cold gas.**

Infrared emission: Dust radiates absorbed starlight via thermal IR continuum (λ>10 μm) = Gas transfers energy to cooler dust grains, which then radiate in IR.

Cooling rate depends on temperature difference and grain abundance.

Balances photoelectric heating in diffuse ISM; dominates cooling in UV-shielded regions.



4- Observational Diagnostics

Hot Ionized Medium (HIM)

- **Temperature**: $\sim 10^{6}$ K
- **Density**: $\sim 10^{-3}$ cm^{-3}

Observational Diagnostics:

- **X-ray Emission**:
  - Thermal bremsstrahlung and line emission (e.g., O VII, Fe XVII)
  - Observatories: *Chandra*, *XMM-Newton,eROSITA*
- **UV Absorption Lines**:
  - O VI (1032, 1038 Å), C IV, N V
  - - Background source: QSOs, hot stars
- **Soft X-ray Background**: Diffuse glow from hot plasma
- **Optical and UV Forbidden Lines**

  Shock-excited lines (e.g., [S II], [O I]) trace cooling gas behind shocks.
- **Radio Synchrotron Emission:** Nonthermal emission from relativistic electrons accelerated in shocks.

Warm Ionized Medium (WIM)

- **Temperature**: ~8000 K
- **Density**: ~ 0.1 cm^{-3}

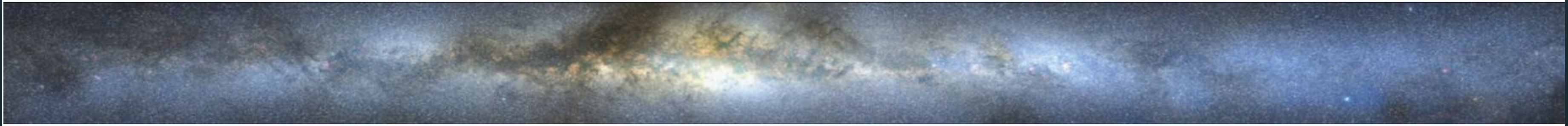
Observational Diagnostics:

- **Hα Emission**:
  - Recombination line at 6563 Å, Balmer
  - Surveys: WHAM, SHASSA, VTSS, EGAPS,LSST
- **Optical Forbidden Lines**:

  [N II], [S II], [O III] line ratios → diagnostics of T and n_e

  > Radio Free-Free Emission: Unaffected by dust extinction; measures ionized gas emission measure.

  > BPT Diagrams : Ratios of strong optical lines used to diagnose ionization mechanisms and physical conditions.



Warm Neutral Medium (WNM)

- **Temperature**: 6000–10,000 K
- **Density:** ~0.3 cm^-3

Observational Diagnostics:

- **H I 21 cm Emission:**
  - Traces distribution and kinematics
- **UV Absorption Lines:**
  - Si II, Fe II, C II
- **Weak Hα Emission:**
  - From partial ionization

Cold Neutral Medium (CNM)

- **Temperature**: 50–100 K
- **Density**: 20–50 cm^-3

Observational Diagnostics:

- **H I 21 cm Absorption**:
  - Against bright radio sources
- **UV Absorption Lines**:
  - Na I, Ca II (narrow features)
- **[C II] 158 µm Emission**:
  - Major coolant line

Molecular Clouds

- **Temperature**: 10–20 K
- **Density**: >10^3 cm^-3

Observational Diagnostics:

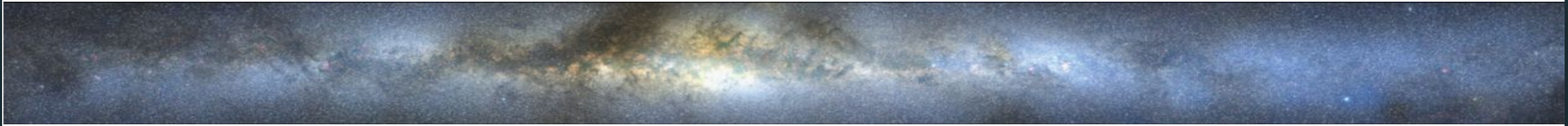
- **CO Rotational Emission**:
  - CO(1–0) at 115 GHz
  - Other molecules (NH_3, HCN, CS) probe density, temperature, and chemistry.
- **Dust Thermal Emission**:
  - Sub-mm/FIR continuum (Planck, Herschel) = Thermal emission from cold dust grains
- **IR Absorption Features**:
  - H2O, CO ices
- **Extinction Mapping**:
  - Near-IR color excess

Photodissociation Regions (PDRs)

> UV-illuminated neutral gas

Observational Diagnostics:

- **[C II] 158 µm, [O I] 63 µm Emission**:
  - Dominant cooling lines
- **PAH IR Emission Features**:
  - 3.3, 6.2, 7.7, 8.6, 11.3 µm
- **H2 Rotational Lines**:
  - Mid-IR transitions
- **Dust Emission**:
  - 20–100 µm continuum



Cosmic Rays, Magnetic Fields, and Dust

Cosmic Rays:

- γ-rays from π^0 decay (Fermi)
- Molecular ions (H3+, OH+) trace ionization

Magnetic Fields:

- **Faraday Rotation**: B-field along line-of-sight
- **Zeeman Splitting**: Field strength (21 cm, OH)
- **Dust Polarization**: Plane-of-sky field structure

Dust Grains:

- **IR Thermal Emission**:
  - SED ⟶ T_{dust} and N_H
  - PAH emission bands (3.3, 6.2, 7.7, 8.6, 11.3 µm) trace small carbonaceous grains.
- **Extinction and Reddening Curves**: Composition, size distribution
- **Polarization**: Indicates grain alignment with magnetic fields; probes grain shapes and magnetic field geometry.

Kinematics

Objective:

- Understand motions of gas (inflow, outflow, turbulence)
- Reveal structure of Galactic rotation, cloud dynamics, shocks, shell expansion, filament motions

Techniques:

- **Doppler Shifts in Emission Lines**:
  - H I 21 cm: Galactic rotation, spiral arms
  - CO lines: velocity fields in molecular clouds
  - Optical lines (e.g., Hα, [N II]): H II region kinematics
- **Line Profiles**:
  - Widths → thermal and turbulent broadening
  - Asymmetries → inflow, outflow, expansion

$$\frac{\Delta\lambda}{\lambda_0} = \frac{v}{c}$$

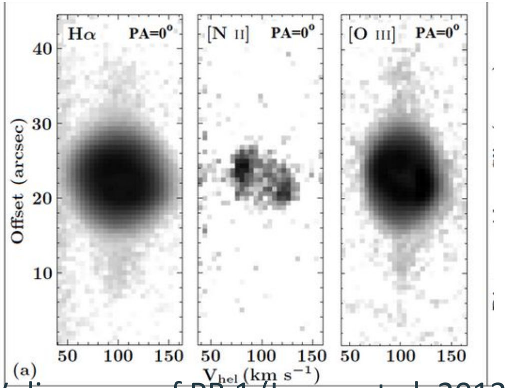
$$\Delta\lambda = \textit{wavelength shift}$$
$$\lambda_0 = \textit{wavelength of source not moving}$$
$$v = \textit{velocity of source} - \textit{line of site}$$
$$c = \textit{speed of light}$$

https://astronomyonline.org/Science/DopplerShift.asp

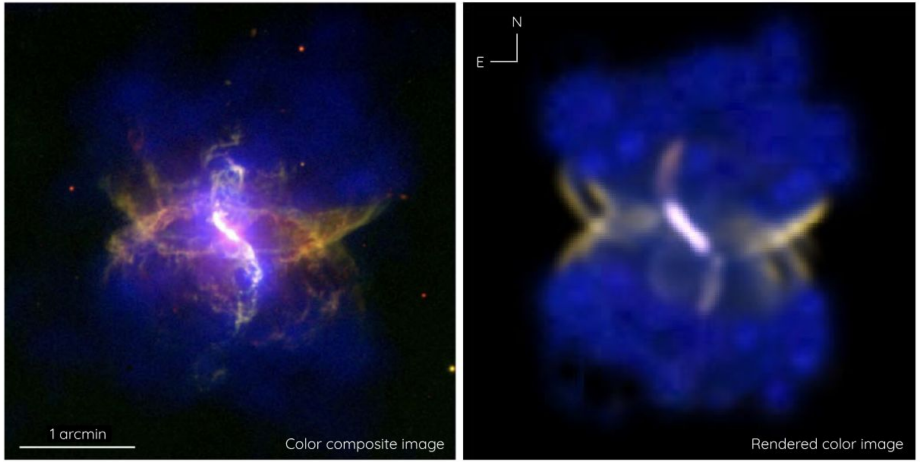
Kinematics: Tools

- **Position-Velocity Diagrams:**

  Combine spatial and spectral data



PV diagrams of PB 1 (Lopez et al. 2012)
The SPM Kinematic Catalogue of Planetary Nebulae.

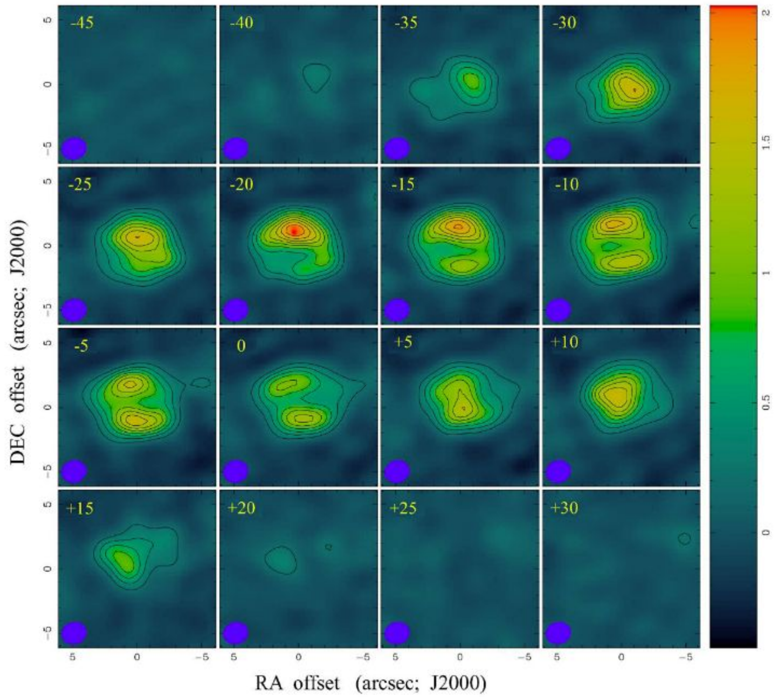


Santamaría et al. 2024. R Aqr

Kinematics: Tools

- **Channel Maps:**

  Images in narrow velocity bins (Tomography)

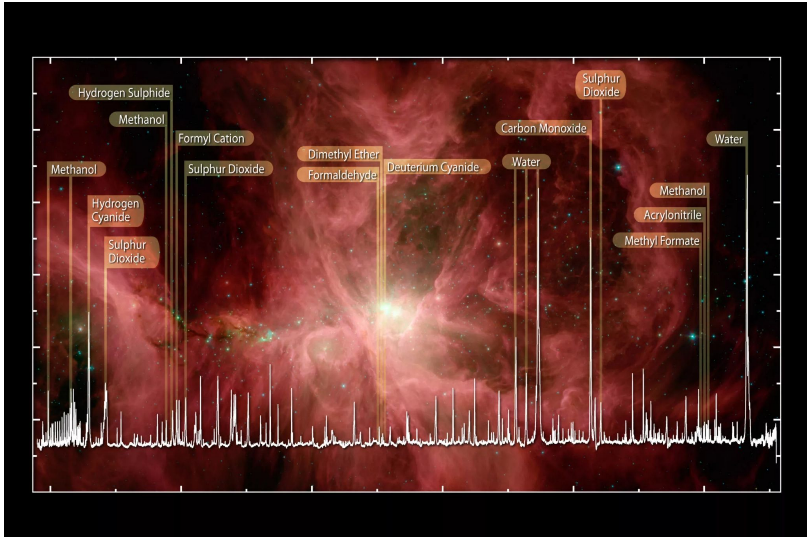


CO J=3-2 emission line of Frosty Leo. Sabin et al. 2019

Chemical composition

Objective:

- Determine elemental and molecular abundances
- Identify depletion patterns and trace enrichment history

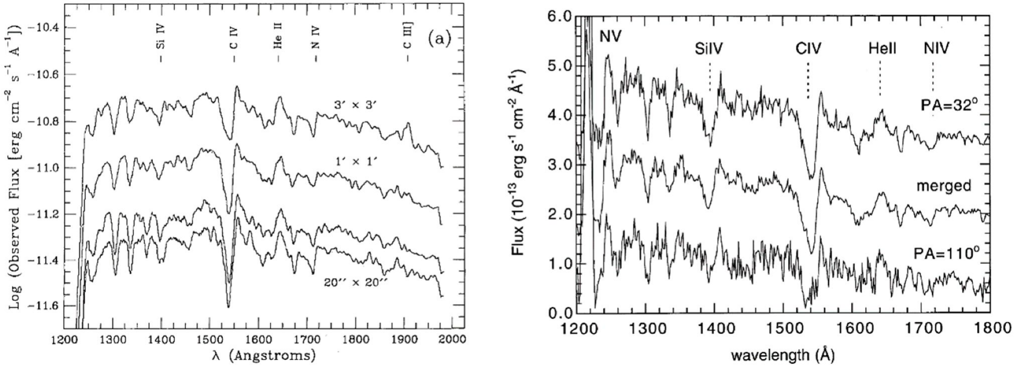


HIFI Spectrum of Water and Organics in the Orion Nebula

© ESA, HEXOS and the HIFI consortium E. Bergin

1- UV and Optical Absorption Lines

- ❖ **Commonly Used Ions**: C II, O I, Si II, Fe II, S II, Mg II, Zn II
- ❖ **Depletion Studies**: Compare observed gas-phase abundances to solar values



IUE spectra of the extragalactic massive stars clusters NGC 2070 (**left**) and NGC 604 (**right**), Leithere, 2020.

2- Emission Line Diagnostics

- **Ionized Gas (H II regions, WIM)**:
  - Line ratios of [N II]/Hα, [O III]/Hβ, [S II]/Hα
  - Empirical or photoionization models estimate abundances
- **Cooling lines**:
  - [C II] 158 μm, [O I] 63 μm for neutral gas phases

Ionization corrections applied using photoionization models (e.g., PyNeb, CLOUDY).

- ★ *Catching a grown-up starfish planetary nebula – II. Plasma analysis and central star properties of PC 22 (Sabin et al., 2021)*
- ★ *Link:*

Tools:

PyNeb : PyNeb (Luridiana V., Morisset C. and Shaw, R. A 2013) is a modern python tool to compute emission line emissivities (recombination and collisionally excited lines).

pyneb 1.1.28

```
pip install pyneb
```

pyCloudy 0.9.15

```
pip install pyCloudy
```

PyCloudy : PyCloudy is a Python library to deal with input and output files of Cloudy (Gary Ferland) photoionization code. Is also allows to generate 3D nebula from various runs of the 1D Cloudy code.

Also: https://sites.google.com/site/pycloudy/

This is the web site dedicated to the Python library pyCloudy, a set of tools to deal with photoionization code Cloudy (www.nublado.org).

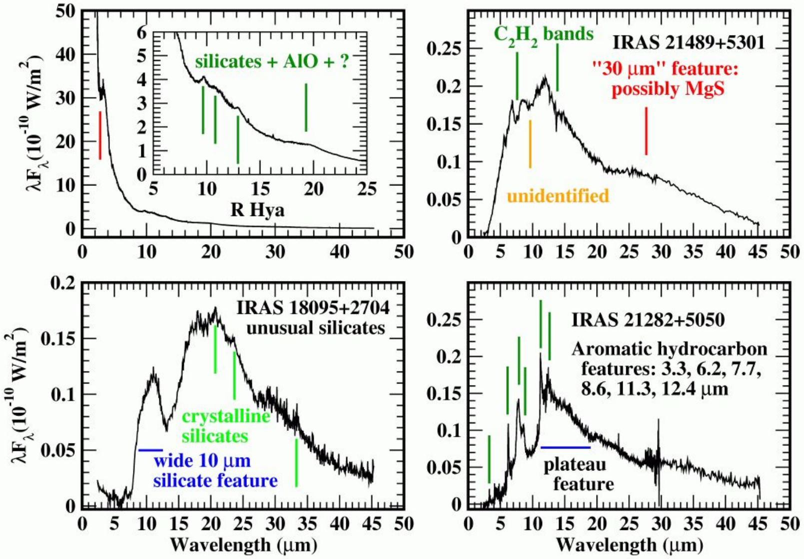
3- Molecular Line Surveys

- ❖ Identify molecular species and isotopologues (e.g., CO, HCN, HCO+, NH3)
- ❖ Derive relative abundances and chemical pathways
- ❖ Trace star formation and dense gas chemistry

- ★ **Molecular line study of the S-type AGB star W Aquilae-ALMA observations of CS, SiS, SiO and HCN, Brunner et al. 2018. Link**
- ★ **Splatalogue**

4- Dust Composition via Extinction and Emission

- ❖ **Extinction Curves**:
  - ➢ UV bump (2175 Å), far-UV rise, IR features
  - ➢ Determine grain composition (e.g., silicates, carbonaceous)
- ❖ **IR Spectroscopy**:
  - ➢ Silicate features (10 & 18 µm), PAHs, ices
  - ➢ Instruments: Spitzer, JWST, ISO
- ❖ Dust/gas mass ratio



https://www.stsci.edu/~volk/features2.html

5- Depletion and Refractory Element Analysis

- Elements like Fe, Mg, Si are depleted from gas phase
- Comparison to undepleted elements (e.g., S, Zn) quantifies dust incorporation
- Insights into dust grain growth, destruction, and cycling
- Elemental depletion: $\delta X = \log10(N_X/N_H)_{ISM} - \log10(N_X/N_H)_{\odot}$, revealing dust-phase incorporation (e.g., >90% Mg/Si in silicates)

- **Tracing Chemical Depletion in Evolved Binaries Hosting Second-Generation Transition Discs. Mohorian et al. 2025**
- **Link**

5- Dynamics

- ❖ The ISM is shaped not just by gravity and radiation, but also by dynamic processes.
- ❖ Such as : Shock waves, collimated jets/outflows, and disks.
- ❖ Each plays a key role in star formation, feedback/yields, and ISM structure:

- ❑ Shocks participate to ISM heating, momentum injection, diagnostics of violent events
- ❑ Jets/Outflows are responsible for Angular momentum regulation, ISM turbulence
- ❑ Disks are the birthplaces of stars and planets, link to feedback via outflows

Interconnected

Shocks

Definition:

- Sudden discontinuities in fluid properties: density, pressure, temperature.
- Occur when relative velocity > local sound speed $\longrightarrow$ *supersonic motion*.
- Governed by conservation laws: mass, momentum, energy.

Physics:

- **Rankine-Hugoniot jump conditions**: Describe pre- vs. post-shock conditions.
- **Key Equations:**
  - $\frac{P_2}{P_1} = \frac{2\gamma M^2 - (\gamma - 1)}{\gamma + 1}$
  - $T_2 \gg T_1, \rho_2 > \rho_1, v_2 < v_1$
- **Cooling time** determines shock type:
  - *Adiabatic (Sedov-Taylor)* vs *Radiative (Cooling length < shock thickness)*

Observational Signatures of Shocks

- Broad emission lines (e.g., Hα, [O III], [S II])
- Infrared emission from heated dust
- X-rays from high-temperature plasma

Tools: MAPPINGS

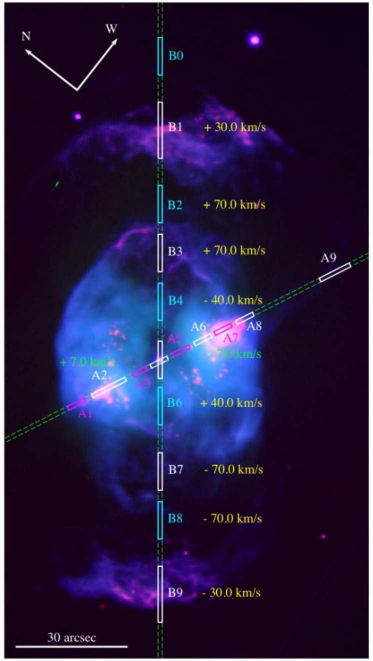
https://mappings.readthedocs.io/en/latest/

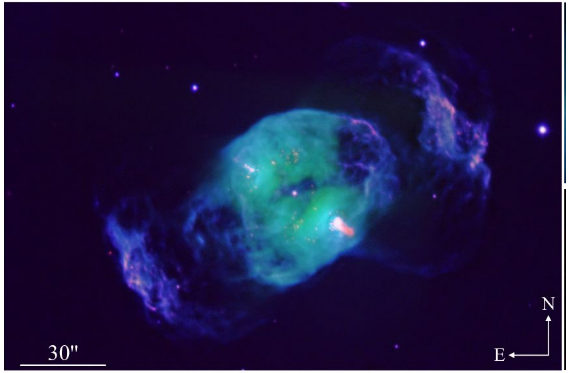
MAPPINGS V

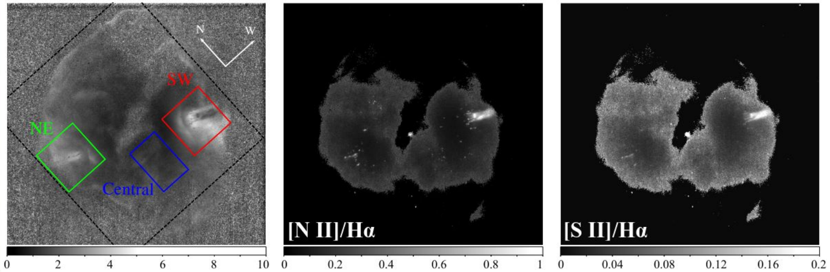
Astrophysical equilibrium and time-dependent photoinisation and steady supersonic shock spectral emission code

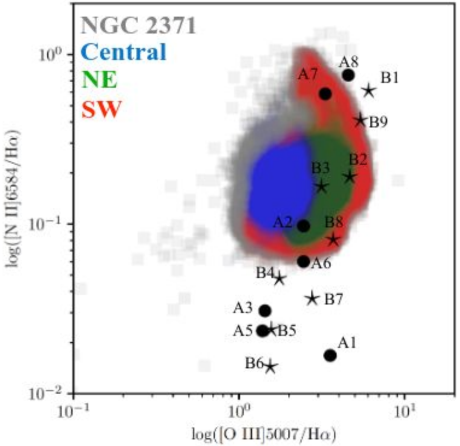
PN NGC 2371 (V. M. A. Gómez-González, 2020)

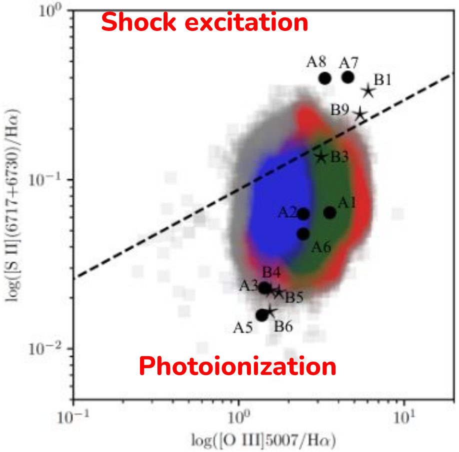
Planetary nebulae with Wolf-Rayet-type central stars - I. The case of the high-excitation NGC 2371









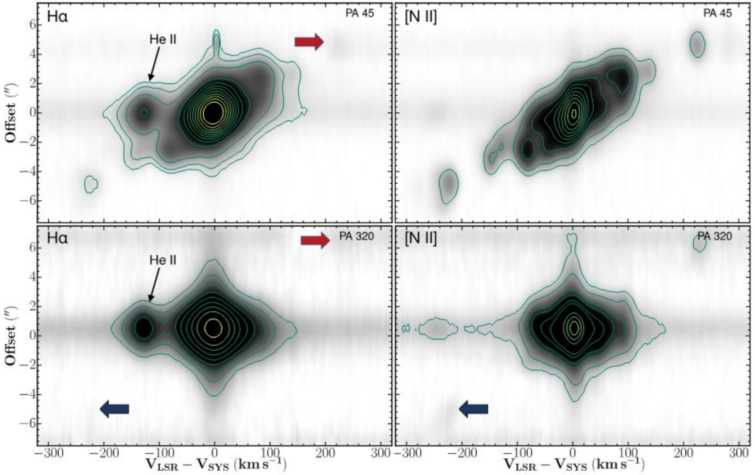


The dashed line in the bottom panel marks the theoretical limit log([O iii]/Hα) = 1.89 × log([S ii]/Hα) + 2.46 (see Section 4 for details) between photoionization (below the line) and shock-excitation (above the line).

Jets and Outflows

- **Jets**: Highly collimated, fast plasma ejections (>100km/s)

- **Outflows**: Slower, less collimated (<100 km/s)
- Coupled to **accretion disks** via magnetic fields



Rechy-García et al., 2022. PN M3-38

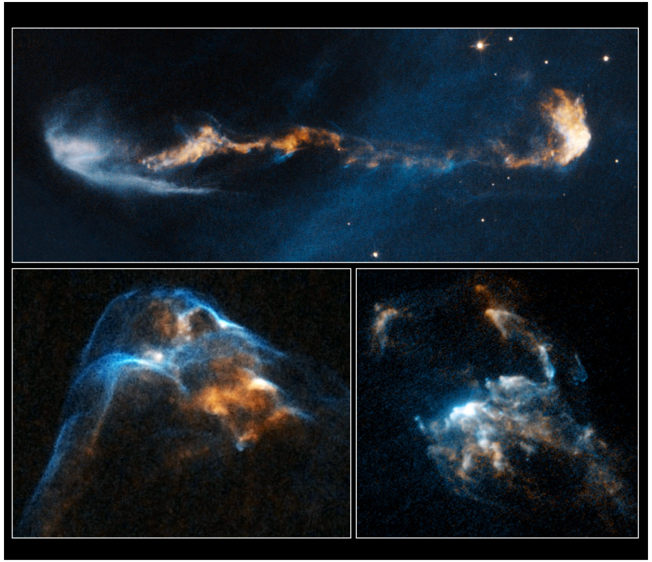
- **Magnetocentrifugal launching**
- **Collimation** by toroidal magnetic fields or external pressure

- Momentum and energy feedback into ISM

- Jet velocity: ~100–1000 km/s; mass-loss rates ~10^{-7}–10^{-5} M⊙/yr

Observations:

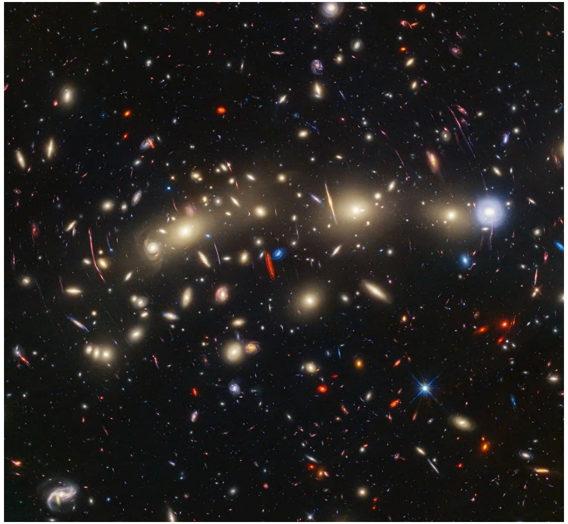
- ❖ Shock-heated knots in jets (e.g. Herbig Haro objects)
- ❖ Emission lines: [O I], [S II], Hα trace bow shocks and jets/outflows
- ❖ IR and radio continuum from non-thermal emission
- ❖ Proper motion studies ⟶ jet speeds and precession



HH, Nasa/ESA

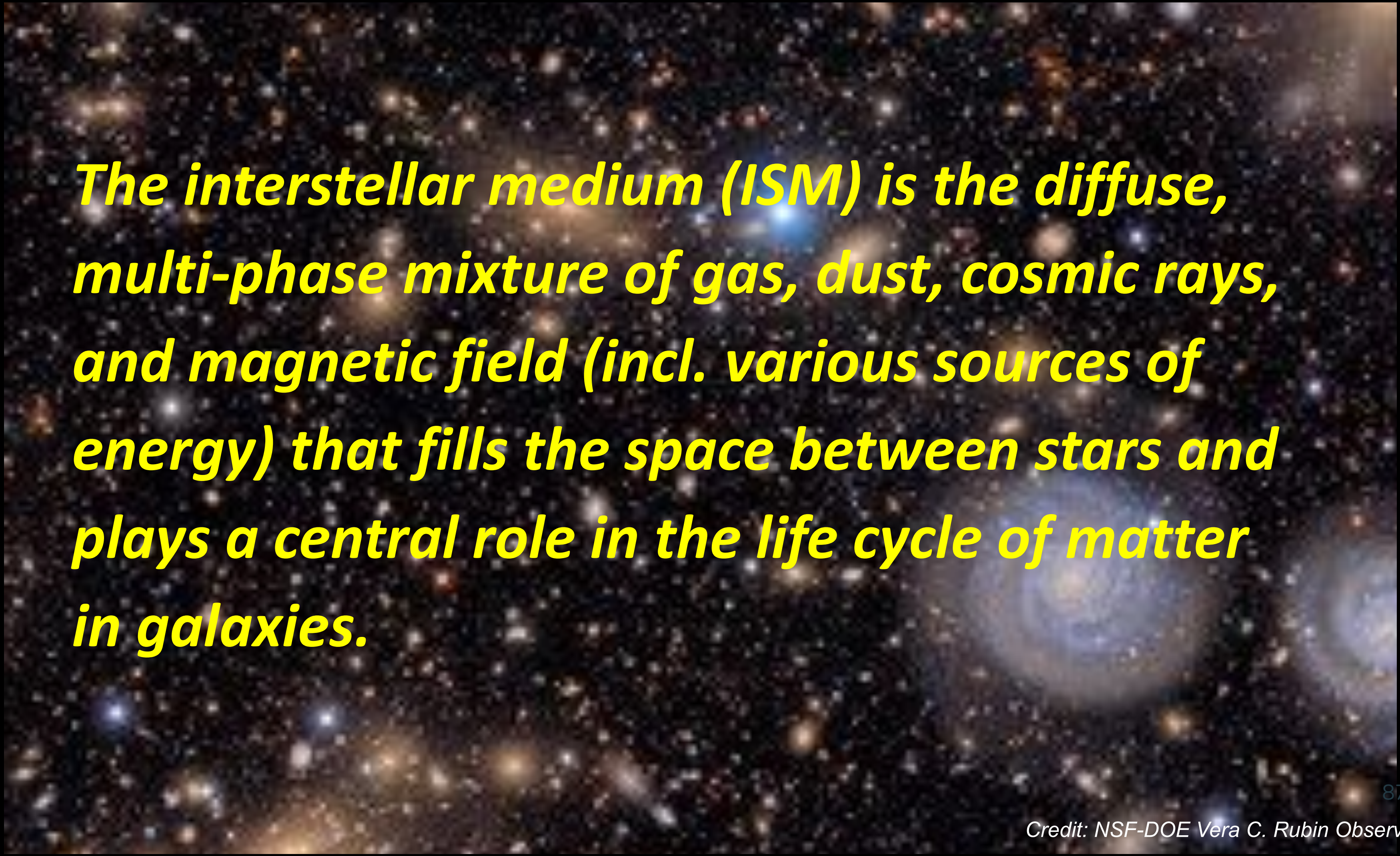
The ISM from the Milky Way and Beyond!

ESO.org



Credit: NASA, ESA, CSA, STScI, Jose M. Diego (IFCA), Jordan C. J. D'Silva (UWA), Anton M. Koekemoer (STScI), Jake Summers (ASU), Rogier Windhorst (ASU), Haojing Yan (University of Missouri)

The interstellar medium (ISM) is the diffuse, multi-phase mixture of gas, dust, cosmic rays, and magnetic field (incl. various sources of energy) that fills the space between stars and plays a central role in the life cycle of matter in galaxies.



Credit: NSF-DOE Vera C. Rubin Observatory