OBSERVATIONAL COSMOLOGY:

INTERSTELLAR MEDIUM

Credit:
https://staff.fnwi.uva.nl/a.dekoter/ISMv1.46.00.pdf
https://adlibitum.oats.inaf.it/pierluigi.monaco/Lectures/ISM.pdf
https://astro.uni-bonn.de/~uklein/teaching/ISM/ISM09Lecture1.pdf

A.A. 2025/2026 | Matteo Costanzi - University of Trieste / INAF

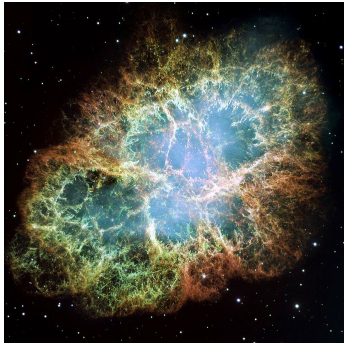
THE INTERSTELLAR MEDIUM

ISM

- **Circumstellar Medium:**

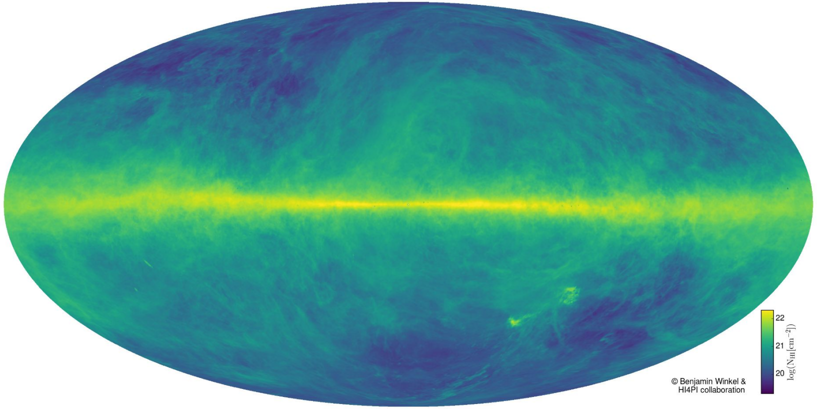
  Related to individual astrophysical objects, generally associated to young and luminous stars or end-life-phases of stars:

- **Reflection Nebulae**
- **HII regions**
- **Planetary Nebulae**
- **Supernova Remnants**



Crab nebula (SN 1054 remnant)

- **Diffuse component:**



HI map produced using data from the 100-m Max-Planck radio telescope in Effelsberg, Germany and the 64-m CSIRO radio telescope in Parkes, Australia. The image intensity reflects the total hydrogen content.

CIRCUMSTELLAR REGIONS

Reflection Nebulae:

- **Non-ionized circumstellar gas that scatters photon of late-type star**
  - **The central star is not sufficiently hot to produce photons with E>13.6eV → H is not ionized by stellar radiation**
  - **Dominant process is elastic scattering of stellar photons by dust grains (d~0.01-0.3 μm) embedded in the gas → shorter λs scatter more efficiently**
- **Lifetime 10^6 - 10^7 yr, set mainly by:**
  - **Duration of proximity to a luminous star (e.g. B-type star ~10^7 yr)**
  - **Survival of the dense dusty environment (stellar wind, radiation pressure, SN feedback)**

Reflection nebula V838 (image from the Hubble Space Telescope)

CIRCUMSTELLAR REGIONS

HII regions:

- **Low-density clouds of partially ionized gas surrounding short-lived, early-type stars**
- **Ionization mechanism:**
  - **Radiation of early-type stars (UV photons with E>13.6 eV)**
  - **Collisional ionization, in presence of shocks due to stellar ejecta (stellar wind)**
- **HII regions are typically associated with regions of recent star formation and with giant molecular clouds; they can extend up to ~100 pc**
- **Typical lifetime 1-10 Myr, mainly set by the lifetime of massive stars (>20 $M_\odot$)**
- **The main observational diagnostics of HII regions in the optical band is the Hα emission line (n=3 → n=2 Balmer line transition @ 656.28 nm)**

Orion nebula. Composite image of visible light and infrared taken by HST

Strömgren sphere:

- **H II regions are in equilibrium; the rate of ionization must equal the rate of recombination; photons must be absorbed and ions must be produced at the same rate that free electrons and protons recombine to form neutral hydrogen atoms.**

La Nebulosa Rosetta. La sfera di Strömgren è visibile al centro dell'immagine.

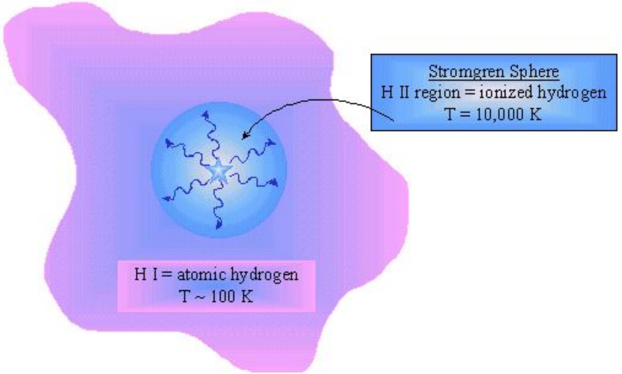
Defining:

- **N = number of ionizing photons per second**
- **α = recombination coefficient**
- **n_H = hydrogen number density**

The radius of the Strömgren sphere is:

$$r_S \simeq \left(\frac{3N}{4\pi\alpha}\right)^{1/3} n_H^{-2/3}$$

Values of r_S range from <0.1 p

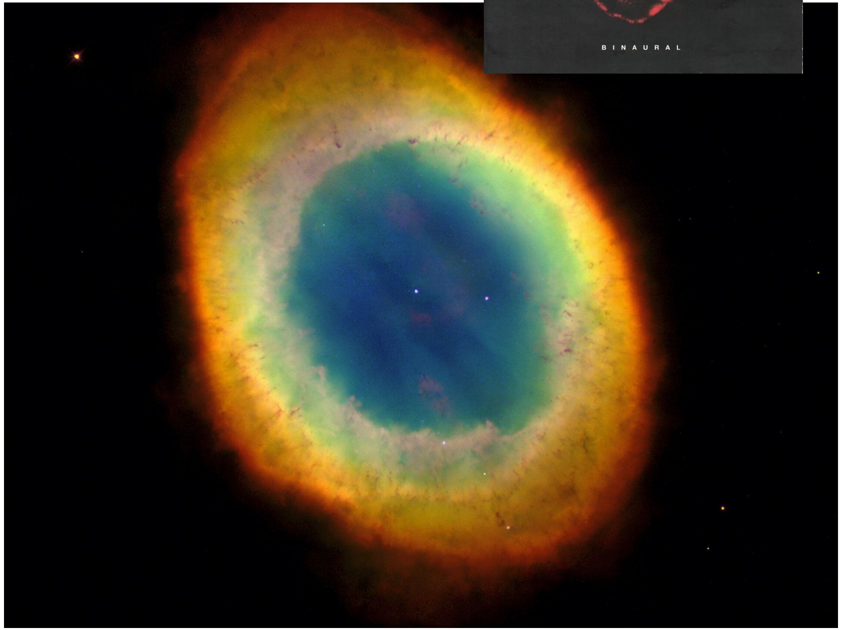


CIRCUMSTELLAR REGIONS

Hourglass Nebula

Planetary Nebulae:

- **Expanding, photoionized shell of gas ejected during the late evolution of low- to intermediate-mass stars (≈ 1-8 $M_\odot$), illuminated by the hot central remnant**
  - **During the red giant phase, the outer layers of the star are expelled by strong stellar winds**
  - **After most of the red giant's atmosphere is dissipated, the remaining hot luminous core emits UV radiation that ionizes the ejected outer layers**
  - **Absorbed UV light energises the shell of nebulous gas, causing it to appear as a brightly coloured planetary nebula (lifetime ~10^4 yr)**



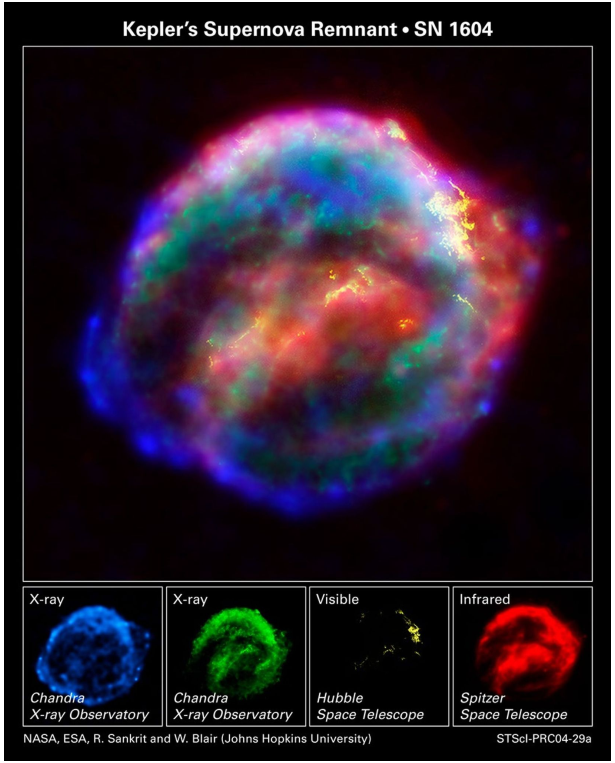
Ring nebula NGC 6720. Composite image of visible light and infrared taken by HST

https://science.nasa.gov/missions/webb/nasas-webb-examines-cranium-nebula/

CIRCUMSTELLAR REGIONS

Supernova Remnants (SNRs):

- Expanding shock structure produced by a supernova explosion interacting with the surrounding interstellar or circumstellar medium
  - The SN explosion expel much or all of the stellar mass with supersonic velocities up to 10^4 km/s
  - The SNRs is bounded by an expanding shock wave, and consists of ejected material expanding from the explosion and the interstellar material it shocks along the way
  - A strong shock wave forms ahead of the ejecta, that heats the upstream plasma to $T>10^6$k
  - The shock continuously slows down over time as it sweeps up the ambient medium. It can expand over tens of pc before its speed falls below the local sound speed. → it eventually merges with the ISM
- Lifetime 10^4 - 10^5 yr



NASA's three Great Observatories - the Hubble Space Telescope, the Spitzer Space Telescope, and the Chandra X-ray Observatory - joined forces to probe the Kepler's supernova remnant, first seen 400 years ago by sky watchers, including famous astronomer Johannes Kepler.

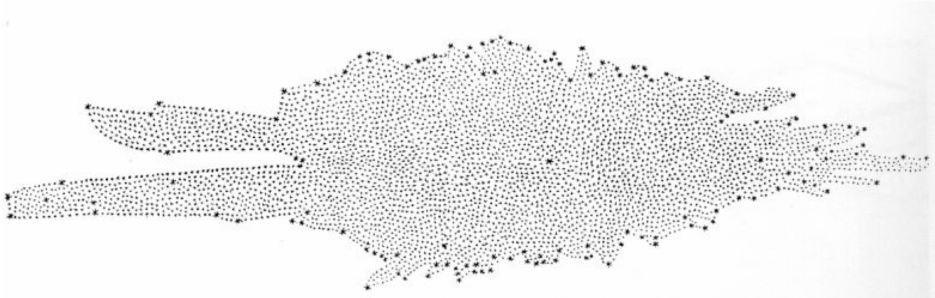
DISCOVERY OF THE ISM

- **1795: Sir W. Herschel compiles the first catalog of "nebulae"**
  - **The stellar distribution was patchy in the sky**
  - **Noticed the existence of dark regions in the sky particularly devoid of star**

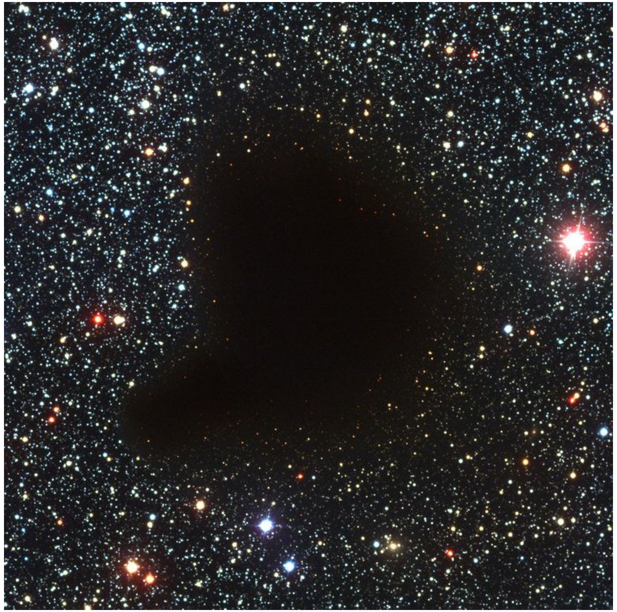
“Hier ist wahrhaftig ein Loch im Himmel”

(Here truly is a hole in the sky)

http://www.klima-luft.de/steinicke/Artikel/Herschel's%20Hole.pdf



Sir W. Herschel’s map of the Milky Way

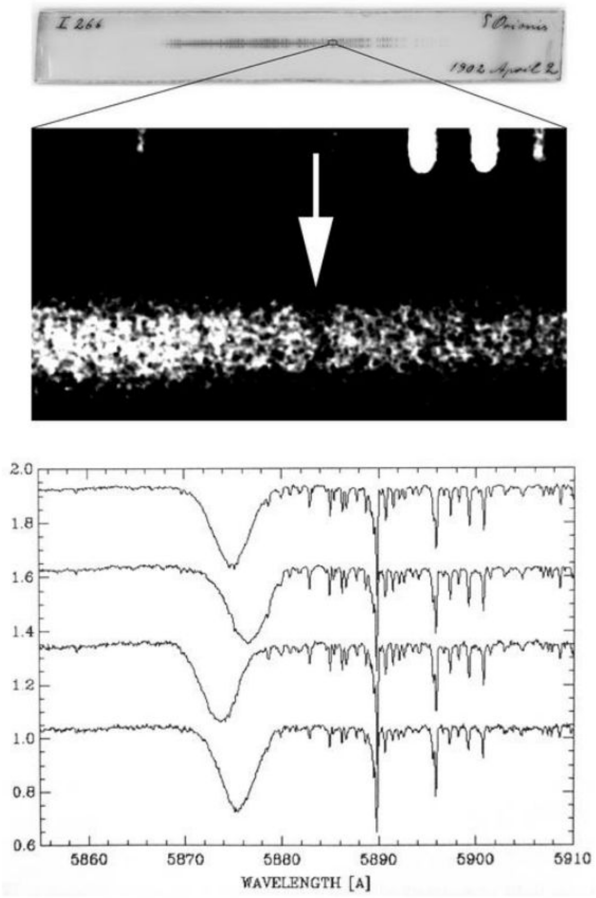


Dark cloud B68 in visible and NIR light

DISCOVERY OF THE ISM

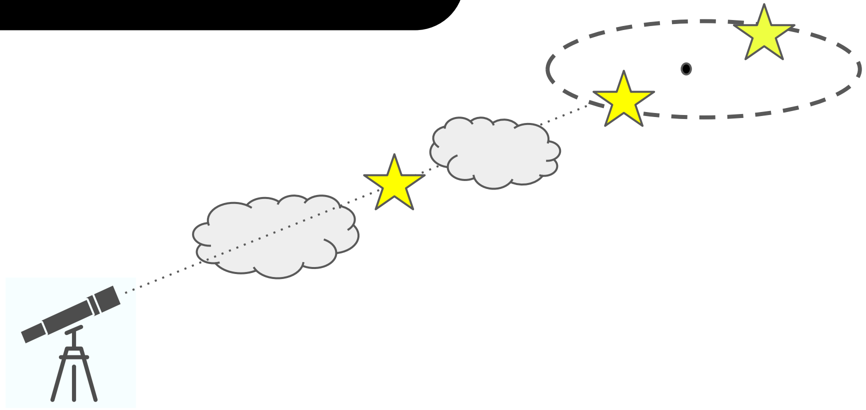
- **1904: Hartmann observed “stationary” CaII absorption lines in the spectrum of the spectroscopic binary δ Ori**

- **1933: Plaskett & Pearce noticed that the CaII absorption line becomes stronger with increasing distance of the background star**



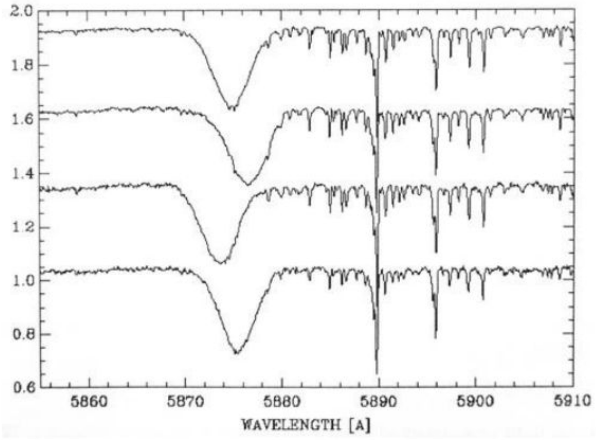
Stationary NaI lines in the spectrum of δ Ori

DISCOVERY OF THE ISM



Interpretation of the results:

- **The star and the gas along the line of sight have, in general, a different radial velocity**
- **If the star is a spectroscopic binary, the stellar lines will regularly shift in radial velocity according to the orbital period of the binary system; interstellar lines, on the other hand, will be "stationary"**
- **The fact that the strength of the CaII absorption line increases with distance of the background star imply that the absorber is not circumstellar but has an interstellar origin**



Stationary NaI lines in the spectrum of δ Ori

- **1930: Trumpler compared the distances of ~100 open cluster derived from the apparent magnitudes and angular diameters finding $D_A \neq D_L$**

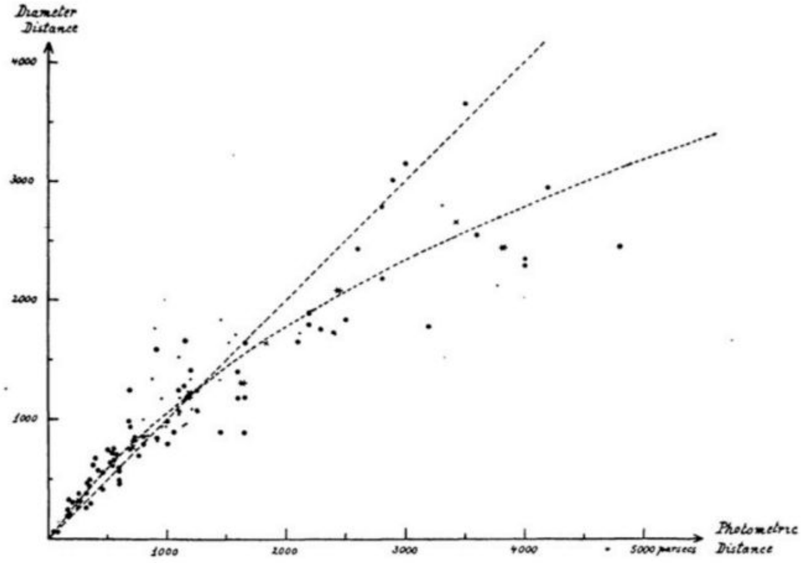


FIG. 1.—Comparison of the distances of 100 open star clusters determined from apparent magnitudes and spectral types (abscissae) with those determined from angular diameters (ordinates). The large dots refer to clusters with well-determined photometric distances, the small dots to clusters with less certain data (half weight). The asterisks and

DISCOVERY OF THE ISM

Interpretation:

- **The apparent size of an open cluster decreases like the inverse of the diameter distance.**
- **The total flux of an open cluster decreases like the inverse square of the luminosity distance.**
- **If open clusters have on average the same size and luminosity, one can get their luminosity and diameter distances from observed flux and angular size.**
- **As we are inside the galaxy, luminosity and diameter distances are the same, so we expect a 1-1 relation**
- **Extinction of more distant objects is revealed by a flattening of the relation of luminosity vs diameter distance.**

$$m - M = 5\log_{10}(d/10\,\mathrm{pc}) + A_V$$

↑ Visual extinction ~ 1mag kpc^{-1}

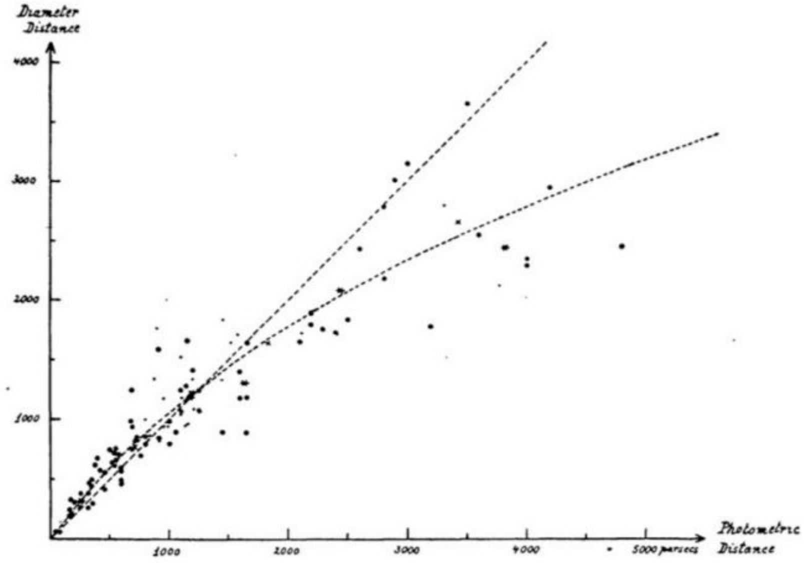


FIG. 1.—Comparison of the distances of 100 open star clusters determined from apparent magnitudes and spectral types (abscissae) with those determined from angular diameters (ordinates). The large dots refer to clusters with well-determined photometric distances, the small dots to clusters with less certain data (half weight). The asterisks and crosses represent group means. If no general space absorption were present, the clusters should fall along the dotted straight line; the dotted curve gives the relation between the two distance measures for a general absorption of 0^{m}.7 per 1000 parsecs.

DISCOVERY OF THE ISM

Further milestones:

- **~1937 the first interstellar molecules CH, CH^+ and CN were discovered**
- **1945 van der Hulst predicted the detectability of the HI 21-cm line**
- **1949 discovery of interstellar magnetic field by polarization measurements**
- **1950`s first maps of the Milky Way in HI**

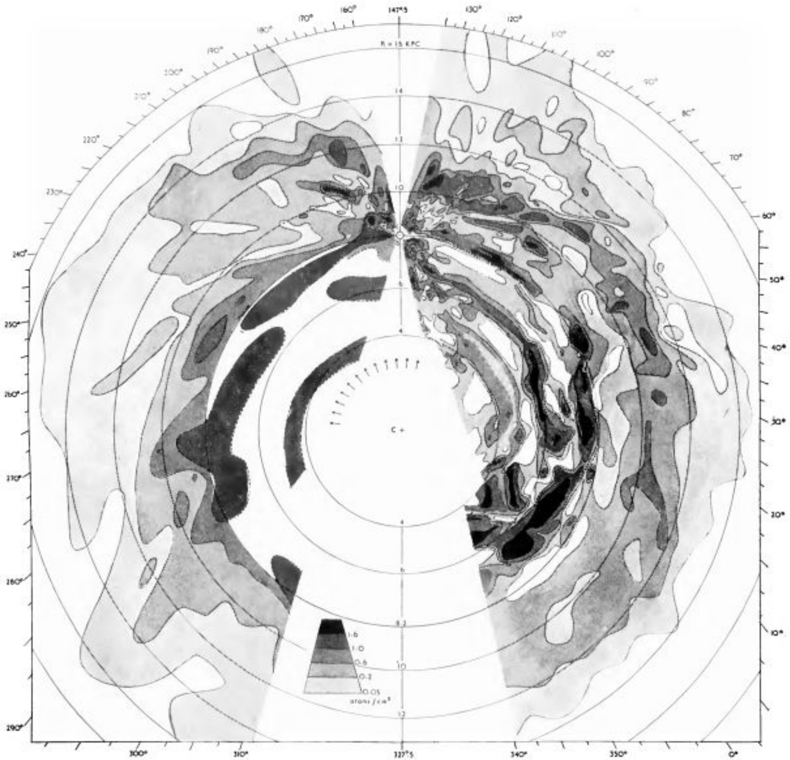
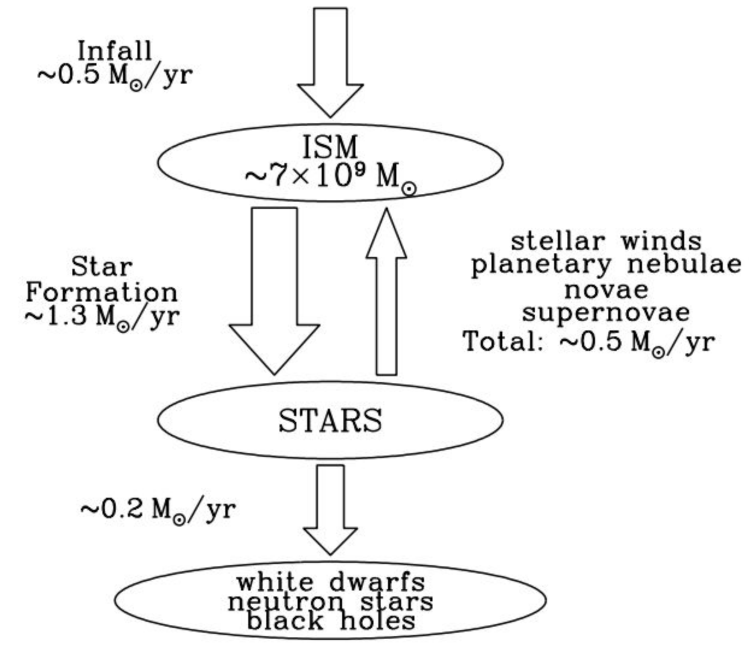


FIG. 4.—*Distribution of neutral hydrogen in the Galactic System. The maximum densities in the z-direction are projected on the galactic plane, and contours are drawn through the points.*

A Oort, J. H.; Kerr, F. J.; Westerhout, G. 1958
https://ui.adsabs.harvard.edu/abs/1958MNRAS.118..379O/abstract

ISM: GENERALITIES

- **The ISM is a non-linear, self-regulated, multiphase system where gravity, turbulence, magnetic fields, and radiative processes interact to govern the baryon cycle of galaxies**
- **The radiation of the ISM is faint and the bulk of photons are emitted in the radio and infrared wavelength regime**
- **The ISM hosts only a few percent of the total mass of a galaxy**
- **The composition of the ISM is continuously modified by the stellar evolution**
- **The distribution and chemical composition of the ISM is continuously modified by accretion of matter by the galaxy**
- **Density and temperature variations within the ISM trigger the star formation rate of a galaxy**



The flow of baryons in the Milky Way. From: Bruce Draine, Physics of the Interstellar and Intergalactic medium.

ISM: GENERALITIES

The interstellar medium is characterized by:

- **Large range of densities: 10^{-3} - 10^{6} cm^{-3}**
- **Large range of temperatures, from ~10 to 10^{6} K,**
- **Large range of ionization states**
- **Complex geometry, complex kinematics**
- **Significant presence of dust**
- **Very long mean free paths for particles → thermodynamic equilibrium is hard to achieve**
- **Several coexisting phases in rough pressure equilibrium**
- **Weak magnetic fields (~5 μG)**
- **Radiation fields**
- **Significant presence of cosmic rays.**

ISM: GENERALITIES

ISM Composition (mass fraction):

- **Gas: ~99%**
- **Dust: ~1%**

In the Milky Way, total ISM mass ~10-15% of the stellar mass.

Chemical composition (mass fraction):

H ~ 74%
He ~ 24%
Metals ~ 1-2%

Component	*Description*	*Density* (cm^{-3})	*Temperature* (K)	*Pressure* (p/k_B)	*Vertical extent*	*Mass* ($\mathcal{M}_\odot$)	*Filling factor*
Dust grains						10^7–10^8	Tiny
large $\lesssim 1$ μm	Silicates, soot		~20		150 pc		
small ~ 100 Å	Graphitic C		30–100				
PAH < 100 atoms Polycyclic aromatic hydrocarbon	Big molecules				80 pc		
Cold clumpy gas	Molecular: H_2	> 200	< 100	Big	80 pc	(2) × 10^9	<0.1%
	Atomic: HI	25	50–100	2 500	100 pc	3 × 10^9	2%–3%
Warm diffuse gas	Atomic: HI	0.3	8 000	2 500	250 pc	2 × 10^9	35%
	Ionized: HII	0.15	8 000	2 500	1 kpc	10^9	20%
HII regions	Ionized: HII	1–10^4	~10 000	Big	80 pc	5 × 10^7	Tiny
Hot diffuse gas	Ionized: HII	~0.002	~10^6	2 500	~5 kpc	(10^8)	45%
Gas motions	$\frac{3}{2}\langle\rho_{HI}\rangle\sigma_r^2$	$\langle n_H \rangle \sim 0.5$	10 km s^{-1}	8 000			
Cosmic rays	Relativistic	1 eV cm^{-3}		8 000	~3 kpc	Tiny	
Magnetic field	$B \sim 5$ μG	1 eV cm^{-3}		8 000	~3 kpc		
Starlight	$\langle \nu h_P \rangle \sim 1$ eV	1 eV cm^{-3}			~500 pc		
UV starlight	11–13.6 eV	0.01 eV cm^{-3}					

ISM: GENERALITIES

ISM Phases: The ISM exists in **multiple thermal phases** that coexist in rough pressure equilibrium

Phase	T (K)	n_H (cm s^{-3})	Comments
Molecular clouds H_2 $f_V \approx 10^{-4}$ $< n_H > f_V \approx 0.2$ cm^{-3}	10–50	$10^3 - 10^6$	Heating by photons from dust Ionization and heating by cosmic rays Often self-gravitating: $p > p$(ambient ISM) Cooling by: – CO line emission – C I fine structure line emission Observed by: – CO 2.6-mm emission – dust far-IR emission
Cool H I (CNM) $f_V \approx 0.01$ $< n_H > f_V \approx 0.3$ cm^{-3}	~100	30	Heating by photons from dust Ionization by starlight, cosmic rays Pressure equilibrium Cooling by: – Fine structure line emission Observed by: – H I 21-cm emission, absorption – Optical, UV absorption lines
Warm H I (WNM) $f_V \approx 0.2 - 0.4$ $< n_H > f_V \approx 0.2$ cm^{-3}	~5000–8000	0.5	Heating by photons from dust Ionization by starlight, cosmic rays Pressure equilibrium Cooling by: – Optical line emission – Fine structure line emission Observed by: – H I 21 cm emission, absorption – Optical, UV absorption lines
(Diffuse) H II gas $f_V \approx 0.15$ $< n_H > f_V \approx 0.002$ cm^{-3}	~ 10^4	$0.3 - 10^4$	Heating by photons from O stars Photo-ionized by O stars Either expanding or in pressure equilibrium Cooling by: – Optical line emission – Free-free emission – Fine structure line emission Observed by: – Optical line emission – Thermal radio continuum
Coronal gas (HIM) $f_V \approx 0.5$? $< n_H > f_V \approx 0.002$ cm^{-3}	$\gtrsim 3 \times 10^6$	$\lesssim 0.004$	Shock-heated Collisionally ionized Either expanding or in pressure equilibrium Cooling by: – Adiabatic expansion – X-ray emission Observed by: – UV and X-ray emission – Radio synchrotron emission

Table 1.1: *Phases of the interstellar medium, ordered from coolest to hottest.* f_V *is the volume filling factor. Following: Draine,* Physics of the Interstellar and Intergalactic Medium.

Phase	T (K)	n_H (cm s^{-3})	Comments
Cool stellar outflows H_2	50–10^3	$1 - 10^6$	Observed by – CO, OH, and other molecules – dust IR emission
Hot stellar outflows H II	8000 – 30000	$0.1 - 10^5$	Observed by – UV absorption lines – Hα, He II 4686 emission – Thermal radio continuum

Table 1.2: *Gas in stellar outflows, ordered from coolest to hottest.*

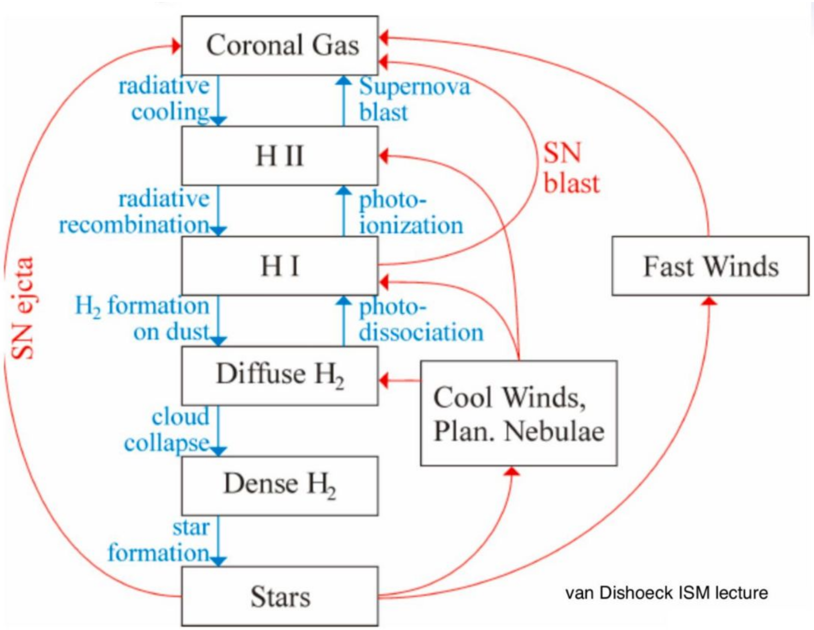
ISM: GENERALITIES

All these components of the ISM interact and influence each other.

In addition, the ISM interacts with stars. Stars form from dense interstellar clouds, and once formed the radiation of stars affects the physical and chemical conditions of the ISM.

Stellar winds and supernovae return much of the stellar material back into the ISM, but these stellar ejecta are enriched in metals due to nucleosynthesis.

Furthermore, stellar ejecta carry energy and momentum into the ISM. The enriched material mixes in the ISM and eventually will be incorporated in new stars (and planets).



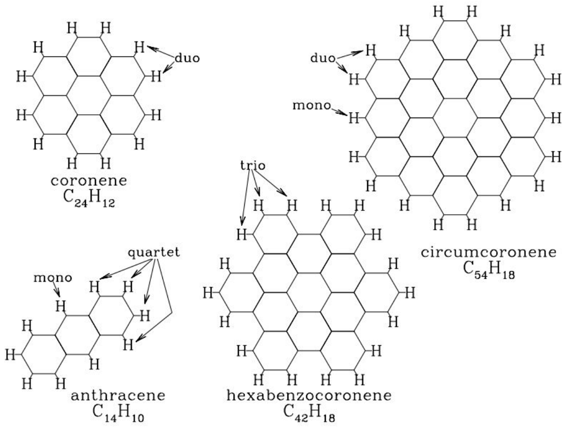
van Dishoeck ISM lecture

ISM: DUST

Properties:

- **Dust grains have typical sizes of ~0.1 μm**
- Constitute only **~1% of the total ISM mass**, but have enormous physical importance
- Mainly composed of **silicates** (large grains ≲1 μm), **graphitic carbon** (small grains ~100 Å), and **PAH molecules** (<100 atoms).

Structure of four PAHs, with their characteristic aromatic rings.



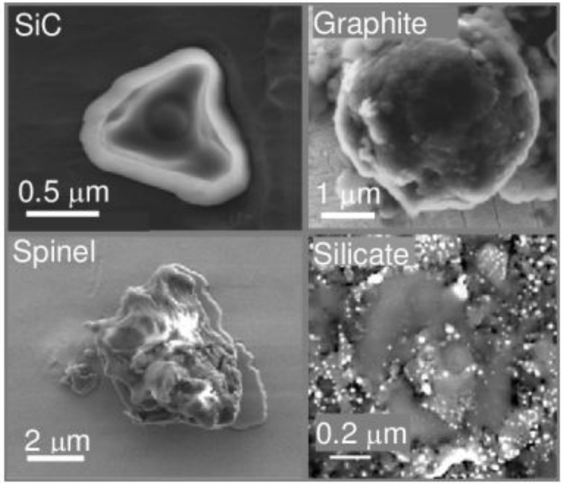
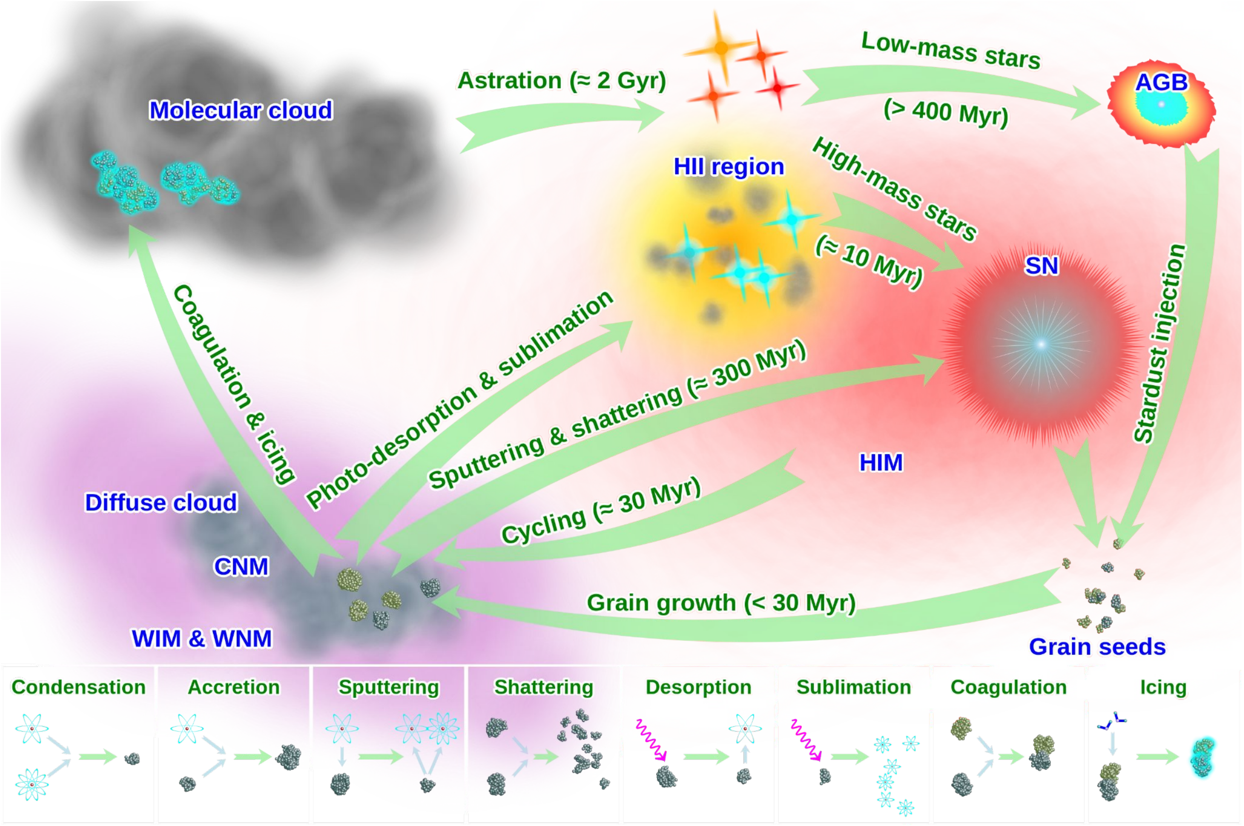


Figure 11.4: *Fotos of presolar grains found in primitive meteorites. Upper left: Silicon carbide (SiC). The isotopic signatures of these SiC inclusions point to an origin in a Type II supernova (SN) explosion. Upper right: Graphite from an asymptotic giant branch (AGB) star or a Type II SN. Lower left: Spinel ($MgAl_2O_4$) from an AGB star. Lower right: a grain consisting of an Al-rich core surrounded by a silicate mantle, also from an AGB star. From: Hoppe 2010. Photo credit: Max Planck Institute for Chemistry.*

ISM: DUST

Dust Lifecycle

- Dust forms in the outflows of AGB stars and Type II supernovae
- processed in the ISM (destruction by shocks, accretion in molecular clouds)
- incorporated into new stars (astration)
- cycle repeats



Credit: https://irfu.cea.fr/Pisp/frederic.galliano/HDR/hdrch6.html

ISM: DUST

Physical effects:

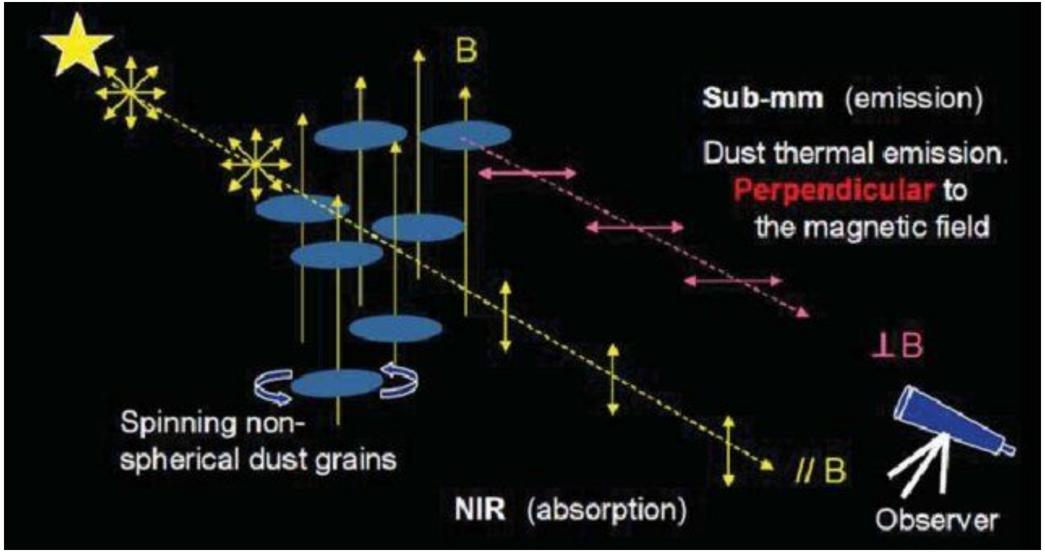
- **Extinction and reddening** of starlight: dust absorbs/scatters UV and optical light more efficiently than infrared
- **Thermal emission**: absorbed energy re-emitted in the FIR (dust grains heated to ~10–20 K in the diffuse ISM $\rightarrow \lambda$ ~ 100 - 200 μm)
- **Coolant**: dust grains radiate energy and help clouds cool
- **Catalyst**: dust grains are the primary formation sites for H_2, critical for star formation
- **Metal depletion**: refractory elements (Ca, Fe, Al, Si) are locked up in grains and depleted from the gas phase

Figure 11.3: *The Horsehead Nebula (or Barnard 33) in the emission nebula IC 434 is a dark nebula in the much larger Orion Molecular Cloud complex at a distance of 1500 lyr. The red or pinkish glow surrounding the horse head like shaped nebula is from an H II region, ionized by the nearby bright binary σ Orionis A (O9V) & B (B0.5V).*

ISM: DUST

Physical effects:

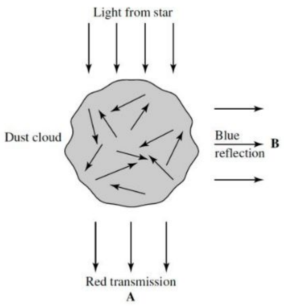
- **Polarization-dependent attenuation of starlight** — elongated dust grains aligned in the galactic magnetic field preferentially absorb/scatter light vibrating parallel to their axis
    - This cause polarization of the transmitted starlight along the magnetic field lines, resulting in a wavelength dependent polarization of light reaching us from reddened stars.
- **Polarized thermal emission** — These same elongated, aligned grains emit thermal radiation that is polarized perpendicular to the magnetic field lines

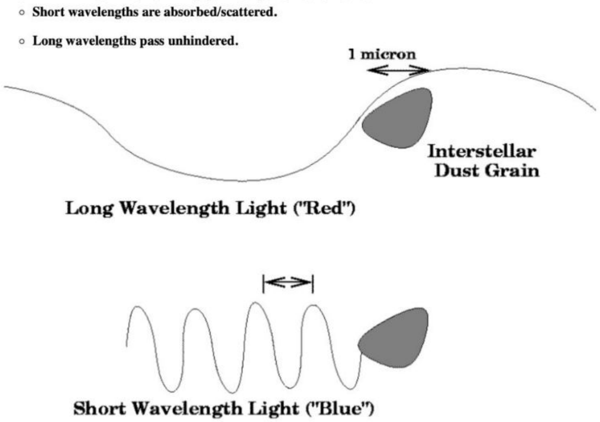


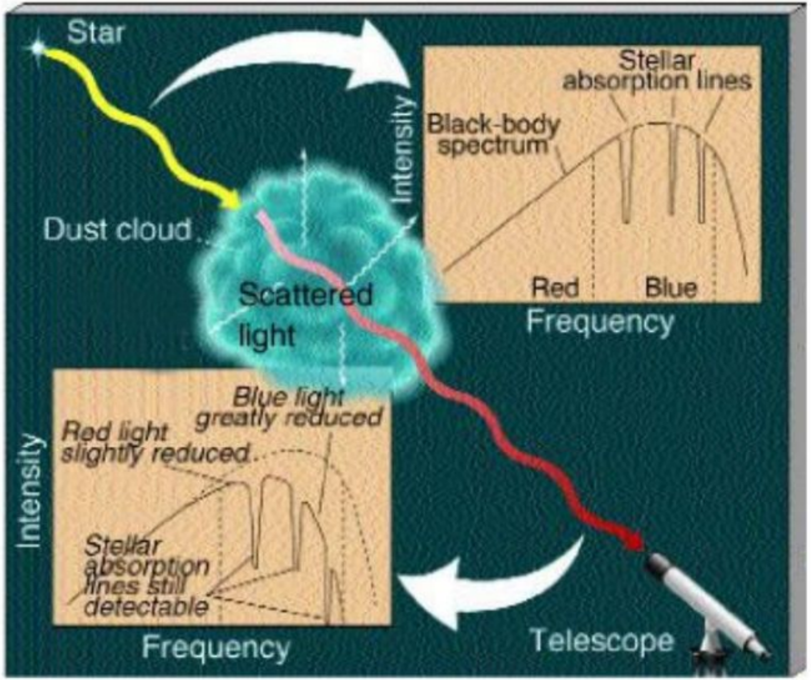
ISM: DUST

Dust extinction :

- Wavelength-dependent attenuation of starlight by absorption and scattering, observable at wavelengths from 0.1 μm to 20 μm.
- This continuum extinction is strongest in the ultraviolet, and weakens towards the infrared, and includes a number of spectral features that provide clues to the grain composition







ISM: DUST

Dust extinction :

- **Reddening (color excess):**

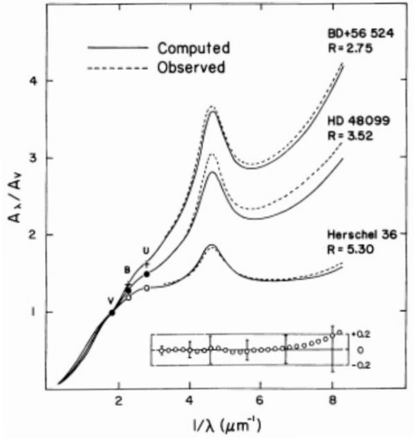
  $E(B\text{-}V) = (B\text{-}V)_{obs} - (B\text{-}V)_{true}$

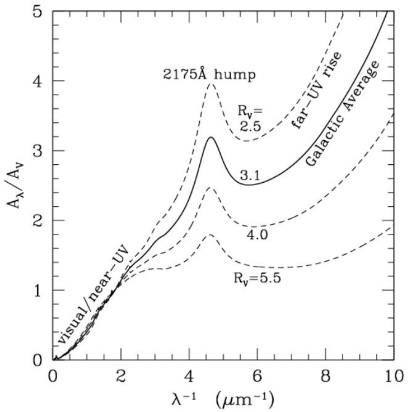
- **Extinction in the V band:**

  $A_V = R_V\ E(B\text{-}V)$ where $R_V \simeq 3.1$

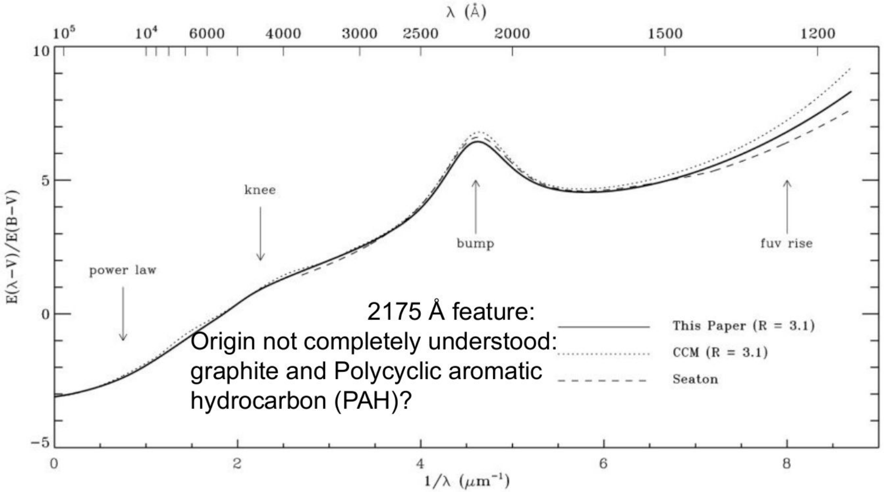
- **Extinction as a function of λ:**

  $A_\lambda = 2.5 \log (F_0(\lambda)/F(\lambda)) = R(\lambda)\ E(B\text{-}V)$





Left: The measured wavelength dependence of the interstellar extinction for three directions into the ISM (dashed lines). The extinction is normalized to the value in the V band (5500 A). ˚ For each direction the best fit value RV and the name of the star that is targeted is given. The extinction in the direction of Herschel 36 – the ionizing star in the H II region M8 – is considered "peculiar". The full lines are fits to the measured Aλ/AV . Right: The Galactic average of the interstellar extinction has RV = 3.05 ± 0.15; often 3.1 is adopted.

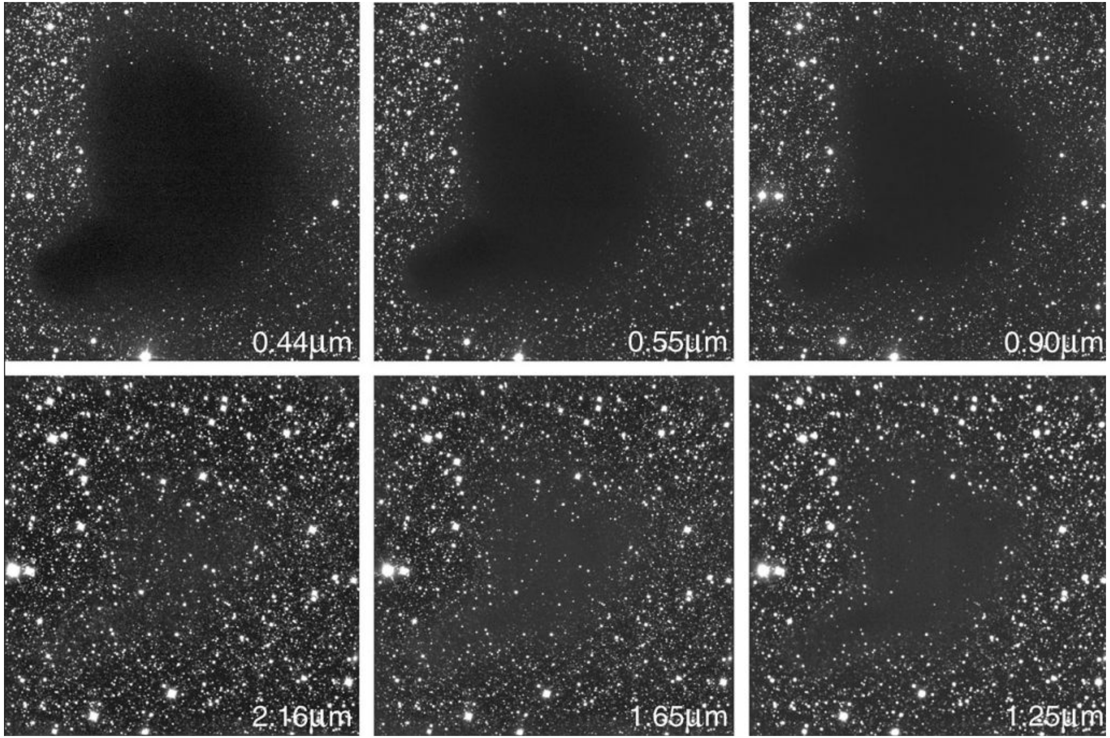


2175 Å feature:
Origin not completely understood:
graphite and Polycyclic aromatic hydrocarbon (PAH)?

ISM: DUST

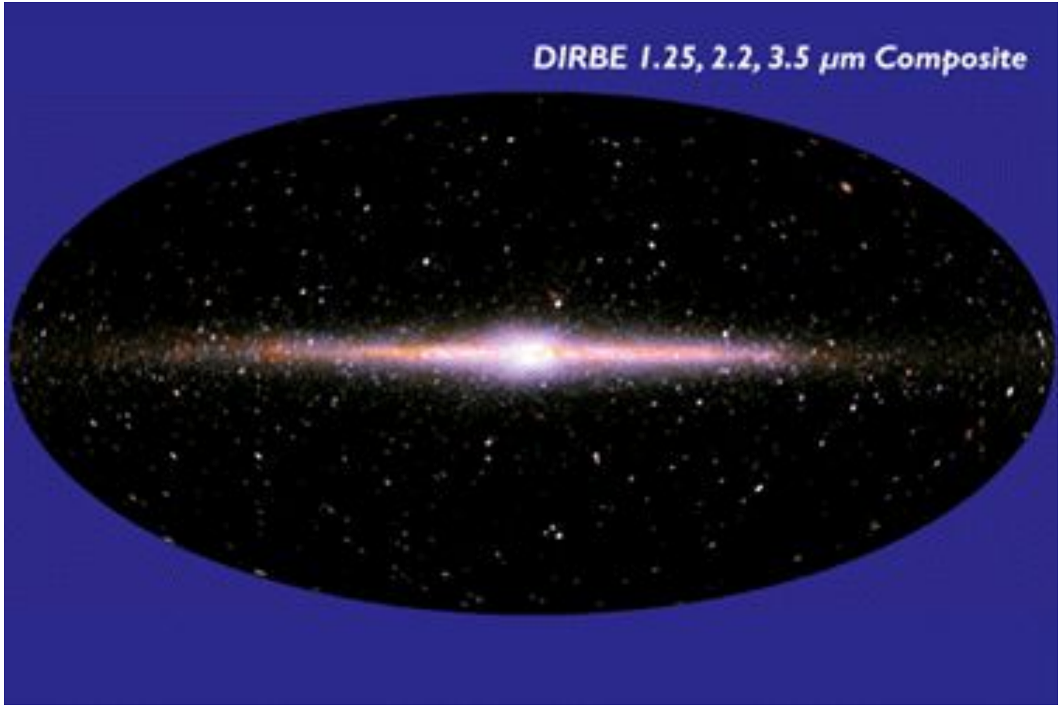
Dark Nebulae

- Dark patches in the visible bands are now understood as **opaque dust clouds**
- Range from tiny **Bok globules** (~0.01 pc) to large clouds tens of parsecs across
- Some are even dark in mid-IR: **Infrared Dark Clouds (IRDCs)**
- Often bright in far-IR (thermal emission from dust heated to ~10–20 K in the diffuse ISM at wavelengths ranging from about 2 μm to the sub-mm)



INTERSTELLAR EXTINCTION: OBSERVATIONS

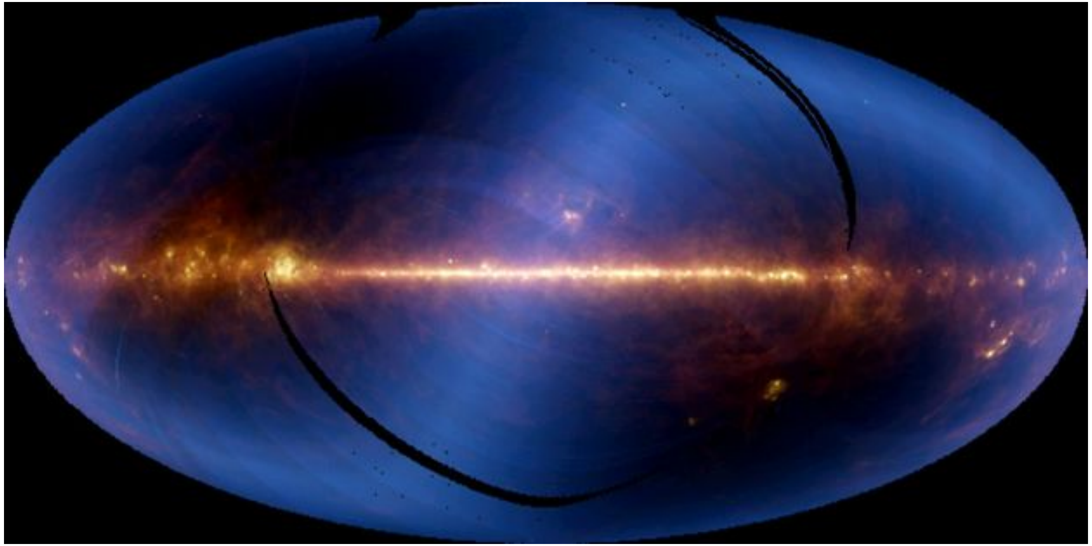
- Extinction is primarily caused by dust within our own MW (i.e. foreground extinction)
- DIRBE / COBE (1989-1993): One of the first direct measurement of the extragalactic background light in the 125 to 5000 μm wavelength region was performed by the Diffuse Infrared Background Experiment (DIRBE) and Far Infrared Absolute Spectrophotometer (FIRAS) on board the Cosmic Background Explorer (COBE)



INTERSTELLAR EXTINCTION: OBSERVATIONS

ISSA: IRAS Sky Survey Atlas

- **Scanned the MW at different wavelengths(12,25,60,100μm)**
- **Determined dust column density and then E(B-V) using B-V colours of elliptical galaxies**
- **Convert to extinction using standard R_v =3.1**
- **Integrated extinction in the line of sight**



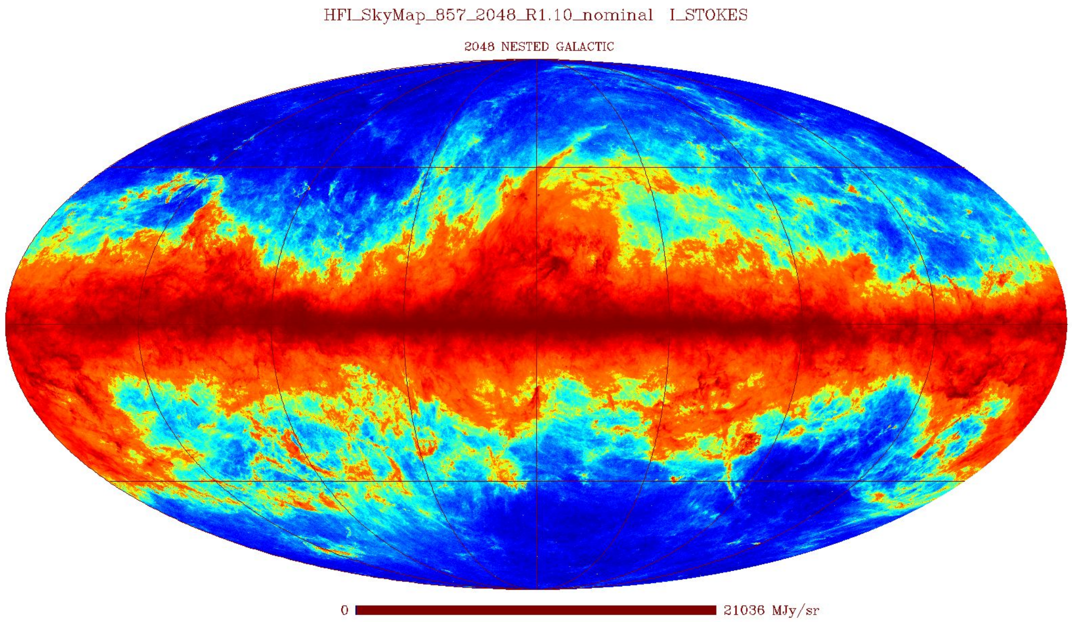
The colours represent infrared emission detected in three of the telescope's four wavelength bands – blue is 12 microns; green is 60 microns, and red is 100 microns.

INTERSTELLAR EXTINCTION: OBSERVATIONS

Wien's Law ($\lambda_{max} \propto 1/T$)

Planck

- Measured the emission of dust across a wide range of frequencies (9 channel from 30 to 857 GHz → 10 - 0.35 mm)
  - Allow to accurately separate foreground and background emission, and thus compute a map of the dust optical depth
  - interstellar dust is not a uniform temperature; Planck provided the most detailed maps of "cold" vs. "warm" dust regions, which is essential for calculating the exact **extinction (A_V)** along different lines of sight.
- Planck's ability to measure the **polarization** of dust emission across the entire sky allowed astronomers to map the **Galactic magnetic field** for the first time on a global scale



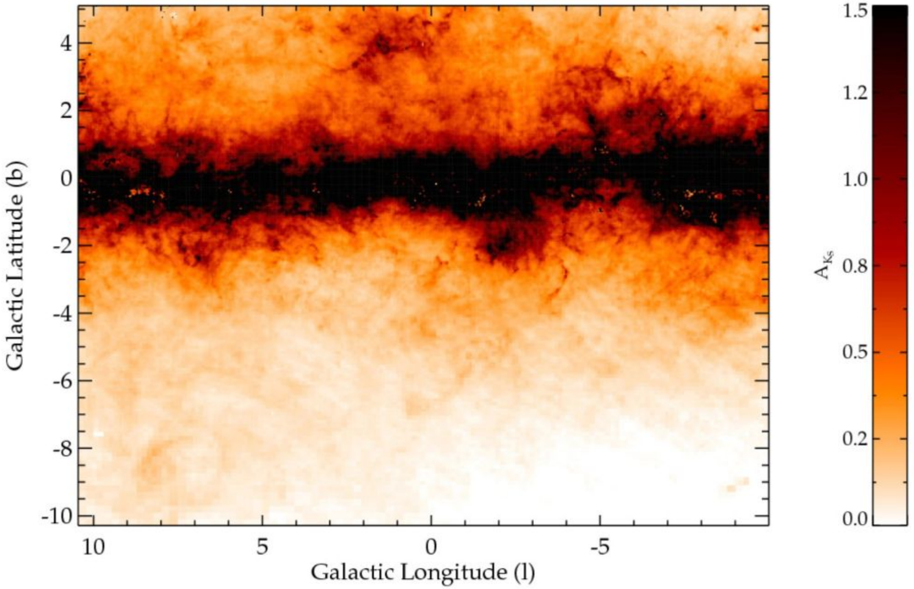
The map displays the intensity in each specific band in units of thermodynamic temperature (K_CMB) for 30-353 GHz and in surface brightness (MJy/sr) at 545 and 857 GHz

INTERSTELLAR EXTINCTION: OBSERVATIONS

Milky Way Extinction:

- Extinction is most intense along the horizontal plane of the Milky Way.
- Because the density of dust and stars is highest toward the **Galactic Bulge**, the extinction and reddening (E(B-V)) are significantly stronger in that direction compared to the galactic poles.
- While concentrated in the disk, dust is present in every direction, requiring astronomers to "integrate extinction in the line of sight" for every extragalactic source.

A_{k_s} extinction in the galactic bulge



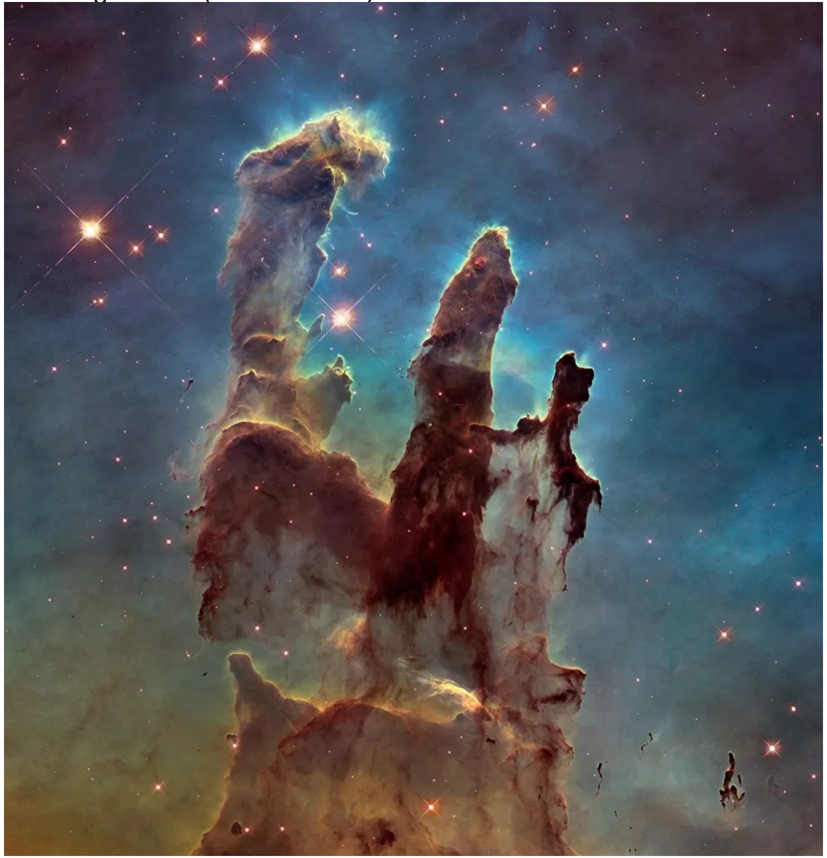
Gonzalez et al. 2012, A&A

ISM: MOLECULAR CLOUDS

Properties:

- **Density**: ~100–1000 cm^{-3}
- **Temperature**: ~10 K
- **Internal velocities**: ~10 km/s (supersonic turbulence)
- **Mass**: $M \sim 10^6 M_\odot$
- **Radius**: R ~ 50 pc
- **Surface density**: $\Sigma_{gas} \sim 100 M_\odot pc^{-2}$
- **Primary components:** H_2, CO, Heavy elements (C,O,N), dust grains
- **Gas tracers**: CO, C^+, HCN

Eagle nebula (Messier 16). NASA, ESA and the Hubble Heritage Team (STScI/AURA)

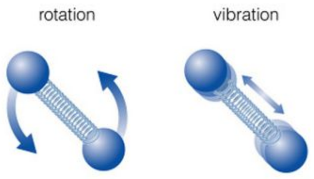


ISM: MOLECULAR CLOUDS

Molecular Hydrogen:

- H_2 is the most abundant molecule in the Universe, but it is **symmetric** and has **no permanent electric dipole moment**. Therefore it only radiates when shocked or irradiated to T ≥ 1000 K. Since most H_2 sits at T ~ 10–100 K, **direct detection is nearly impossible**.

- Polar molecules have a non-zero electric dipole moment and radiate due to rotational and vibrational modes. For a diatomic molecule, the rotational energy at quantum level J is:



$$E_{\text{rot}} = \frac{J(J+1)\hbar^2}{2I}, \text{ where } J = 0, 1, 2, \ldots$$

Only transitions between states J and J±1 are permitted (ΔJ = ±1). The emitted frequency:

$$\nu = \frac{\hbar J}{2\pi m r_{\text{eq}}^2}$$

ISM: MOLECULAR CLOUDS

CO as molecular gas tracer:

- Because H_2 is very difficult to observe directly, we use CO – the second most abundant molecule in the Galaxy – to trace the molecular gas content of the Milky Way (and other galaxies, too!)
- J=0→1 transition: **λ = 2.6 mm (115 GHz)**
- J=1→2 transition: **λ = 1.3 mm (230 GHz)**
- Excitation temperatures: ~11 K (J=0–1) and ~17 K (J=1–2)
- Critical density, at which collisional excitation is in equilibrium with emission for CO J=1–2: ~700 cm^{-3}, typical of giant molecular clouds in the MW
- The conversion between CO intensity and H_2 mass:

$$X_{CO}=2\times10^{20} \text{ molecules cm}^{-2}(\text{K km s}^{-1})^{-1}$$

- This factor is roughly constant in the Milky Way, but is **unlikely to be universal** in other galaxies — a major source of uncertainty in extragalactic studies.

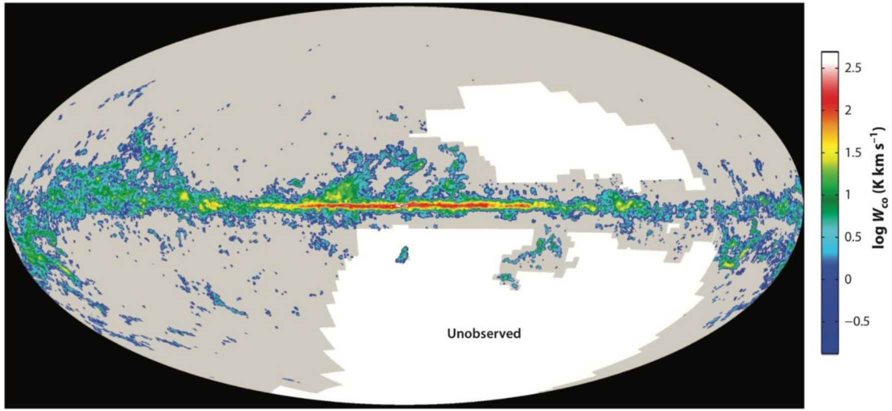


Figure 3

An image of ^{12}CO J = 1–0 emission constructed from the recent Center for Astrophysics campaign to examine the high-latitude sky and the composite surveys of Dame et al. (2001) and Mizuno & Fukui (2004).

ISM: MOLECULAR CLOUDS

Key Results (Heyer & Dame 2015)

1. The total H_2 mass of the Milky Way is $(1.0 \pm 0.3) \times 10^9\ M_\odot$ (from CO surveys)
2. Most of the H_2 gas (60-70%) is located inside the solar circle (R_{sun} = 8.5 kpc)
3. H_2 gas is largely confined to the Galactic plane within a Gaussian layer **~90 pc** FWHM thickness in the inner Galaxy that subsequently broadens to several hundred pcs for radii greater than 10 kpc
4. Molecular gas is **mainly confined to the Galactic spiral arms**

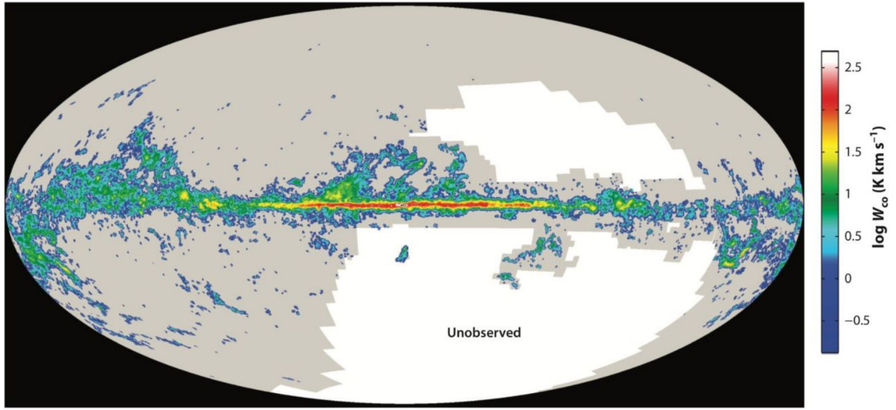
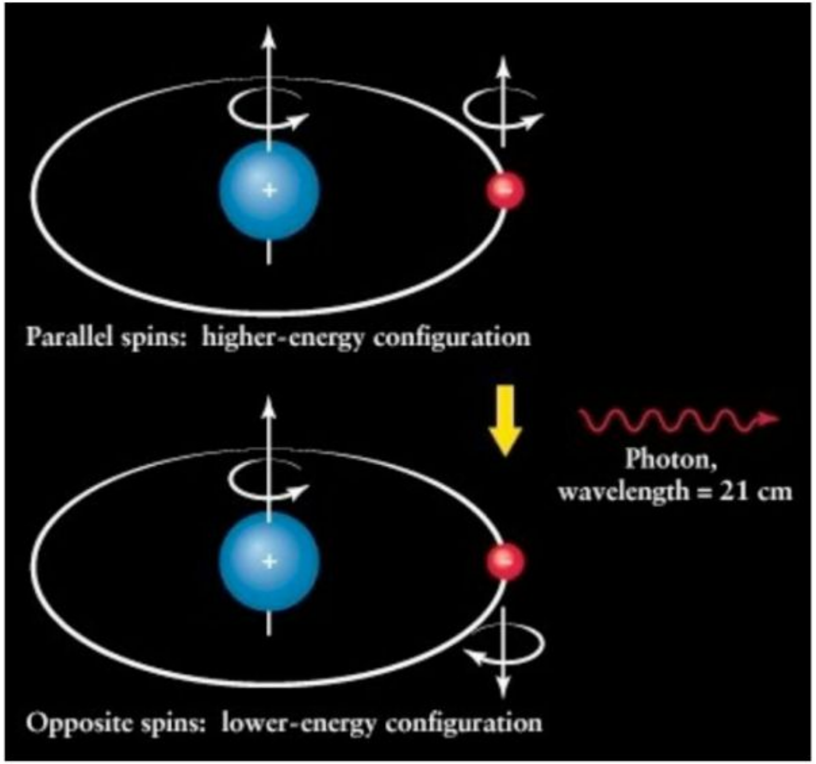


Figure 3

An image of $^{12}CO\ J = 1$–0 emission constructed from the recent Center for Astrophysics campaign to examine the high-latitude sky and the composite surveys of Dame et al. (2001) and Mizuno & Fukui (2004).

ISM: HI and 21cm line

Hydrogen is the most abundant element in the Universe and in the interstellar medium (ISM) of the Milky Way. The cold interstellar gas does not emit radiation at visible wavelength but at radio wavelengths due to a hyperfine line from two closely spaced energy levels in the ground state of the neutral H atom (HI). An HI atom with the spins aligned will spontaneously flip back to the lower energy, non-aligned, state after sometime.



Hyperfine transitions are a consequence of coupling between nuclear spin and the magnetic field generated by the orbiting electron.

ISM: HI and 21cm line

- **The frequency of the centre of this line is defined from quantum mechanics:**

$$\nu_{10} = \frac{8}{3} g_I \left(\frac{m_e}{m_p} \right) \alpha^2 (R_M c) = 1420.406\,\text{MHz}$$

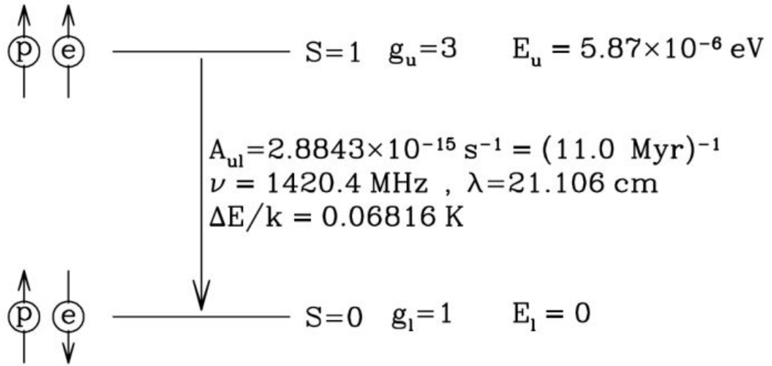


Figure 3.4: *Schematic illustration of hyperfine splitting of the ground state of atomic hydrogen. From: Gould 1994.*

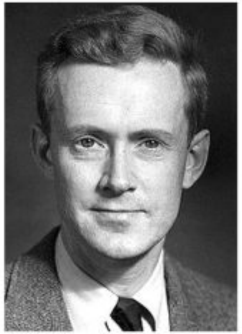
The spontaneous radiative **de-excitation coefficient** (Einstein A-coefficient) for this transition is **A = 2.87 × 10^{-15} s $^{-1}$ = 11 Myr^{-1}** . An individual hydrogen atom therefore spends on average ~ 10^7 years in the upper level before it de-excites spontaneously, with the emission of a 21-cm photon. However, the weak emission per hydrogen atom is compensated by the enormous amount of hydrogen in interstellar space, and the 21 cm radio emission is ubiquitous in the Galaxy.

ISM: HI and 21cm line

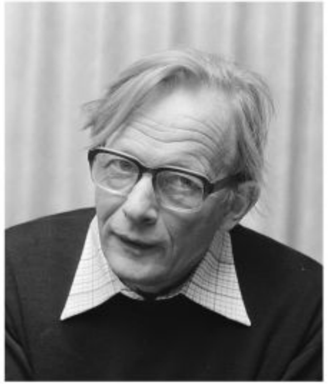
History of 21cm line:

- **1947: Van de Hulst predicted that 21cm line from ISM should be easily detectable**
- **Oort and his student Mueller used a radar antenna from WWII in Wurzburg to detect 21cm line, but a fire destroyed the equipment**
- **At the same time Edward and Ewen built a horn-antenna to detect 21cm line**
  - **First time detected on easter of 1950**
- **Waited until Oort and Mueller rebuilt their experiment and published together (1951)**

Jan Oort



Edward Mills Purcell



Henk van de Hulst

Harold Ewen

ISM: HI and 21cm line

Mapping the Milky Way in HI:

- By measuring the **Doppler shift** of the 21-cm line, we can determine the **radial velocity** of HI clouds:

$$z = \frac{\lambda_{\rm obs} - \lambda_{\rm em}}{\lambda_{\rm em}} = \frac{\nu_{\rm em} - \nu_{\rm obs}}{\nu_{\rm obs}} \text{ and } v = cz$$

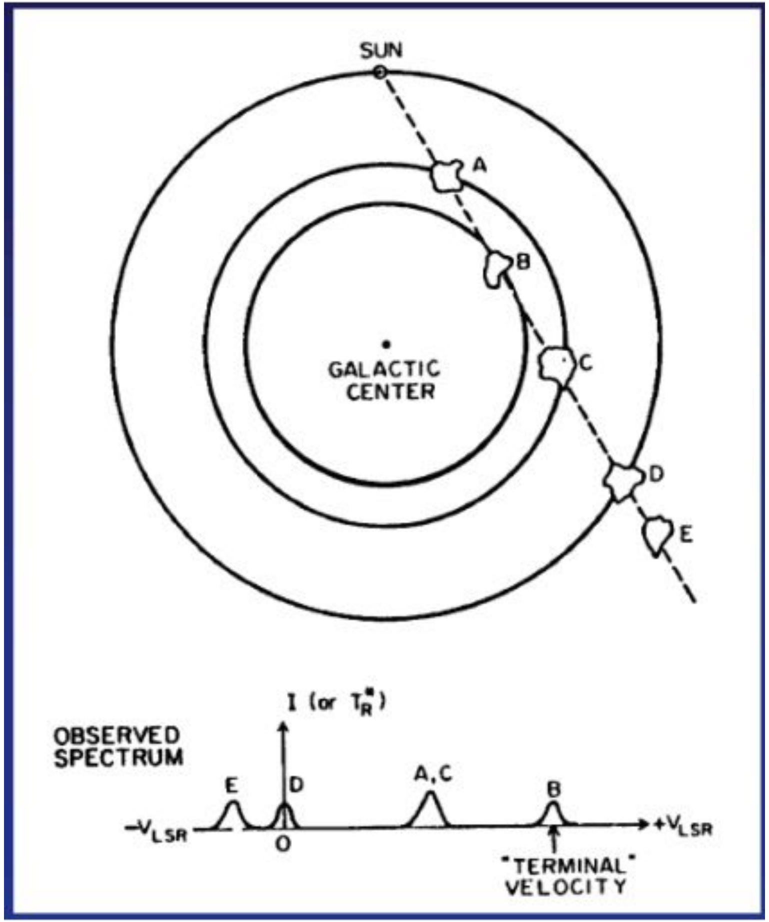
- Integrating the observed intensity over frequency gives the HI column density:

$$N(\text{H I}) = 1.821 \times 10^{13} \int_{\rm line} T\, \tau_v \, dv,$$

ISM: HI and 21cm line

Mapping the Milky Way in HI:

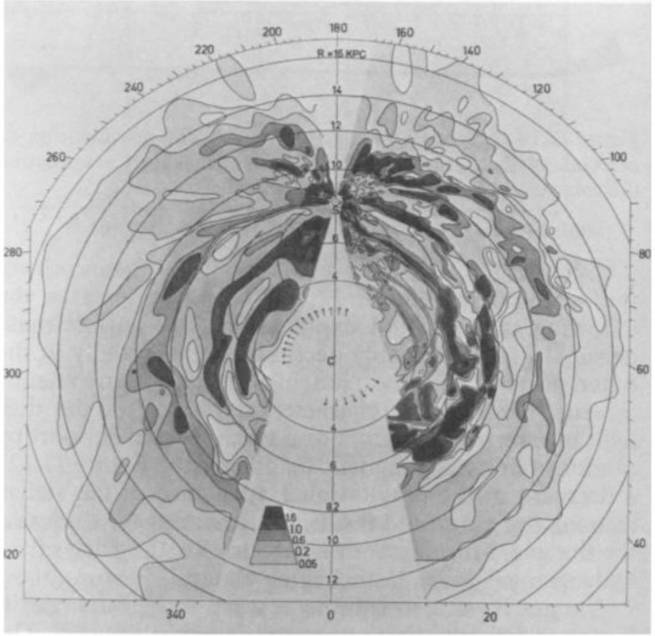
- The **HI spatial distribution** can be reconstructed from a kinematic analysis of 21-cm emission profiles at different Galactic longitudes
- The reconstruction is based on a kinematical model of Galactic rotation, w(R)
  - It is assumed that interstellar clouds at Galactocentric distance R move in orbits with angular velocity ω(R)
  - From the observed radial velocity at a given longitude one can estimate the cloud distance using a model of Galactic rotation ω(R)
  - The method works only for $R<R_{sun}$



ISM: HI and 21cm line

Mapping the Milky Way in HI:

The existence of **spiral arms was first proven** with this technique (Oort et al. 1958).



Oort et al. 1958, MNRAS

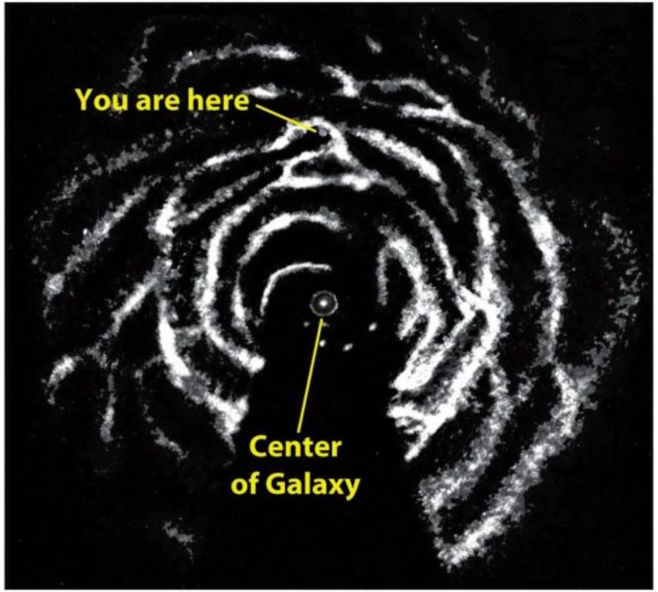


Figure 23-14
Universe, Ninth Edition

Map of the Milky Way obtained by Doppler measurements of the 21-cm line.

ISM: HI and 21cm line

Mapping the Milky Way in HI:

21 cm emission shows that hydrogen gas is concentrated along the plane of the Galaxy

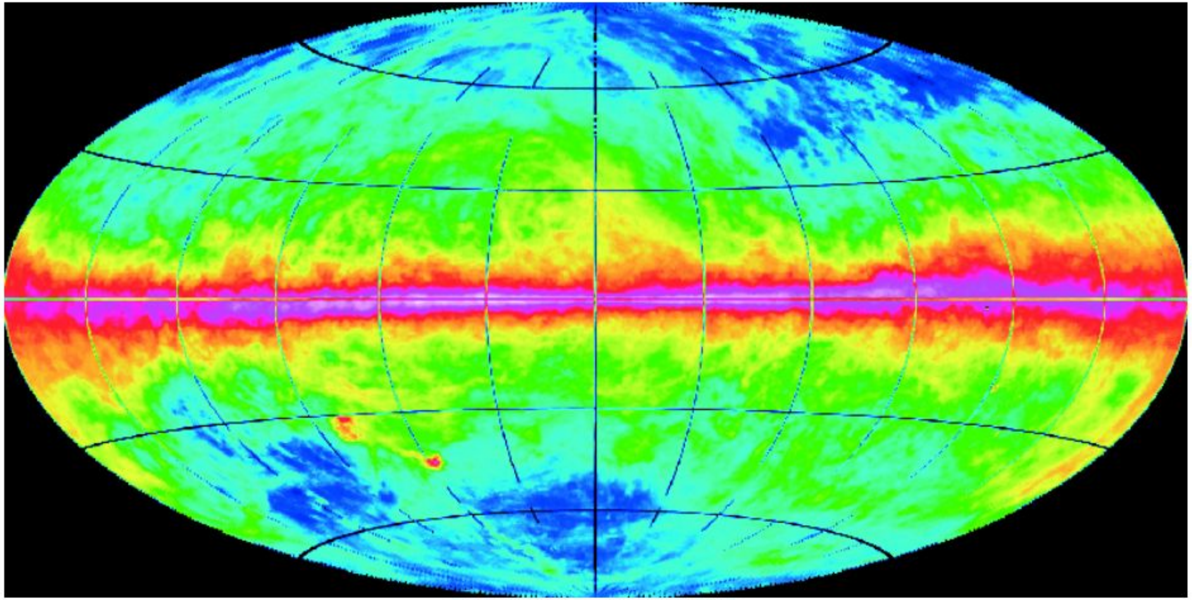
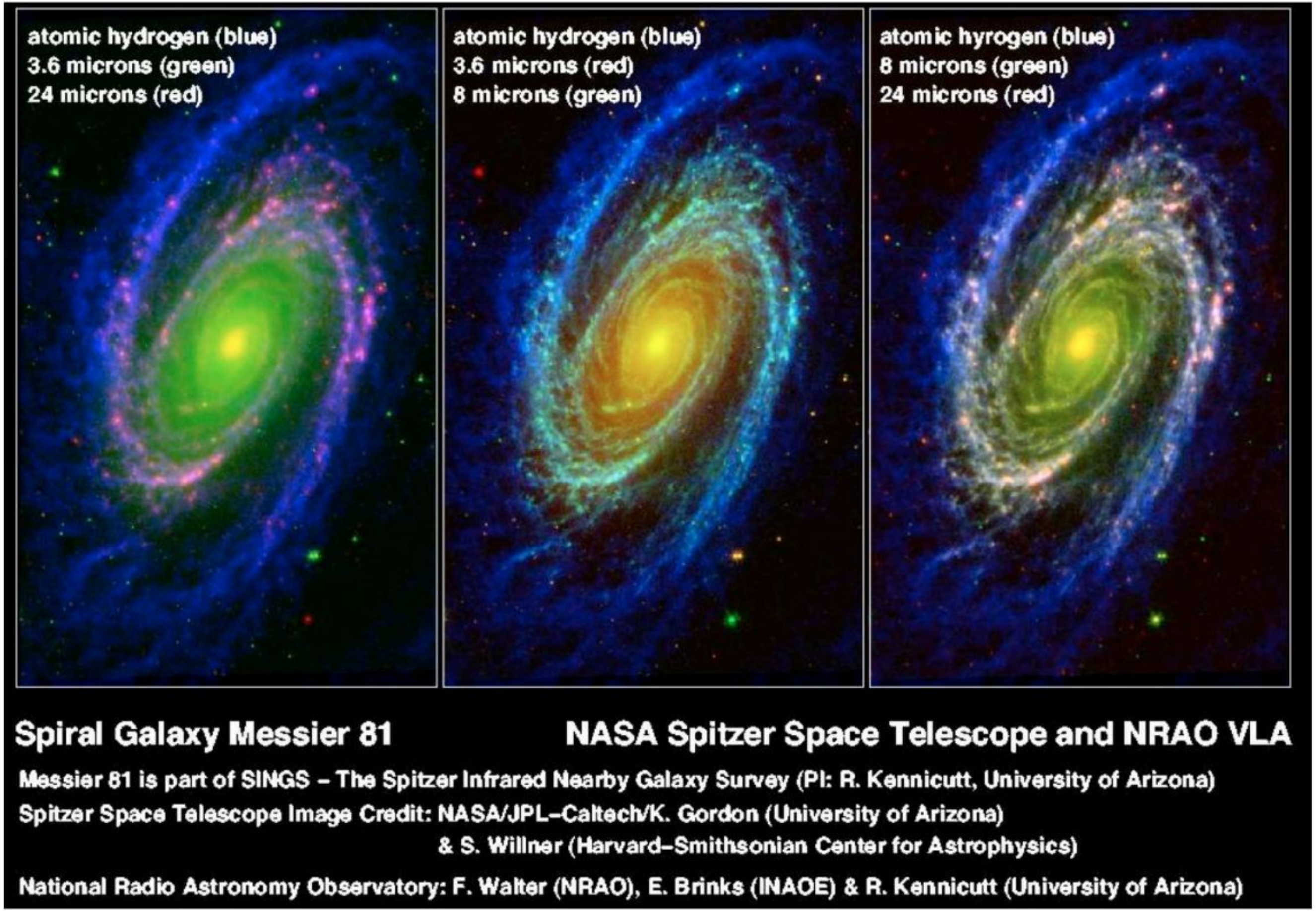


Figure 7.1: *H* I *emission integrated over the velocity range* $-400 < v < +400\,\mathrm{km\,s^{-1}}$ *in the Leiden-Argentine-Bonn (LAB) dataset, shown in Hammer-Aitoff projection centered on the Galactic Anti-Center. The angular resolution is 36-arcmin. The LMC and SMC are visible, with a connecting H* I *'bridge'. The integrated emission* ($0 < N(\mathrm{H\,I}) < 2 \times 10^{22}$ *atoms* $\mathrm{cm^{-2}}$*, on a logarithmic scale) yields column densities under the assumption of optical transparency. This assumption may be violated at*

ISM: HI and 21cm line

Neutral atomic gas (HI) and dust (seen in IR) are largely confined in the spiral arms



ISM: HI and 21cm line

ISM of Galaxies:

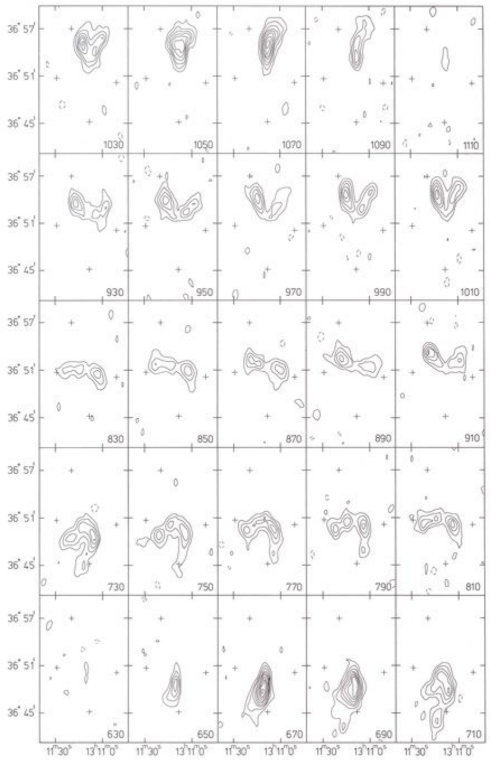
Observations in e.g.,Hα (ionized hydrogen) and 21 cm line in galaxies allow to map gas distribution

Measure the intensity from of these emissions from every position across the galaxy to create detailed maps.

Observations are conducted in narrow frequency ranges, or "channels" – typically, each covers a few kilometers per second in velocity – to isolate specific velocities of the medium.

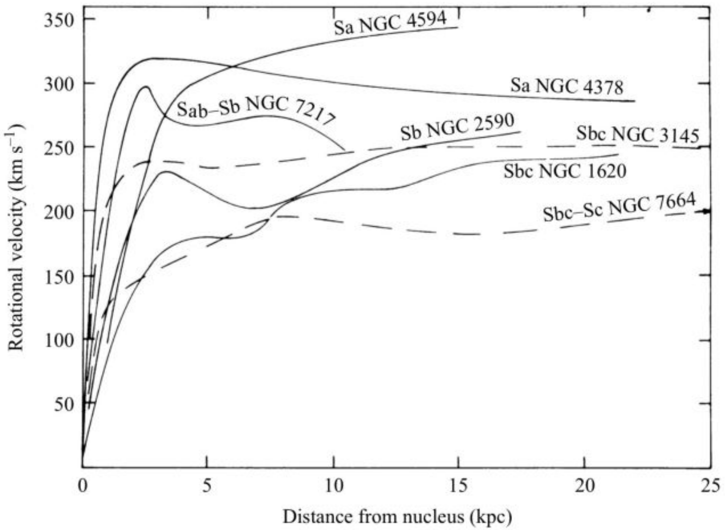
For the most part, HI in galaxy disks is optically thin; the 21 cm line suffers little absorption, so the mass of gas is just proportional to the intensity of its emission.

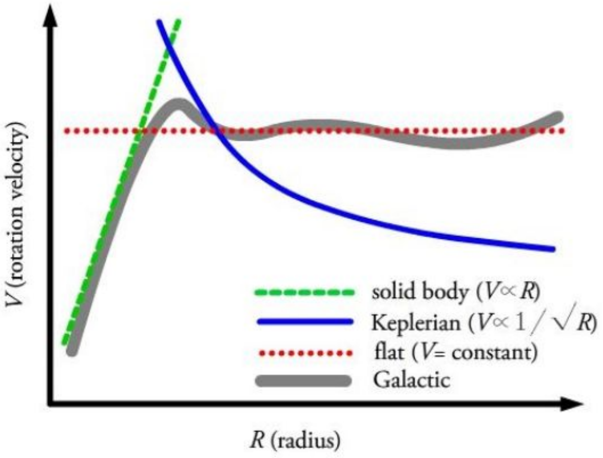
$$\mathcal{M}(\mathrm{HI}) = 2.36 \times 10^5 \mathcal{M}_\odot \times d^2 \int F_\nu\left[1421\,\mathrm{MHz} \times \left(1 - \frac{V_\mathrm{r}}{c}\right)\right] \mathrm{d}V_\mathrm{r}.$$



Maps of the 21 cm line radiation of NGC 5033. The heliocentric velocity (in km s^{-1}) of each channel map is indicated in the lower right corner

Galaxy rotation curves from 21 cm:





21-cm observations also provided the second (after Zwicky's measurements of Virgo galaxy cluster mass) major evidence for **dark matter** through **rotation curves** (Vera Rubin, 1970s): the observed flat rotation curves cannot be explained by visible matter alone.

ISM: HI and 21cm line

21 cm cosmology:

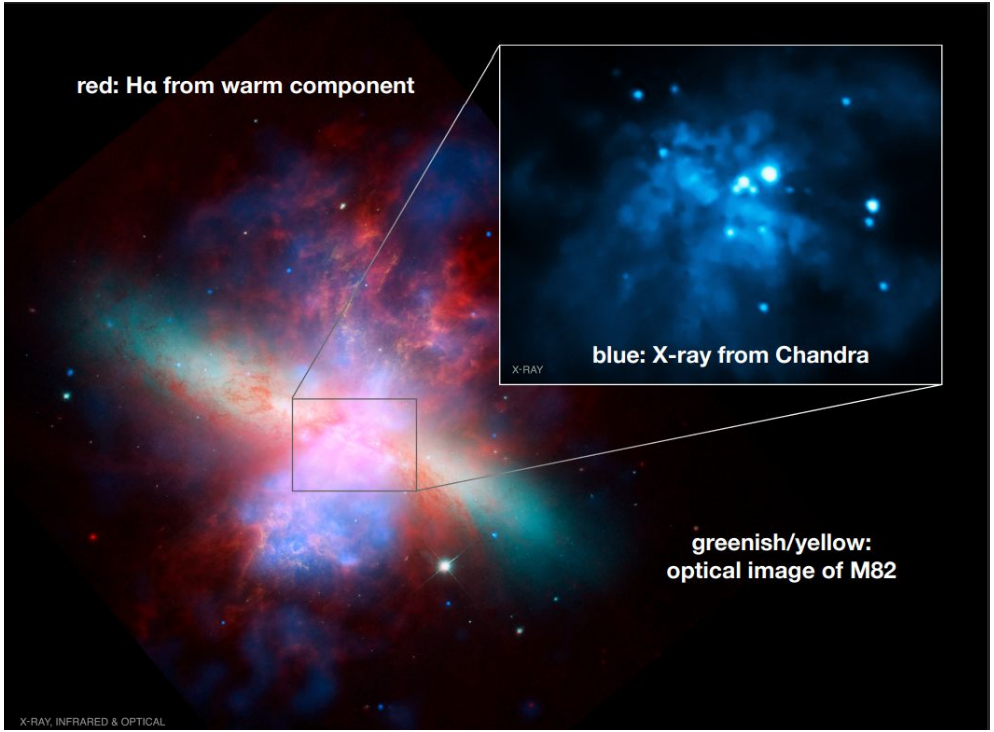
ISM: Hot Ionized Medium

Origin:

- The HIM is primarily created and energized by SN and the intense radiation from High-mass stars.
- Hottest phase of the interstellar cycle, following the "Stardust injection" from stellar deaths.

HIM properties:

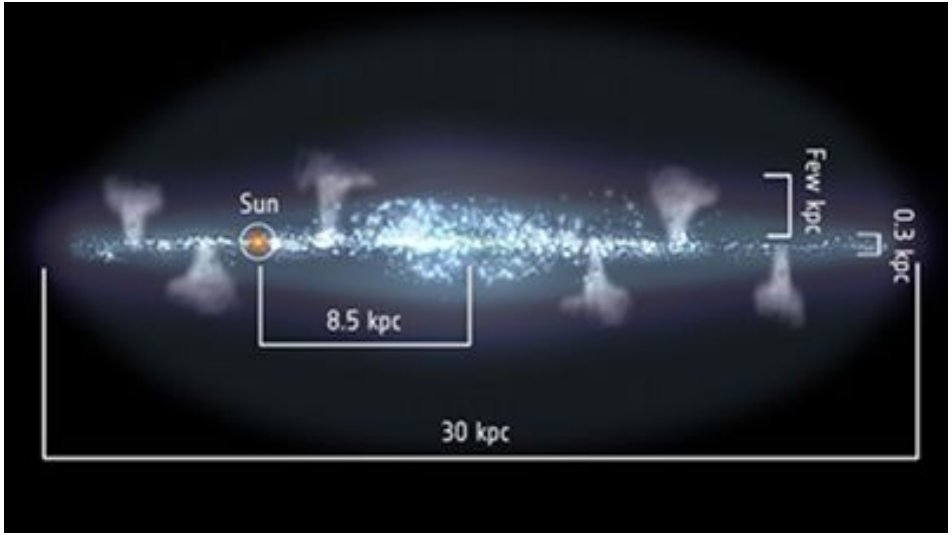
- density: ~10^{-3} cm^{-3}
- temperature: ~10^6 K → almost completely ionized gas
- thermal velocities: 100 km/s
- complex kinematics
- gas tracer: X-rays, high-ionization absorption lines: OVI, CIV, NV etc. (far UV)



ISM: Hot Ionized Medium

HIM properties:

- **Occupies ~50% of the volume of the ISM**
- **The vertical scale height of this gas is ~3 kpc, so it is sometimes referred to in the literature as the hot 'corona' of the galaxy**
- **This hot gas is often buoyant and appears as bubbles, with characteristic dimensions of ~20 pc, and fountains high above and below the disk.**
- **The gas is collisionally ionized and cools – primarily through adiabatic expansion and X-ray emission – on ~Myr timescales**

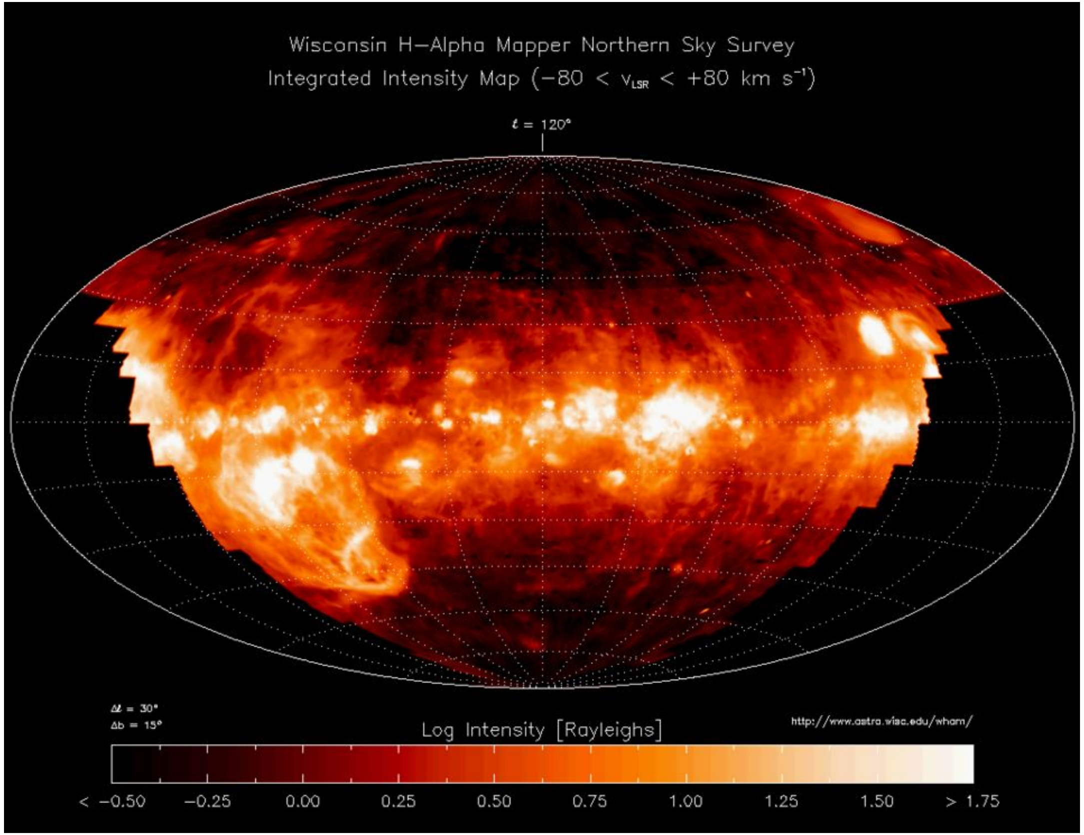


Supernova-driven turbulence in the interstellar medium of the Milky Way contributes to the formation of galactic fountains. *Credit: ESA*

ISM: Warm Ionized Medium

Warm ionized medium (WIM) or Diffuse ionized gas (DIG) properties:

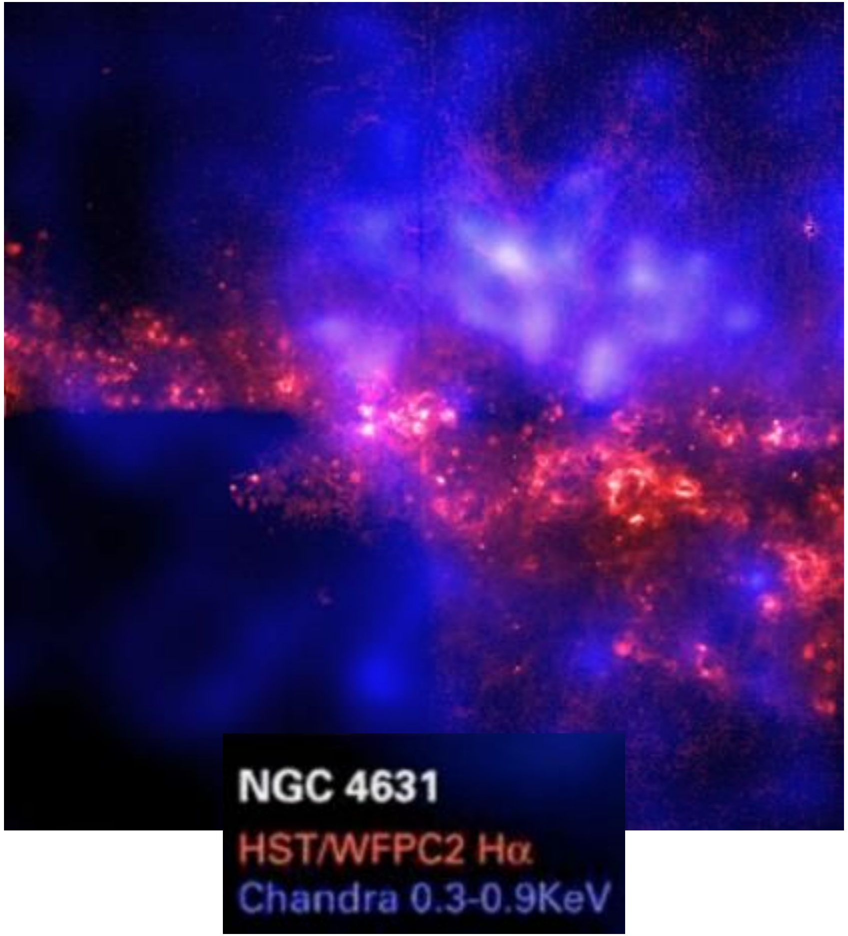
- **Density: ~0.2 cm^{-3}**
- **Temperature: ~10^4 K**
- **Ionized by photons escaping from HII regions**
- **Constitutes ~90% of all ionized hydrogen mass in the Galaxy (~10^9 $M_\odot$)**
- **Fills ~20% of the ISM volume**
- **Transition Phase: It sits between the high-energy HIM and the cooler Diffuse Clouds**
- **Produces a faint, pervasive Hα emission – red visible light that occurs when electrons recombine with hydrogen nuclei in "warm" gas – seen in every direction across the sky**



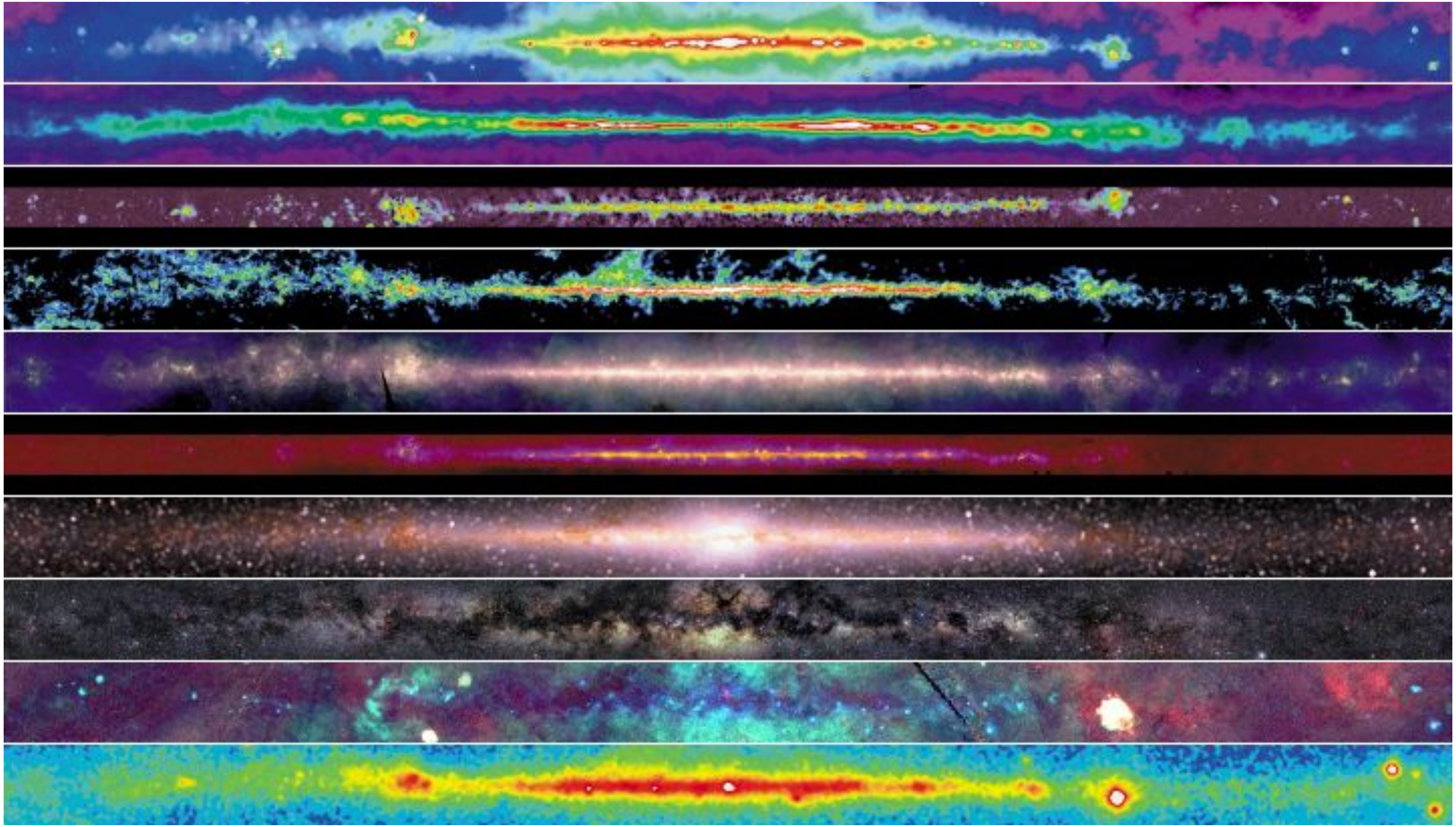
ISM: Warm Ionized Medium

Warm ionized medium (WIM) or Diffuse ionized gas (DIG) properties:

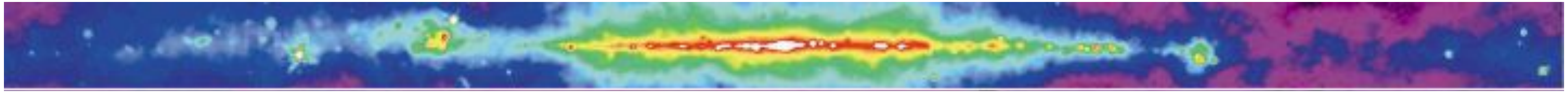
- In other galaxies, observed as discrete loops, filaments, and shells not directly associated with HII regions
- The DIG accounts for **30–50% of the total Hα emission** of each galaxy
- The Hα intensity is measured across different frequency channels to understand the range of velocities caused by the **Doppler effect**.



HOW DO WE OBSERVE THE ISM



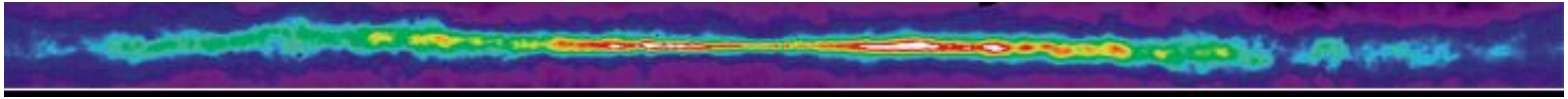
HOW DO WE OBSERVE THE ISM



Radio continuum (408 MHz)

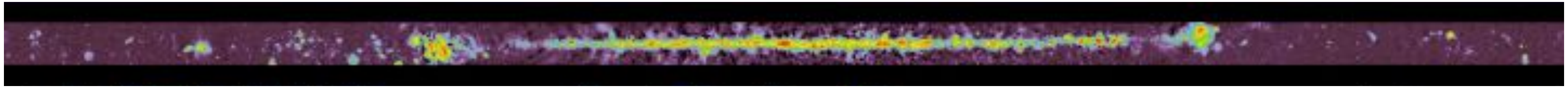
Synchrotron radiation from relativistic electrons (accelerated by SN shocks and pulsars) spiraling in the ~μG galactic magnetic field

HOW DO WE OBSERVE THE ISM



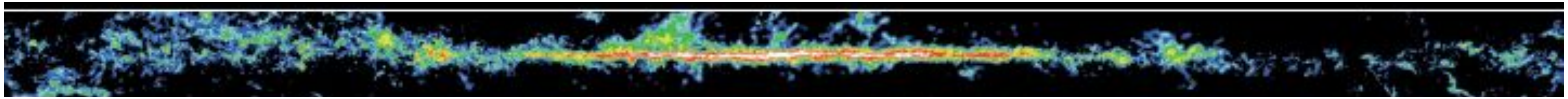
Atomic hydrogen (21 cm) **HI** neutral atomic hydrogen, hyperfine transition

HOW DO WE OBSERVE THE ISM



Radio continuum (2.5 GHz) Synchrotron + **bremsstrahlung** (free-free) from supernova remnants and hot gas

HOW DO WE OBSERVE THE ISM



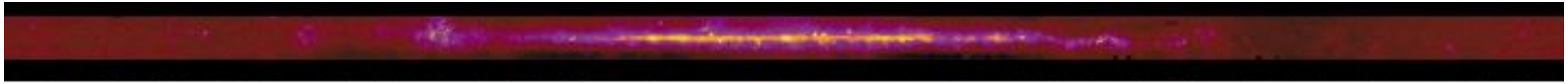
Molecular hydrogen (CO) Traces **molecular gas** in the Galactic plane

HOW DO WE OBSERVE THE ISM

Far Infrared	Thermal emission from **dust** — heated by old stars (diffuse "cirrus") or by young massive stars in molecular clouds

HOW DO WE OBSERVE THE ISM

Mid Infrared **PAH emission lines** from polycyclic aromatic hydrocarbons in the diffuse dust



HOW DO WE OBSERVE THE ISM

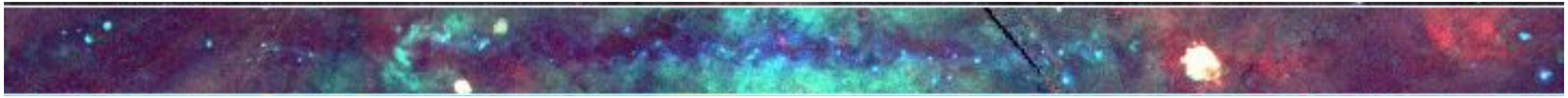
Near Infrared Emission from **old stars** (main sequence + giants) with little dust absorption

HOW DO WE OBSERVE THE ISM

Optical   Emission from stars **with dust absorption**

HOW DO WE OBSERVE THE ISM

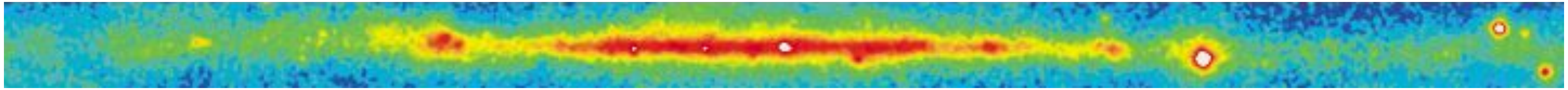
X-ray **X-ray binaries** + diffuse hot gas; some absorption by neutral hydrogen



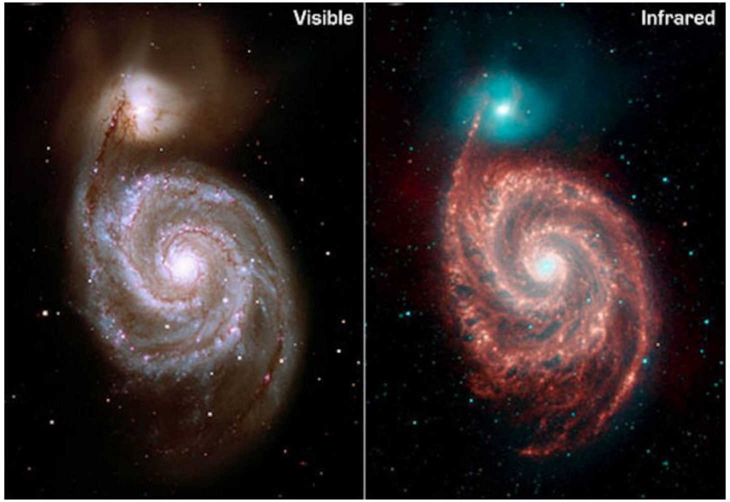
HOW DO WE OBSERVE THE ISM

Gamma-ray

Compact sources + gamma-ray photons from cosmic ray collisions with diffuse gas



HOW DO WE OBSERVE THE ISM



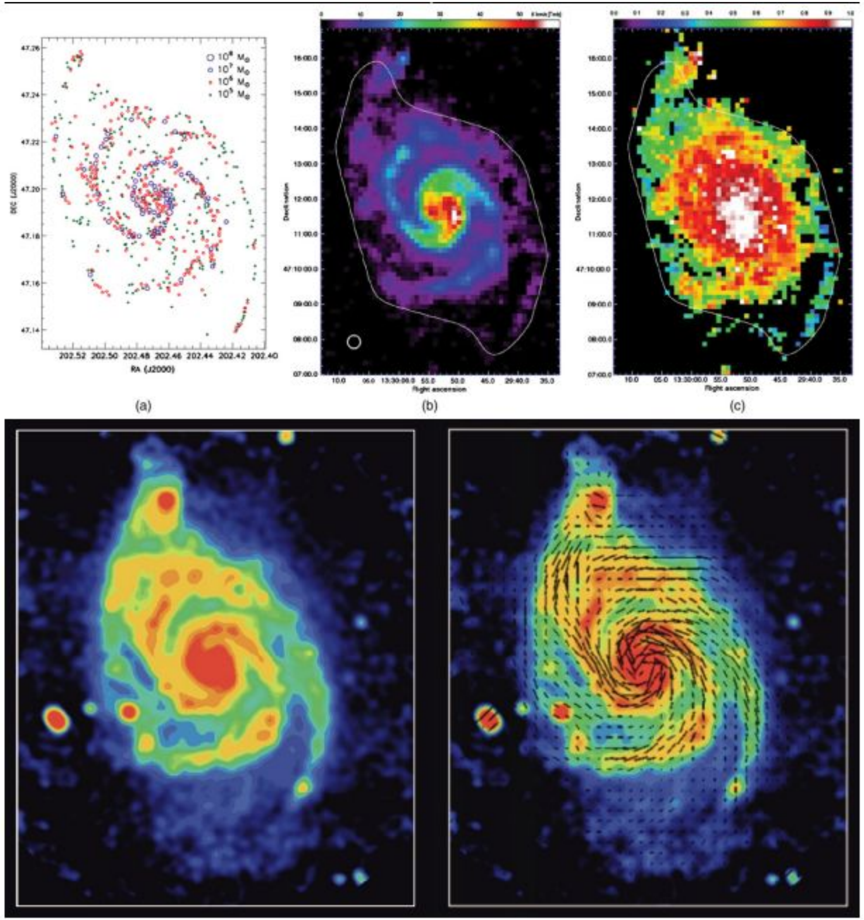


Figure 1.2: *M51a (NGC 5194, the Whirlpool galaxy) and its companion M51b (NGC 5195). Top panels: Visible-light image, with conspicuous dark dust lanes located along the spiral arms, and bright blue star forming regions. Near-infrared image in false blue (3.6 μm) and false red (8 μm) colors. The dust lanes, dark in the left panel, are glowing in 8 μm PAH emission. Note the numerous 'holes', where PAH emission is weak. (From: NASA/JPL-Caltech / R. Kennicutt). Middle panels, from left to right: Location of giant molecular clouds (GMCs) with masses $> 4 \times 10^5\ M_\odot$ (detected in CO 1–0). CO 1–0 line intensity image, smoothed over a 22" beam (circle in lower left corner); violet is 5 $\mathrm{K\,km\,s^{-1}}$, red = 50 $\mathrm{K\,km\,s^{-1}}$. H_2 fraction $2N(H_2)/\ [2N(H_2) + N(\mathrm{H\,I})\ ]$: green = 0.5, white = 1 (from Koda et al. 2009). Bottom panels, from left to right: 5 GHz emission, mainly synchrotron radiation from relativistic electrons. Magnetic field polarization of 5 GHz emission, revealing that the magnetic field is aligned with the spiral arms. (From NRAO/AUI/NSF / R. Beck and C. Horellou).*