The Interstellar Medium and Gas Dynamics

Astronomy 670

Spring 2015

Overview

- Study of the diffuse interstellar gas & dust
  - Energy sources
  - The radiation field
  - Non-thermal components: cosmic rays & ***B***
- Emphasis on Galactic ISM & aspects of ISM in external galaxies
- Connections to Galactic structure, star formation & feedback
- Broad & evolving subject
  - An exhaustive discussion neither desirable nor possible

Literature

- Core
  - Bruce Draine, “Physics of the Interstellar and Intergalactic Medium” (Princeton 2011)
  - James Lequeux, “The Interstellar Medium” (Springer 2005)
  - L. Spitzer, Jr., “Physical Processes in the Interstellar Medium” (Wiley 1978)
  - D. E. Osterbrock, "Astrophysics of Gaseous Nebulae and Active Galactic Nuclei" (University Science 1989)
  - F. H. Shu, “The Physics of Astrophysics” Volumes 1 & 2, (University Science Books, 1991,1992)
  - A. G. G. M. Tielens, “The Physics and Chemistry of the Interstellar Medium” (Cambridge 2005)
  - G. B. Rybicki & A. P. Lightman, "Radiative Processes in Astrophysics" (Wiley, 1979)

Literature

- Additional resources
  - D. J. Hollenbach & H. A. Thronson (eds.), “Interstellar Processes” (Reidel 1987) (M. Wolfire has a copy…)
  - W. W. Duley & D. A. Williams, “Academic Press” (IoP, 1984)
  - J. Graham and A. Glassgold’s (Berkeley) notes of AY216 at http://astro.berkeley.edu/~ay216/08/NOTES/

1. Introduction: Discovery & History of the ISM

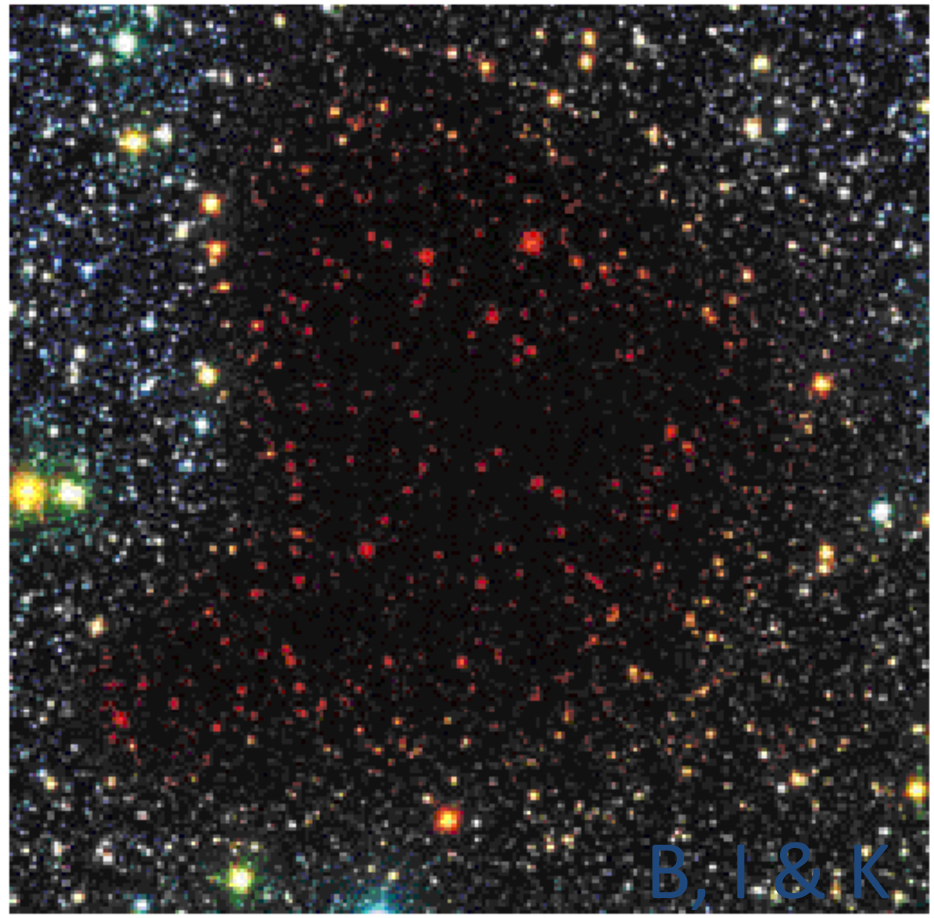
History

- 1656 Huygens, observes Nebula in Orion
- 1755/1796 Kant, Laplace nebular hypothesis
- 1787: Messier's catalog of nebulae
  - 1758-1860: W., C. & J. Herschel list 5079 objects in the "General Catalog"
- 1860-1900: W. Huggins & J. E. Keeler (Lick), spectra of nebula
  - Andromeda (stellar) vs. Orion (line)
- 1904: Hartmann, stationary Ca II H & K in spectroscopic binary δ Ori (ApJ 19, 268)
  - Interstellar or circumstellar?
- 1909: V.M. Slipher (one of the discoverers of galaxy redshifts) argues for interstellar origins
- 1912: V. Hess, discovery of ionizing "die Höhenstrahlung" during balloon flights
  - Not solar

History

- 1909-1915 Kapteyn, uses star counts to conclude we are near the center of the universe
- 1917 Curtis observes dark bands in spiral nebulae, likens them to ZOA in Milky Way
- 1919 H.N. Russell argues that ZOA is caused by dust
- 1919: E. E. Barnard (Lick), catalog of dark nebulae
  - Holes in stellar distribution or obscuring matter?
- 1926: Eddington predicts interstellar H_2. Influential lecture on "Diffuse Matter in Space" at Royal Society: people paid attention
- 1927-34: Clay, Bothe, Kohlörster & Alvarez, cosmic rays are high energy charged particles not γ rays
- 1930: R. Trumpler (Lick), proof of interstellar extinction
  - Comparison of luminosity & angular diameter distances to open clusters
- 1930: Plaskett & Pearce, narrow Ca II & Na I absorption is interstellar
  - Struve shows stronger CaII K in more distant stars

Barnard 68

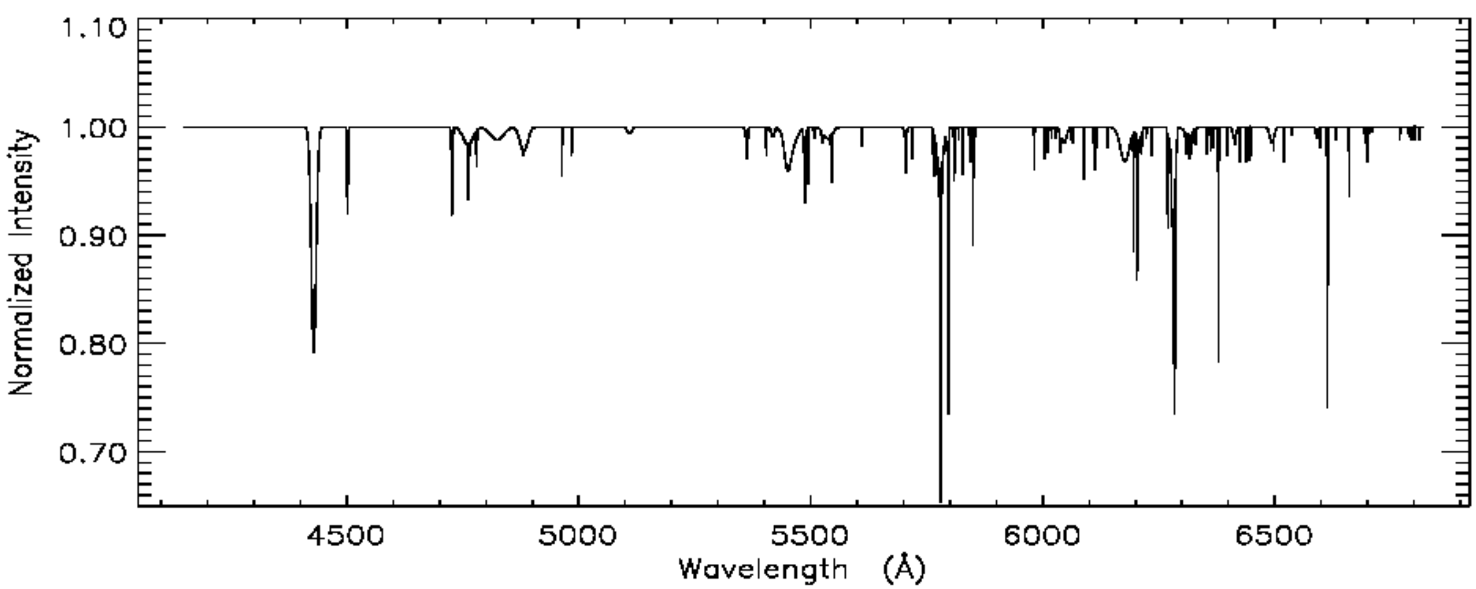


History

- 1932: K. Jansky discovers extraterrestrial radio emission
- 1934: P. W. Merrill, diffuse interstellar bands
- 1938: G. Reber (d. 2002) backyard radiotelescope discovers the Milky Way
- 1937–40: Swings, Rosenfeld, McKellar & Adams: first interstellar diatomic molecules
  - CH, CH^+, CN
- 1945: van de Hulst, predicts 21-cm line of HI
- 1949: Hall & Hiltner, polarization of starlight correlated with reddening
  - Aligned grains & interstellar magnetic field

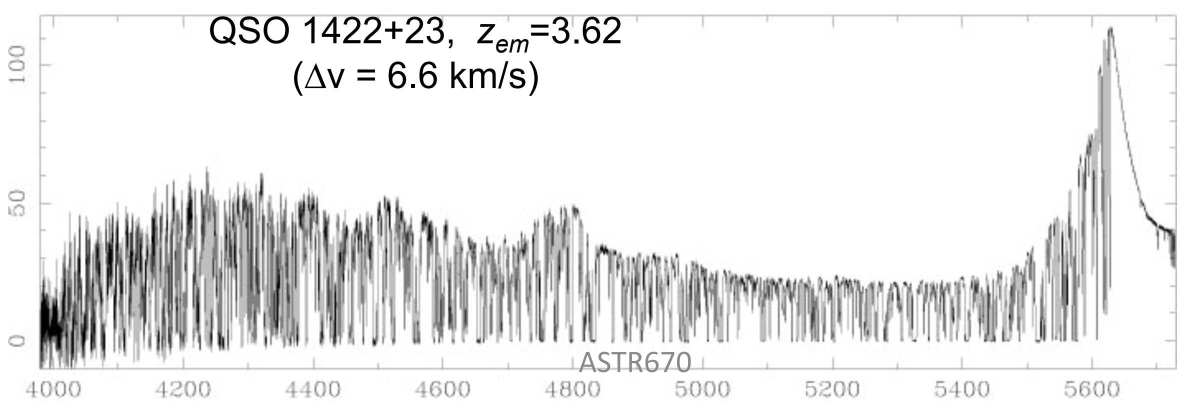
Diffuse Interstellar Bands

- ~ 200 DIBs known
- Most DIBs are unidentified
- Some DIBs may be due to large carbon-bearing molecules
  - C_{60}^{+} is a candidate for $\lambda\lambda$ 9577, 9632 bands



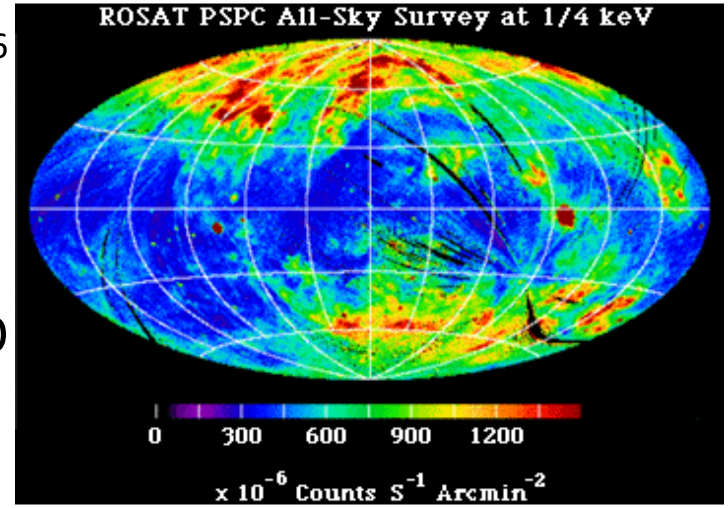
History

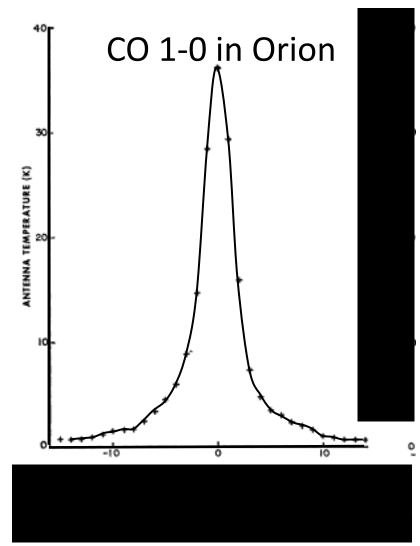
- 1950's: Cosmic rays consist of heavy particles (protons, α particles, etc.)
- 1951: Ewen & Purcell- Muller & Oort, detection of 21 cm line
- 1950's – 60's: 21 cm maps of the Galaxy
  - Disk contains 5×10^{9} $M_{\odot}$ of gas (≈10% of disk mass)
- 1963: A. Barrett (MIT): OH in absorption against Sgr A
- 1963: Weinreb, Townes et al., interstellar OH masers
- 1966: Lynds & Stockton, the Lyman α forest
- 1968: Townes, NH_3 (first polyatomic molecule), H_2O



History

- 1960's: Soft X-ray background from local 10^6 K gas
- 1968: Verschuun observation of Zeeman effect at 21cm
- 1970: Wilson, Jefferts & Penzias, 2.6 mm CO 1–0 emission
- 1973: Carruthers, UV lines of H_2
- 1970's – 80's: Infrared
  - H_2 infrared lines, small dust particles, very large molecules
- 1980's – 90's: Sub-millimeter
  - Warm interfaces of molecular clouds, cold protostellar regions

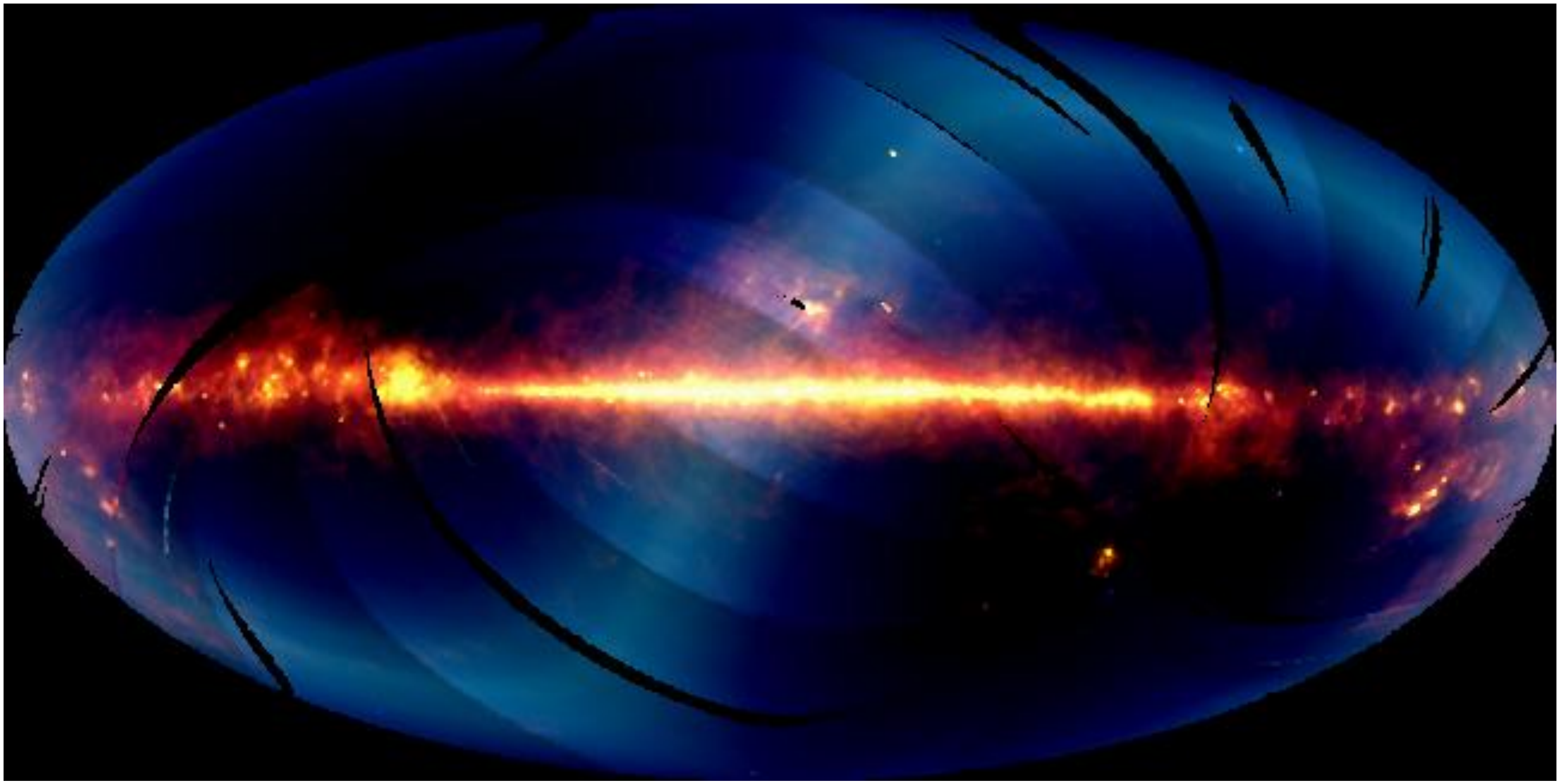




Impact of Space Astronomy

- 1973 – 80: Copernicus UV satellite
  - Detection of H_2 for many lines of sight
  - Highly ionized atoms (e.g., O VI) $\rightarrow$ very hot & tenuous component of ISM
  - Depletion of refractory elements from gas into grains
- 1983: IRAS
  - First all-sky survey at 12, 25, 60 & 100 μm
  - Cirrus clouds and dust properties

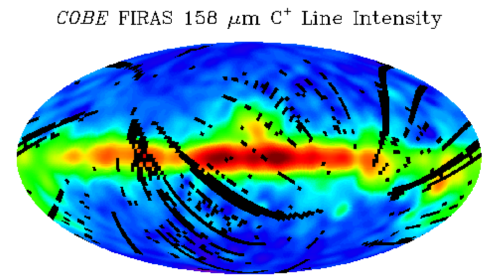
IRAS

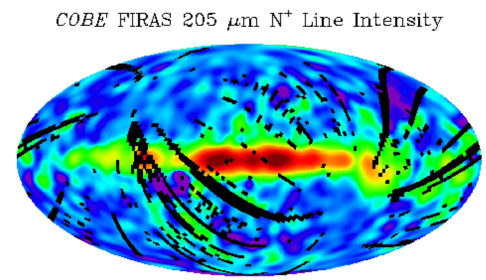


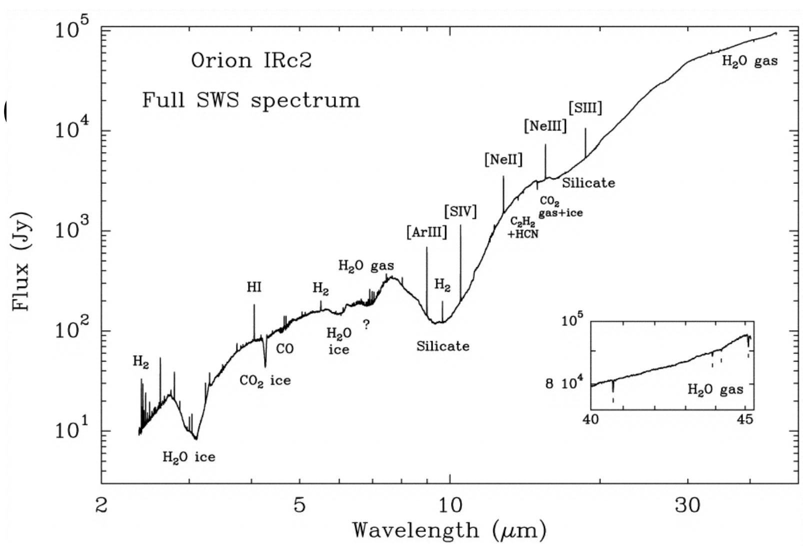
Blue: 12 µm Green: 60 µm Red: 100 µm

The Impact of Space Astronomy

- 1990 – 91: COBE
  - Galactic distribution of C^+ & N^+
- 1995 – 98 : ISO
  - Mid- and far-IR spectroscopy
  - Nature of grains (silicates, ices) and PAHs
  - H_2 lines as probe of shocks an PDRs
  - Excitation of gas by stars & Active Galactic Nuclei

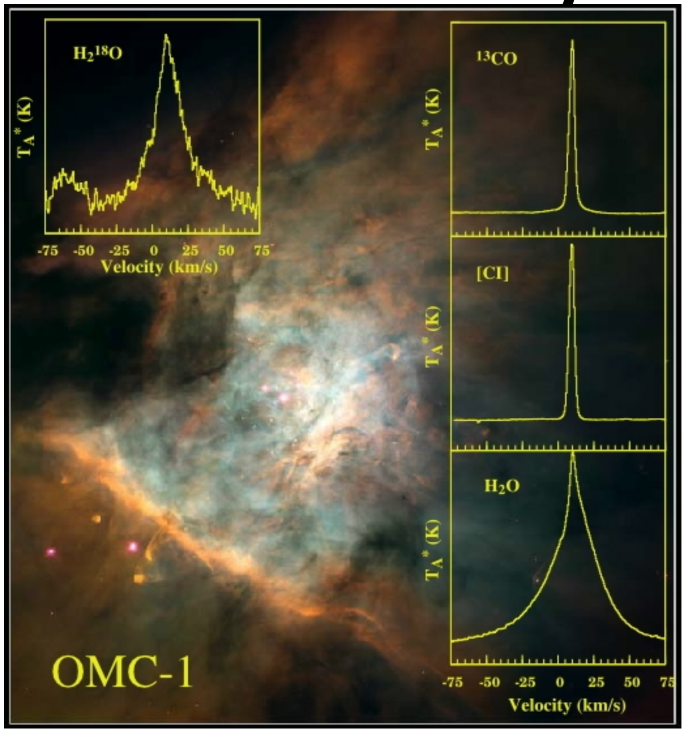


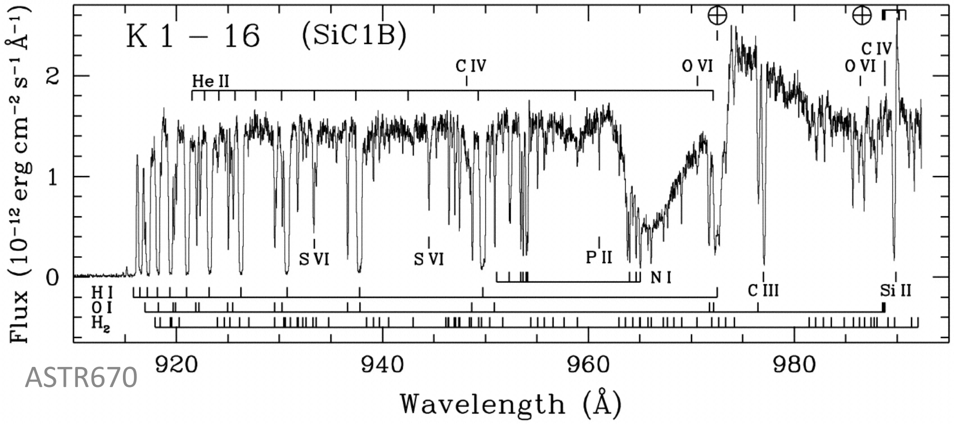




The Impact of Space Astronomy

- 1998 – 2001: SWAS (Submillimeter Wave Astronomy Satellite)
  - High frequency (~500 GHz) Pointed observations of H_2O, $H_2^{18}O$, O_2, CI, & ^{13}CO
  - Chemistry, composition & collapse of molecular clouds
- 2000 – 01: FUSE (Far-UV Space Explorer)



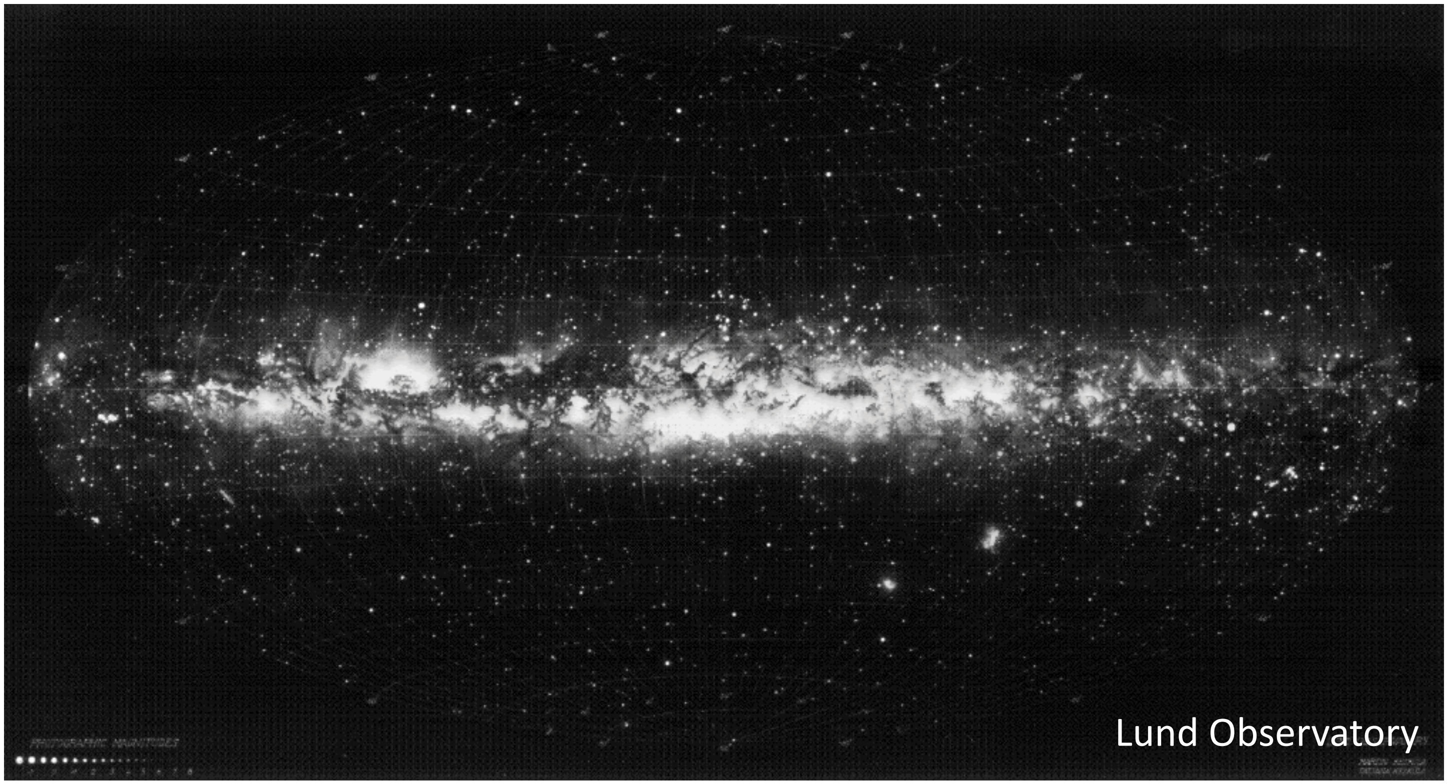


- 2004: SIRTF -> Spitzer

The Galactic Perspective

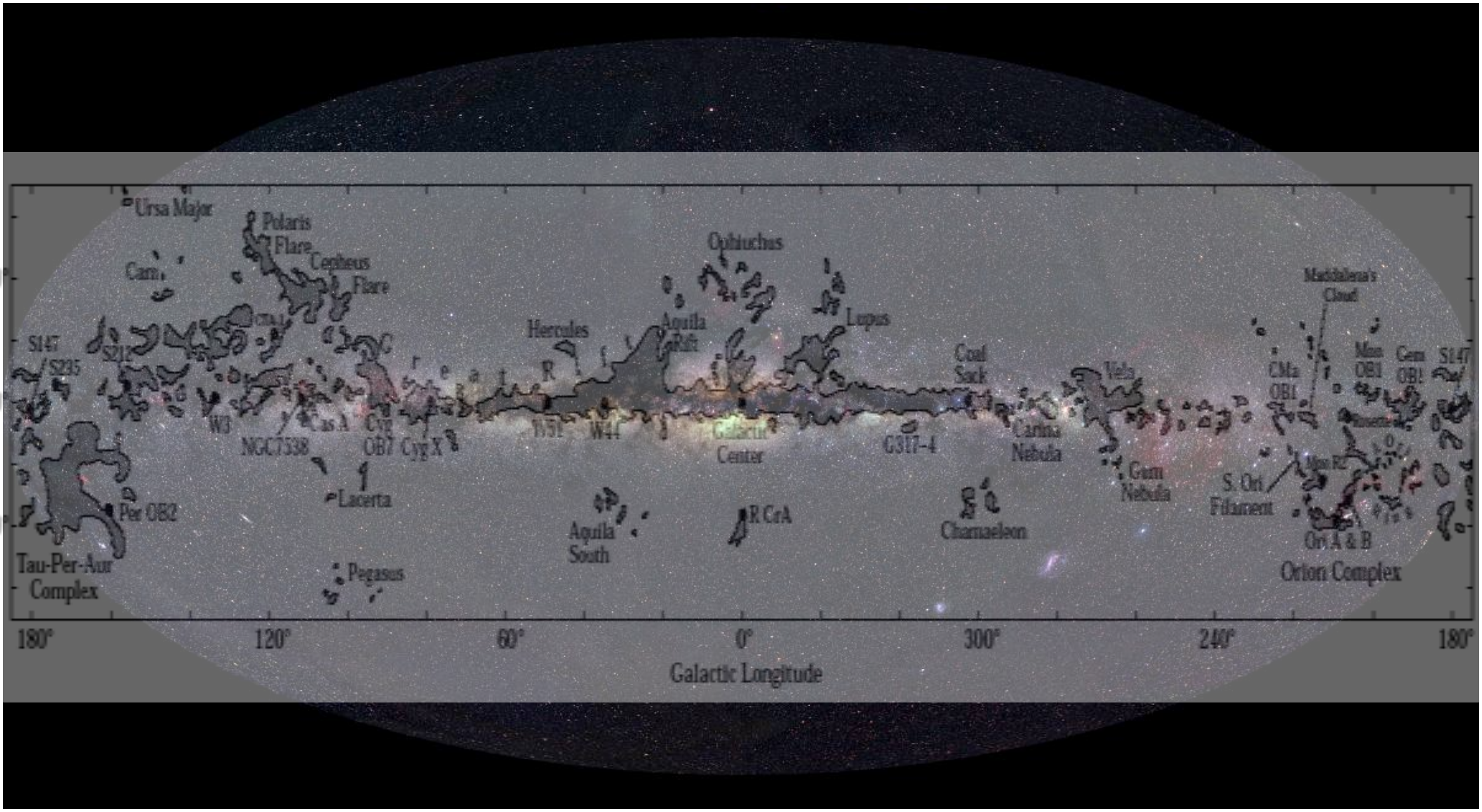
- The Galaxy, like other spirals, has matter between the stars
- The ISM constitutes ~ 1% of the total mass
  - ~ $10^9\ M_\odot$ out of ~ $10^{11}\ M_\odot$
- The ISM has a profound effect upon the evolution of the galaxies
  - It is the site of star formation
- The ISM is inconspicuous optically
  - Much of the ISM is either cold (< 100 K: IR) or hot (> 10^6 K: x-ray)
  - Nature & importance have only been discovered in the last 100 years

Optical Observations of the Milky Way

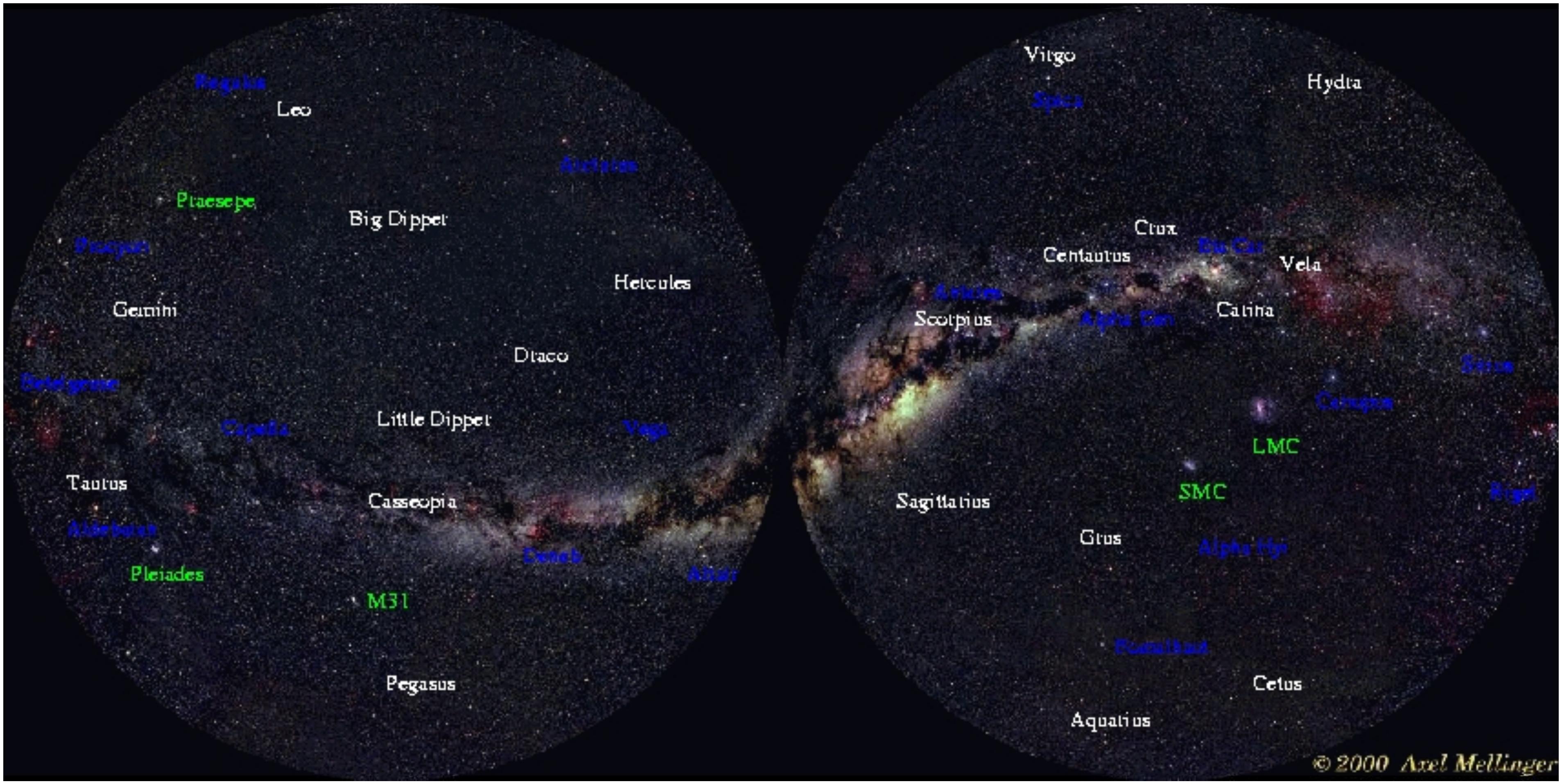


- All-sky optical images traces material between the stars (1953-1955)
  - Depicts 7000 brightest stars
- Dark clouds dominate a large sector of the Galaxy to the left of the center
  - l = 10-50^{o}
  - Next inner-most spiral arm, the Sagittarius-Carina

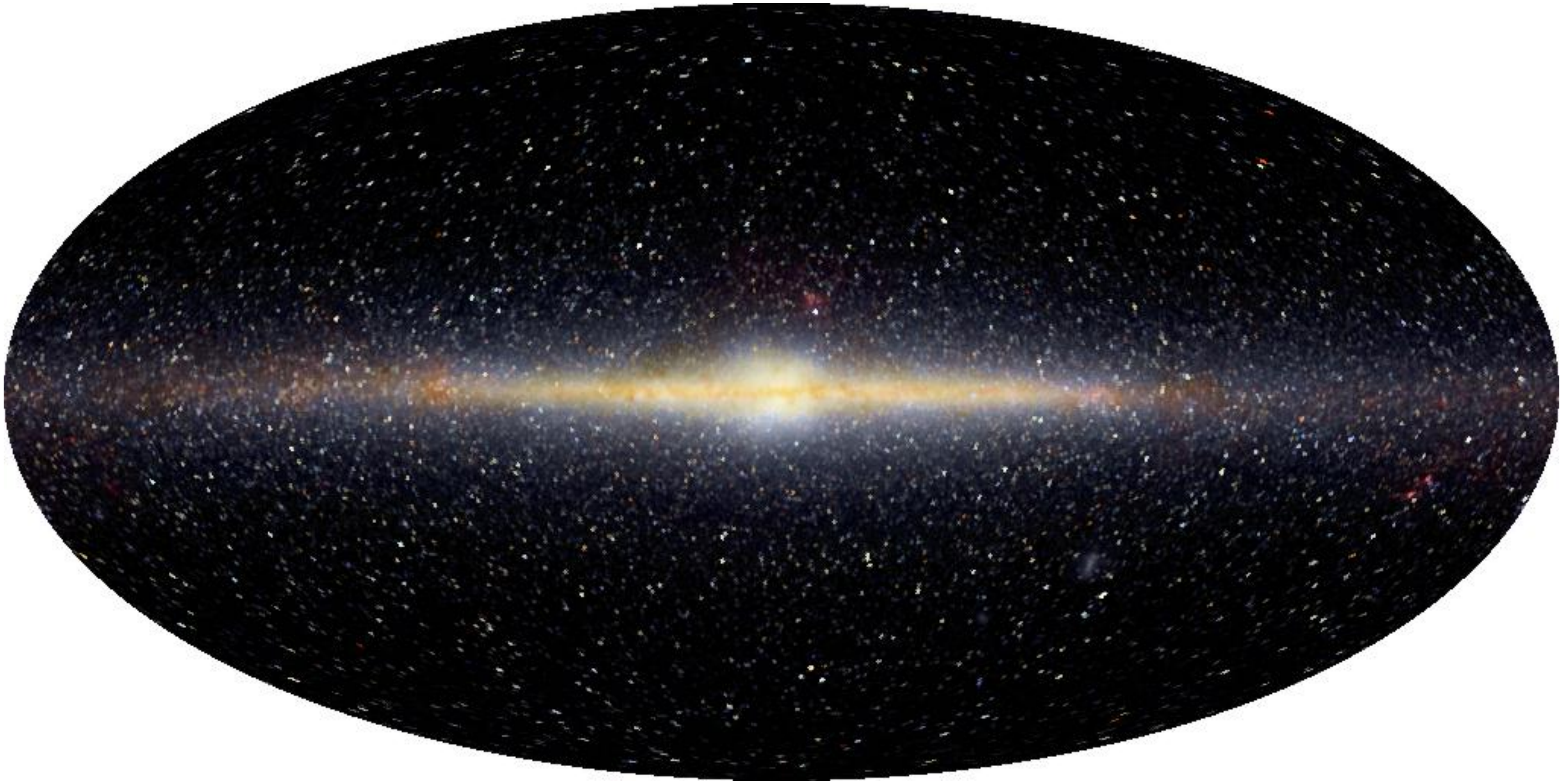
Galactic Coordinates



Equatorial Coordinates

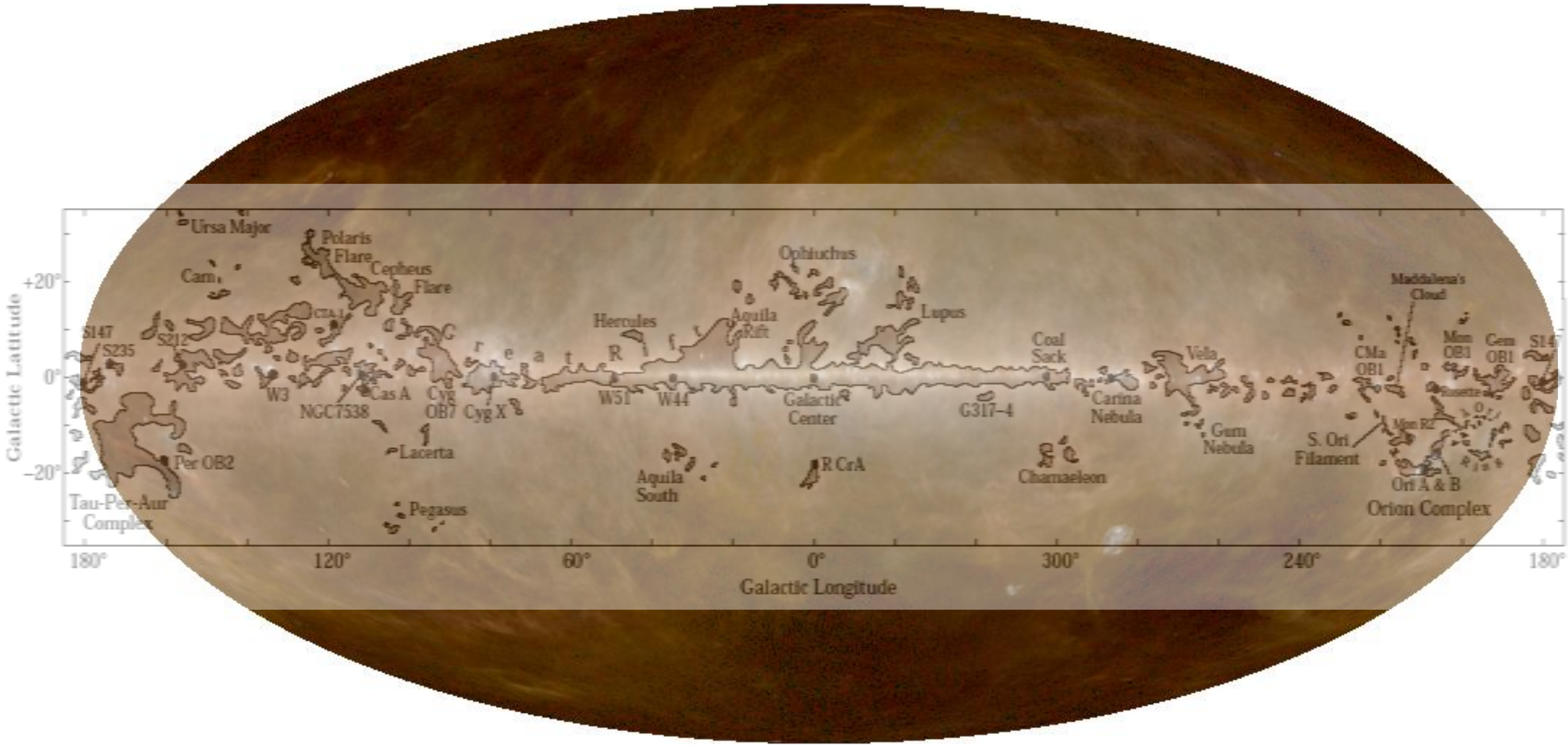


The Galaxy in the Near-IR



- A different picture of the sky emerges in the IR
  - COBE maps the sky between 1.3µm and 4 mm
  - The near-IR (J, K & L) shows mostly stars & reduced ISM absorption
  - The disk-like nature of our Galaxy with its bulge is evident

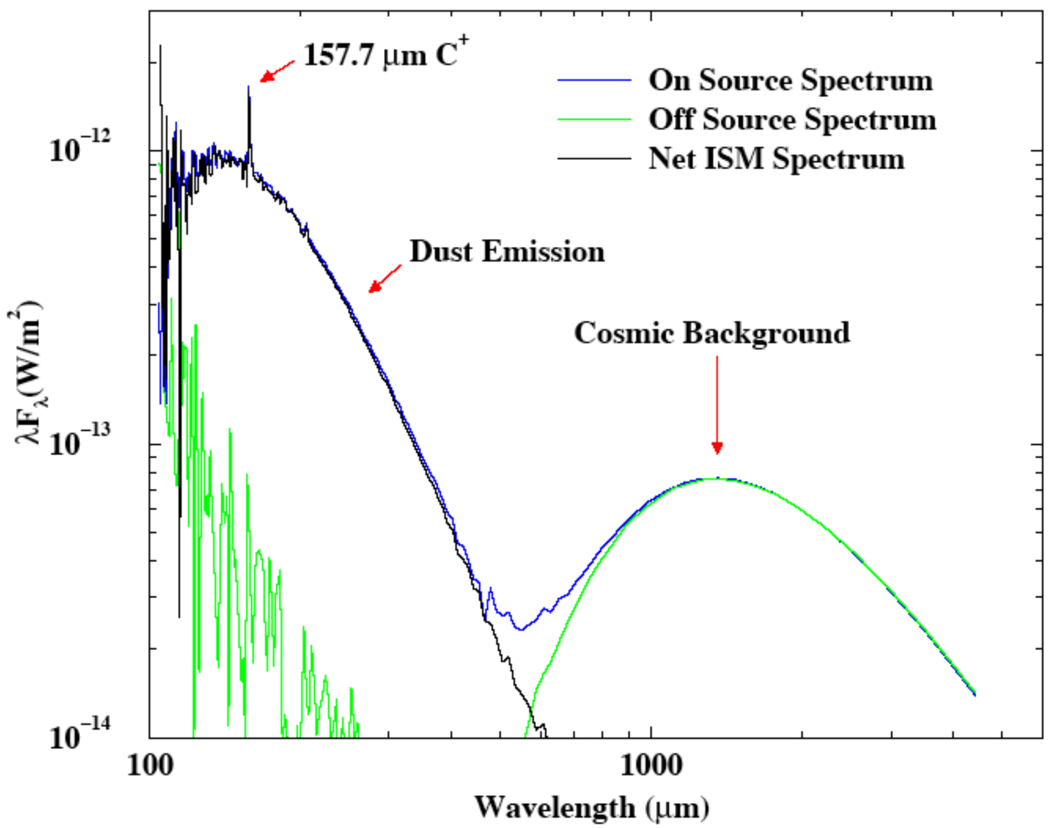
The Galaxy in the Far-Infrared



- 100, 140 & 240 μm
  - No ordinary stars, only a few with circumstellar dust shells are weakly detected
  - The bulk majority of emission is from clouds of cool dust (≤ 20 K)

Far-IR Spectrum of the ISM

- COBE spectrum of the Galactic plane, 0.1-4 mm
- Cool dust peaks at ≈ 140 µm
  - T_{dust} ≈ 20 K
- C^+ $^2P_{3/2}$ - $^2P_{1/2}$ 157.74 µm
  - Diffuse WIM
  - C ionized by UV photons
  - *hν* > 11.25 eV
    - 911.76 Å Lyman edge
    - 1101.72 Å C edge
- C^+ is common near FUV sources
  - Hot, young stars
  - Includes a large fraction of the Galactic disk



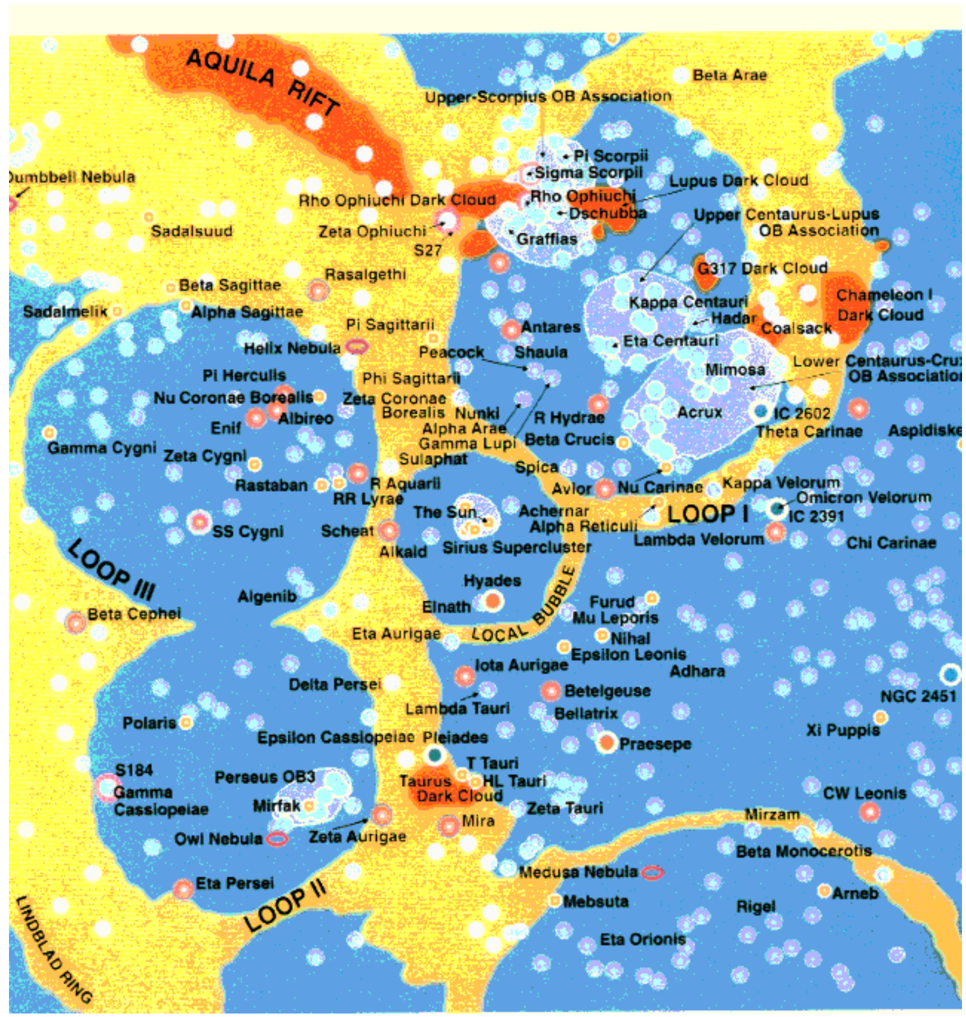
The Local ISM (120 pc)

- **Sun** is at the center, Galactic Center at top
  - –OB stars (blue), AFG (yellow), and ; KM (orange)
  - –Rings of denser gas (yellow)
    - 3-d shells of "warm"gas (~5000 K), containing low-density, hot gas (~$10^{5\text{-}6}$ K)
    - Supernovae & winds from stars in OB associations
- Interior of the Local Bubble
  - –n ~ 0.05 - 0.07 cm^{-3}
- Local Bubble is not spherical
  - –The long axis ⊥ to the Galactic plane
  - –Density gradients or colliding SNR
- Above Arcturus is the "Wall" of denser gas
  - –Like Loop 1, the wall appears to be driven by the Sco-Cen association
- *Local Fluff* is a denser region (~ 0.1 cm^{-3}) recently encountered by the Sun
  - –The Sun is headed to the left at ~ 20 km/s plowing through the Local Fluff

Henbest & Couper "Guide to the Galaxy"

The Local ISM (500 pc)

- **Sun** is at the center
  - Brightest stars (giants & supergiants)
  - Denser portions of the ISM (orange)



General Properties of the ISM

- Mostly confined to the disk
  - Some gas in the halo, as in ellipticals
- Large ranges in temperature & density
  - $T \approx 10 \ldots 10^6$ K, $n \approx 10^{-3} \ldots 10^6$ cm^{-3}
- Even dense regions are "ultra-high vacuum"
  - Lab UHV is 10^{-10} Torr ($n \approx 4 \times 10^6$ cm^{-3})
    - $n \approx 3 \times 10^{19}$ cm^{-3} at STP
- Far from thermodynamic equilibrium
  - Complex processes & interesting physics

Cosmic Abundances

Element	Abundance	Element	Abundance
H	1.00	Mg	4.2×10^{-5}
He	0.075	Al	3.1×10^{-6}
C	4.0×10^{-4}	Si	4.3×10^{-5}
N	1.0×10^{-4}	S	1.7×10^{-5}
O	8.3×10^{-4}	Ca	2.2×10^{-6}
Na	2.1×10^{-6}	Fe	4.3×10^{-5}

- Mass fraction of H, He and "metals"
  - $X = 0.71$, $Y = 0.27$, $Z = 0.02$
- Reference abundances are
  - Solar - presumably ISM 4.5 x 10^9 yr ago
  - HII regions- gas phase only
  - B-star atmospheres - recent ISM
    - Considerable disagreement, e.g C:

Cosmic Abundances

Element	Abundance	Element	Abundance
H	1.00	Mg	4.2×10^{-5}
He	0.075	Al	3.1×10^{-6}
C	2.7×10^{-4}	Si	4.3×10^{-5}
N	6.8×10^{-5}	S	1.7×10^{-5}
O	5.0×10^{-4}	Ca	2.2×10^{-6}
Na	2.1×10^{-6}	Fe	4.3×10^{-5}

Asplund et al. (2009)

- Mass fraction of H, He and “metals”
  - $X = 0.71$, $Y = 0.27$, $Z = 0.02$
- Reference abundances are
  - Solar - presumably ISM 4.5×10^9 yr ago
  - HII regions- gas phase only
  - B-star atmospheres - recent ISM
    - Considerable disagreement, e.g C:

ISM Classified by Ionization State

- Composition similar to Solar System
  - H is the most abundant element (≥ 90% of atoms)
- ISM regions characterized by state of hydrogen
  - Ionized atomic hydrogen (H^+ or H II) "H-two"
  - Neutral atomic hydrogen (H^0 or H I) "H-one"
  - Molecular hydrogen (H_2) "H-***two***"
- Regions are H II, H I, or H_2
  - Transition zones H II → H I → H_2 are thin

Ionized Gas

- H II regions surrounding early-type (OB) stars
  - Photoionized
  - $T \approx 10^4$ K
  - $n_e \approx 0.1 \ldots 10^4$ cm^{-3}
  - Bright nebulae associated with regions of star formation & molecular clouds
- Warm Ionized Medium
  - $T \approx 8000$ K
  - $\langle n_e \rangle \approx 0.025$ cm^{-3}
- Hot Ionized Medium: tenuous gas pervading the ISM
  - Ionization by electron impact
  - $T \approx 4.5 \times 10^5$ K
  - $n \approx 0.035$ cm^{-3}

H I Regions

- Cool "clouds" (CNM)
  - $T \approx 100$ K
  - $n \approx 40$ cm^{-3}
- Warm neutral gas (WNM)
  - $T \approx 7500$ K
  - $n \approx 0.5$ cm^{-3}
- Lyman α forest
  - Intergalactic clouds $N_{HI} > 10^{13}$ cm^{-2}

Molecular Clouds (H_2 Regions)

- Cold dark clouds ($M \approx 10 - 1000\ M_\odot$)
  - $T \geq 10$ K
  - $n \approx 10^2 - 10^4$ cm^{-3}
- Giant molecular clouds ($M \approx 10^3 - 10^5\ M_\odot$)
  - $T \geq 20$ K
  - $n \approx 10^2 - 10^4$ cm^{-3}
- Molecular material exhibits complex structure including cores and clumps with $n \approx 10^5 - 10^9$ cm^{-3}
- Molecular clouds are the sites of star formation

Other Ingredients of ISM

- Heavy elements
  - He (≈ 10 %)
  - C, N, O (≈ "cosmic" abundances)
  - Si, Ca, Fe (depleted onto grains)
- Grains (≈ 0.1 μm size, silicates or carbonaceous material, ≈ 1% by mass of ISM)
- Photons
  - CMB
  - Star light (average IS radiation field)
  - X-rays (from hot gas & the extragalactic bacground)
- Magnetic fields & cosmic rays

Energy Densities in Local ISM

$$u_{thermal} = \tfrac{3}{2} p = 0.39 \frac{p/k}{3000\,\mathrm{cm}^{-3}\mathrm{K}} \ \mathrm{eV\,cm^{-3}}$$

$$u_{hydro} = \tfrac{1}{2} \rho \langle v^2 \rangle = 0.13 \frac{n_H}{\mathrm{cm}^{-3}} \left(\frac{v_{rms}}{5\,\mathrm{km\,s^{-1}}} \right)^2 \ \mathrm{eV\,cm^{-3}}$$

$$u_{magnetic} = \frac{B^2}{8\pi} = 0.22 \left(\frac{B}{3\mu\mathrm{G}} \right)^2 \ \mathrm{eV\,cm^{-3}}$$

$$u_{starlight} = 0.5 \ \mathrm{eV\,cm^{-3}}$$

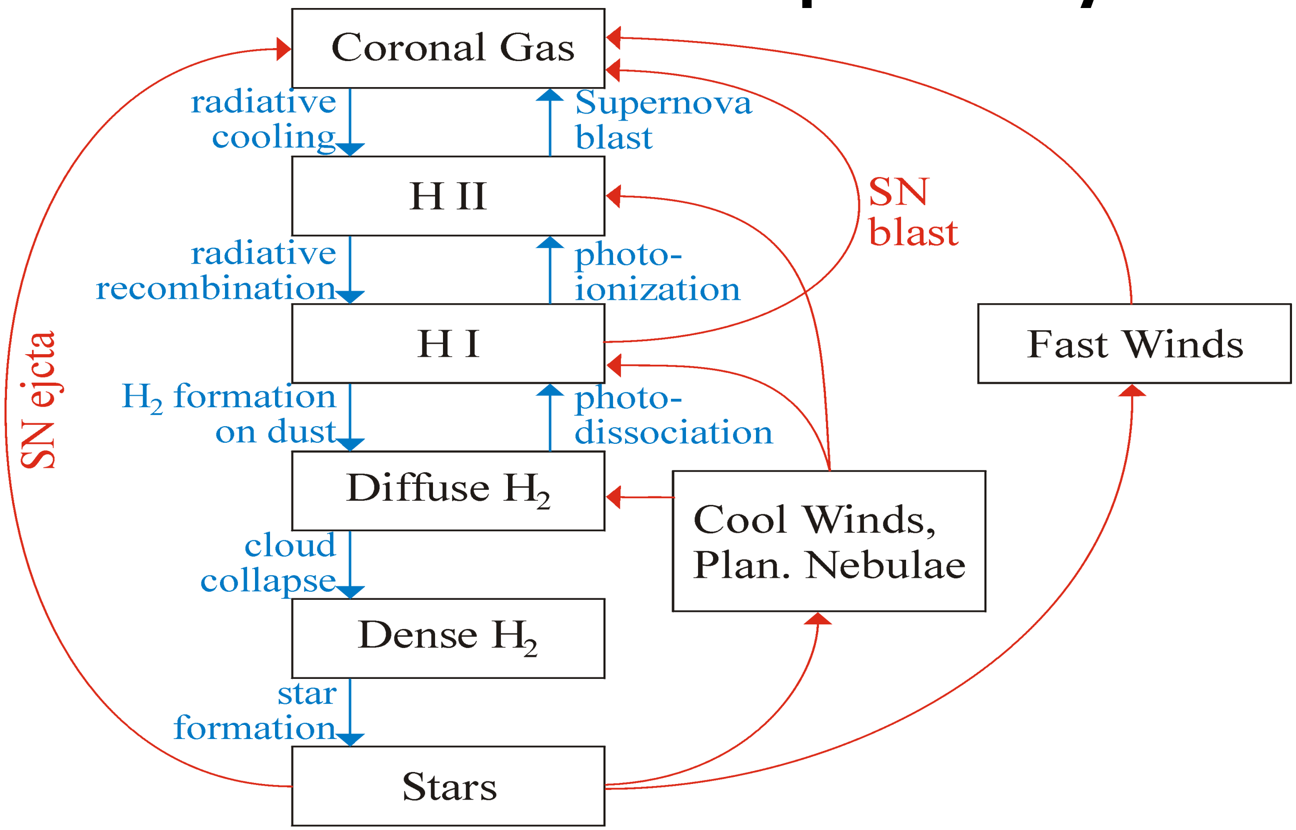
$$u_{cosmic\ rays} = 0.8 \ \mathrm{eV\,cm^{-3}}$$

$$u_{3\mathrm{K}\,CBR} = 0.25 \ \mathrm{eV\,cm^{-3}}$$

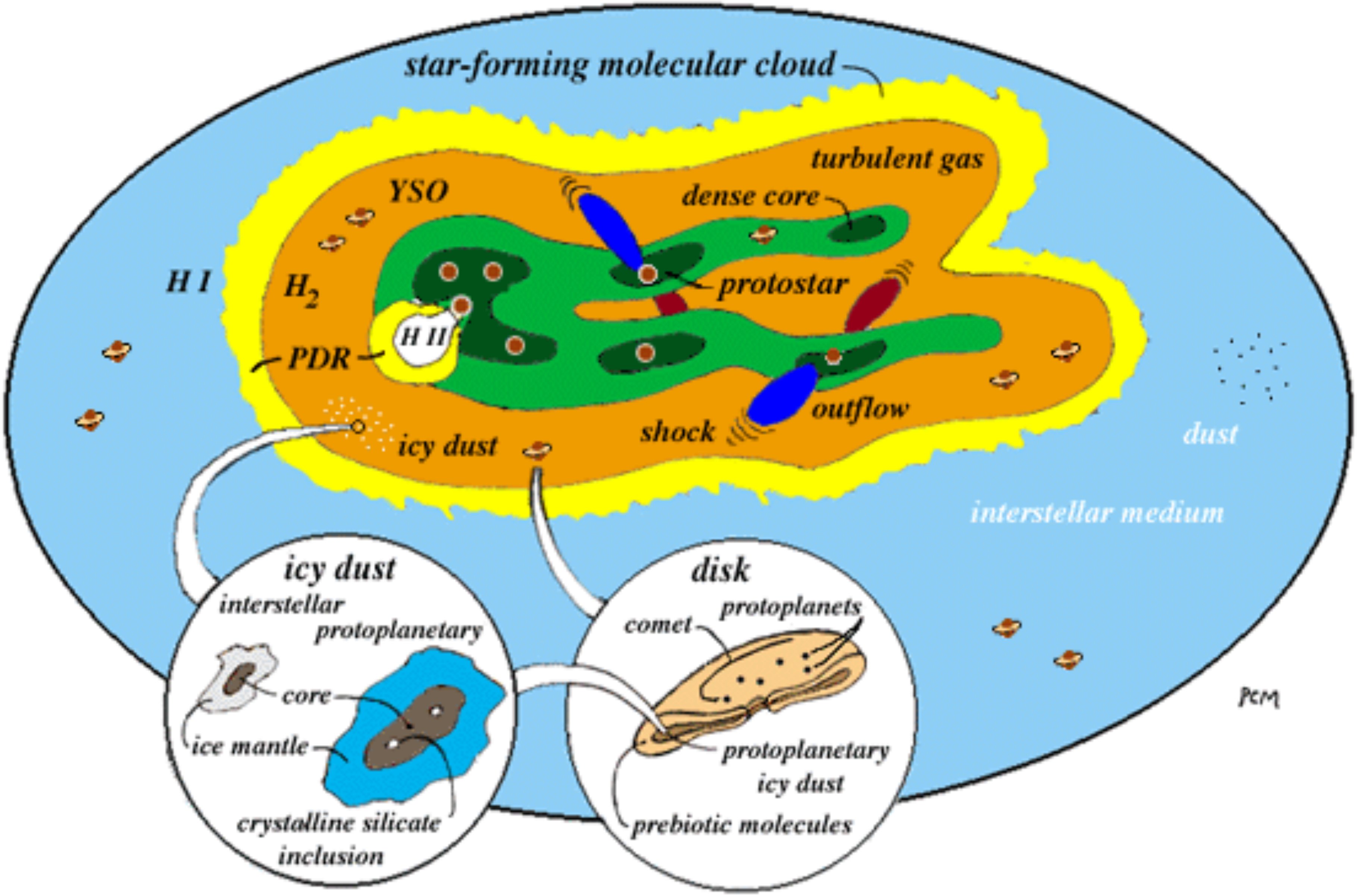
Coupling between Energy Densities

- All six energy densities are of comparable magnitude
  - $u_{thermal}$, u_{hydro}, $u_{magnetic}$ are coupled (magneto-) hydrodynamically
  - $u_{thermal}$ is (weakly) coupled to $u_{starlight}$
  - u_{CR} is (weakly) coupled to u_{hydro}
  - $u_{3\mathrm{K}\ CBR}$ couples via inverse Compton to u_{CR}

The ISM as a Complex System

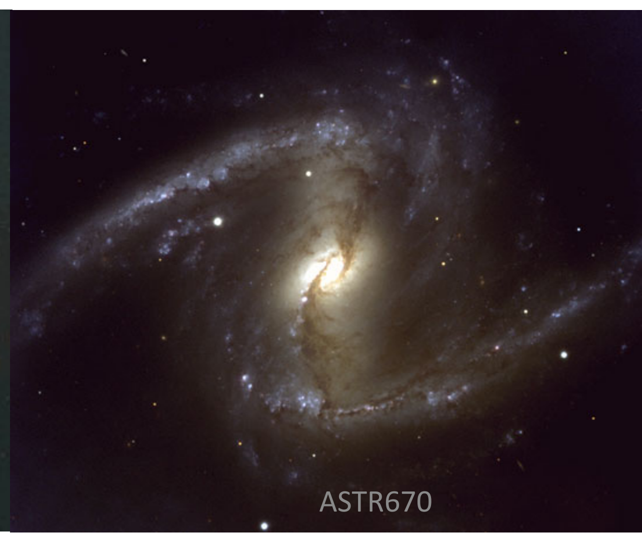


- Understanding the ISM means
  - Understanding the physical processes which drive mass, momentum and energy exchange between stars and its phases


star-forming molecular cloud
turbulent gas
YSO
dense core
H I
H_2
protostar
H II
PDR
outflow
shock
icy dust
dust
interstellar medium
icy dust
interstellar
protoplanetary
core
ice mantle
crystalline silicate
inclusion
disk
comet
protoplanets
protoplanetary
icy dust
prebiotic molecules
PCM

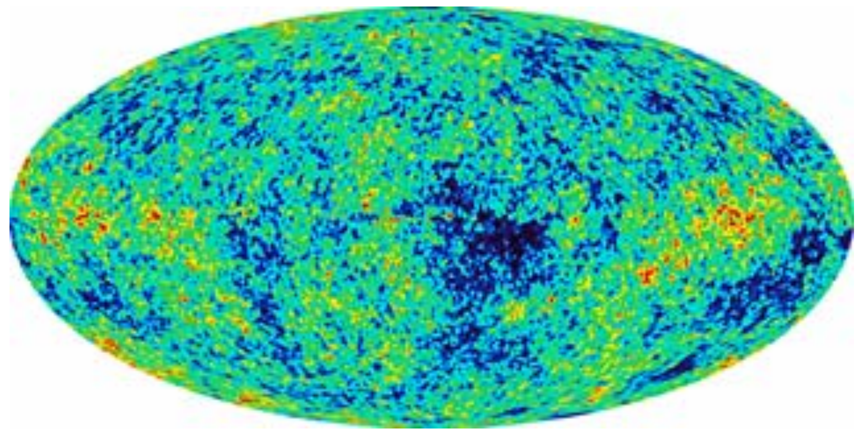
Motivation

- Star formation is the fundamental process which determines the obsevational properties of galaxies
  - History of star formation yield the Hubble sequence


Basic Questions

- How are baryons transformed into stars?
  - Subject to
    - Gravity (well understood)
    - Radiation pressure (small)
    - Magnetic fields
    - Turbulent stresses



- Fundamental questions
  - Why does star formation occur mostly in spiral arms
  - What triggers star formation
  - What determines the star formation rate in different Hubble types?
  - What determines the initial mass function of stars?
  - Why do stars form in multiples?
  - How do planets form?