The Interstellar Medium : JAP course
Galaxies and ISM

Lecture 5

M.Das
Indian Institute of Astrophysics, Bangalore

Optics of Grains

- The size and shape of IS grains will affect the surrounding radiation. We can treat the effect of grains on light as the diffraction of e.m. waves by small solid dust particles. We will briefly describe it here.
- Let the intensity of light I be given by : $I = I_0 \exp[-\int_0^L \alpha dl]$ where α is the absorption coefficient. Also let, a=grain size n_g=grain number density Q_{ext}= extinction efficiency.
- Then , $I = I_0 \exp[- n_g \pi a^2 Q_{ext} L]$
- Also, there is both absorption and scattering. Hence, $Q_{ext} = Q_{abs} + Q_{sca}$
- The albedo γ (gamma) of the grains measures the the fraction taken out by scattering and is given by, $\gamma = Q_{sca} /[Q_{abs} + Q_{sca}]$
- The amount of absorption and scattering by the grains depends on (i) the refractive index of the grains which can be complex and (ii) the ratio of grain circumference to wavelength (also called α) where $\alpha=2\pi a/\lambda$. When Q_{abs} is small we get the Rayleigh scattering dependence i.e. Q_{ext} proportional to λ^{-4}.

The Origin of Dust in the ISM

1. Condensation from general Interstellar Gas : after hydrogen the most common elements are C, O and N. Bi-atomic molecules such as CO, CH and CN condense out in interstellar clouds. After that molecules with 10 to 20 atoms can grow in dense clouds.

2. Condensation in atmospheres of cool giant stars : Dust forms in the cool dense stellar atmospheres of giant stars. Such atmospheres have super saturated vapour where elements such as graphite, SiC and silicates may form. The elements are blown out as dust particles by the radiation pressure of emission from the stars. Giant stars also have outflows that push these materials into the ISM.
Good example are the carbon stars where many elements that constitute dust are formed.

Infrared spectroscopic observations of such stars have confirmed that the elements found in dust are present in the stellar envelopes of stars. But it is not enough to account for all the dust.

The Origin of Dust ….. continued

3. Condensation during star formation : During the process of star formation, gas clouds contract and fragment into smaller clouds or sub-clouds. Then finally when the density and temperature is high enough in the cloud/sub-clouds protostars form. Finally when the temperature is high enough nuclear reactions are triggered and the star becomes luminous.

In this process, very high temperatures can exist in the outer envelopes of the clouds. After a star is formed the remaining gas in the envelope may form a rotating disk that fragments and forms planetary systems. During disk formation many elements can form such C_2SiO_4, Al_2SiO_4, Fe, Ni.

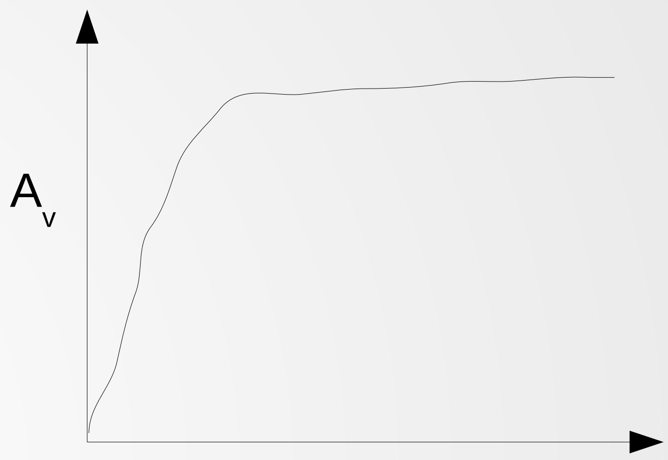
The stellar wind blows out the dust particles into the ISM.

4. Depletion of elements : Certain elements in the ISM gas have a much lower abundance compared to the sun. Elements such as silicates and titanium which are stable at high temperatures (refractory elements). This maybe because as gas moves away from a star such as the sun, it cools and these elements form dust . Hence they are present in IS dust but not in the ISM gas.

Determing Dust Distribution in Galaxies

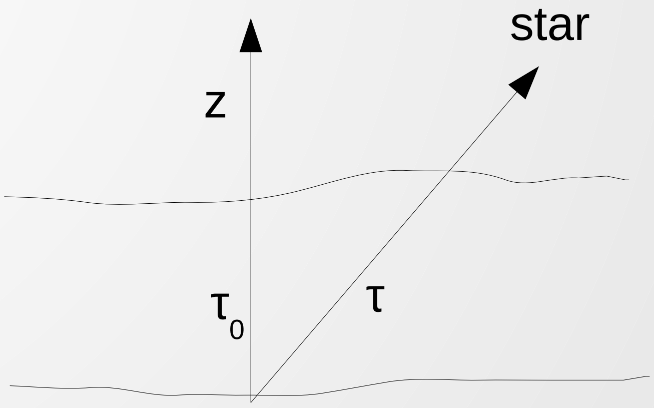
- We can determine the spatial distribution of dust in our Galaxy plane from the observed reddening of stars, E(B-V).

- Stars with known M_V and E(B-V) can be used with the relation $R_V \sim 3 = A_V/E(B-V)$ to determine the extinction A_v and the distance can be determined using the well known relation : $m - M = 5\log D - 5 + A_v$. Along different lines of sight we can get plots for A_V against distance (see figure on the right which is for some value of l,b).



- Consider a line of sight towards a star at an altitude angle b (angle between the star direction and vertical z direction). If the optical depth is τ, then the intensity is given by,

$$I = I_0 \exp(-\tau)$$



- So the change in magnitude due to dust extinction is

$$\Delta m = -2.5\log(I/I_0) = 1.086\,\tau$$

Determining Dust Distribution …….. contd

- Let κ be the mass absorption coefficient per unit dust mass and ρ_d be dust density profile along line of sight in the galaxy. Then the extinction is given by

$$Av(r) = 1.086\, \kappa \int_0^r \rho_d(r)dr$$

- If we know the reddening of stars along different directions then we can apply the above relation to derive the dust mass distribution $\rho_d(r)$. Surveys of stars in our Galaxy, such as Hipparcos and Gaia, have been important for mapping the dust distribution within the solar neighbourhood. The dust distribution mainly follows the clouds and the molecular hydrogen.

- Dust to gas mass ratio : The density of dust is a good indicator of gas (HI) and follows the following relation in our galaxy.

$$\rho_d / \rho_{gas} \sim 0.6 \times 10^{-2}$$

- This can be shown using the H(H) and Av ratio (given for H.W.).

The Formation of Molecular Hydrogen (H_2) on Grains

- Grains are made of elements such as silicates and graphite. They have a crystalline structure. The surface of grains acts as a 3^{rd} body on which many different molecules in the ISM form. But the most important molecule forming on dust grains is molecular hydrogen H_2.

- In laboratory conditions molecules can need a 3^{rd} body for stabilisation or like a catalyst. This happens in ISM as well. For H_2 formation the reaction is,

$$H + H \rightarrow H_2$$

- Let us assume that the reaction has an efficiency of 1. Let the rate of arrival of H atoms on grains be $= n(H)\pi a^2 n_g v$ where a=grain radius, n_g=number density of grains/volume, v=most probable velocity of H atoms and n(H)=number density of H atoms. But the column number of grains N_g along a line of sight can be derived from the extinction coefficient ie. $A_v = Q_{ext} \pi a^2 N_g R$. Assuming that Q_{ext} =1, we can use the extinction coefficient to obtain $\pi a^2 n_g$.

- Generally the value is $\pi a^2 n_g = (3\times10^{-26}\ n) m^{-1}$ so that we get :

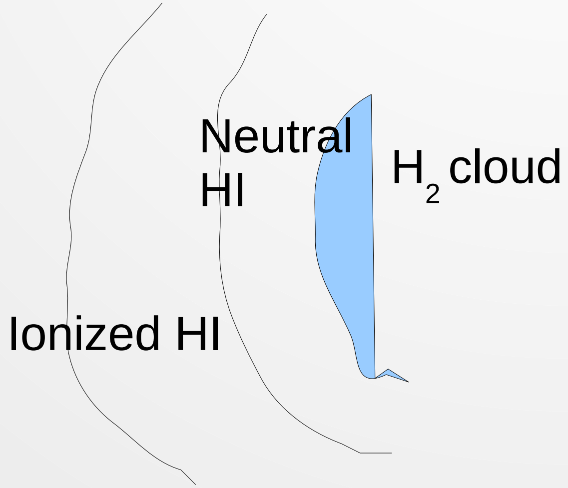
$$d/dt\ n(H_2) = 3\times10^{-26}\ n.1/2\ n(H) \times v$$

- where n= total density of hydrogen = $n(H) + 2n(H_2)$. If the grains are in thermal equipartition then $v^2 = 3kT/m_H$. So the rate of formation of molecular hydrogen is given by

$$d/dt\ n(H_2) = 2.4\times10^{-23}\ n.\ n(H)\ m^{-3}\ s^{-1}$$

The Balance of H_2 Formation and Dissociation on grains

- To estimate the net formation rate of H_2 in the ISM we have to balance the formation rate with dissociation by starlight.
- But apart from dissociation, the H_2 molecules can be excited to higher electronic states and then cascades down to lower levels. About 10% of such excitations lead to the dissociation of H_2
- In the ISM, the H_2 clouds are embedded deep within HI and ionized or photodissociation regions so that the UV photons of starlight cannot dissociate the H_2 molecules. The photodissociation regions shield the H_2 clouds from dissociation.
- The photodissociation rate depends on the column density of H_2 molecules in the cloud.
  For a column density $N(H_2)$ m-^{2} < 10^{18} m^{-2} dissociation rate is 10^{-10} s^{-1}
  For a column density $N(H_2)$ m-^{2} < 10^{24} m^{-2} dissociation rate is 10^{-14} s^{-1}



The denser is the cloud, the lower is the photodissociation rate. For a cloud of H_2 number density ~10^8 cm^{-3}, the formation rate balances the dissociation rate.

The Physical Process of the Formation of H_2 on Grains

- The minimum requirement of H_2 formation is that an H atom is retained on grain surfaces long enough for a second atom to arrive on the grain and locate it.
- On a grain, the H atom experiences a long range van der Waals force with other atoms of the grain and hence does not leave the grain.
- The H atom will move laterally over the grain surfaces or will remain bound to a lattice site. The H atom transfers energy to the lattice phonons and remains bound to the grain lattice.
- The mobility of H atoms on the grain surface is due to two processes : 1) thermal diffusion and 2) quantum tunneling. The astrophysically relevant surfaces are amorphous carbon and olivine.
- Some H atoms maybe lost due to evaporation if the following condition is satisfied.

$$n(H)\pi a^2 v_H > v\exp\{-q/kT\}$$

- where T is the grain temperature, v is the grain velocity, q is the potential well depth and a is the radius. The velocity of the H atom is v_H

The Formation of H_2 in early Epochs when there was no star formation

- At low redshifts H_2 is formed on grains. But at early epochs when there was little or no star formation, there was no grain surfaces. But the first stars needed cold gas to form. Also there are warm regions where H_2 is present but little dust.

- So the other mechanism by which H_2 molecules are formed is in the gas phase when the temperatures and densities are high enough. There are two main reactions:

1) $H + e \rightarrow H^- + h\nu$

   $H^- + e \rightarrow H_2 + e$

2) $H + H^+ \rightarrow H_2^+ + h\nu$

   $H_2^+ + H \rightarrow H_2 + H^+$

- The first reaction is faster than the second one. The main factor for the formation of H_2 in the gas phase is the dust/gas ratio. If it falls below a critical value then the above reactions become important.Temperature and gas density are the important parameters.

- The two cases where it is important are :
  1) Warm atomic gas in our Galaxy and 2) star formation at early epochs.

End of Fifth Lecture