AY 20 Fall 2010

Interstellar Gas &Dust

Reading: Carroll & Ostlie, Chapter 12.1

OPTICAL CLASSIFICATION OF INTERSTELLAR CLOUDS – GASEOUS NEBULAE

DUST (FROM CONDENSATION IN ENVELOPES OF LATE-TYPE STARS) ALSO IMPORTANT COMPONENT

DARK NEBULAE

REGIONS WHERE STARLIGHT SUFFERS EXTINCTION – "DARK" IN CONTRAST TO SURROUNDINGS

REFLECTION NEBULAE

LIGHT FROM "EMBEDDED" STARS IS SCATTERED BY ADJACENT DUST – BLUER LIGHT OBSERVED

EMISSION NEBULAE

≡ H II REGIONS: BRIGHT IONIZED GAS EMISSION AROUND O AND B STARS

RECALL: DUST TEMPERATURE IN ISM 10-20K
- NEAR HOT STAR 100-600K
- H II REGIONS 70-100K

DUST ABSORBS UV RADIATION (AS WELL AS SCATTERS) AND RE-RADIATES IN IR → SIGNPOST OF NEW EMBEDDED STAR

H II REGIONS INDICATE GAS IN ISM


ρ Ophiuchi star forming cloud

From last class

$m - M = 5\log d\,(pc) - 5 + A_\lambda\,(mag)$ (to include extinction)

change of magnitude due to extinction ≈ optical depth in line of sight: $A_\lambda \approx \tau_\lambda$

$\tau_\lambda = \sigma_\lambda N_d$, where N_d = column density of dust particles

$\therefore\ A_\lambda \approx \tau_\lambda = \sigma_\lambda N_d$

extinction ∝ number of grains in line of sight if σ_λ constant

Mie scattering: when particle size ~ wavelength of radiation, $\sigma_\lambda \propto 1/\lambda$

optical radiation is reddened since blue light scattered preferentially

∴reddening distorts T_e, distance modulus etc

Correct using color excess: $E_{B-V} = (B-V)_{measured} - (B-V)_0$

Empirically, $E_{B-V} = 3A_v$

determining distance of reddened objects

(B-V) from observations. $(B-V)_0$ from spectral type.

$\therefore$ color excess $E_{B-V} = (B-V) - (B-V)_0$

And $A_v = 3\ E_{B-V}$

Hence distance from $m-M = 5\log d - 5 + A_v$

e.g. Suppose a star has $B = 14^m.41$. $V = 13^m.54$ and $E_{B-V} = 0^m.25$

$\therefore B-V = 14.4 - 13.54 = 0.87$

Intrinsic color $(B-V)_0 = B-V - E_{B-V} = 0.87 - 0.25 = 0.62$

Hence BC = 0.07 and $T_{eff} \sim 5800K$ (from tables)

$\therefore M_v \sim M_\odot = 4.7$, and $A_v = 3E_{B-V} = 0.75$

$\therefore 5\log d = 5 - 0.75 + 13.54 - 0.07 - 4.72 = 0.28 + 12.72 = 13.0$

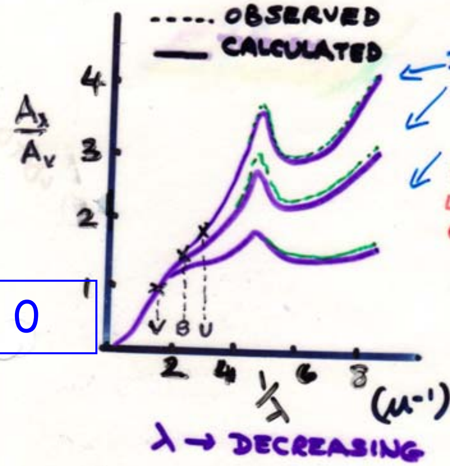
$\rightarrow$ d corrected for reddening

WHAT IS "DUST"?

FROM MIE THEORY & OBSERVATIONS →

PARTICULATE MATERIAL ≡ GRAINS

PLOTS OF $\frac{A_\lambda}{A_V}$ v. λ^{-1} OR $\frac{A_\lambda - A_V}{A_B - A_V}$ v. λ^{-1} TO COMPARE THEORY AND OBSERVATIONS



As λ increases, $A_\lambda \to 0$

THEORY & OBSERVATIONS AGREE UNTIL ULTRAVIOLET

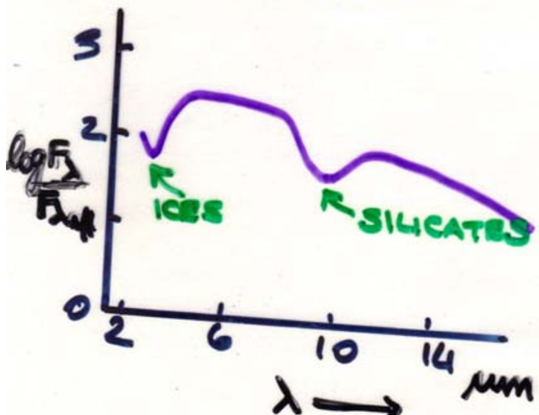
UV 'BUMP' AT 2175 Å

NOTE: EXTINCTION INCREASES AS λ DECREASES

'BUMP' DUE TO GRAPHITE [C] INTERACTION WITH LIGHT – A RESONANCE LINE A 2175Å

or PAHS

SIZES ≳ 0.3 μm



ABSORPTION FEATURES DUE TO ICES

" SILICATES

" PAHS (3.3–12μm)

PAHS FEW × Å

SILICATES LIKE GRAPHITE

⇒ CORES + ICY MANTLES

I/S POLARIZATION MEASUREMENTS

⇒ NON-SPHERICAL PARTICLES

Gas in the ISM

~1900: some absorption lines in the spectra of binary stars remain fixed as other lines reflect binary motions

circumstellar or interstellar lines?

- radial velocities of fixed lines match Milky Way arms
- fixed lines very narrow (gas colder, more diffuse than in stellar photospheres)
- same line seen multiple times ≡ different cloudlets (or different arms)

→ interstellar origins for lines

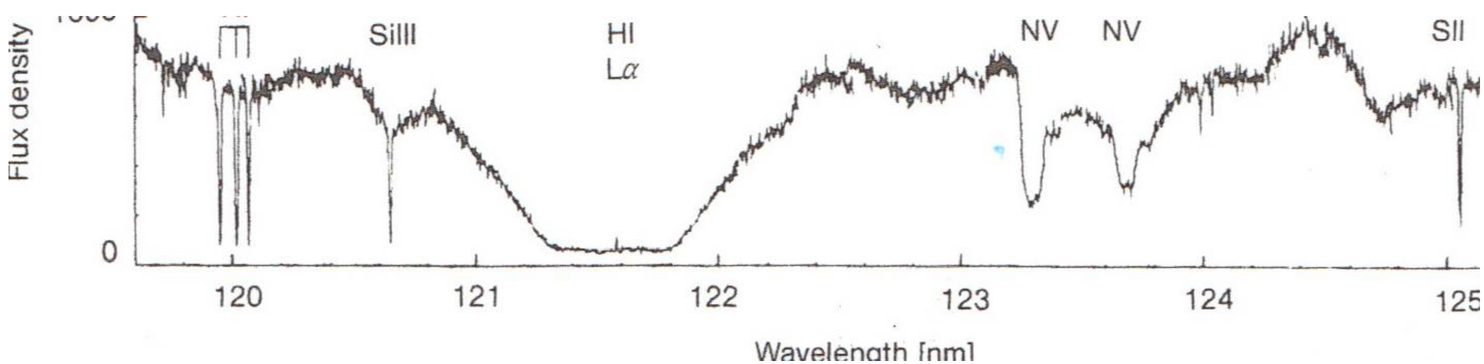
Typical lines: visible – NaI, CaII; UV - Lyman α (1216 Å)

ionized lines due to UV radiation from new stars

Lyman α (HI mostly in n=1 state) requires rocket measures

more recently: satellites

i/s absorption lines towards ζ Ophiuchi



ISM mostly HI, HII, or H_2 (molecular hydrogen)

(70% H, 28% He, 2% metals)

gas, dust well-mixed: $n_{dust} \sim 10^{-13}/cm^3$, $\langle n_{gas} \rangle \sim 1/cm^3$

mass ~ 100 X dust mass

BUT dust opacity/unit mass >> gas opacity/unit mass

Five phases of interstellar gas

	T(K)	n (cm^{-3})
Very cool molecular clouds (mostly H_2)	20	> 10^3
Cool clouds (mostly HI)	100	20
Warm neutral gas envelopes of cool clouds	6000	0.5-0.3
Hot ionized gas (HII regions)	8000	>0.5
Very hot diffuse ionized "coronal" gas ionized, heated by supernovae explosions	10^6	10^{-3}

OBSERVING NEUTRAL HYDROGEN HI

- TYPICALLY IN GROUND STATE & COOL
  - ∴ NO ELECTRON TRANSITIONS OBVIOUS

BUT: HYDROGEN ATOM – PROTON, ELECTRON
Z-COMPONENTS OF SPIN ANGULAR MOMENTUM
ALIGNED OR ANTI-ALIGNED

⇒ 2 ENERGY STATES

PHOTON FROM SPIN-FLIP {ALIGNED TO ANTI-ALIGNED}

$\lambda = 21.1$ cm

$\nu = 1420$ MHz **

21 cm LINE:
- (ZEEMAN EFFECT) → MAGNETIC FIELD INFO
- → DOPPLER SHIFTS
- → MORPHOLOGY

$\tau_H \propto N_H$ = COLUMN DENSITY OF HI

(OPTICAL DEPTH AT LINE CENTER)

STRUCTURE & KINEMATICS
MILKY WAY
OTHER GALAXIES

** SPONTANEOUS EMISSION COMPETES W. COLLISIONS (EXCITE OR DE-EXCITE) ~ 1/10^6 YRS ~ 1/100 YRS

ISM – VERY LOW DENSITY – UNATTAINABLE IN TERRESTRIAL LABS
⇒ STATISTICALLY POSSIBLE TO HAVE SPIN-FLIP TRANSITION

N.B. PREDICTED BY VAN DE HULST 1940's; DETECTED '51

Observations of 21 cm line $\rightarrow$hydrogen column density since optical depth at line center $\tau_H = N_H/T\,\Delta v$, where Δv = full width at half-maximum (km/s)

For dust, $A_V \propto \tau_D = \sigma_V N_D$

Observations of N_D and N_H towards different stars show that for small A_V, $N_D \propto N_H$

Thus gas and dust coexist

For $A_V > 3$, correlation invalid

In optically thick clouds, dust shields hydrogen from UV radiation

$\rightarrow$reduced dissociation of H

$\rightarrow H_2$ formation rate enhanced

i.e. hydrogen still present but in molecular form

MOLECULAR CLOUDS [INTERSTELLAR]

FOR $n > 10^3$ particles/cm^3

$T \sim 10K$

$H + H \rightarrow H_2$ = MOLECULAR HYDROGEN

CATALYTIC GRAIN REACTION
DUST ABSORBS EXCESS ENERGY, MOMENTUM

∴ IN COLDER, DENSER REGIONS OF SPACE CANNOT USE 21 CM MEASURES TO PROBE PROPERTIES OF ISM (T VERY LOW)

cannot measure directly in cold clouds

H_2 - NO DETECTABLE LINES UNLESS $T > 2000K$

TRACERS CO AND OTHER MOLECULES* HAVE TRANSITIONS → RADIATION AT MM WAVELENGTHS

ASSUME N_{CO} or N_H → H_2 DENSITY, TEMP, KINEMATICS

* CO = $^{12}C^{16}O$ BUT ISOTOPOMERS $^{13}C^{16}O$, $^{12}C^{18}O$ etc ALSO USED

SIMILARLY CS, CH, SiO, N_2H^+

DARK DARK NEBULAE ≡ MOLECULAR CLOUDS

LARGE FRACTION OF ISM IN FORM H_2

Table 16.4. Some molecules observed in the interstellar medium

Molecule	Name	Year of discovery
Discovered in the optical and ultraviolet region:		
CH	methylidyne	1937
CH^+	methylidyne ion	1937
CN	cyanogen	1938
H_2	hydrogen molecule	1970 ← COPERNICUS SATELLITE [UV]
CO	carbon monoxide	1971
Discovered in the radio region:		
OH	hydroxyl radical	1963
CO	carbon monoxide	1970
CS	carbon monosulfide	1971
SiO	silicon monoxide	1971
SO	sulfur monoxide	1973
H_2O	water	1969
HCN	hydrogen cyanide	1970
NH_3	ammonia	1968
H_2CO	formaldehyde	1969
HCOOH	formic acid	1975
HCCNC	isocyanoacetylene	1991
H_2CCCC	cumulene carbene	1991
$(CH_3)_2O$	dimethyl ether	1974
C_2H_5OH	ethanol	1975
$HC_{11}N$	cyanopentacetylene	1981

COLLISIONS OF [FOR EXAMPLE] CO, H_2

→ EXCITED STATE CO [FIRST ROTATIONAL STATE]

→ SPONTANEOUS DOWNWARD TRANSITION

SPECTRAL LINE AT 2.6 mm (115GHz)

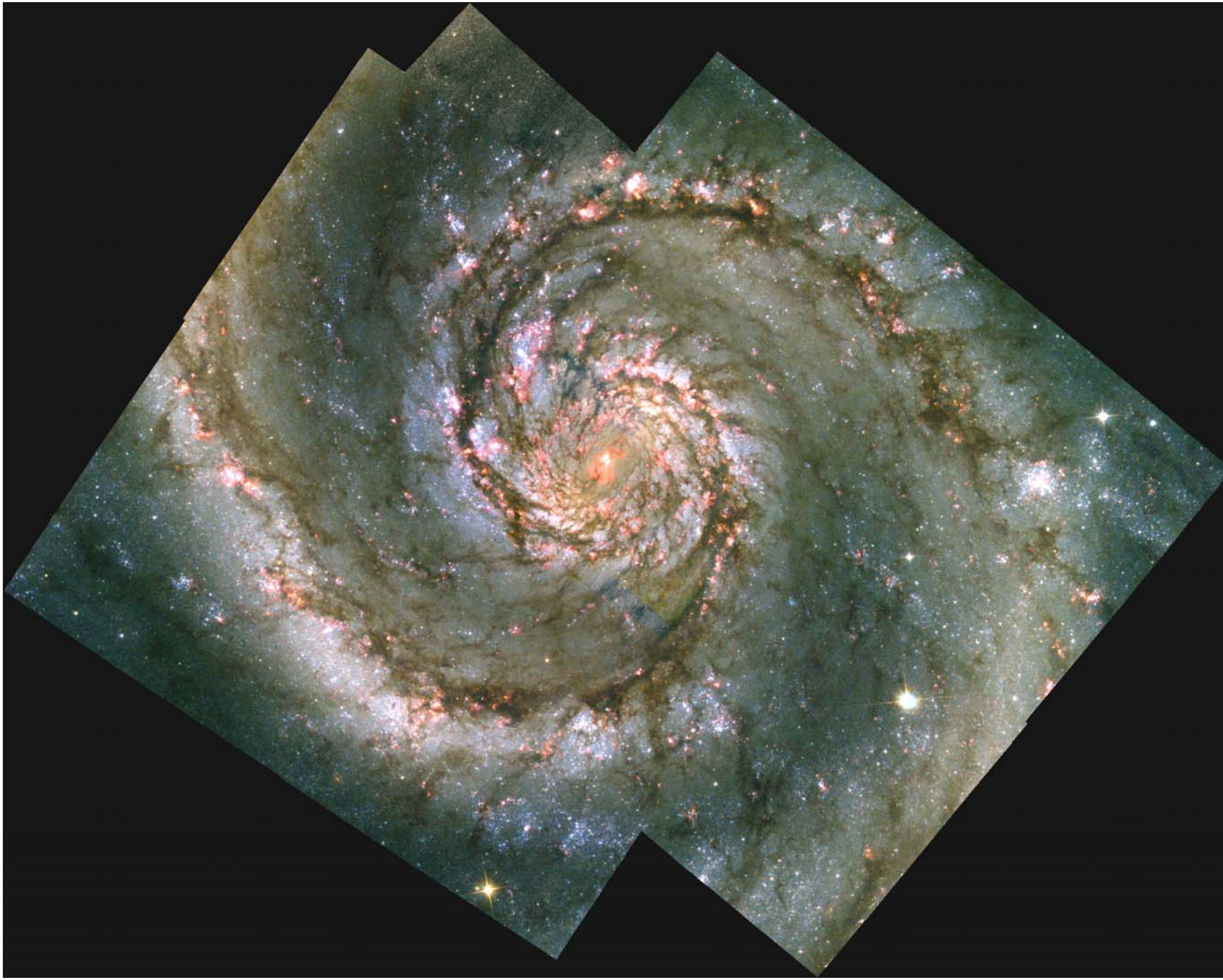
GIVES TEMP, DENSITY, VELOCITIES etc. OF MOLECULAR HYDROGEN

Properties of interstellar gas and dust

FOR GALAXY			i.e 100/1
Mass fraction	10%	0.1%	
Composition	H I, H II, H_2 (70%) He (28%) C, N, O, Ne, Na, Mg, Al, Si, S... (2%)	Solid particles $d = 0.1 - 1$ μm H_2O (ice), silicates, graphite + impurities	
Particle density	1 cm^{-3}	10^{-13} cm^{-3} = 100 km^{-3}	
Mass density	10^{-21} kg m^{-3}	10^{-23} kg m^{-3}	
Temperature	100 K, 10^4 K, 50 K (H I, H II, H_2)	10 – 20 K	
Method of study	Absorption lines in stellar spectra. Optical: Ca I, Ca II, Na I, K I, Ti II, Fe I, CN, CH, CH^+ Ultraviolet: H_2, CO, HD Radio lines: hydrogen 21-cm emission and absorption; H II, He II, C II recombination lines; molecular emission and absorption lines	Absorption and scattering of starlight. Interstellar reddening Interstellar polarization Thermal infrared emission	

Phenomena caused by ISM

Observable phenomenon	
Interstellar extinction and polarization	Non-spherical dust grains aligned by magnetic field.
Dark nebulae, uneven distribution of stars and galaxies	Dust clouds
Interstellar absorption lines in stellar spectra	Atoms and molecules in the interstellar gas
Reflection nebulae	Interstellar dust clouds illuminated by nearby stars
Emission nebulae or H II regions (optical, infrared and radio emission)	Interstellar gas and dust cloud, where a nearby hot star ionizes the gas and heats the dust to 50 – 100 K
Optical galactic background (diffuse galactic light)	Interstellar dust illuminated by the integrated light of all stars
Galactic background radiation:	
a) short wavelength (<1 m)	Free-free emission from hot interstellar gas
b) long wavelength (>1 m)	Synchrotron radiation from cosmic ray electrons in the magnetic field
Galactic 21-cm emission	Cold (100 K) interstellar neutral hydrogen clouds (H I regions)
Molecular line emission (extended)	Giant molecular clouds, dark nebulae
Point-like OH, H_2O and SiO sources	Maser sources near protostars and long-period variables



OPTICAL & RADIO RECOMBINATION SPECTRAL LINES → EMISSION NEBULAE

RECOMBINATION: (H, He, C LINES SEEN)

e.g. UV PHOTON FROM STAR

|

IONIZES H ATOM

|

ELECTRON EJECTED

|

RE-COMBINES WITH FREE PROTON

|

'CASCADES' TO GROUND STATE PRODUCING LOWER ENERGY PHOTONS

(SHU: CHAPTER 11)

DOMINANT TRANSITION/PHOTON

$n=3 \rightarrow n=2$

= BALMER Hα

∴ HII REGIONS RED (Hα 6565Å)

RECALL: $1/\lambda = R_H\left(1/n_1^2 - 1/n_2^2\right) = R_H\left(1/4 - 1/n^2\right)$ (BALMER)

C&O P.134 →

$\therefore \lambda = 1/109677 \cdot 1/(1/4 - 1/9) \cdot 1/10^8$

WIEN'S EQUATION ⇒ TEMPERATURES

- HII REGIONS NEAR HOT, MASSIVE STARS (O AND B STARS)

RECALL WIEN: $\lambda T \sim 0.29$

∴ FOR $T_{eff} \sim 20{,}000K$

$$\lambda = \frac{29 \times 10^{-2}}{2 \times 10^{4}} \sim 15 \times 10^{-6}\ \text{cm}$$

∴ PEAK EMISSION AT ~ 1500Å

RECALL: PHOTONS WITH $\lambda \leq 912$Å CAN IONIZE HYDROGEN → HII

∴ TO IONIZE HI NEED STAR OF TEMPERATURE $T = \frac{29 \times 10^{-2}}{912 \times 10^{-8}}$

$$\sim \frac{3 \times 10^{-2}}{10^{-6}} \sim 3 \times 10^{4}$$

∴ TO CREATE AN HII REGION CENTRAL STAR MUST HAVE

$T > 30{,}000K$