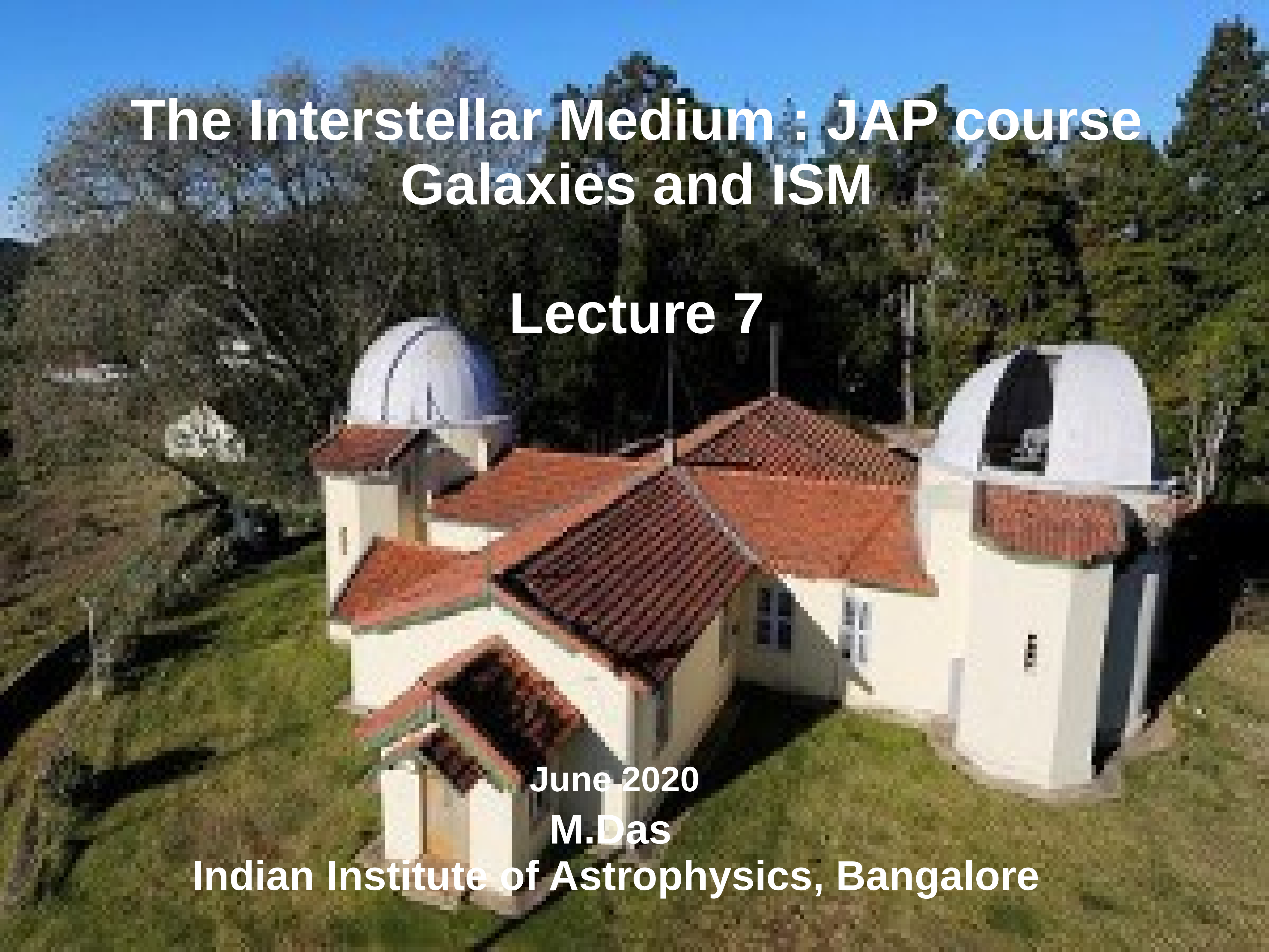

The Interstellar Medium : JAP course
Galaxies and ISM

Lecture 7

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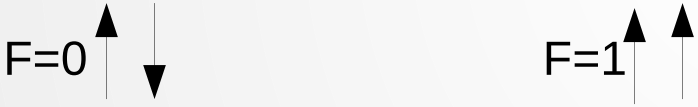
Neutral Hydrogen (HI) in Galaxies

- The presence of HI line emission from galaxies was predicted by van de Hulst in 1944. It was first detected in our Galaxy in 1951 by several independent groups in the Netherlands, USA and Australia.
- 2 years later it was detected in the nearby Magellanic Clouds (SMC and LMC). By the early 1970’s it was detected in many more galaxies using single dish telescopes such as Greenbank, Nancy and Effelsberg. Radio interferometric arrays (e.g. VLA and GMRT) are used to study the distribution of HI in nearby galaxies (with $z<\sim 0.05$).
- **The HI 21cm Line :** The HI line is due to the transition between the hyperfine states F=0 and 1 of the H atom, which is interaction between the spin of the nucleus (p) and electron.



The frequency of the line is one of the best measured physical quantities $\nu(1 \rightarrow 0)=1.42040575\text{GHz} \sim 1.42 \text{ GHz}$

- The Einstein A coefficient for the 2 levels is : $A(1\text{-}0) = 2.868\times10^{-15}\ s^{-1}$. So the half life of the F=1 state is $t_{1/2} \sim 1/A(1\text{-}0) = 3.5\times10^{14}\ s = 10^{7}$ years.
- So we would generally not expect to detect the HI line since the transition takes so long. But there is so much HI in our Galaxy and nearby galaxies, that we are able to detect it very easily.

The Spin temperature of HI

- The number of atoms in the states 1 and 0 is governed by the Boltzmann equation,
$$N_1/N_0 = (g_1/g_0)\exp(-h\nu/kT_s)$$
where T_s is called the spin temperature.

- T_s depends on (i) the radiation field of HI, (ii) the rate of collisions of H atoms with other H atoms and electrons, (iii) pumping by Lyα photons (a photon excites H atom from ground state n=1 to n=2 state).

- (when a H atom decays from n=2 --> 1 , the atom goes into the F=1 state, which has a spontaneous decay tiime of 10^7 yrs. But collisions occur every ~400 yrs. Hence T_s is mainly determined by collisions and the radiation field.

- In terms of radiative equilibrium, a cloud of optical depth τ and spin temperature T_s in a radiation field T_r follows the relation,
$$T_b(v) = T_r\exp[-\tau(v)] + T_s(1 - \exp[-\tau(v)])$$
where τ(v) measures how the optical depth varies across the line profile.

- 2 cases : (i) Over much of a galaxy disk, collisions determine T_s. Then T_s is close to the kinetic gas temperature T_k which is much greater than T_r. Hence $T_b \sim T_s$ for $\tau \ll 1$. (ii) In outer disk regions, the HI is more diffuse and T_s is regulated by the radiation field at 21cm and Lyα radiation. The equilibrium is more complicated.

HI in Galaxies : Importance and Overview

- HI is the starting point for cloud collapse and star formation (SF). It is hence the star formation gas reservoir for a galaxy. When the HI is used up, there can be no more SF, which means no new stars are formed in the galaxy. Hence, HI is very important for galaxy evolution. For example ellipticals usually have no HI gas and show no ongoing star formation.
- HI is usually 1 to 5% of the stellar mass of a galaxy. In some gas rich dwarfs or low luminosity galaxies M(HI)~M(stars) but this is not generally true.
- The HI distribution within a galaxy generally follows the stellar light distribution. It thus has a exponential type distribution but extends out to larger radii. In most galaxies the HI peaks in the center but in some there is an HI hole in the center.
- The vertical HI disk has a thickness close to the optical disk thickness ~ 150 to 200pc.
- Since the HI gas closely follows the stellar disk distribution, it responds to disk instabilities which arise in the stellar disk first. For example, when there are bars and spiral arms in the disk, the HI follows the spiral pattern and often settles in the resonance rings.
- It is very affected by galaxy interactions, forming tails and tidal arms.

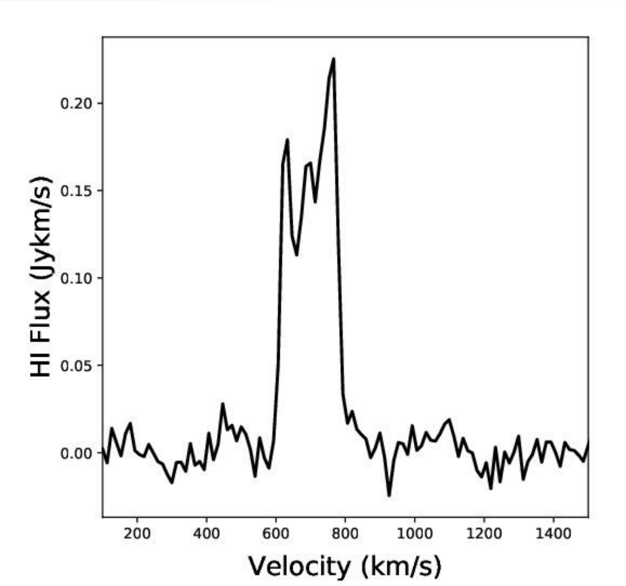
Mass of HI in Galaxies

- The mass of HI in galaxies is derived from the flux of HI radiation at 21cm that is observed from any region. The mass in solar mass Msun units is given by,

$$M(HI) = 2.356\times10^{5} \times D^{2} \times \int S(v)dv \;\; M_{sun}$$

Where D = distance of the source in Mpc
S(v)dv = flux integrated over the HI line in Jykms-1

- The flux is observed using single dish telescopes such as GBT, Nancy.
- The HI profile for galaxies usually has a broad linewidth of ~ 400 to 500 km/s. The HI line may have a double horned profile which represents the HI in a rotating disk (see figure below).



The figure on left is the HI line observed from the galaxy NGC4701 (Das et al. 2019).
Note that there is a double horned structure due to the gas rotating in a disk.
The approximate flat rotation velocity can be determined from half the line width.
Can you see what it is?

Representation of HI data

There are 2 types of HI observations, the single dish observations (e.g. Greenbank) and the interferometric observations (e.g. GMRT).

Single dish data : Uses single dish telescopes to obtain the total HI flux from the source. Good for detecting HI signal and hence is used in blind HI surveys and high-z HI observations.

The total HI flux obtained is used for determining the HI mass in the source. Approximate rotation velocity can be derived from ½ of the total HI linewidth.

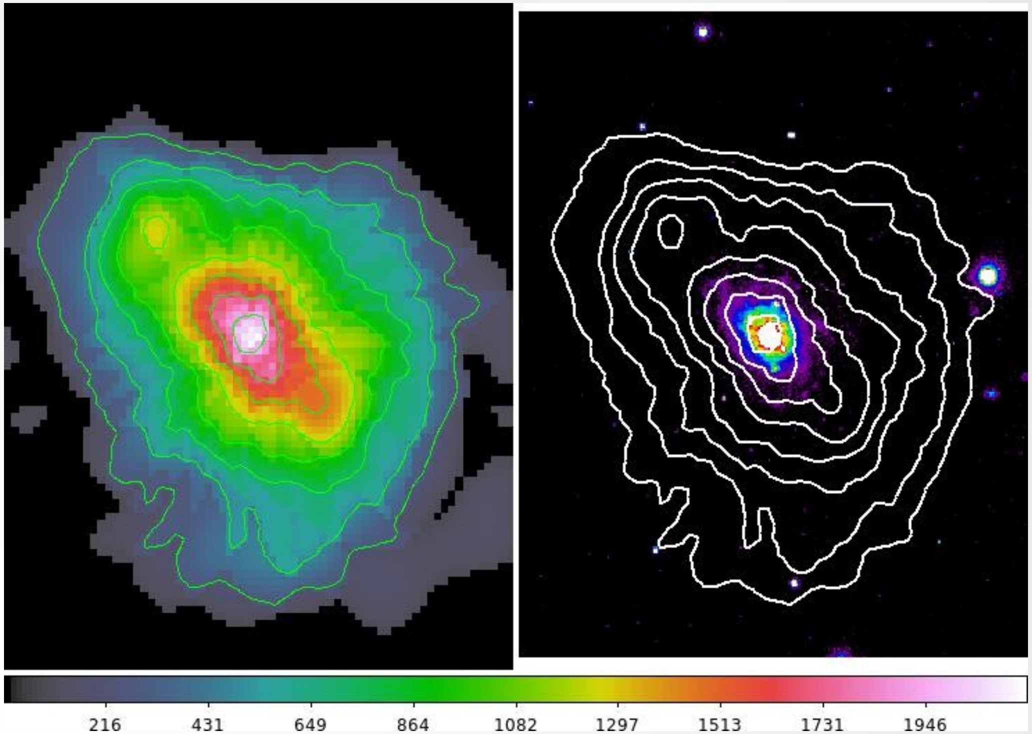
Interferometric data : Uses an array of several telescopes and the technique is called radio interferometry (e.g. GMRT). The data is in the form of a data cube, with the 3 axes as (RA, dec, velocity). So for any pointing in source we will get (RA, dec, v, I) where I is the intensity of the flux in units of Jy/beam.

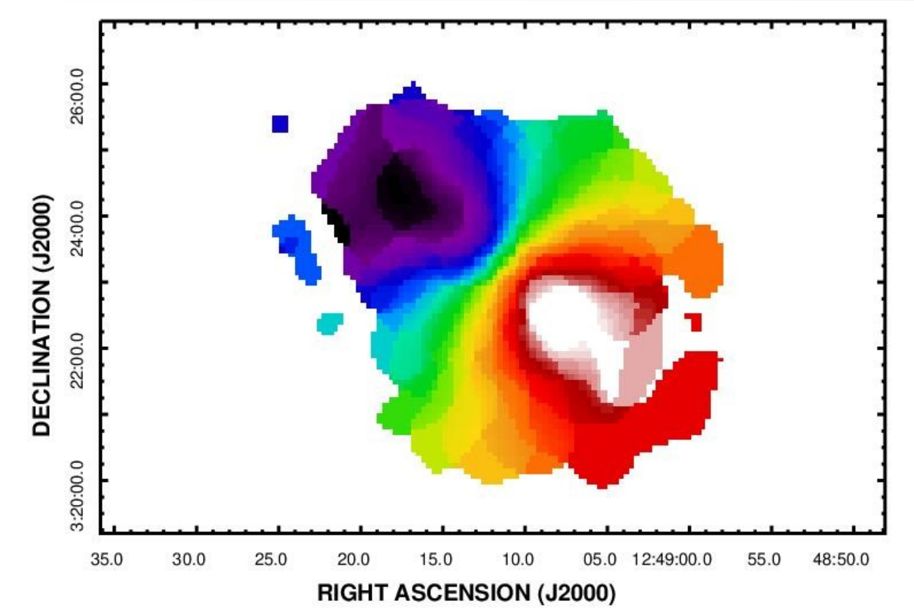
- From the data cube we can construct moment maps.
  Zeroth moment map = HI intensity distribution = $I_0 = \int I(v)\,dv / \int dv$
  Moment 1 map = HI velocity field = $I_1 = \int I(v) v\,dv / \int I dv$
  Moment 2 map = HI velocity dispersion = I_2
- We can use the moment 1 map to derive the rotation curve of the galaxy by computing average velocities in concentric circles or ellipses about the galaxy center.

Example of HI intensity and velocity in galaxies

HI images made with Interferometric data :

- The first image on the right panel is the HI intensity distribution or moment 0 (I_0) image of the gas rich dwarf spiral galaxy NGC4701. The observations were done using the GMRT (Das et al. ApJ, 2019). The contours are shown overlaid in green. The second image in the panel shows the I_0 contours overlaid on the optical B band image.
- The lower panel shows the moment 1 map (I_1) or HI velocity field, with the characteristic doppler shift in velocities (receding blue and approaching side in red). It is called a “spider diagram” because of the shape.
- We can use the velocity field to determine the rotation curve of the galaxy.





Importance of HI for understanding Galaxies

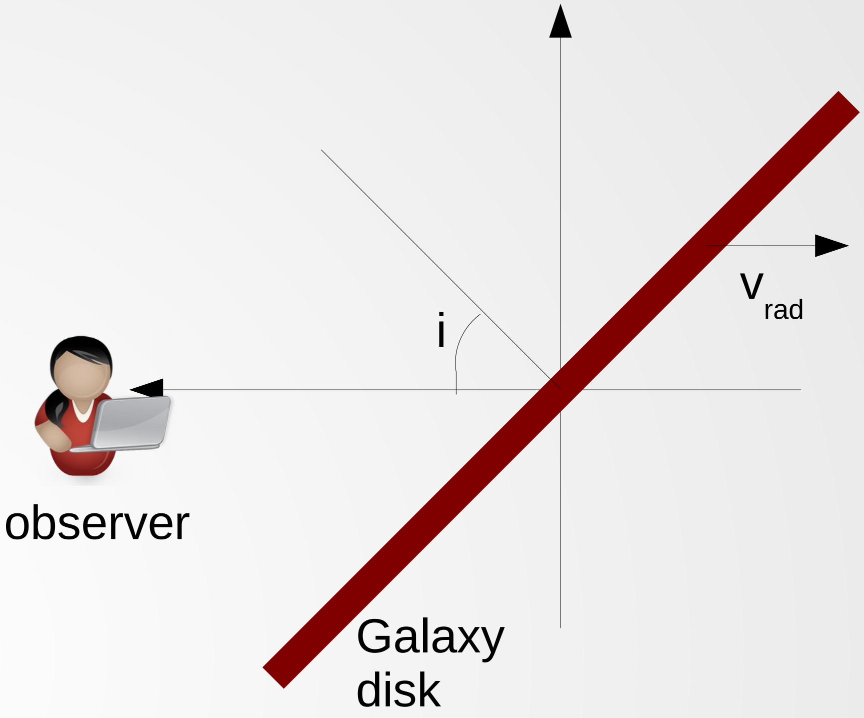
The HI in disk or spiral galaxies is the most extended component and hence it is the best tracer of galaxy rotation. It can also reveal the total or dynamical mass distribution. In this section we will discuss rotation curves, their importance for dark matter studies and the Tully Fisher relation.

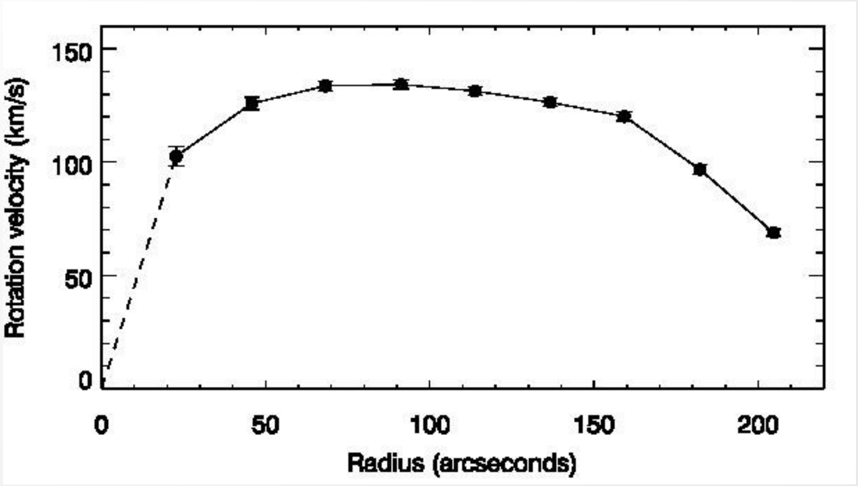
- **(i) Rotation curves :** It is the plot of galaxy disk rotation vs the radius (see lower figure). It is derived from the moment1 map (previous slide) by taking average velocities in ellipses aligned with the major axis of the galaxy projected on the sky (also called position angle). If the galaxy has an inclination angle "i" (angle between the normal to disk and line of sight of observer) then at an angle φ wrt the major axis, the line of sight velocity v_{rad} is given by,

$$v_{rad} = v_{rot} \mathrm{Cos}\varphi \mathrm{Cos}(90-i) = v_{rot} \mathrm{Cos}\varphi \mathrm{Sin}(i)$$

$$\text{or,} \qquad v_{rot} = \langle v_{rad} \rangle / \mathrm{Sin}(i)$$

- In the bulge region the rotation velocity is solid body, or v_{rot} is proportional to r. Then v_{rad} is proportional to the y axis and the velocity contours in the bulge region are elongated normal to the major axis of the galaxy.





(ii) Rotation Curves and dark matter : If a spiral galaxy was only composed of a disk of stars and gas then since this mass is centrally concentrated, we would expect the rotation velocity to have keplerian fallof with radius i.e. v_{rot} proportional to $r^{-1/2}$ (because $v^2 \sim GM/r$ and M is constant after the visible disk ends). But instead the rotation continues to be flat. This indicates that there is mass that we cannot detect i.e. a dark matter halo which provides the potential for the rotation curve.

We can determine the total or dynamical mass using rotation curve flat velocities and the extent. $M_{dyn} = Rv_{rot}^2/G$

The dark matter mass is given by : $M_{dm} = M_{dyn} - [M(stars) + M(gas)]$

- Mas to Luminosity (M/L) ratio : This gives the stellar mass. It is usually determined using the 3.6 micron MIR band emission or the K band emission from a galaxy. This is because these wavebands avoid the dust contamination of the light and trace the old stellar population which makes up the bulk of the stellar mass.

A cartoon sketch of the decomposition of a galaxy rotation curve traced by HI. The outer rotation part cannot be explained by baryonic mass.

- **(iii) The Tully Fisher (TF) relation for disk galaxies :** When the virial theorem (2T+V=0) is applied to rotating disks we get the approximate relation : v_{max} proportional to M^{α} . If the luminosity is proportional to stellar mass then we should get a relation

  $$v_{max} = \text{constant x } L^{\alpha}$$

  where α ~ 1/4. This relation was first found by Tully & Fisher (1977) using the HI observations of a large sample of galaxies. For bright galaxies this relation can also be used as a good distance indicator as long as the HI linewidth is known. This has led to a powerful technique to measure the distances to galaxies as long as the HI linewidth and luminosity are observed. The measured luminosity is compared with the TF predicted luminosity in order to obtain the correct distance.

  Later studies have shown that the TF is actually a relation between the disk baryonic mass (stars and gas) and the flat rotation velocity of the disk and is given by :

  $$M(\text{disk}) = \text{constant x } v_{rot}^{4}$$

  It is called the baryonic Tully Fisher relation (Mcgaugh et al. 2000) and has important implications for measuring the total masses of galaxies.

- **(iv) HI in interacting galaxies :** HI is the most extended component of galaxy disks and so it is the most affected by tidal encounters between galaxies. The HI gas is pulled out or the disk is warped. The effect depends on the orientation of the encounter and is the largest when the interaction is prograde.

- **(v) HI deficiency in cluster galaxies :** Disk galaxies that lie close to the centers of clusters often have falling rotation curves, HI tails or are stripped of their HI due to tidal interactions. Another well known phenomenon is the ram pressure stripping of HI gas.

End of Sixth Lecture