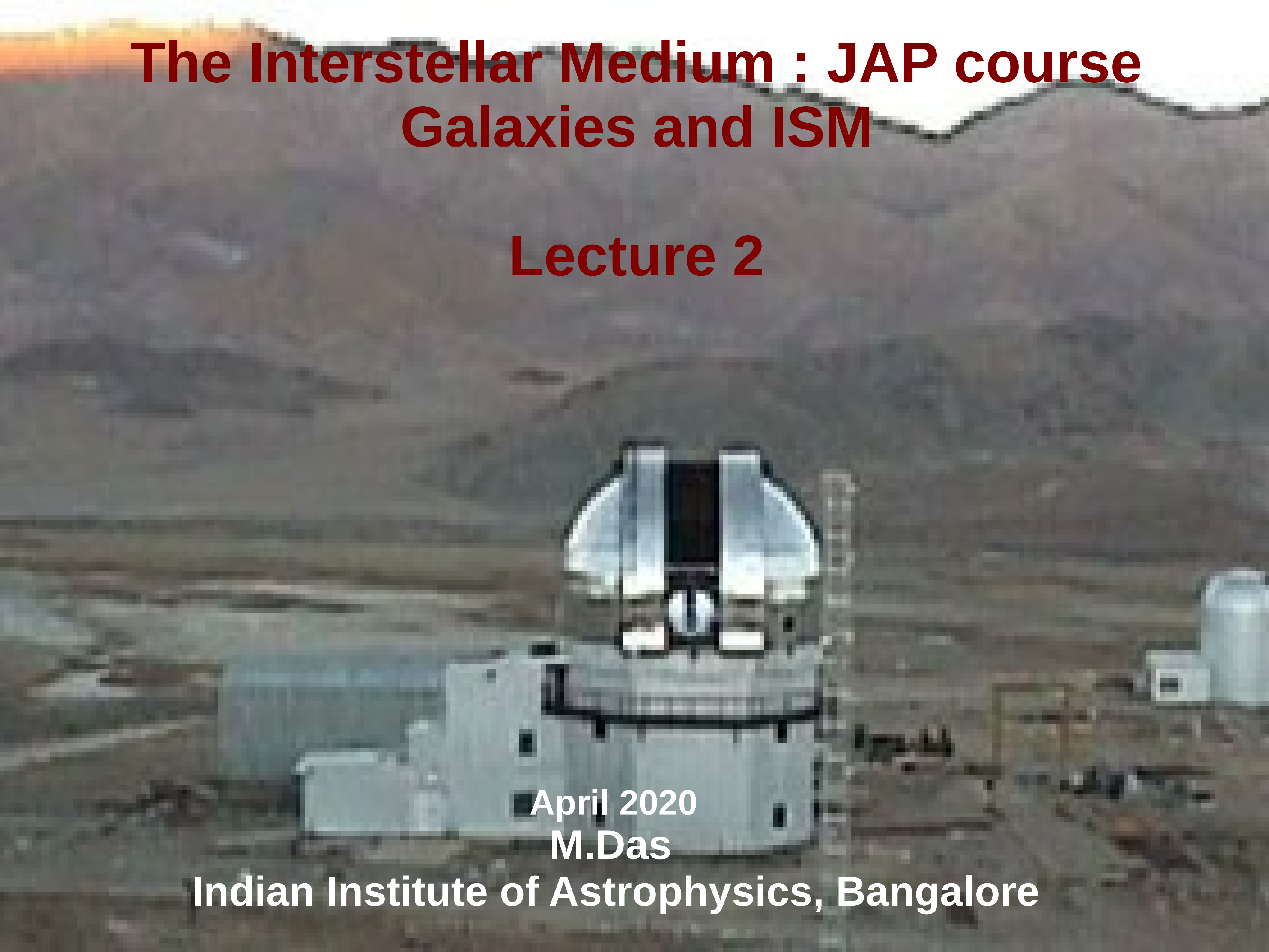

The Interstellar Medium : JAP course
Galaxies and ISM

Lecture 2

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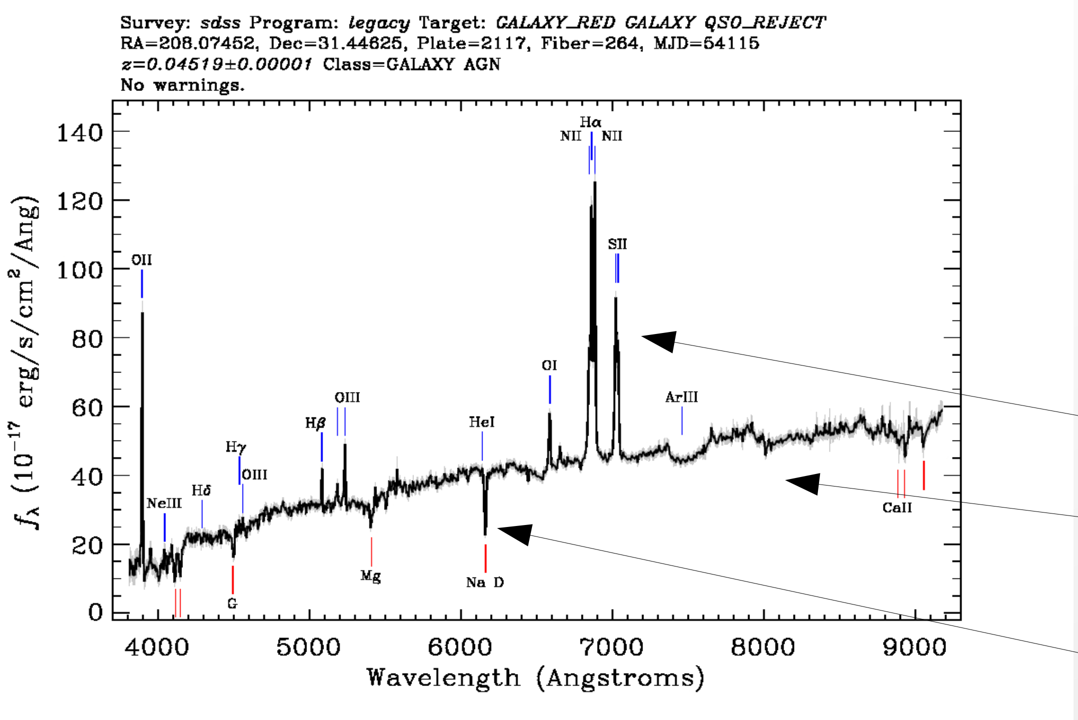
Emission from the ISM

The ISM can be studied in emission or absorption using spectral lines. It can also be studied using the continuum emission from gas and stars.

- Emission lines are due to the energy emitted when ion/atom/molecule goes from an excited state to a lower energy state. Absorption lines are due to energy absorbed by intervening medium. Both types of lines have intrinsic shapes and also depend on the nature of the source. Continuum emission is the emission spread over a continuous range of frequencies and arises due to the deceleration of charged particles.
- An example of a spectrum (quasar 3c293) showing the 3 types of emission is given below.



SDSS DR12 spectrum of 3c293 showing emission lines, absorption lines and a steeply rising continuum spectrum in the red region.

Factors affecting emission line shape

The shape of a spectral line depends on the following :
1. Natural line shape 2. Doppler broadening 3. Collisional broadening (not important for the ISM

- **Natural line shape** : We will treat this classically. Let the emitting atom/molecule be an oscillator of natural frequency ω_0. Then we can apply the equation of damped harmonic oscillator :

$$d^2r/dt^2 + \omega_0 r = -\gamma\, dr/dt$$

where γ is the damping coefficient and is given by $\gamma = e^2\omega_0^2 / 6\pi\varepsilon c^3 m$

- The solution of this equation is a decaying electric field. The fourier transform gives the amplitude or intensity of the emission to be:

$$I(\nu) = I_0\gamma / 2\pi[(\omega - \omega_0)^2 + (\gamma/2)^2]$$

- This line shape is called Lorentzian. The line center is at ω_0 and the line width is proportional to γ. This line width can also be calculated quantum mechanically, where 2γ is the Einstein A coefficient and measures the spontaneous transition probability of excited atoms.
- Then A= 2γ and 1/A is the occupation time in upper level. Then using uncertainty principle, $\Delta\nu \sim h/2\pi\Delta t \sim (h/\pi)\gamma$

emission line shape …….. Contd

- **Doppler broadening of lines** : The emission line is broadened due to the random motion of the atoms. For a line emitted at a frequency ν_0 if the atoms are moving with a mean random velocity of v, we know that the frequency spread is

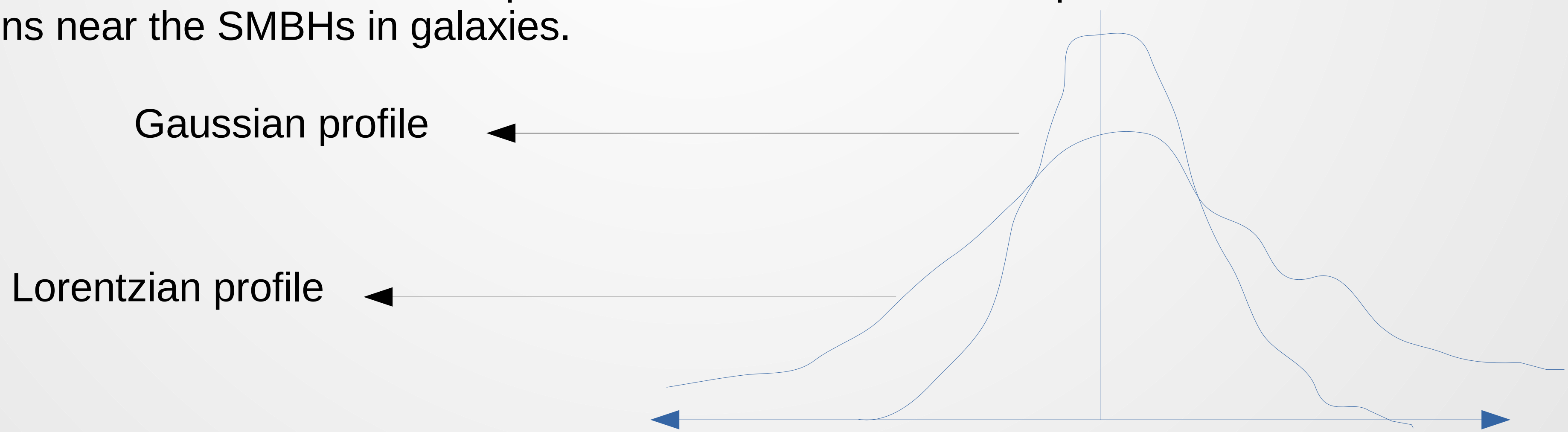
$$(\nu - \nu_0)/\ \nu_0 = \Delta\nu\ /\nu_0 = v/c$$

- If the atoms have a maxwell distribution of velocities then, $dN \sim \exp\{-mv^2/2kT\}$ or $dN \sim \exp\{-(\nu - \nu_0)^2/2\delta^2\}$ where $\delta^2 = (\nu_0/c)^2 kT/m$

- So the spread in frequency is due to the spread in the velocities of the atoms/molecules in the gas. So the spread in intensity if proportional to :

$$I(\nu) \sim \exp\{-(\nu - \nu_0)^2/2\delta^2\}$$

- The doppler spread produces a gaussian profile of the line. Doppler broadening can be due to the turbulent velocities of clumps in clouds, velocities of clumps in the ISM and in dense regions near the SMBHs in galaxies.



The Equivalent Widths of Spectral Lines

- An emission line is usually a combination of gaussian and lorentzian profiles. For weak lines it is hard to separate and measure. An alternative way to measure lines is to use the equivalent widths of lines 'W' (see figure 2.2 in a Dyson and Williams. It is especially relevant for absorption lines. It is given by :

$$W = \int (1 - I(\nu)/I(0))\, d\nu \quad \text{or} \quad \int (1 - I(\lambda)/I(0))\, d\lambda$$

- We will use the equation of radiative transfer $dI(\nu)/ds = -\kappa I(\nu)$, where κ is the absorption coefficient of the medium and is a function of frequency. The equation for an absorption line is the following.

$$I(\lambda) = I(0)\exp(-\tau_\lambda) \quad \text{where } \tau_\lambda = \int \kappa\, ds \,.$$

Then, $$W = \int (1 - \exp(-\tau_\lambda))\, d\lambda$$

For emission line the κ is negative.

- In the visual and UV regions we can neglect stimualted emission . Then a quantum treatment gives $\tau_\lambda \sim (\pi e^2/m_e c^2)\lambda_0 \psi(\lambda) f N \Delta\lambda$ where $\psi(\lambda)$ is the normalised line profile shape, f is the oscillator strength for absorption by the atom and N is the column density (in typical units of cm^{-2}).
- We get 3 regions corresponding to **weak, moderate and strong lines.**

The Curve of Growth or (logW vs logN) plot

There are 3 types of lines depending on the optical depth τ_λ. It is a measure of how dense the region is.

- **Weak lines :** $\tau_\lambda << 1$, means that $(1 – \exp(-\tau_\nu)) \sim \tau_\lambda$. Then,

  $W \sim \tau_\lambda \Delta\lambda \sim (\pi e^2/m_e c^2)\lambda_0 \psi(\lambda) f N \Delta\lambda$ and for weak lines $\psi(\lambda) \sim 1$, $\Delta\lambda \sim \lambda_0$

  So we get $W \sim (\pi e^2/m_e c^2) f N \lambda_0^{\,2}$ So that **W is proportional to N**

- **Moderately Strong Lines :** $\tau_\lambda \geq 1$, means that the doppler broadening and radiative damping are both important. We use $\psi(\lambda) \sim (\pi^{1/2}/\Delta\lambda_D)\exp-(\Delta\lambda/\Delta\lambda_D)^2$

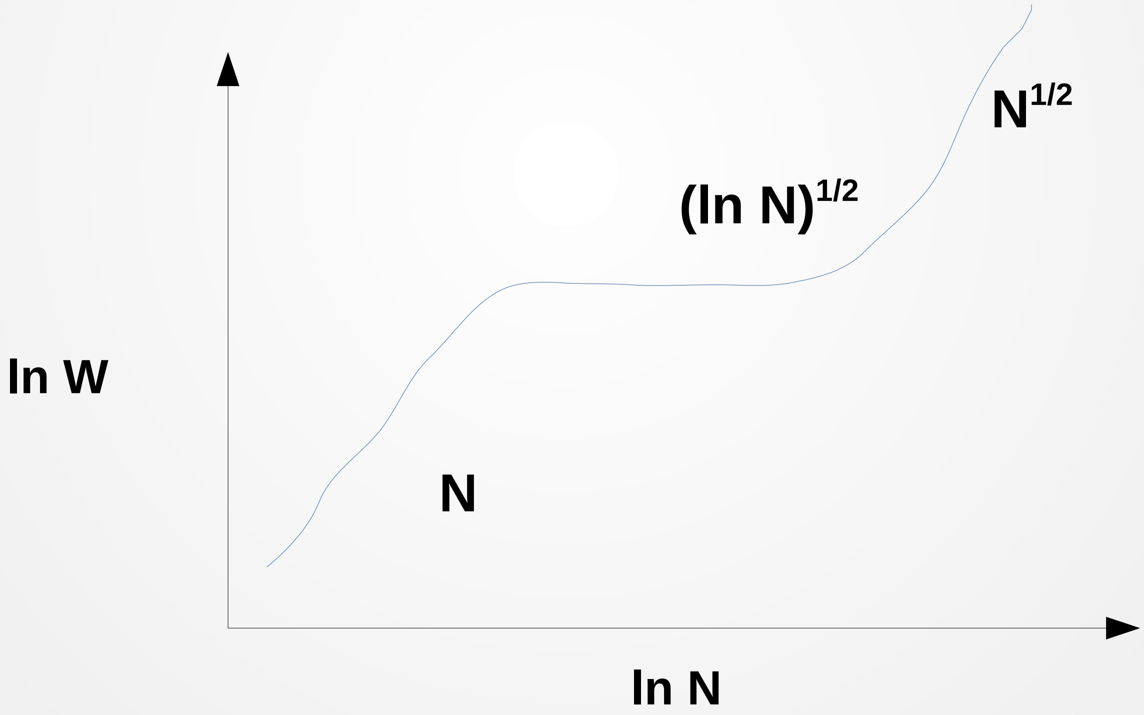
  The integral is : $W = 2\Delta\lambda_D \int (1-\exp(-\tau_0 \exp(-x^2)))dx$ from $x=0 \rightarrow \inf$ and $x=\Delta\lambda/\Delta\lambda_D$

  For large τ_λ values **W is proportional to (ln N)$^{1/2}$**

- **Strong Lines :** The absorption in the line wings is also important. The line profile is Lorentzian. Then **W is proportional to N$^{1/2}$**

The Curve of Growth plot

- **Weak lines :** $\tau_\lambda << 1$ **W is proportional to N**
- **Moderately Strong Lines :** $\tau_\lambda \geq 1$ **W is proportional to (ln N)$^{1/2}$**
- **Strong Lines :** $\tau_\lambda >> 1$ Then **W is proportional to N$^{1/2}$**



So what do spectral lines tell us about the ISM?

So to summarize spectral lines can give us information about:

1. What is the relative motion of the cloud wrt us (from the central velocity of the line v_0)?

2. What is the turbulent velocity inside the gas cloud (from the doppler width of the lines).

3. What is the column density of atoms or molecules inside the cloud? This can be derived using equivalent line widths and curve of growth.

4. What is the local density and temperature inside a cloud? This can be derived using the optical depth.

The Sources of Spectral Lines

- Spectral lines in the ISM arise from ions, atoms and molecules. The **optical emission** lines can be recognised from their :

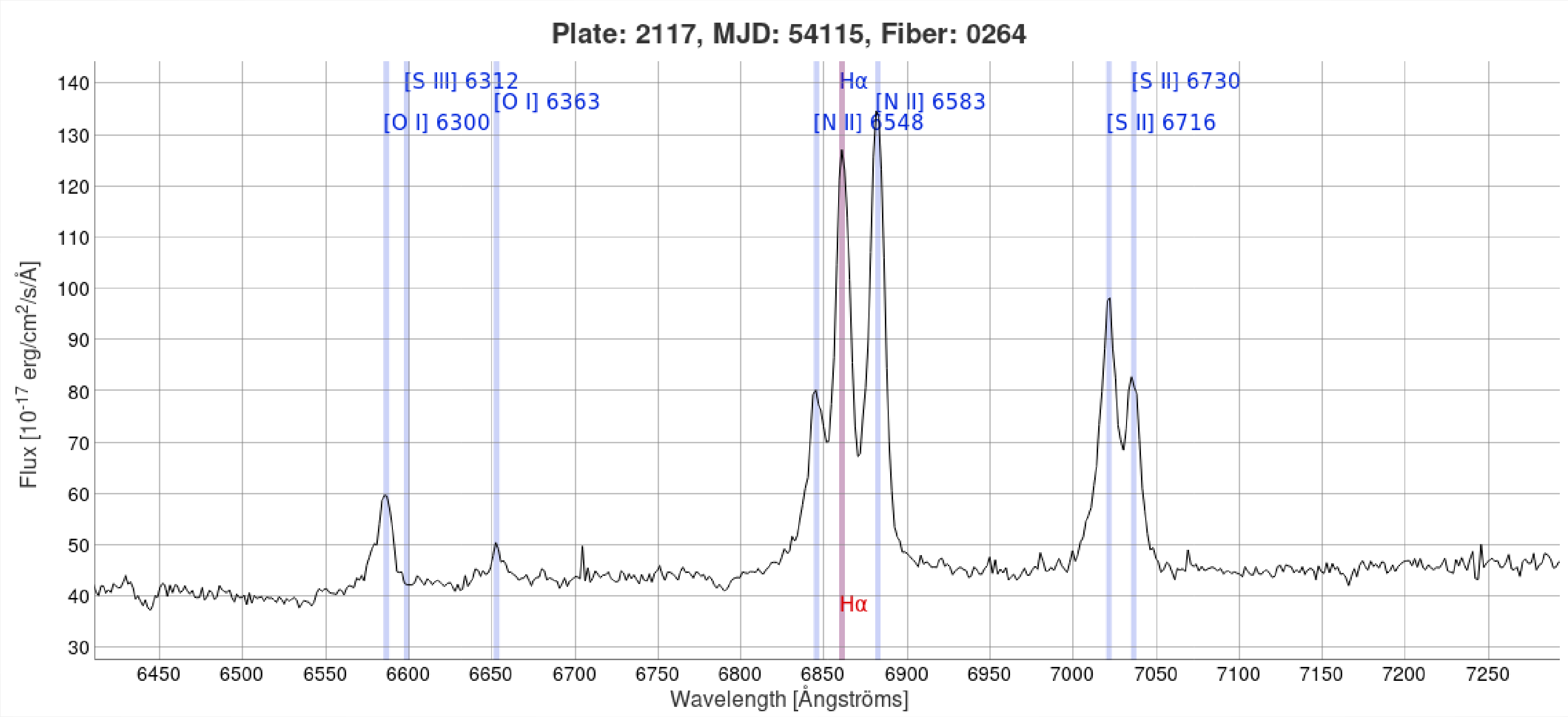
  (1) approximate wavelength : Sometimes the line maybe shifted due to redshift, but approximate lines near it can help identify it.

  (2) Line shapes : The intrinsic shapes of lines and whether they lie in doublets or triplets can identify it.

- The absorption lines also have intrinsic shapes e.g. Na doublet at λ=5890 and 5896 Angstrom.

- A good example of an emission line that arises due to recombination in optical wavelengths is the Hα line (6563 Angstrom) or Balmer line (n=3 to 1). It is widely used to trace star forming regions. The Lyman α line (n=2 to 1) lies in the UV range and is more difficult to trace (needs space telescopes).

Optical Spectral Lines Example

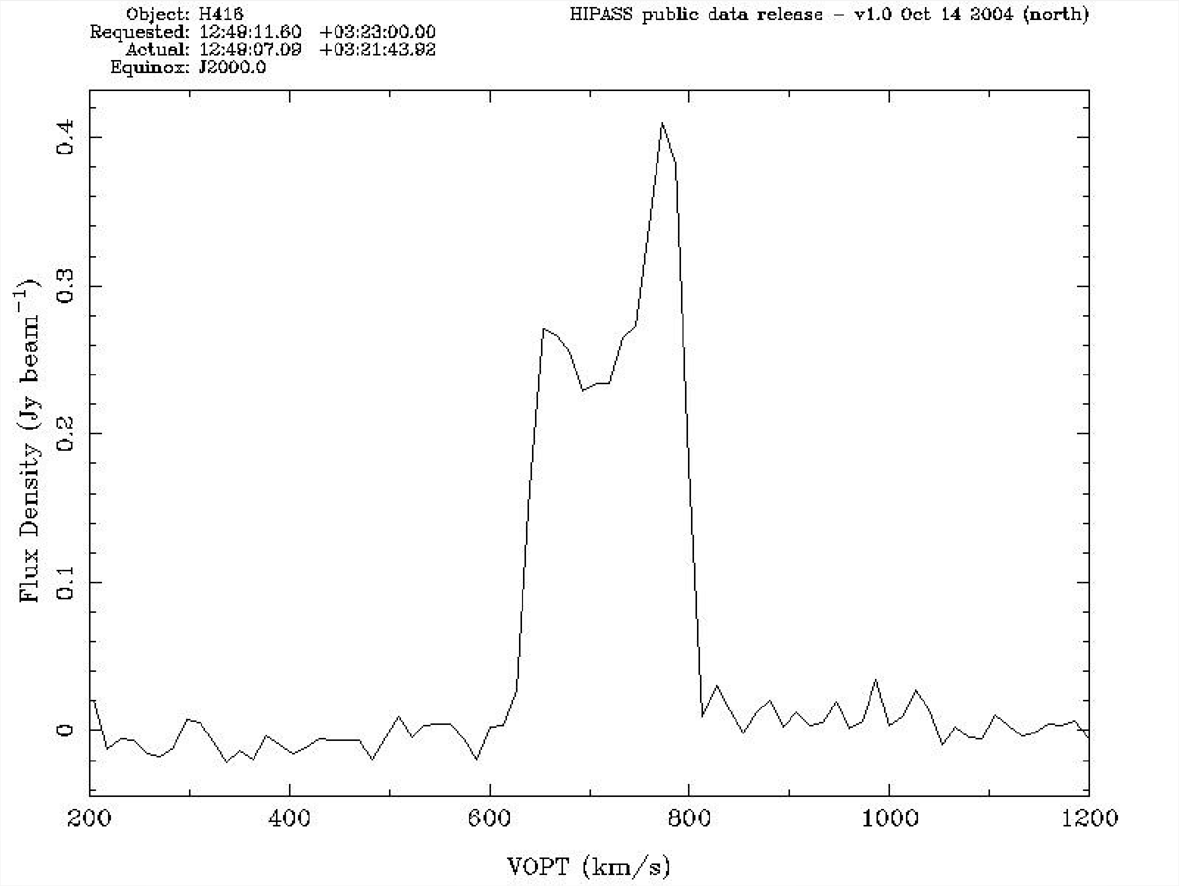


- The above plot shows an example of the Hα line (6563 Angstrom) or Balmer line (n=3 to 1). It is widely used to trace star forming regions. The [NII] lines are next to it. Spectrum detail is from SDSS DR9.

Spectral Lines : radio emission lines

- Spectral lines in the **radio wavelength range** from the ISM usually arise from atoms and molecules, although some ions are important. The most important ISM radio line is the neutral hydrogen (HI) line. Here we briefly discuss it.
- The HI line is at a wavelength of 21cm and arises due to hyperfine transition between F=0 and 1 (antiparallel and parallel electron-proton spin states). It has a natural decay timescale of 10^7 years and hence we detect it in emission mainly because it is very abundant in disk galaxies.
- The HI emission line has a double horned profile when it comes from a rotating disk. One side is receding and the side is approaching. This is due to the doppler effect.
- The HI line is also observed in absorption. In some galaxies the central HI emission is absorbed by the ISM. Also high redshift HI is detected in absorption in the radio spectrum.

Example of HI radio emission spectrum



- The HI line from the galaxy NGC4701 from the HIPASS data release. There is a double horned profile due to the HI coming from a rotating disk. The two sides are usually of equal intensity (height on y axis) but sometimes the HI gas distribution is uneven (often called lopsided).

End of Second Lecture