The Interstellar Medium : JAP course
Galaxies and ISM
Lecture 8

June 2020

M.Das
Indian Institute of Astrophysics, Bangalore

References for HI and H_2 Gas in Galaxies

- HI in galaxies : “Galactic and Extragalactic Radioastronomy” by Kellerman and Verschur, Pg. 522 Chapter on HI by Giovanelli & Haynes

  https://ned.ipac.caltech.edu/level5/Sept04/Giovanelli/Giovanelli1.html

- NRAO science website : https://www.cv.nrao.edu/course/astr534/HILine.html

- For molecular gas H_2 :

  F.Comes, Annual Review of astronomy and Astrophysics, 1989, 1991.

Molecular Gas and Star Formation in Galaxies

- In this lecture we will study the molecular hydrogen H_2 gas distribution in galaxies and its importance for star formation. At the end we will do a brief summary of the process of star formation. Since molecular cloud collide, they are the most dissipative component of galaxy disks and are hence confined mainly to the disk plane.

Importance of H_2 in galaxies :

- (i) Fuel for star formation : Stars form due to the collapse of cold molecular gas. Hence H_2 gas is essential for forming new stars and hence also important for galaxy evolution. (ii) Role in disk instabilities : H_2 gas clouds are always clumpy and embedded in HI and photodissociation regions. This is because the H_2 molecules have to be shielded against dissociation by UV photons from star light. The clouds hence undergo collisions and dissipate energy. So during the formation of disk instabilities such as bars and spiral density waves, the H_2 gas clouds collide, form shocks ==> the shocked gas cools, fragments and stars can form in the cold, dense H_2 gas. (iii) Important mass component in galaxy disks : The H_2 gas mass in galaxies is similar to the HI mass (1 to 5% of M(stars)). But the molecular clouds themselves have masses ranging from 10 to 10^5 M_{sun}. Hence they can perturb the motion of stars in the disk plane, this is also called the gravitational scattering of stars by gas clouds (Spitzer & Schwarzchild 1951, 1953).

The CO molecule as a tracer of H_2 gas

- H_2 gas was detected using baloon borne observations in UV absorption lines (Carruthers 1970). The H_2 emission is due to the electronic transition of the molecule.
- As mentioned in earlier lectures, the H_2 molecule does not have a dipole moment and hence it is not easy to detect. Only IR emission lines or UV absorption lines can be used for its detection. An easier method however, is to use the CO molecule as a tracer of the H_2 molecule.
- The CO molecule is the most abundant molecule after the H_2 molecule and it has a dipole moment. The rotational lines of CO (1=>0 and 2=>1) can be easily detected in the mm range (115 GHz and 230 GHz) using radio telescopes. So CO is used as a tracer of H_2 gas.
- To determine the H_2 gas mass, we convert the CO intensity I(CO) to H_2 column density $N(H_2)$ using the X ratio, i.e., $X = N(H_2)/I(CO)$
Then $M((H_2) = \text{Volume} \times N(H_2)/L \times 2m_p$ where L=cloud diameter and m_p = proton mass
- The factor X is found to be approximately constant within our Galaxy and was determined from the H_2 column density measured towards ~100 stars in UV absorption by Copernicus satellite.

Empirical Mass Estimate of H_2 gas and Virial Equilibrium

- (i) Mass from CO Luminosity : The H_2 gas mass can be determined from the CO luminosity using the following relation,

$$M(H_2)\ M_{sun} = 1.5\text{x}10^4 D_{Mpc}^{\ 2} \int Sdv$$

where Sdv is the CO flux integrated over the line width in units of $Jykms^{-1}$ and D_{Mpc} is the galaxy distance in Mpc.

- (ii) Mass using X factor : Within our Galaxy, the H_2 gas mass is calculated from the CO luminosity using the $X=N(H_2)/I(CO)$ ratio. This may also be used for nearby galaxies.

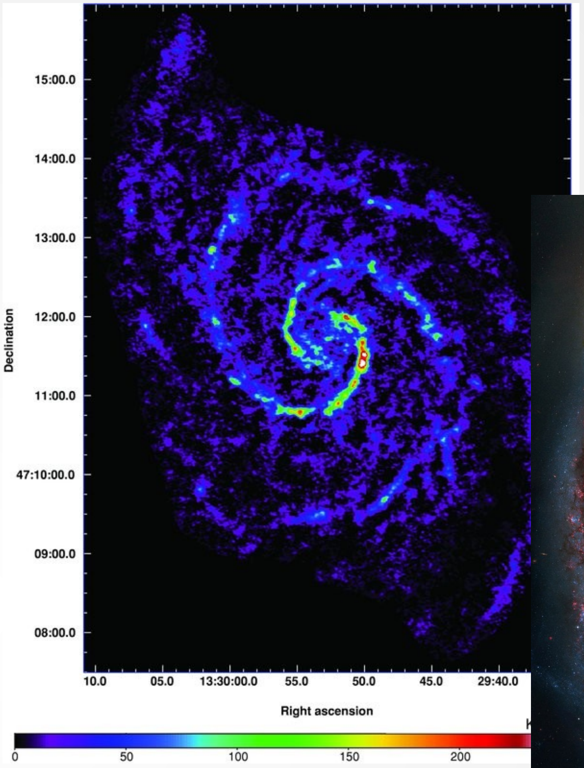
- Virial Equilibrium of H_2 gas clouds : Early studies have shown that H_2 gas clouds have a wide variety of masses from 10 to 10^5 $M_{sun.}$ The largest are called the giant molecular clouds (GMCs) and are often composed of smaller clouds (e.g. Orion molecular cloud, Ophiucus molecular cloud). From the width of the CO emission line across the cloud Δv and the cloud size it was found that the clouds are in approximate virial equilibrium i.e.

$$GM_c/R \sim (\Delta v)^2 \quad \text{where } M_c = \text{cloud mass and R=cloud radius}$$

- When the CO luminosity L(CO) is plotted against virial mass M(virial) there is a good correlation, which shows that L(CO) is good indicator of the mass of H_2 clouds.

The Large Scale Distribution of H_2 gas in Galaxies

- CO interferometric surveys (e.g. with BIMA, CARMA , NOEMA mm telescopes) of nearby galaxies show that H_2 gas is concentrated within the central regions of disks and well within the optical disks. In both early and late type spirals the H_2 gas radius is less than half the stellar disk i.e. < $0.5R_{25}$ radius.
- But the ratio of $R(CO)/R_{25}$ radii varies from early to late type spirals. Late types spirals have relatively larger R(CO).
- The HI gas is in sheet-like layers in the disk but the H_2 gas is clumpy. The H_2 clouds are especially found to lie along the spiral arms and are nearly always associated with star formation (see figures).



CO image of the molecular H_2 gas in the galaxy M51 : Image Credit : Koda et al. (ApJ, 2012). The H_2 gas is clearly clustered along the spiral arms. The image on the right is the HST image of the same galaxy but is a color composite of of the star forming regions in color and the dark patches are due to dust.

Distribution of H_2 gas in Different tpes of Galaxies

- Barred and unbarred spirals : the molecular gas H_2 is more concentrated in the bar and hence is usually more centrally concentrated in barred galaxies. However, the overall radial distribution of H_2 is similar for barred and unbarred galaxies.
- Only a small fraction of ellipticals have been detected in CO emission. The gas is usually in a disk within the central 5 to 10kpc (see figure).The H_2 gas is thought to have been accreted via mergers with gas rich galaxies.
- Star formation and H_2 gas are closely correlated (see next few slides). Also H_2 gas is always associated with dust lanes (see lower right figure).

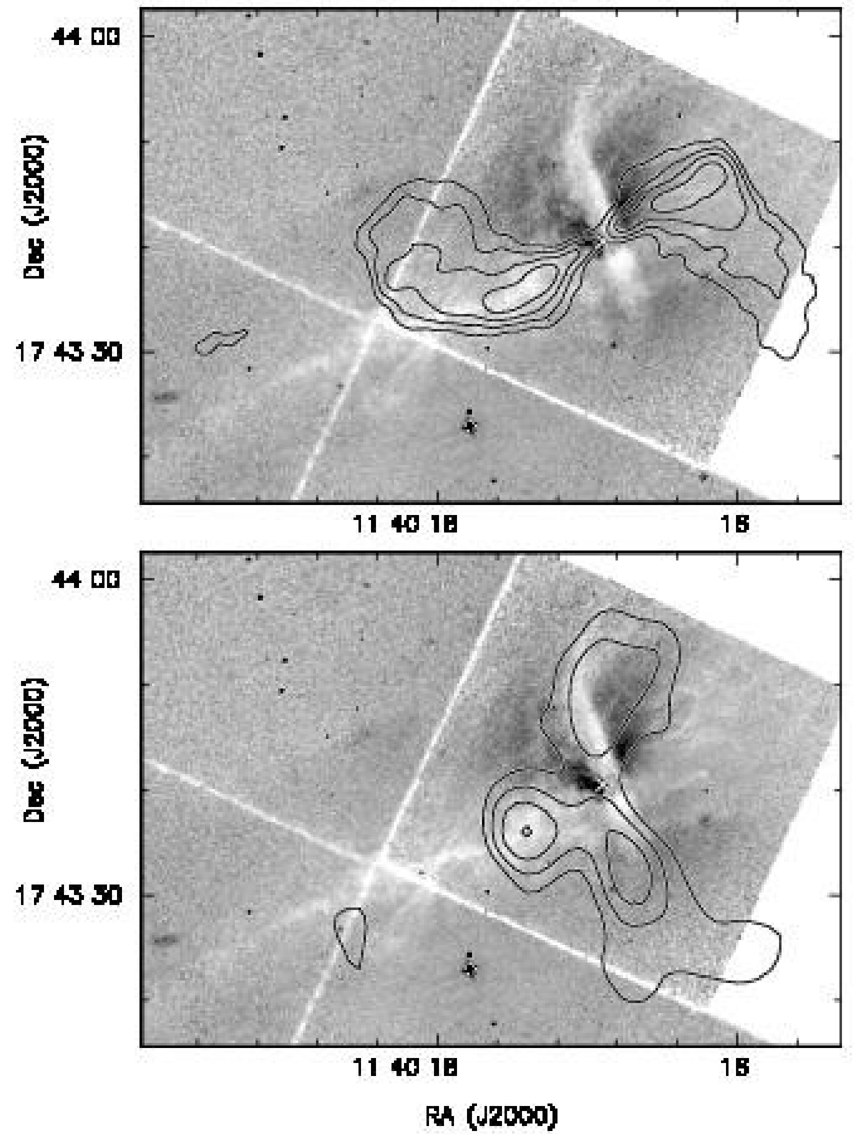


FIG. 5.—VLA 20 cm radio continuum (*top*) and BIMA velocity-integrated CO (1–0) emission (*bottom*) overlaid on *HST* F555W image of NGC 3801. The 20 cm and CO (1–0) images are contoured as in Figs. 2 and 3, respectively. The *HST* image has been processed to remove the radial gradient in light from the host galaxy so as to better reveal dust features. The galaxy nucleus is marked with a cross.

CO image of the molecular H_2 gas in the radio loud elliptical galaxy NGC3801 : Image Credit : Das et al. (ApJ, 2005). The H_2 gas is clearly concentrated along the dust lanes.

Star Formation : the basic process

- Stars form due to the gravitational collapse of cold, dark clouds of molecular hydrogen (H_2).
- This leads to a core that starts burning nuclear fuel and forms a protostar. There maybe outflows and a protostellar disk.
- Finally planet system forms.

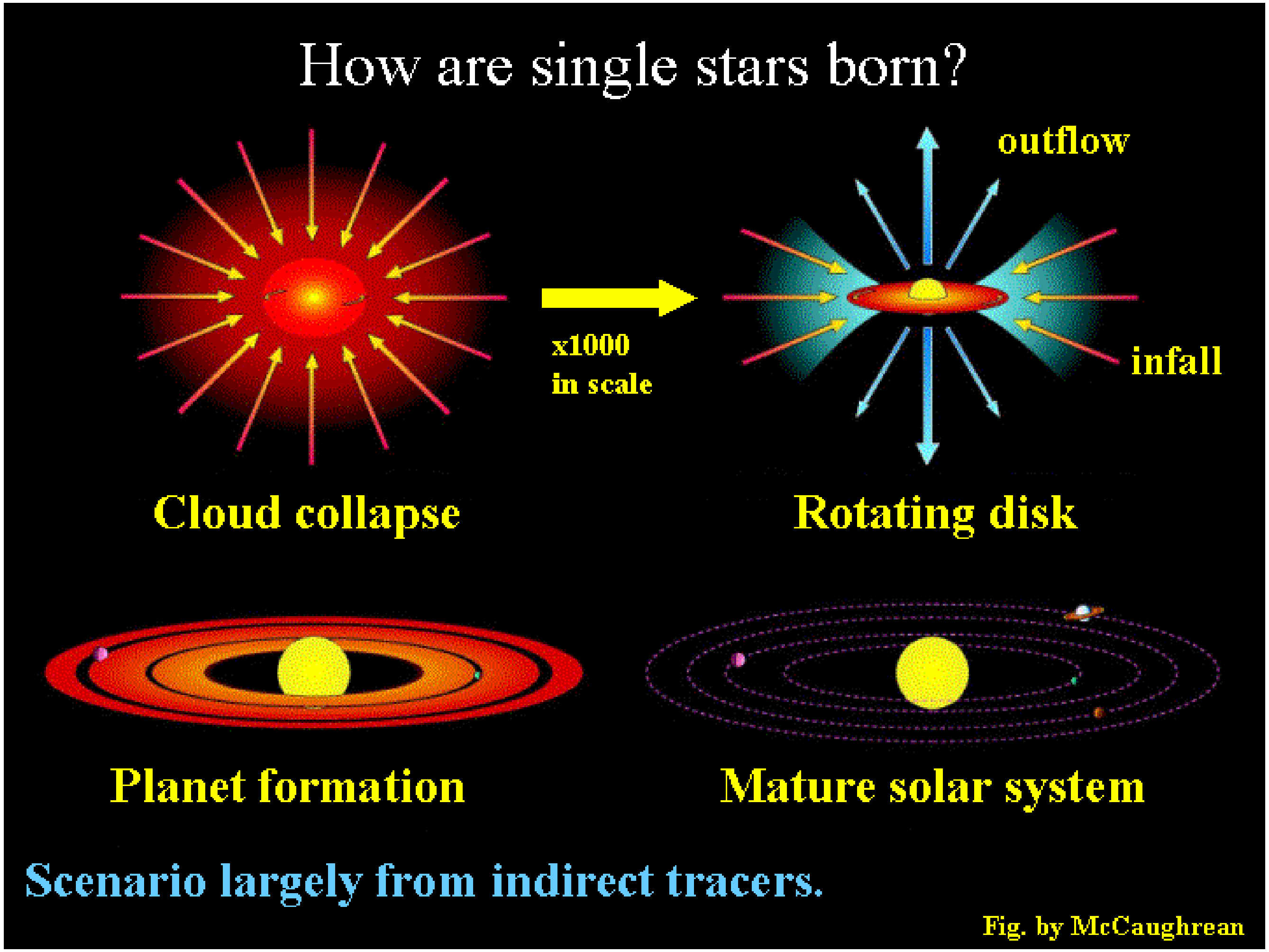


Image Credit : CALTECH Homepage

The Equilibrium of a Single Diffuse Cloud :

- The equilibrium of a single cloud is under 3 forces : internal pressure, self gravity of cloud and surface pressure exterted by the medium.
- Consider a spherical cloud and a shell at radius r. The we have : $dM(r) = 4\pi r2\rho(r)dr$
- The pressure balances the gravity so : $4\pi r^2 dP(r)dr = -GM(r)dM(r)/r^2$
- Then if V(r) is the volume of the mass within radius r, then lhs becomes :

  $$3V(r)\, dP(r) = -GM(r)dM(r)/r$$

- We can integrate both sides using limits $0 \Rightarrow R_c$ and $P_{CO} \Rightarrow P_s$ where P_S=surface pressure and P_{CO} = central pressure. Integrating by parts the lhs becomes,

  $$3\int (\text{limits } P_{CO} \text{ to } P_s)V(r)\, dP(r) = 3V_c P_s - 3\int (\text{limits } V_C = 0 \text{ to } V_c)\, PdV$$

- For a monatomic gas the internal energy per unit volume is $\varepsilon_i = 3/2 \times P$. So we have,

  $\int (\text{limits } V_C = 0 \text{ to } V_c)\, PdV = 2/3 \times \varepsilon_T$ where ε_T= internal thermal energy of cloud

- Hence if $\Omega = -\int GM(r)dM(r)/r$ is the self gravity of the cloud, then we have

$$\mathbf{3P_s V_c = 2\, \varepsilon_T + \Omega}$$

Collapse of a Cloud and sound crossing time :

- Clouds are in equilibrium under self gravity and internal pressure. Cloud collapse happens when self gravity is much higher than cloud internal pressure.
- For $2\,\varepsilon_T + \Omega < 0$ ===> cloud contraction
- For $2\,\varepsilon_T + \Omega = 0$ ===> cloud equilibrium
- For $2\,\varepsilon_T + \Omega > 0$ ===> cloud expansion
- So the condition for cloud collapse is,

  $3V_c P_c - 3/5\, GM_c^2/R_c < 0$ where P_c = uniform cloud pressure
- Or the condition becomes : $3/5\, GM_c^2/R_c > 4\pi R_c^3 P_c$
- If we take the pressure in terms of the temperature then $P_c = kT_c/m_H\mu$ where m_H is the mass of H atom in gm and μ is the atomic weight. We also know that the sound speed 'c_s' in a medium at temperature T_c is given by $c_s^2 = kT_c/m_H\mu$.
- So the condition for cloud collapse becomes, $GM_c/5R_c >= c_s^2$
- But since the sound travel time across the cloud $t_s \sim R_c/c_s$ the condition becomes,

$$\mathbf{t_s >= \sqrt{15/4\pi G\rho_0}}$$

Where ρ_0 is the mean density of the cloud.

Free Fall Collapse of a Cloud

- Let us now consider the motion of a shell as the cloud collapses. Consider the outermost shell of the cloud at a radius $r=r_0$ which moves inwards under gravity. The equation of motion is,

$$d^2r/dt^2 = -4/3\pi G\rho_0 r_0^3/r^2$$

- The solution of this equation is given as a H.W. problem. The free fall time can be calculated to be, $t_{ff} = \sqrt{3\pi/32G\rho_0}$
- But since the sound travel time across the cloud $t_s \sim R_c/c_s$ and the condition is

$$t_s >= \sqrt{15/4\pi G\rho_0}$$

- We get the following relation : $t_s >= 2\sqrt{10}/\pi \text{ x } t_{ff}$

$$\text{Or we have } t_s >= 2\, t_{ff}$$

- Physically this means that the cloud collapses when the free fall time is less than the sound crossing time in the cloud. There are many assumptions in this derivation (uniform cloud density etc) but the concept is important.

What starts cloud collapse:

- Cloud collapse and star formation can be triggered by several processes and they are all related :

  (i) Spiral arms

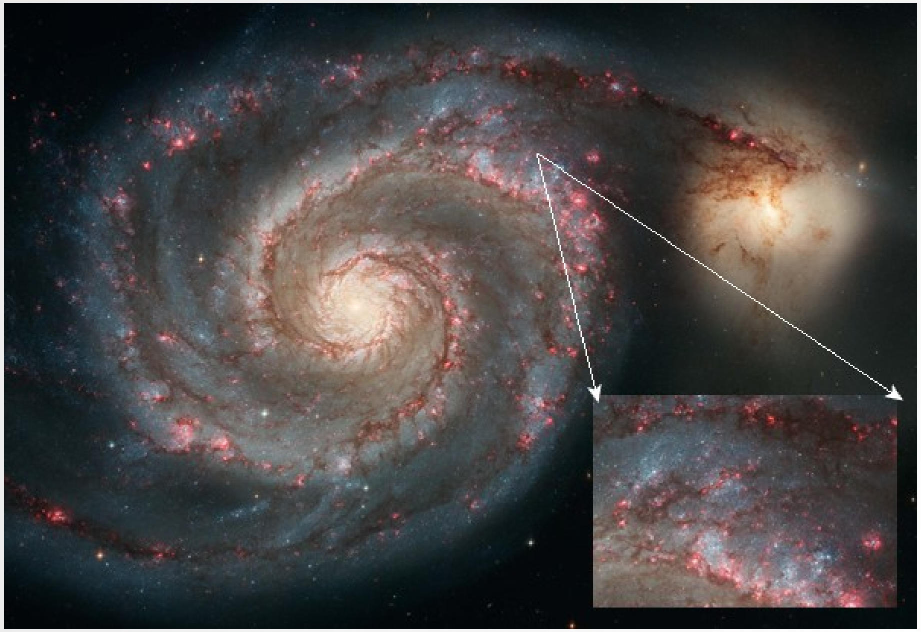
  (ii) Bars in galaxy disks

  (iii) Winds from star formation or supernova (leading to cloud compression and shocks)

  (iv) Galaxy interactions : which perturb the galaxy disks

  (v) Gas accretion onto the outer disks of galaxies

Star Formation triggered by spiral arms and bars :



- Star formation driven by spiral arms : the gas flows into the spiral arms where cloud collisions drive shocks into the gas. The shocked gas cools and then becomes unstable. The clouds fragment and contract leading to star formation.
- Bar driven star formation : cloud collisions along the bar orbits and in the spiral arms results in star formation. Note the prominent dust lanes associated with the bars.

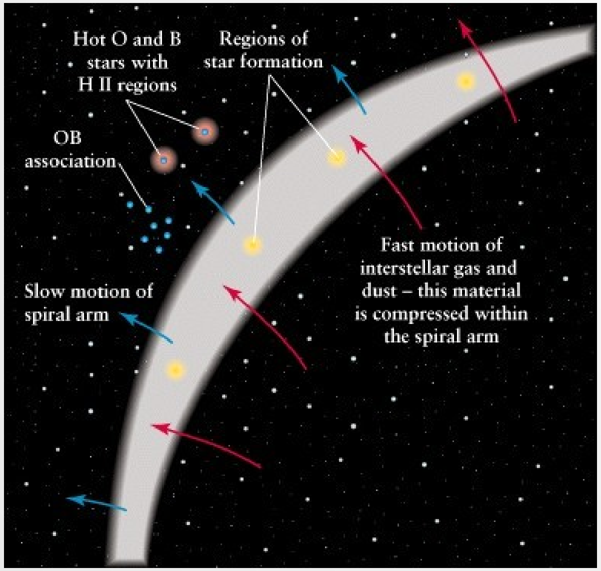
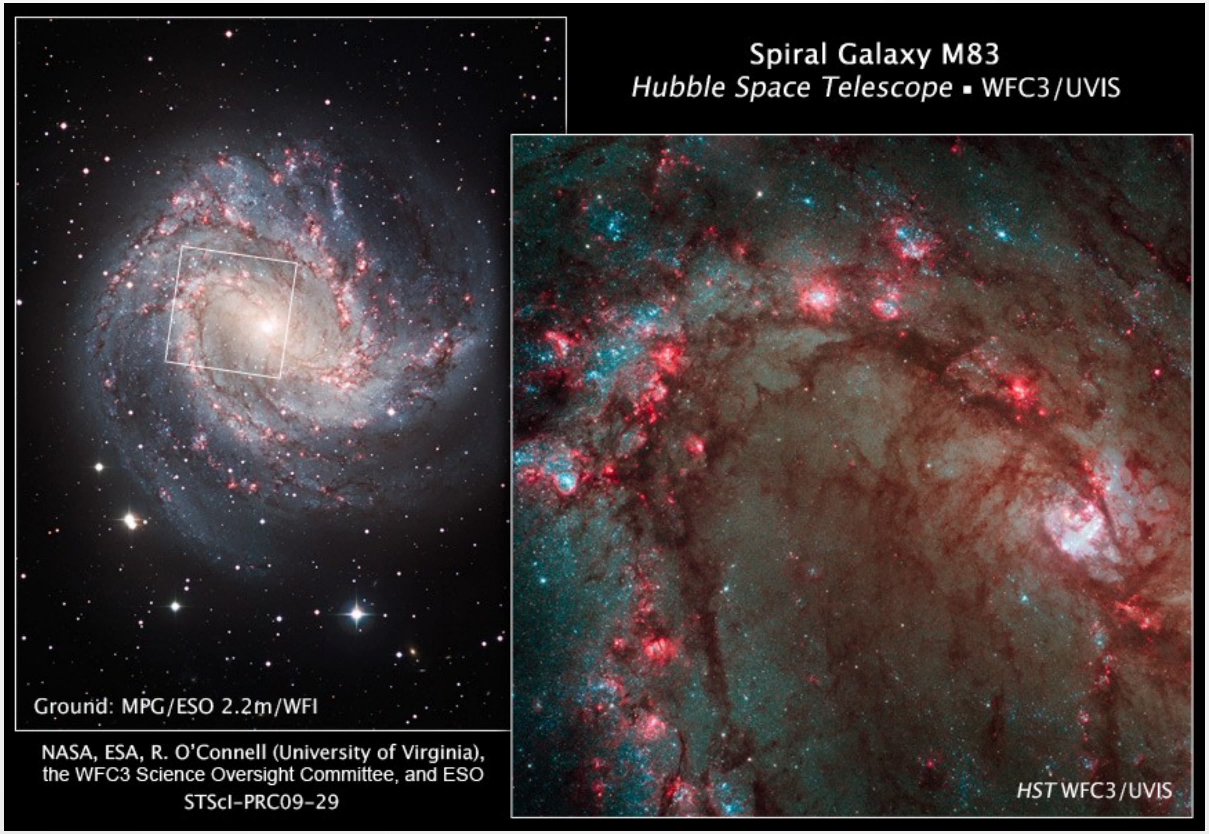


Image Credit : Eskridge Homepage

Image Credit above and top left : Hubble Space telescope homepage

Where does Star Formation occur?

- Most of the star formation in disk galaxies is associated with the spiral arms. The most massive stars (O and B type) form in these arms. Hence star clusters are formed mainly in the arms. During galaxy interactions, star formation also occurs in the tidal arms or interacting disks.
- If the gas accumulates in the galaxy center, such as during interactions when there is gas infall to galaxy center, then there is also massive star formation in the inner few kpc. For example starburst galaxies are known for their enhanced central star formation.
- The dust lanes are good tracers of molecular gas and hence are often good indicators of star formation (see figure below).



Star Formation due to cloud collapse triggered by winds/shocks

- Star formation in galaxies can be triggered by shocks.
- The shocks can be due to supernova, strong stellar winds or winds driven by nuclear activity.
- It can also be due to collisions between molecular clouds.

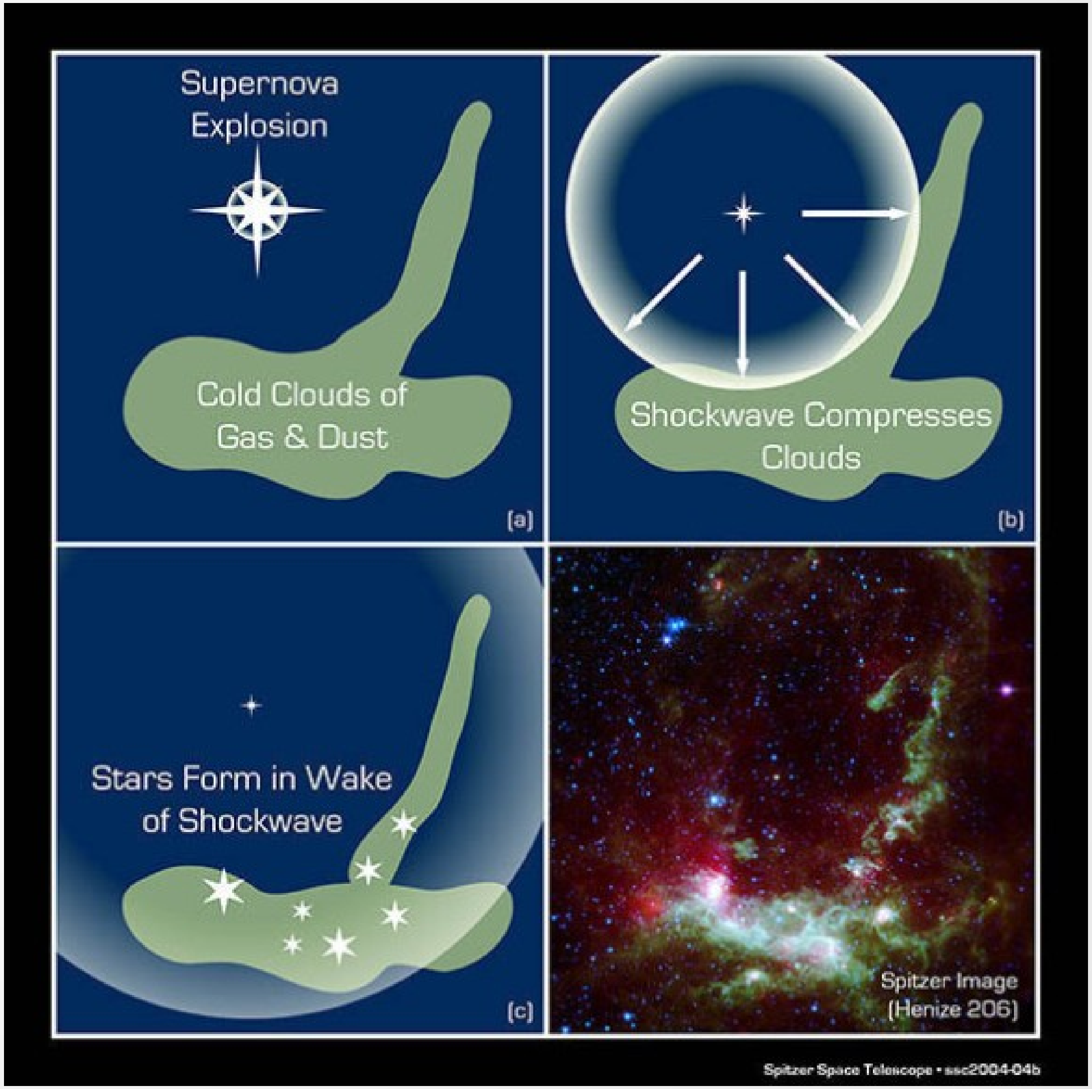
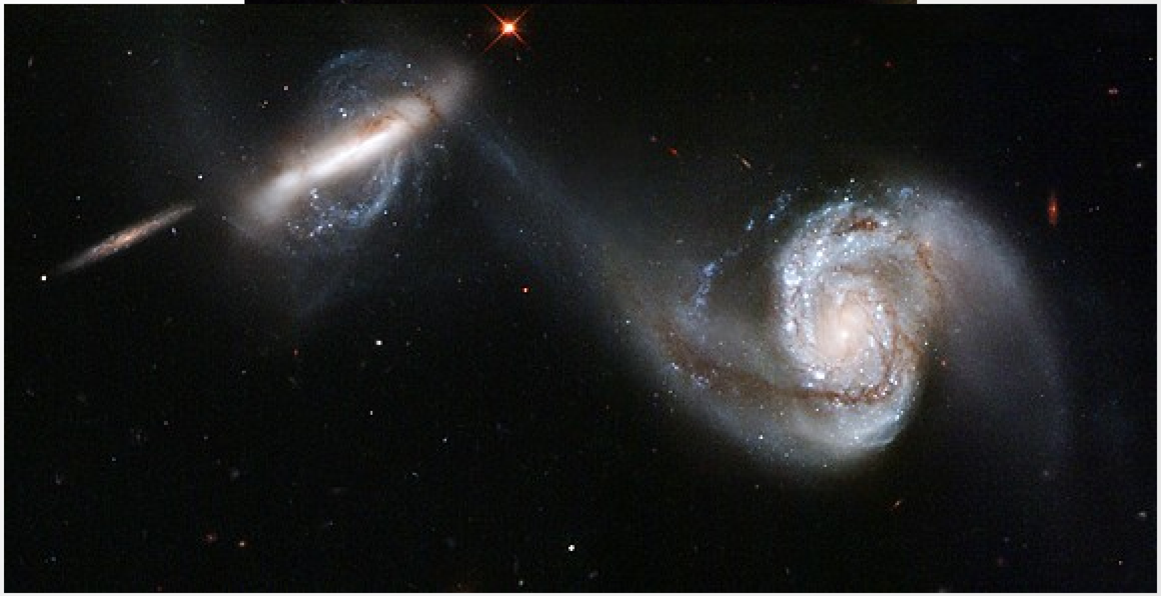


Image Credit : Spitzer NASA Homepage

Star Formation due to Galaxy Collisions

- Very large bursts of star formation are triggered by galaxy collisions or interactions.
- Galaxy interactions or mergers disturbs the galaxy potentials and causes cloud collisions leading to shocked gas which cools and forms stars.



mage Credit : HST/APOD Homepage

Star Formation in tidal debris of colliding galaxies

- When galaxies collide, gas and stars are tidally pulled out.
- Star formation can occur in the tidal tails or bridges between the galaxies.
- Usually only low mass stars are formed, sometimes leading to formation of tidal dwarf galaxies.

Image Credit : Trancho et al. 2012

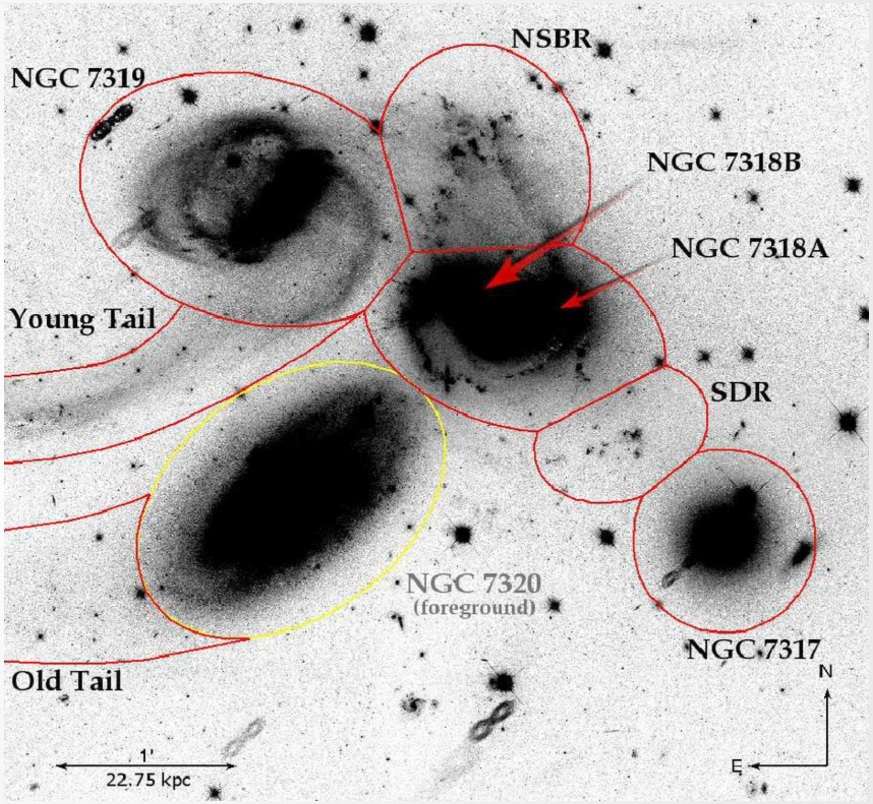


Image Credit : Chandra and Optical images (O'Sullivan et al.)

star formation and galaxy evolution sequence

- Star forming galaxies are generally blue in color whereas red galaxies have finished their SF (quenched galaxies). This is clear in the color magnitude plot for galaxies.
- The gas rich, star forming galaxies are in the blue cloud.

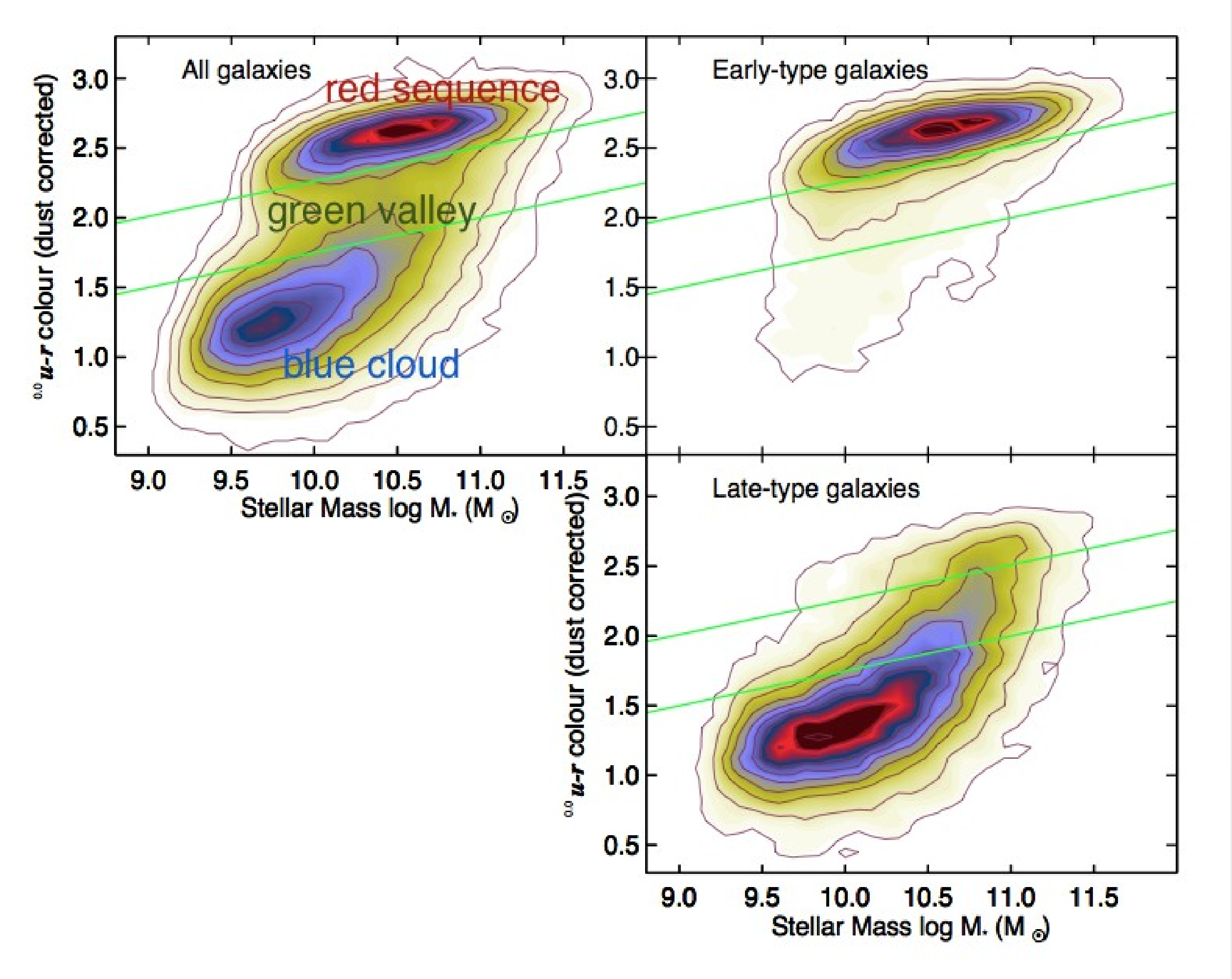
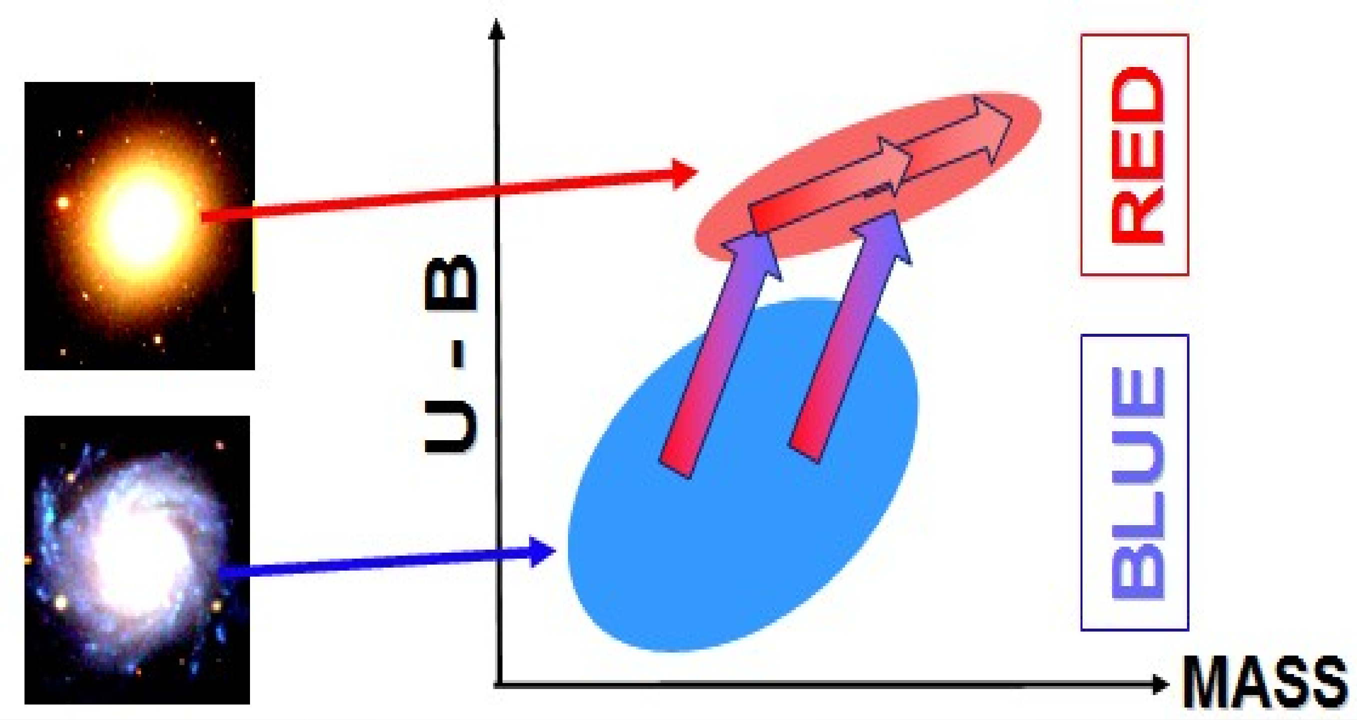


Image Credit : Galaxy Zoo

star formation and galaxy evolution sequence



- Just like the main sequence for stars, galaxies follow a blue to red galaxy sequence, through the driving force of star formation.

Image Credit : University of Oxford

End of Eighth Lecture