Recap, with questions ;), from previous Lecture

- What is a Galaxy ? And what are its components
  - Stars, remnant, ISM, CRs, DM
- How many stars there are in a Galaxy ?
- How many galaxy there are in the Universe ?
  - How many stars there are in the Universe ?
- What's the mass of the Milky Way ?
- Morphology of Galaxy: how many types ?
- Name at least 3 spatial/kinematic components of the Milky Way ?
- Name this galaxy !
- And this one !
- When is thanksgiving ?

Interstellar Medium

Inter-Stellar Medium (ISM)

- Stars are separated by ~2pc, they fill very little space
- What's in between them ?
- The ISM: H, He and higher Z materials
  - Gas phase + solid/ice

- How do we know the ISM exists ?
  - Extinction (1 mag per kpc l.o.s, unobscured)
  - Reddening (scattering of high-freq. radiation)
    - *If you know the star true color/spectrum then we can measure the column density of the ISM*
  - Stationary lines (lines in spectra of binaries that are not redshifted)

- Sense of scale:
  - ISM density $n \sim 1$ cm^{-3} / Dense MC cores 10^5 cm^{-3}
  - Star density $n \sim 5$ cm^{-3}
  - This room $n \sim 3\times10^{19}$ cm^{-3} (mole/22.4l)
  - Best human-made vacuum: 3×10^4 cm^{-3}

- The total mass of the ISM is estimated $\sim 6.7\times10^9\ M_\odot$
  - We know this from galaxies rotation curves (measures total mass) and assumption on the gas/stars ratio
- Why is it important ?
  - ISM is the birthplace of stars, ISM includes the collection of the ashes from the previous generation stars -> Metallicity slowly increases
  - Its constant evolution/enrichment drives galaxy evolution

ISM

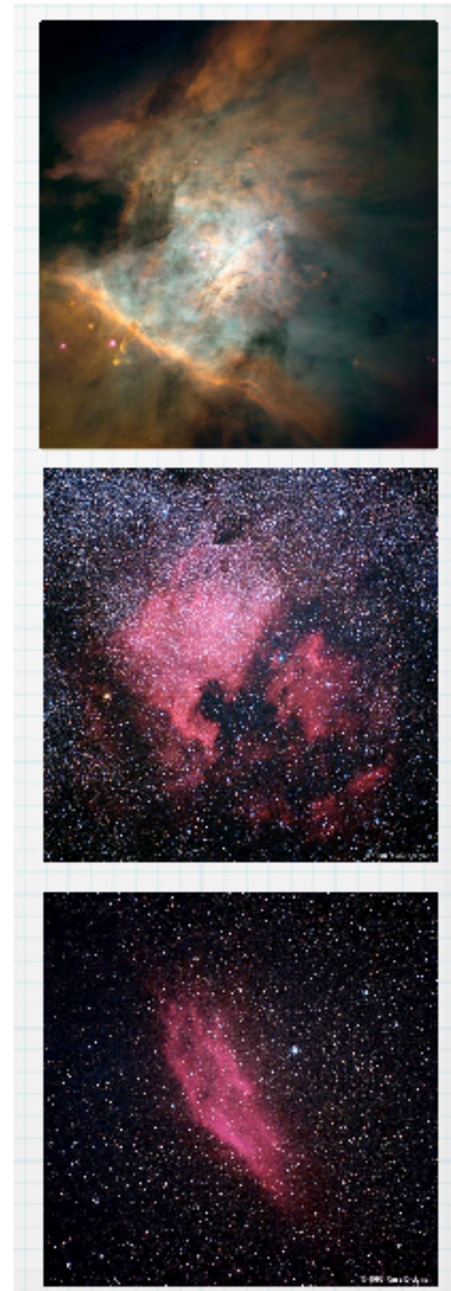
- Objects:
  - HII regions
  - Reflection Nebulae
  - Dark Nebulae
  - Photo-dissociation regions (PDRs)
  - SNRs

- These are all visible manifestation of different phases:
  - Neutral atomic gas
  - Ionized gas
  - Molecular gas
  - Coronal gas

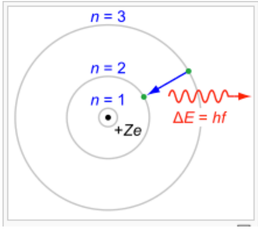
HII Regions

- HII regions surrounding early type (<B1, T_{eff}~25,000K) stars
  - Emit lots of >13.6 eV ionizing photons
  - Ionized gas, bright visible objects
  - $T \sim 10^4$ K
  - $n \sim 10^3$-10^4 cm^{-3} for compact 0.5pc^3 nebulae, $n \sim 10$ cm^{-3} for larger

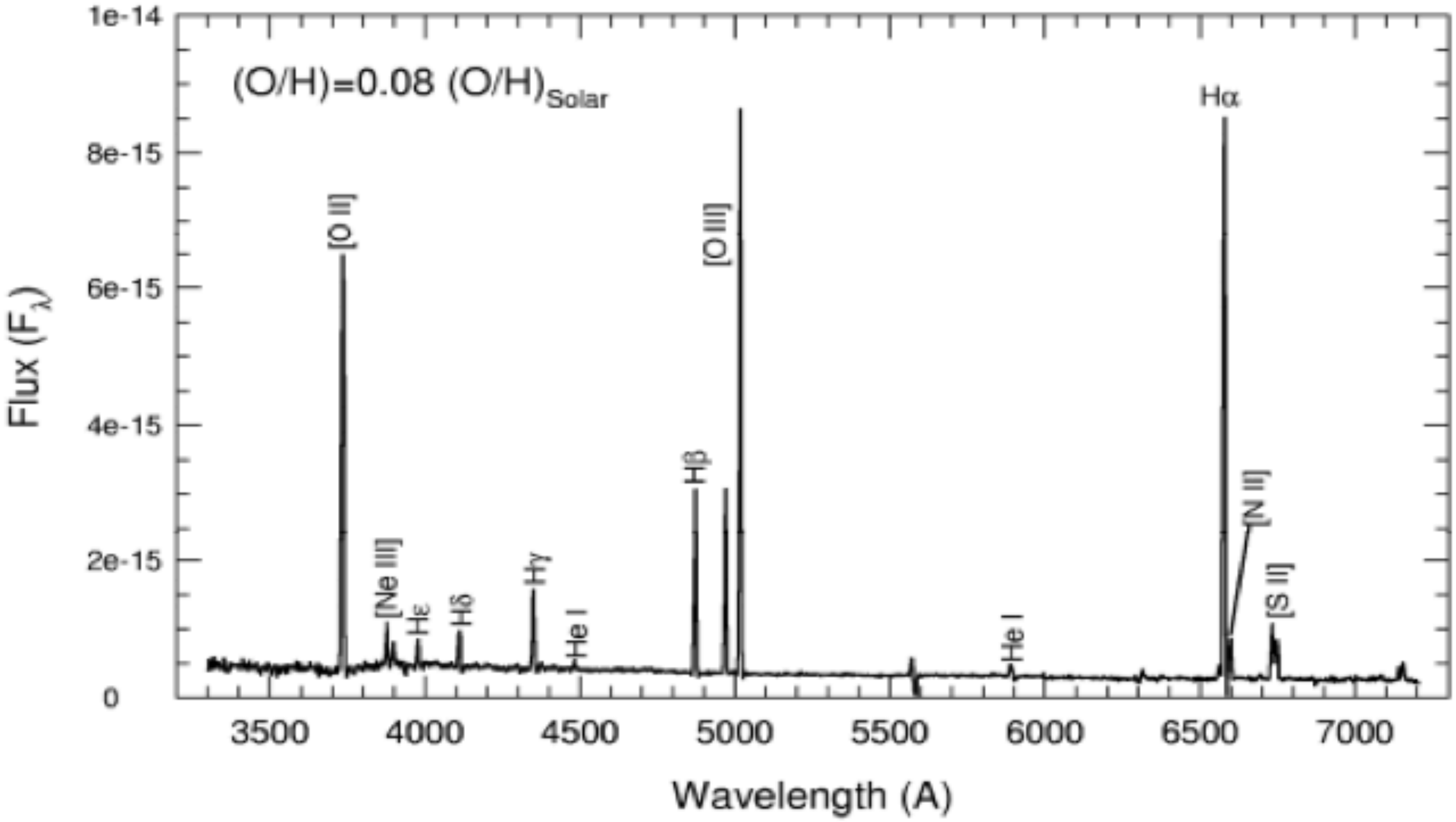
- Associated with star forming regions and molecular clouds
- Optical spectra dominated by H and H_e recombination lines
- Strong emission from thermal radio emission, warm dust



HII Optical Spectrum



- Hα and Hβ lines and O[III] (double ionized) and O[II] (ionized) oxygen



Reflection Nebulae

- Bluish nebulae reflecting light from nearby stars:
  - NGC 1977 in Orion;
  - emission around the Pleiades
- No radio emission, but infrared emission from warm dust present (less intense than from HII regions)
- Illuminated by stars later than B1 (less emission short of Lyman limit)
  - Otherwise they would be emission nebulae (and ionized)
- Less denser than HII regions ($n<10^3$ cm^{-3})
- Either cloud material from which star was formed; or chance encounter (Pleiades!); sometimes ejecta of late-type

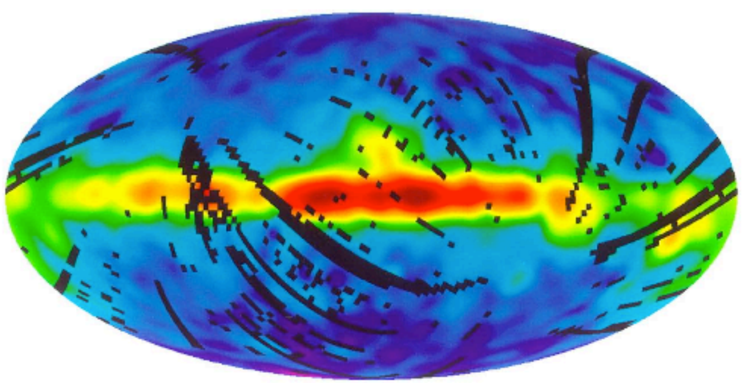
Dark Nebulae

- Dark stripes in the MW, Bok globules, horsehead nebula
- Faint in Optical, bright in IR, sometime seen against bright foreground

Photo-dissociation Regions

- Transition zones between atomic (HI) and molecular (H_2) gas near bright O, B stars
- Neutral regions where >6eV (FUV) photons are the main source of heat, dissociate and ionize molecular gas. Most photons absorbed by dust, but some add to heating through photoelectric effect -> few hundred K
- PDRs bright in IR dust continuum

PDR Emission



Cobe FIRAS map of the Galaxy (C^+ line, 157.7μm)

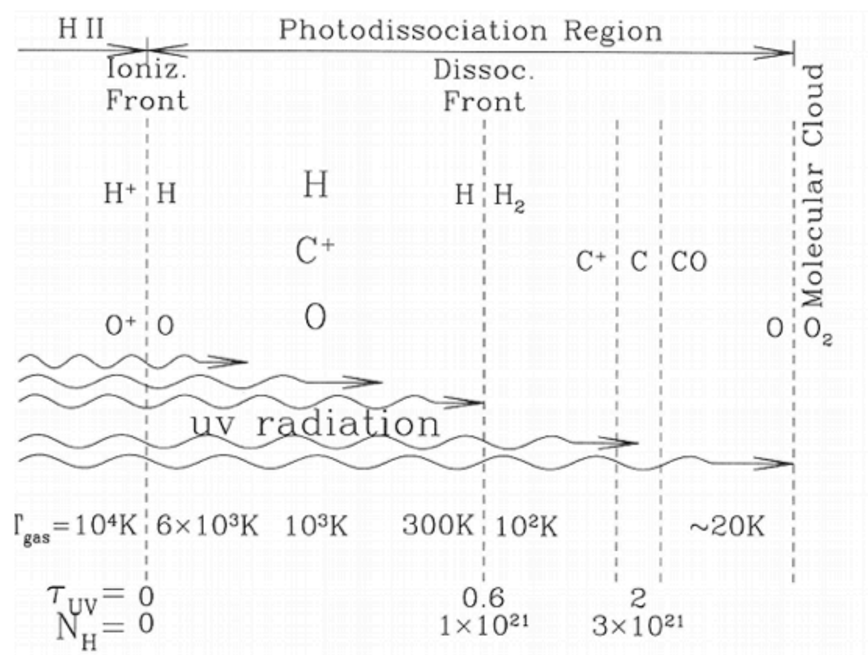


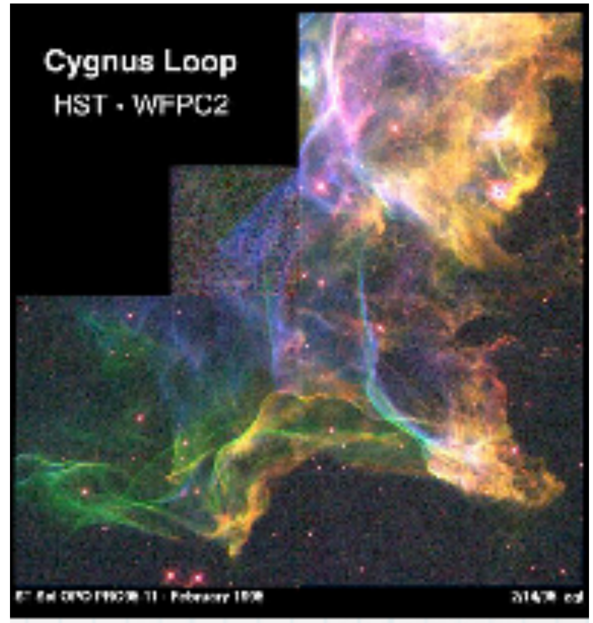
Figure 31.2 Structure of a PDR at the interface between an H II region and a dense molecular cloud.

SNRs

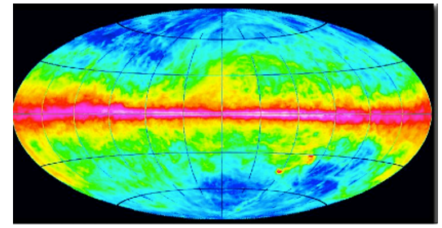
- Left over ejecta from SN explosion
- About 100 SNRs visible in MW

- Long, filamentary structures (but some compact, e.g., crab), emitting line radiation

- Strong in radio due to synchrotron emission; and clear in X-rays because of hot (10^6 K gas)

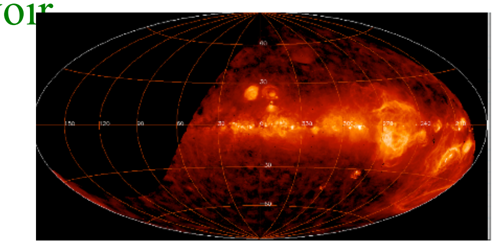


Phases



- Neutral gas:
  - Cold, diffuse HI clouds: ~100K CNM (cold neutral medium)
  - Warm inter-cloud gas (8000 K): WNM
  - Galactic distribution

- Ionized gas:
  - Hα emission, found in HII regions but also in huge diffuse reservoir
  - Warm Ionized Medium (WIM), 0.1 cm^{-3}, 8000K

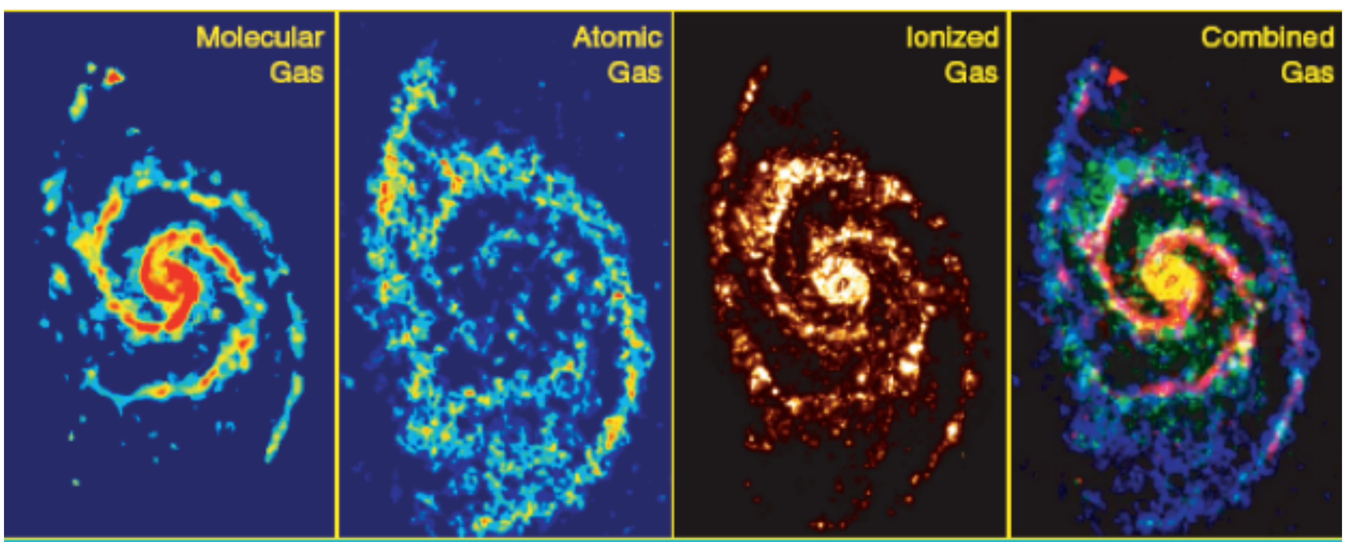


- Molecular Gas:
  - Traced by CO lines at mm
  - Concentrated in giant MC, 40 pc, 4×10^5 $M_\odot$, 200 cm^{-3}, 10 K
  - Sites of star formation
  - H_2 very common but other molecules detected as well

- Coronal Gas:
  - 10^{5-6}K gas seen through highly ionized species, CIV, SVI, NV, OVI in absorption against background stars; also: free-free emission, radiative recombination, UV, Xray lines
  - Fills most of the halo; disk less clear

Distribution in the Milky Way

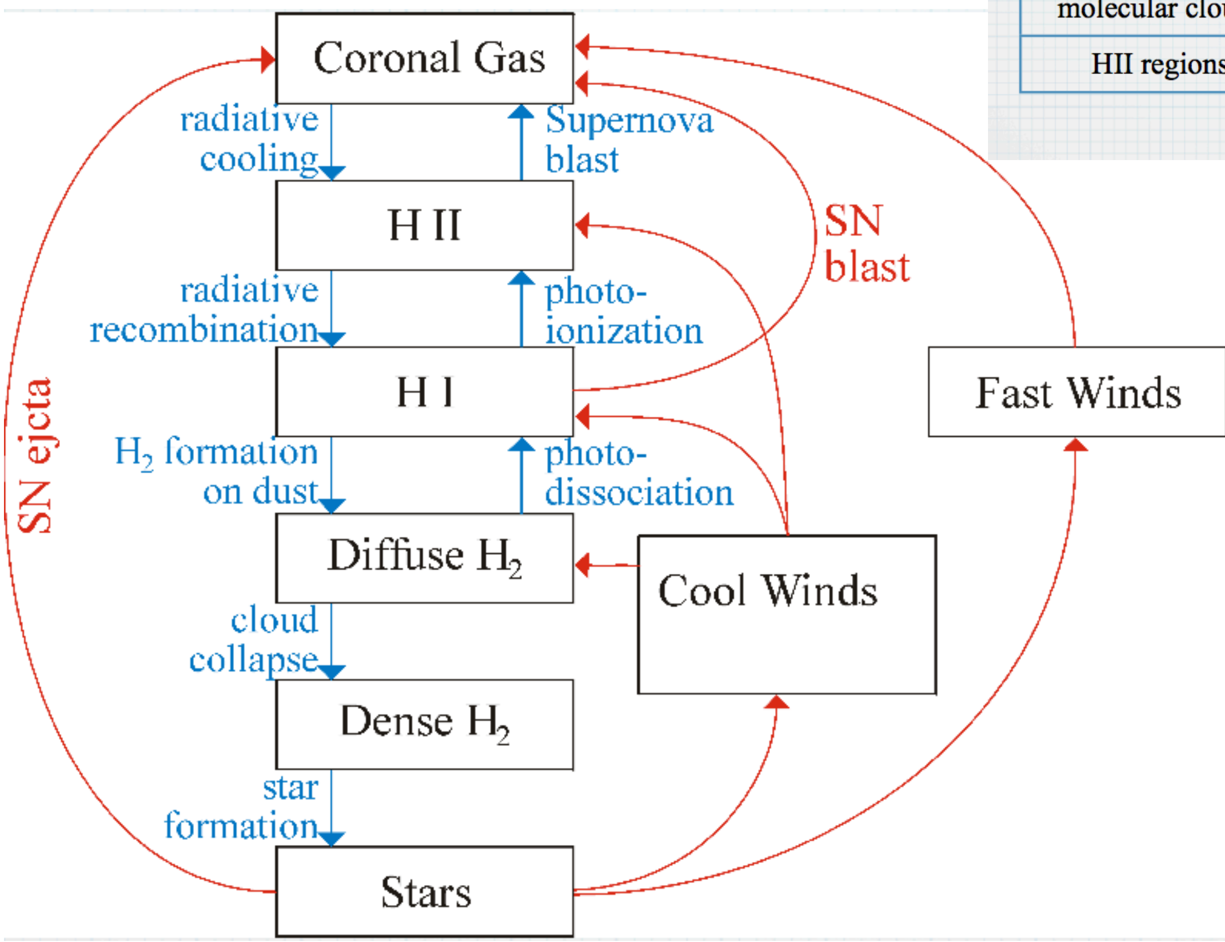
- MW = Sb/Sc ordinary spiral galaxy
- Atomic gas in flat distribution out to 18 kpc
- Molecular gas concentrated in 3 kpc molecular ring
- Spiral structure, difficult to figure out from inside the plane
- Other spiral galaxies: HII and dust along spiral arms. HI also interarm gas.



Summary & Pause

- Cycle of Gas

phase	n (cm^{-3})	T (K)
hot, intercloud	0.003	106
warm, neutral	0.5	8000
warm, ionized	0.1	8000
cold, neutral	50	80
molecular clouds	>200.	10
HII regions	1-10^5	104

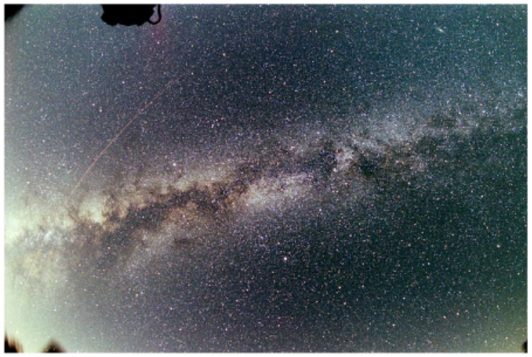


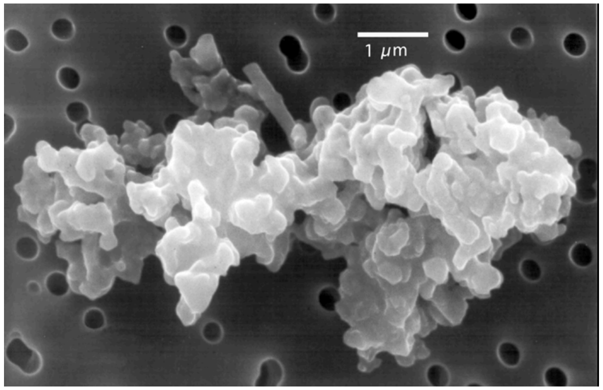
Hubble/GALEX/Spitzer

Dust

- Dust represents only 1% of the ISM mass
- Easily seen as `dark foreground’ against bright background (e.g. horsehead nebula) or in our galaxy

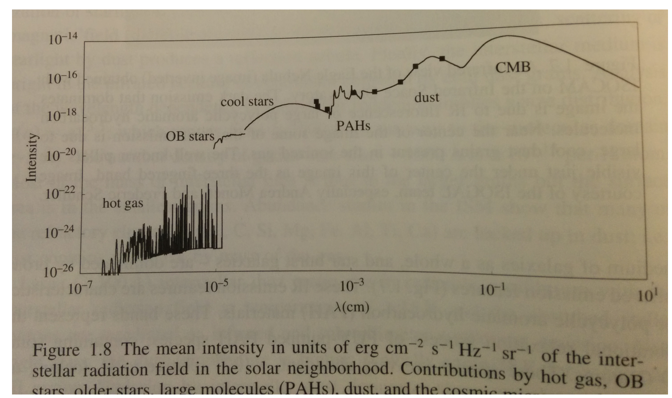
"Sure it's beautiful, but I can't help thinking about all that interstellar dust out there."





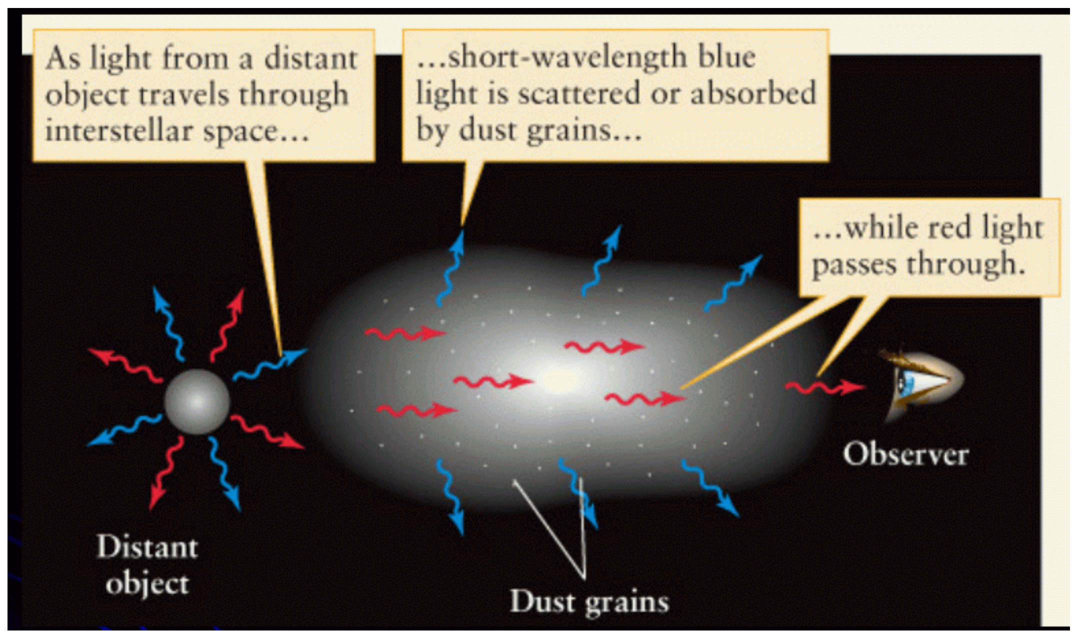
Why is Dust Important ?

- Made of silicates/graphite
  - Dust locks a substantial fraction of the ISM heavy elements: Mg, Si, Fe, C
- Provides the principal source of opacity of the ISM
  - The ISM is very `smoggy', if it had the density of the Earth's atmosphere, the extinction would be 1 mag/meter: worst than NY or Beijing !!
- Dust grains come in all sizes from ~5 Å to ~3000 Å, $n(a) \approx a^{-3.5}$
  - Most grains are small, but most of the mass is in the larger ones
- They have a variety of compositions:
  - Silicates grains, carbonaceous grains, amorphous carbon, and polycyclic aromatic hydrocarbons (PAHs)
  - grain properties **not the same from galaxy to galaxy or place to place**



How do we see Dust ?

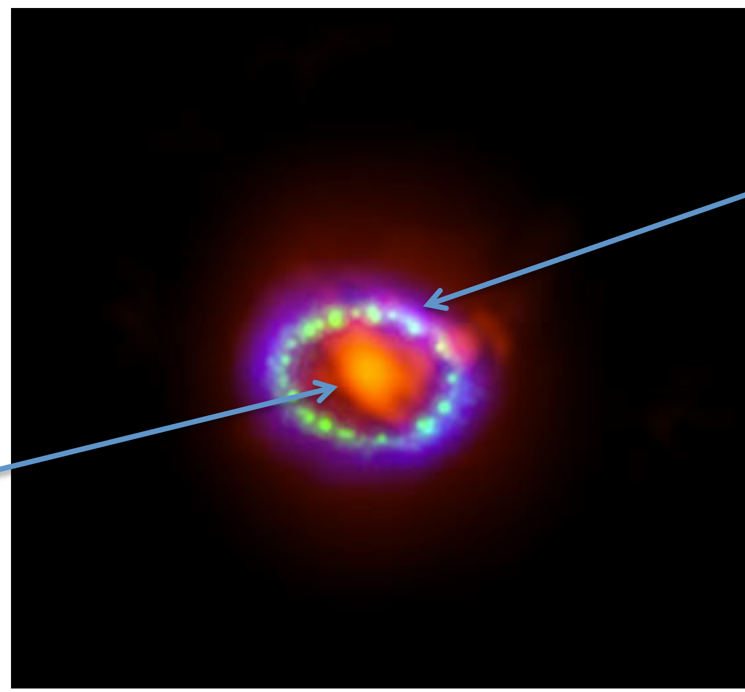
- Dust attenuates and scatters UV/optical/NIR
  - E.g. in star formation regions UV light from stars is absorbed by dust and re-emitted in the IR, also near black holes
  - The process depends on grain size distributions and properties
- Scattering produces reflection nebulae !
- Polarization of star light
- Large grains in radiative equilibrium with the IRF ~15 K
- Smaller grain ~75 K



First Evidence of Dust Production

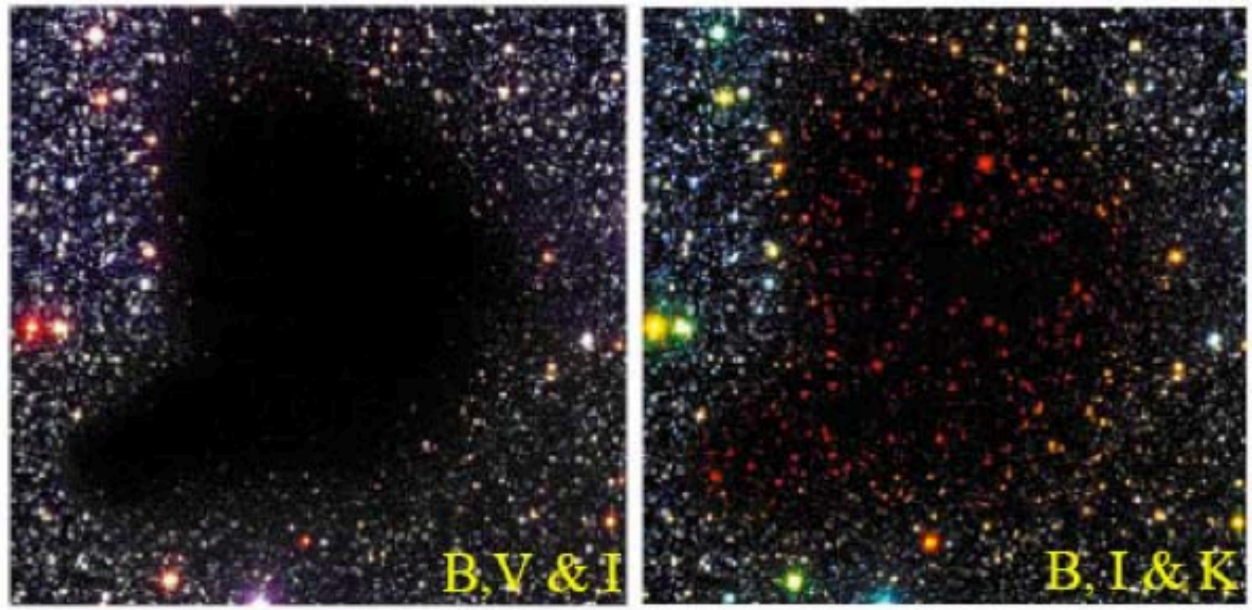
- The first dust evidence appeared in SN1987a's spectrum after 450 days
- Herschel/Alma observation show 0.4-0.7 $M_{\odot}$ of dust in ejecta!

Alma image, showed at AAS 2014



Examples of the Effects of Dust

B68 dark cloud
extincted stars
appear red

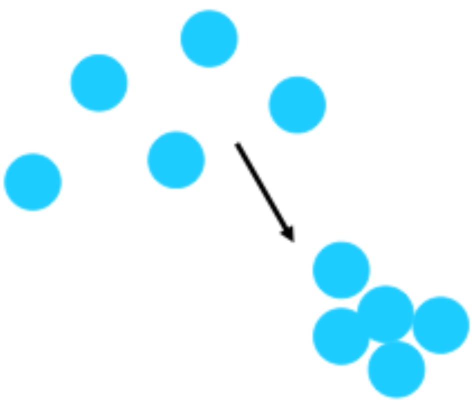


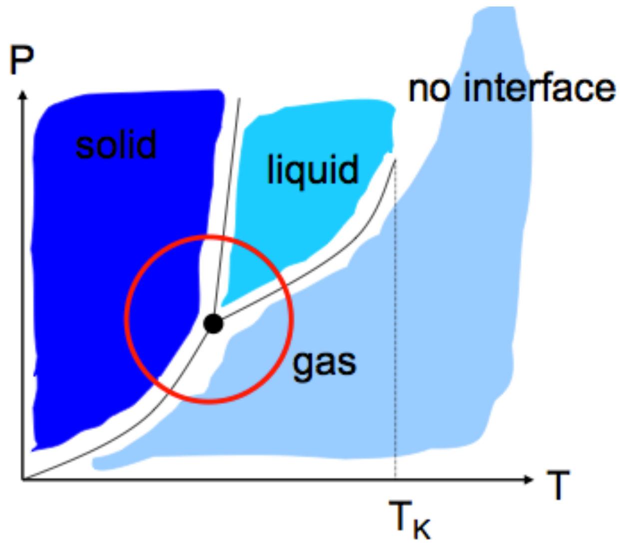
Pleiades starlight
scattered by dust

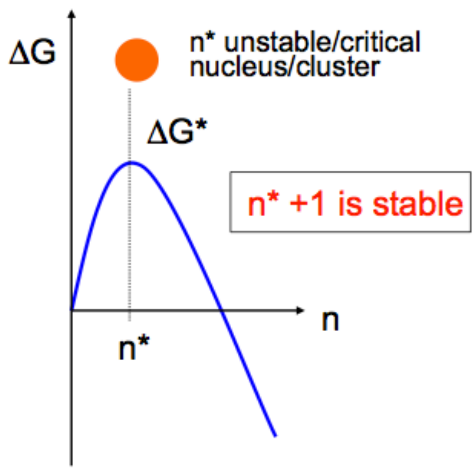
Dust Formation

- Dust forms by Nucleation
  - Phase change from gas to solid ☺
  - Matter can exist in different states at same T,P
  - To form a nucleus you need to spend energy to form the surface
- Discuss formation rates
- End point
  - Dust form in hot/dense environments (e.g. stellar ejecta)
    - *WR star ejecta colliding with the wind from a companion*
  - Accretion also depends on T

Nucleation of carbon dioxide bubbles around a finger.

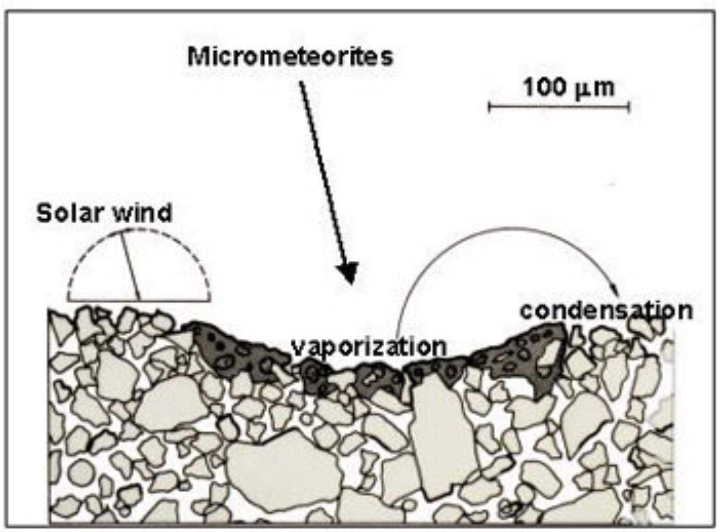






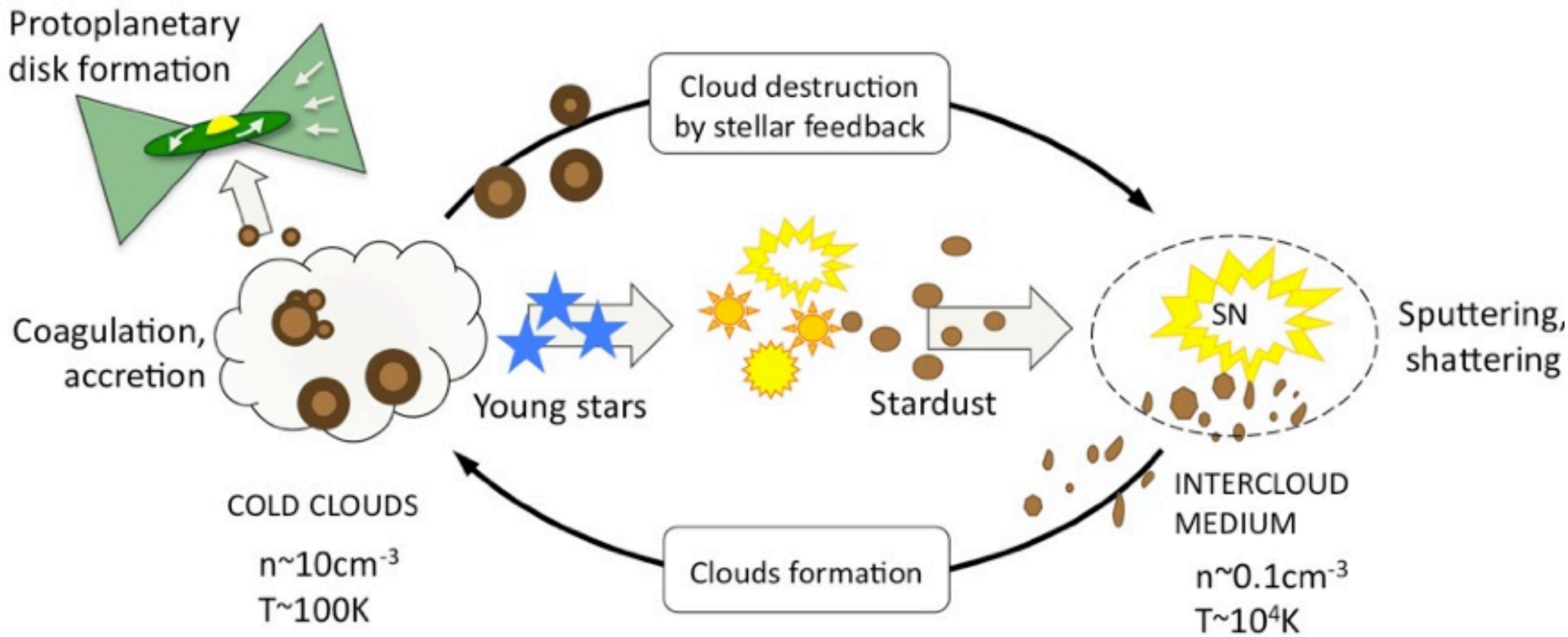
Dust Destruction

- Dust is destroyed by strong shocks in the warm phases of the ISM
  - Returns grain material to the gas phase
- 2 processes:
  - Sputtering, energetic ions hit grain
    - *At low energy (<100 eV/amu) nuclear interactions dominate, while at high Energy electronic excitations are more important. Atoms can also generate a cascade*
    - *Sputtering also important in tokomaks for contamination of the plasma !!*
  - Grain-grain collision leads to vaporization
    - *Also studied for micro-meteorites impacting on space vehicles*



Roughly ~8$M_\odot$/year are destroyed

Dust life cycle in the Milky Way



Dust – two distinct populations: carbonaceous and silicate grains

Dust around young stars is old, and dust around old stars is young!

Zhukovska & Gail (2011)

Recap