# *The Interstellar Medium*
## Astronomy 216
## Spring 2008

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# Lecture 1 - Introduction to the ISM

1. Overview
2. Summary of properties
3. Motivation for this study

## Plan of This Course

Part 1 (6 weeks)   - Basic Processes & Applications
Part IIA (3 weeks) - Molecular Astrophysics
                    *Spring Break*
Part IIB (3 weeks) - Molecular Clouds & Cores
Part III (3 weeks)  - Cosmic Gas In Time

# Tentative Syllabus for Part I

## PART I DIFFUSE ISM

1/18    Lec 1 Discovery and history of the ISM
1/22    Lec 2 Radiation transfer & interstellar absorption lines

1/29    Lec 3 Photoionization of hydrogen; HII regions
1/31    Lec 4 Thermal properties of HII regions; forbidden lines

2/5     Lec 5 Optical properties of interstellar dust
2/7     Lec 6 Composition & thermal properties of dust

2/12    Lec 7 Observed phases and physical processes
2/14    Lec 8 Ionized Phases (WIM, HIM)

2/19    Lec  9  Cosmic rays and magnetic fields
2/21    Lec 10 Tracing HI

2/26    Lec 11 Neutral phases (WNM/CNM); theory of  phases
2/28    Lec 12 SNRS, winds, and bubbles

# Reference Texts

## Core Monographs

L Spitzer, Jr., "Physical Processes in the Interstellar Medium" (Wiley 1978)
AGGM Tielens, "Physics and Chemistry of the Interstellar Medium" (Cambridge, 2005)
D Osterbrock & G. Ferland, "Astrophysics of Gaseous Nebulae and Active Galactic Nuclei" (2nd Edition, University Science 2005)

## Basic Books

FH Shu, "The Physics of Astrophysics" (2 volumes, University Science 1991,1992)
GB Rybicki & AP Lightman, "Radiative Processes in Astrophysics" (Wiley, 1979)

## Additional Texts & References

E van Dishoeck, "Interstellar Chemistry" (BAD Lecture Notes 2000)
MA Dopita & RS Sutherland, "Astrophysics of the Diffuse Universe" (Springer 2002)
JE Dyson & DA William, "Physics of the Interstellar Medium" (IoP 1997)

# 1. Overview and background

*What is the ISM?*

Just what it says: The stuff between the stars in and around galaxies, especially our own Milky Way:
*Gas, dust, radiation, cosmic rays, magnetic fields.*

*Why do we study the ISM?*

Gas is where it all started back then at "Recombination". Part of the effort to understand the evolution of baryonic matter through time.

*Why is the ISM important?*

Stars form from the ISM, and then activate it dynamically and chemically. Gas is the active chemical ingredient of galaxies.

# Observing the ISM

*Can we see the ISM the way we see the Sun and the stars shine?*

In principle, yes, but it's hard because gas at temperatures of the surfaces of stars cools rapidly unless heated, e.g., by being close to a star. This kind of gas is called *nebular* and has characteristic *emission* lines.

Most of the gas in galaxies is relatively cool and, since a typical wavelength is inversely proportional to temperature, it is only observable in *emission* in bands outside of the visible, unavailable until the second half of the 20th century.

Large volumes of gas are hot, and require short wavelength observations (UV & X-rays) with satellite observatories.

# A Little Bit of History

Discovery of the Orion Nebula (1610) fueled speculation about gas clouds

Nebulae figured prominently in the Messier Catalog (1787).

Nebular hypothesis of Kant & Laplace (1755/1797)

Nebular emission lines discovered visually in NGC 6543 by Wm. Huggins (1864); detection in the Orion Nebula by M. Huggins (1889).



HST (O'Dell)

First photograph of the Orion Nebula by Henry Draper (1880):
http://www.aip.org/history/cosmology/tools/tools-spectroscopy.htm

# Discovery of Interstellar Clouds

First interstellar absorption line: Hartmann's Potsdam observations (reprinted in ApJ 19, 268, 1904) of a stationary narrow dip in broad oscillating Ca II stellar absorption line of binary $\delta$-Ori (O9.5)

For 75 years, high spectral resolution (R = 300,000 or 1 km/s) measurements of absorption lines in the optical spectra of nearby bright stars was the only way of studying cool interstellar clouds, especially low IP systems like Na I, K I, Ca II .

Space Astronomy had a strong impact in 1973 with the UV satellite *Copernicus*, which allowed the main transitions of abundant species to be measured, e.g., HI Ly$\alpha$, H2, low & high-IP lines of heavy atoms (diagnostic of warm and cool gas). *Copernicus* was followed by *IUE , HST and FUSE.*
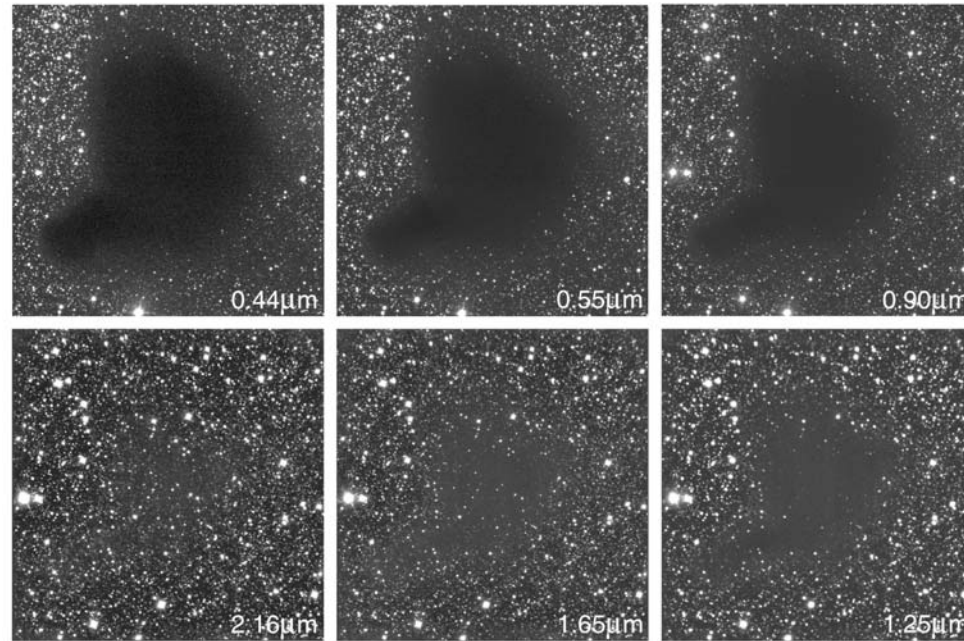
# Interstellar Clouds Appear Dark
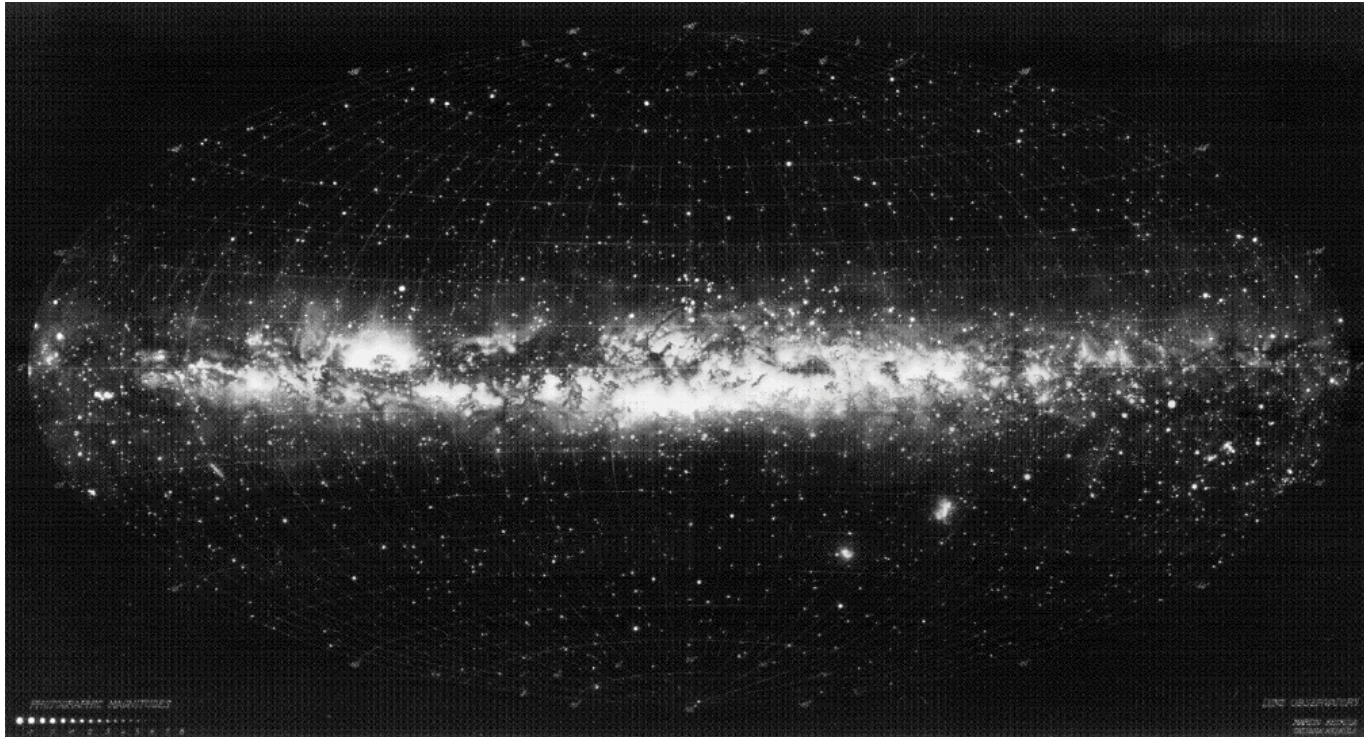


Lund Observatory Composite Photo of the Milky Way

These long-known dark regions were studied by Barnard in the 1$^{st}$ quarter and by Bok in the 3$^{rd}$ quarter of the 20$^{th}$ century. They appear dark here because (1) they do not emit at optical wavelengths and (2) their *dust* blocks the light of the stars.

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# The Well-Studied Dark Cloud B68



The Dark Cloud B68 at Different Wavelengths (NTT + SOFI)

ESO PR Photo 29b/99 ( 2 July 1999 )  © European Southern Observatory

Stars gradually appear as the observing band changes from B to K due to the decreasing absorption efficiency of small dust particles with wavelength .

Trumpler (Lick Observatory, 1930) had confirmed general galactic extinction by comparing luminosity and angular-diameter distances of open clusters.

# Earth's Atmosphere and Space Astronomy

Much of the electromagnetic spectrum is obscured by molecules in the Earth's atmosphere:
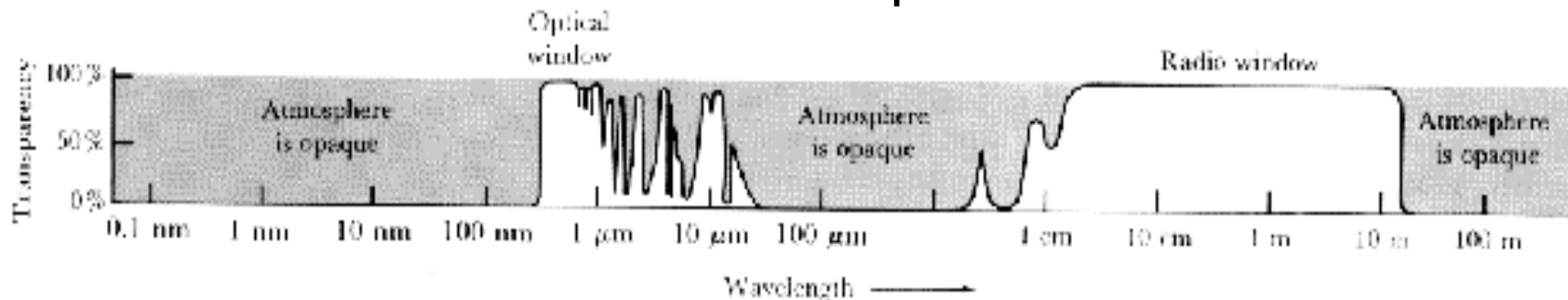


The two main bands for space astronomy are $\lambda < 0.1\,\mu m$ (EUV-X-rays) and the MIR-FIR between 10-1000 $\mu$m, both relevant for small macroscopic dust particles that absorb continuously across the entire spectrum.

Dust particles efficiently absorb the short-wavelength radiation emitted by stars. They re-radiate the energy at long wavelengths characteristic of their relatively low temperatures, especially from 10-1000$\mu$m: Observing dust emission requires observations from space.

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# Atmospheric transparency from Mauna Kea
## (A. Tokunaga, in Allen's "Astrophysical Quantities")

NIR

MIR

microns
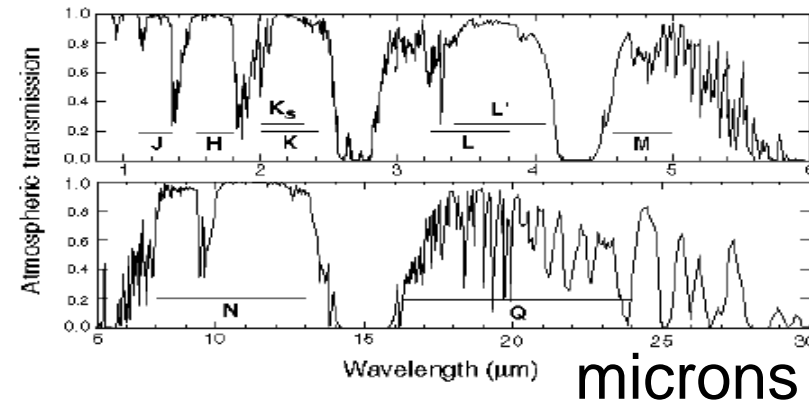
**Figure 7.1.** Atmospheric transmission from 0.9 to 30 $\mu$m under conditions appropriate for Mauna Kea, Hawaii. Altitude = 4.2 km, zenith angle = 30° (air mass = 1.15), precipitable water vapor overhead = 1 mm. $\lambda/\Delta\lambda$ = 300 for 1–6 $\mu$m and 150 for 6–30 $\mu$m. Spectra are calculated by Lord [1]. The infrared filter band passes are shown as horizontal lines; see Table 7.5 for definitions. Note that the filter transmission is modified by the atmospheric absorption. For the atmospheric transmission at Kitt Peak, see [2]. For ESO, see [3]. See also [4].

FIR

cm$^{-1}$
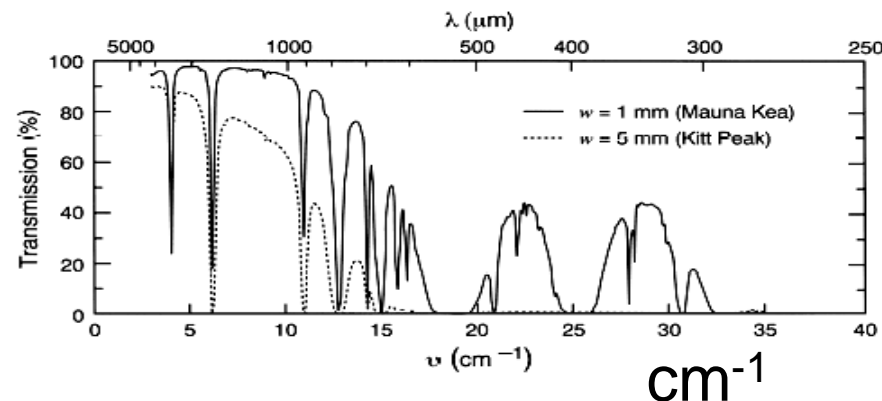
**Figure 7.2.** Atmospheric transmission from 0.25 to 3 mm, adapted from [5]. The precipitable water vapor is denoted by $w$. See also [6–9]. For the South Pole, see [10].

# Milestones in Infrared Space Astronomy

Major IR space observatories of the last 25 years:

IRAS 1983
COBE 1990
ISO 1995
SPITZER 2003
HERSCHEL 2008

Originally considered an embarrassing obstacle to astronomical observing, the scientific study of **cosmic dust** is a challenging and important part of astronomy, e.g., the terrestrial planets and the rocky cores of giant planets were formed from circumstellar dust.

# IRAS All Sky Image of the Milky Way
## (0.5° resolution)

Ophiuchus
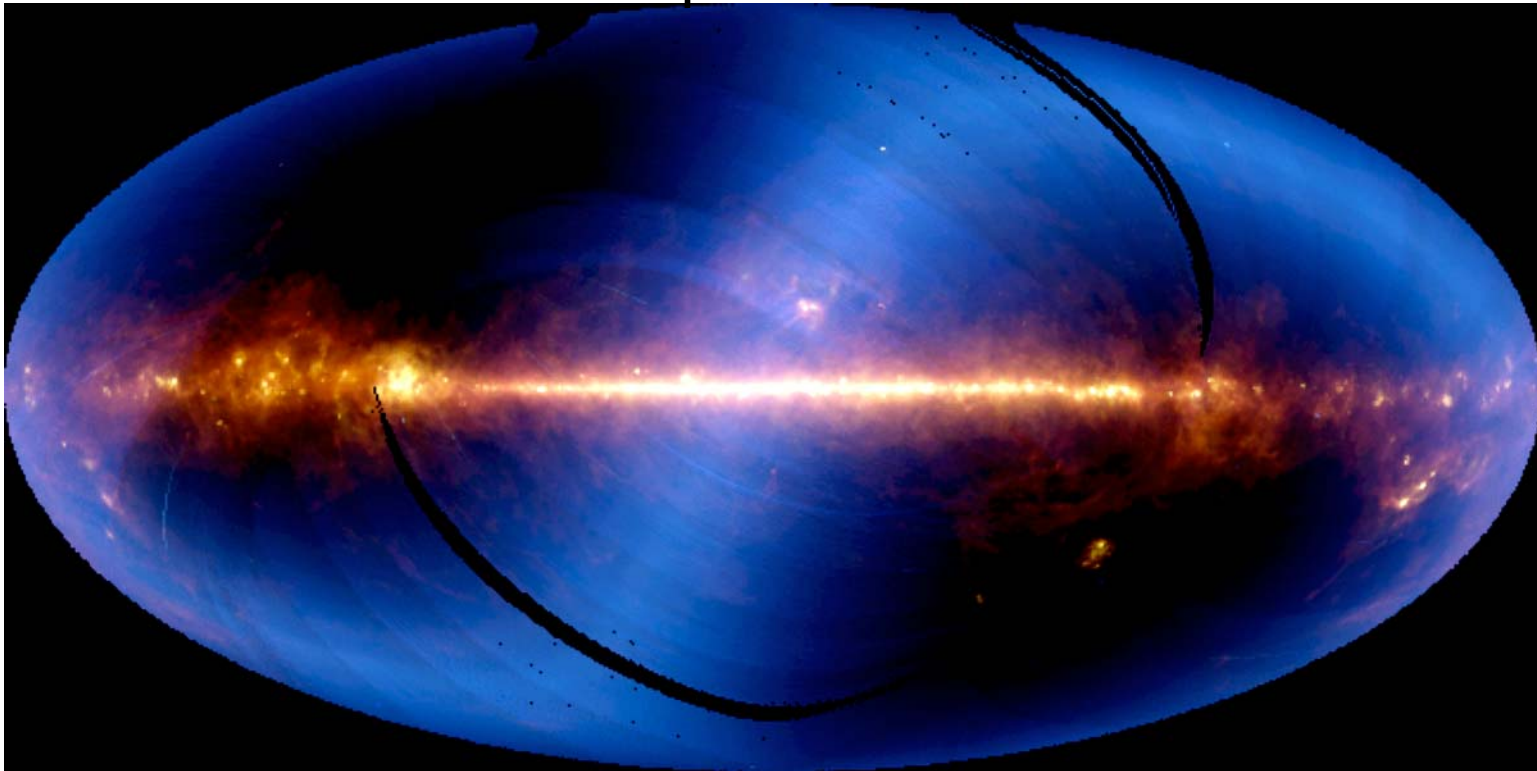


Zodiacal light (S - shape)          LMC          Orion

Blue: 12 μm
Green: 60 μm
Red: 100 μm

Notice the wide distribution of 100 μm "cirrus" emission just out of the Milky Way plane.

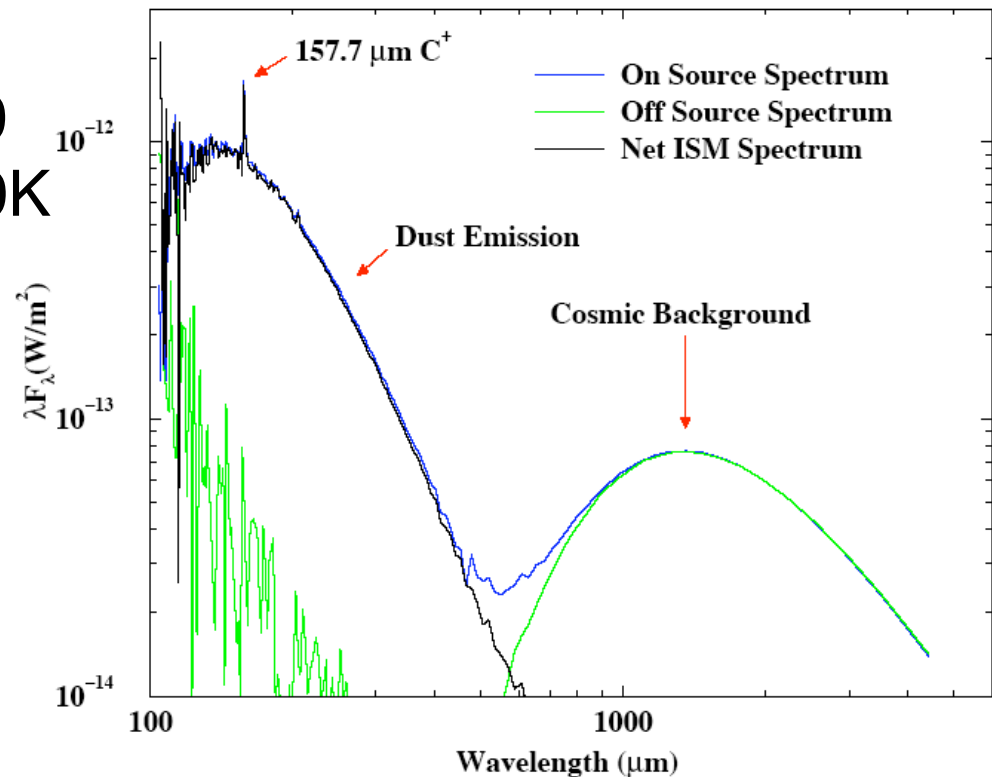Galactic coordinates with $l$ =0 at center

# Far-IR Spectrum of the ISM

## COBE spectrum of the galactic plane, 0.1- 4 mm

Two main components: Dust & CMB; dust peaks near 140 $\mu$m, corresponding to $T_d \approx 20K$

There are also lines!

The most prominent is the ground state fine-structure transition of

$C^+$ at 158 $\mu$m, with an energy level spacing of 93K.



The 158 $\mu$m line is characteristic of warm partially-ionized gas from much of the Milky Way, where C is ionized by far UV photons ($hv > 11.25$ eV).

# Radio Astronomy: Early ISM Milestones

Rapid development from WWII radar.
H 21-cm line: predicted by van de Hulst (1945);
detected by Ewen & Purcell and Muller & Oort (1951).
Seen everywhere in the sky; e.g., Weaver (1970)

Early optical detections of interstellar molecules:

   CH   Dunham et al. (1937)
   CN   Swings & Rosenfeld (1937)
   CH+  McKellar (1940)

Radio detection of molecules pioneered by Townes:

   OH   Weinreb et al. (1963)
   $NH_3$, $H_2O$  Cheung et al. (1968, 1969) [Townes & Welch]
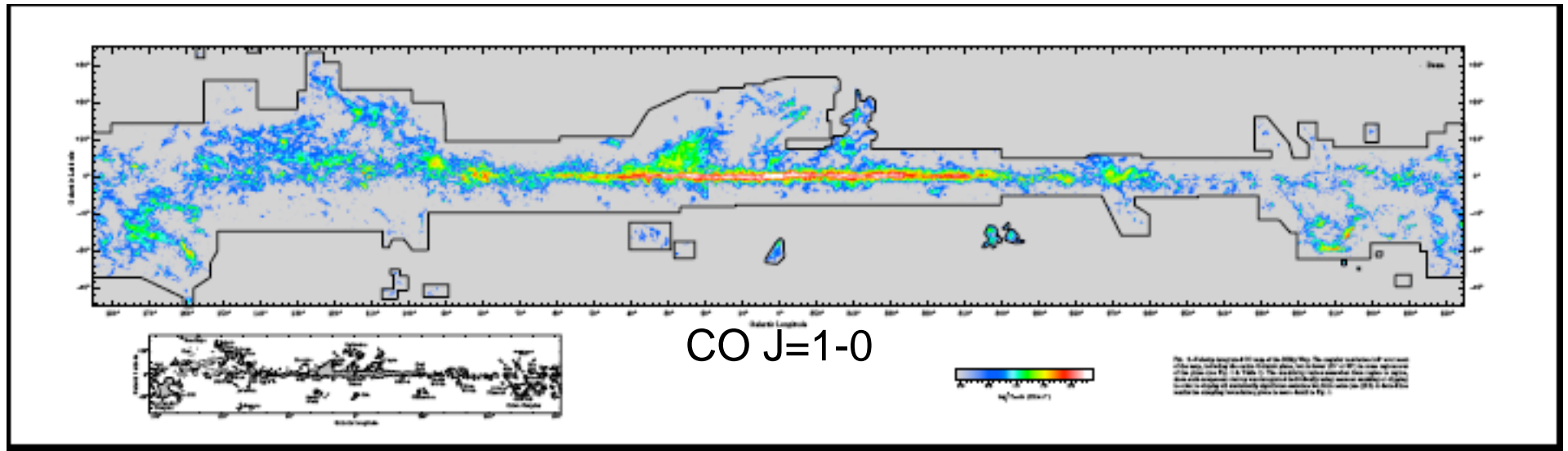   $H_2CO$   Snyder at al. (1969)
   CO   Wilson, Jefferts, & Penzias (1970)

CO and the > 145 interstellar molecules are crucial
for studying the dense gas in galaxies.
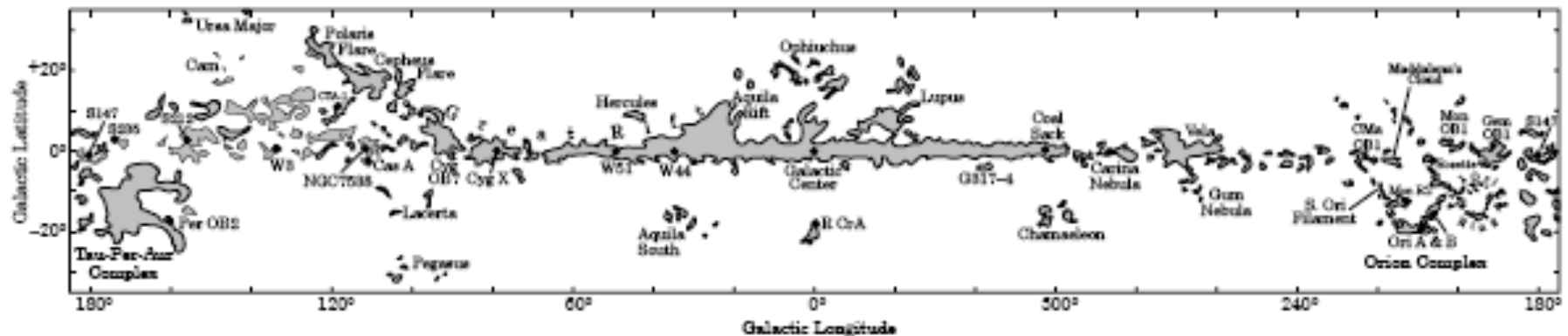
# CO Map of the Milky Way
## Columbia/CfA mini-telescope project (Dame et al. 2001)



CO J=1-0

Tau-Per-Aur          Galactic Center, Ophiuchus                          Orion



Key to map: most sources are the sites of star formation

# 2. General Properties of the ISM

- Mostly confined to the disk
    with some dilute gas away from the disk

- Large range in temperature & density
    $T \approx 10 - 10^6$ K        $n \approx 10^{-3} - 10^6$ cm$^{-3}$

- Even dense regions are "ultra-high vacuum"
    lab UHV:$10^{-10}$ Torr  ($n \approx 4 \times 10^6$ cm$^{-3}$)
    (STP conditions: $n \approx 3 \times 10^{19}$ cm$^{-3}$ )

- Multi-component medium
    with inhomogeneous spatial distributions

- Far from equilibrium and steady state:
    complex processes & challenging physics

# Classification by Ionization State of Hydrogen

The composition (distribution of the elements) of the ISM is similar to the Sun (see the next slide), but probably closer to much younger B-star atmospheres.

    **H is the most abundant element  (≥ 90% of nuclei)**

The spatial distribution of the gas is inhomogeneous, and the ionization state ranges from slightly to highly ionized. The regions of interest are characterized roughly by the 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-subtwo"

Labeled as H II, H I, or $H_2$  regions, they are usually separated by thin transition zones.

# Solar Abundances

| Element | Abundance | Element | Abundance |
|---------|-----------|---------|-----------|
| H | 1.00 | Mg | $3.4 \times 10^{-5}$ |
| He | 0.085 | Al | $2.3 \times 10^{-6}$ |
| C | $2.5 \times 10^{-4}$ | Si | $3.2 \times 10^{-5}$ |
| N | $6.0 \times 10^{-5}$ | S | $1.4 \times 10^{-5}$ |
| O | $4.6 \times 10^{-4}$ | Ca | $2.0 \times 10^{-6}$ |
| Na | $1.5 \times 10^{-6}$ | Fe | $2.8 \times 10^{-5}$ |

Asplund et al., ASP Conf Ser, 336, 25, 2005

Mass fractions of H, He and heavy elements:

$$X = 0.738, \ Y = 0.250, \ Z = 0.012$$

Typical reference abundances are:

Sun - presumably like the ISM $4.5 \times 10^9$ yr ago

Chondritic meteorites - similar to the Sun, except for volatiles

HII regions- gas phase only

B-star atmospheres - samples recent ISM with many uncertainties, e.g., C

# Properties of Ionized Gas

**H II regions** - bright nebulae associated with regions of
star formation & molecular clouds; ionized by stellar UV
photons from early-type (OB) stars

$$T \approx 10^4 \text{ K} \quad \& \quad n_e \approx 0.1 - 10^4 \text{ cm}^{-3}$$

**Warm Ionized Medium** (WIM)

$$T \approx 8000 \text{ K} \quad \& \quad n_e \approx 0.025 \text{ cm}^{-3}$$

**Hot Ionized Medium** (HIM) - tenuous gas pervading the
ISM, ionized by electron impact

$$T \approx 4.5 \times 10^5 \text{K} \quad \& \quad n_e \approx 0.035 \text{ cm}^{-3}$$

**Our goal**: To understand how these phases are
observed and how they are heated and ionized.

# Properties of Neutral Gas

**Cool clouds** (CNM)

$$T \approx 100 \text{ K} \qquad \& \quad n \approx 40 \text{ cm}^{-3}$$

**Warm neutral gas** (WNM)

$$T \approx 7500 \text{ K} \qquad \& \quad n \approx 0.5 \text{ cm}^{-3}$$

**Cold dark clouds** ($M \approx 10 - 1000 \text{ M}_\odot$)

$$T \geq 10 \text{ K} \qquad \& \quad n \approx 10^2 - 10^4 \text{ cm}^{-3}$$

**Giant molecular clouds** ($M \approx 10^3 - 10^5 \text{ M}_\odot$)

$$T \geq 20 \text{ K} \qquad \& \quad n \approx 10^2 - 10^4 \text{ cm}^{-3}$$

with high density cores & clumps that form stars.

**Our goal**: To understand how these properties are determined, what the relevant thermal and ionization processes are, how atomic and molecular clouds are related, and how the latter lead to star formation.

# Other Components of the ISM

**Dust Grains**: $\approx$ 0.1 μm sized particles, composed of silicates or carbonaceous material, constituting $\approx$ 1% of the mass of the ISM.

NB We consider PAHs (polycyclic aromatic hydro-carbons) as *large molecules*, even though they play a similar role as dust.

**Photons**: diverse components and roles: CMB (mm), starlight (eV), X-rays (keV)

**Magnetic fields:** typical value 10μG

**Cosmic rays**: not measured directly, except in the solar system above ~ 1 GeV

NB Although difficult to measure, cosmic rays play important roles in the dynamics and ionization of the ISM

# Energy Densities in the ISM

1. Random (thermal & turbulent) motions
2. Organized fluid motion
3. Starlight
4. Magnetic fields
5. Cosmic rays
6. Cosmic Background Radiation

Estimates (e.g., the next slide) for the local ISM give typical numbers that are all about 0.5 eV cm$^{-3}$, which suggests that these components interact significantly with one another.

Dealing with the time-dependent properties of these components, driven by stellar and galactic evolution, is a daunting task for understanding the ISM. The subject is still largely undeveloped, especially in the broader context of galaxy formation over time.

James Graham's numerical estimates of average energy densities in the ISM (AY216-06)

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

$$u_{hydro} = \frac{1}{2}\rho \langle v^2 \rangle = 0.54 \left(n_H/\mathrm{cm}^{-3}\right)\left(\sigma_{1d}/5\,\mathrm{kms}^{-1}\right)^2 \mathrm{eV\,cm}^{-3}$$

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

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

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

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

- All six energy densities are of comparable order of magnitude

# James Graham's Conception of
# The ISM as a Complex System
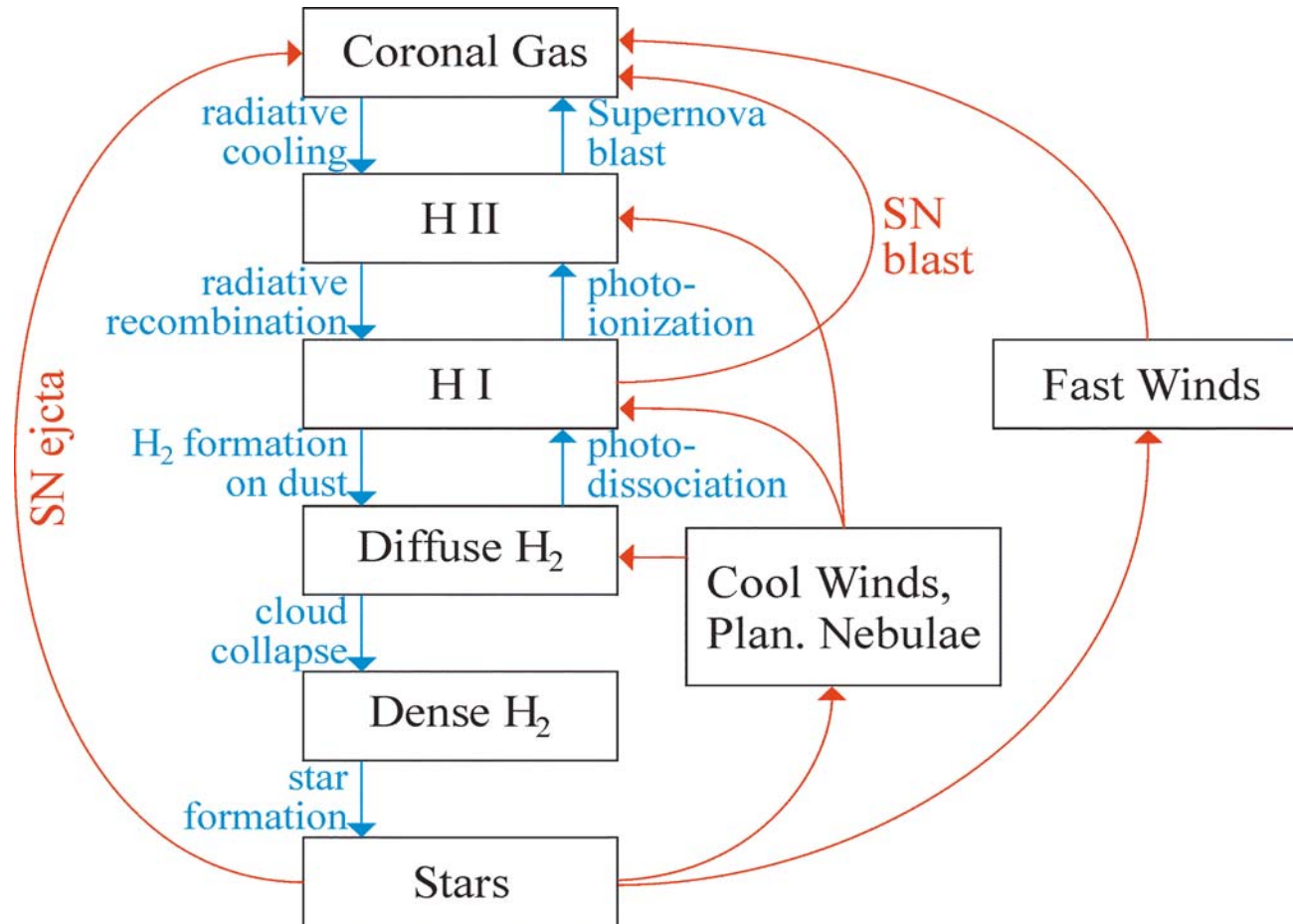


**Understanding the ISM means understanding the physical processes which drive mass, momentum and energy exchange between the stars and the components of the ISM.**

# 3. Motivation for Studying the ISM

Star formation from the ISM is the fundamental process that determines the properties of galaxies.

The basic question is: How is  the interstellar gas transformed into stars under the influence of:

| | |
|---|---|
| gravity | (well understood) |
| radiation pressure | (small) |
| ionizing fluxes | (important) |
| magnetic fields | (poorly known) |
| large scale motions | (measurable) |
| turbulent stresses | (poorly understood) |

as affected by stellar and galactic evolution, through all of cosmic time and not just for the Milky Way and nearby galaxies.

# Issues for Local Star Formation

- Why does star formation occur mostly in spiral arm?

- What triggers star formation

- What determines the initial mass function of stars?

- Why do stars form in multiples?

- How do planets form?

- What determines the star formation rate in different Hubble types ?

The history of star formation should yield the Hubble sequence: smooth elliptical (E), spiral disk (S) & irregular (I) galaxies

# Appendix 1. Astronomical Constants

- Angular measure
  - arc second = 1/206,265 radian $\approx$ 4.85 $\mu$ rad
- Length
  - $\mathring{A}$ = $10^{-8}$ cm, 1 $\mathring{A}$ = 0.1nm, 10,000 $\mathring{A}$ = 1 $\mu$m
  - AU = Earth-Sun distance = 1.496 $\times 10^{13}$ cm
  - pc = parsec = 206,265 AU = 3.086 $\times 10^{18}$ cm
- Mass
  - $M_\odot$ = solar mass = 1.99 $\times 10^{33}$ g
- Energy
  - eV = 1.602 $\times 10^{-12}$ erg
- Radiation
  - $L_\odot$ = solar luminosity = 3.83 $\times 10^{33}$ erg s$^{-1}$
  - magnitude = -2.5 $\log_{10}(F/F_0)$
  - Jansky = $10^{-23}$ erg s$^{-1}$ cm$^{-2}$ Hz$^{-1}$
  - Rayleigh = $10^6/4\pi$ photons s$^{-1}$ cm$^{-2}$ sr$^{-1}$
- Miscellaneous
  - Debye = $10^{-18}$ esu cm = 3.335 $\times 10^{-30}$ C m
  - 1 km s$^{-1}$ x 1 Myr = 1.02 pc