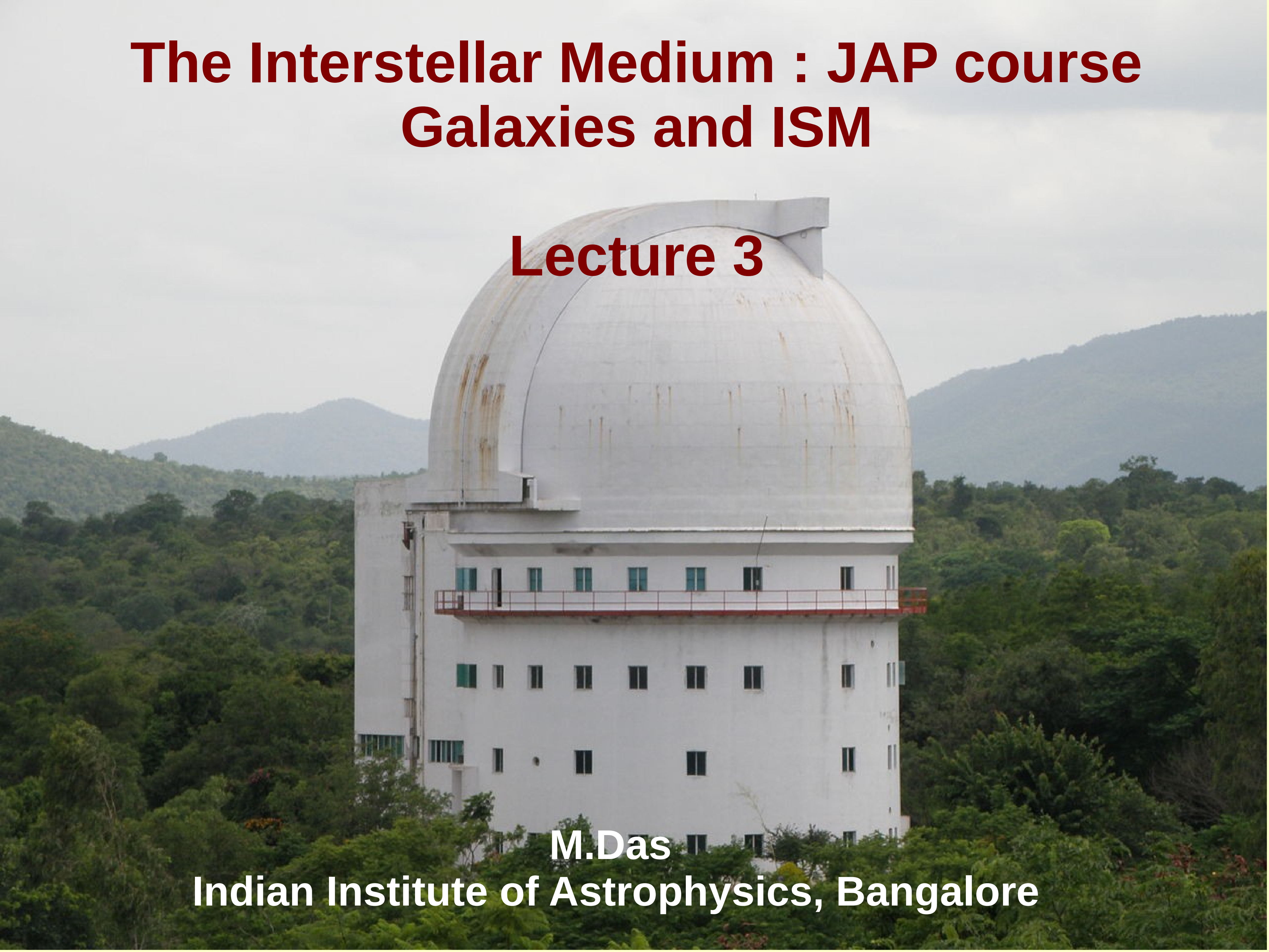

The Interstellar Medium : JAP course
Galaxies and ISM

Lecture 3

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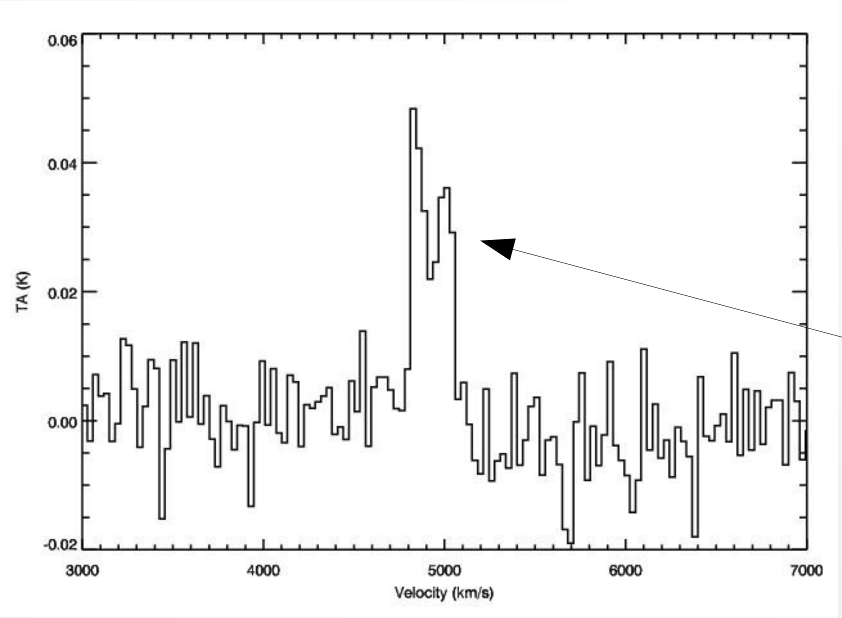
Molecular Line Emission from the ISM

- One of the main contributers to ISM emission lines are molecules. For example molecules like : CO, CS, CN, HD. They can also be studied in emission or absorption. The atoms in a molecule can I) rotate ii) vibrate about their common center of mass or iii) the molecule can have electronic transitions to higher states. All 3 processes produce emission lines but in different wavelengths.
- Rotational line usually fall in millimeter range (CO in millimeter range), vibrational molecular lines in the infrared (e.g. HD, OH) and electronic transition lie in the shorter wavelength range like UV (e.g. H_2 molecular excitations in UV).
- We will discuss **rotational lines** that usually lie within radio wavelengths:



The figure shows the CO(1-0) emission line detected from the galaxy SBS1325 at 115GHz using the Nobeyama millimeter telescope (Das et al. 2015). Note the double horned profile shape indicating that the emissiion comes from gas in a rotating disk.

CO(1-0) Emission Line

Rotational Emission Lines

The rotational emission lines the molecule must have a dipole moment. Hence homo-nuclear molecules such as H_2 cannot have rotational emission lines. Using quantum mechanics the energy levels can be derived and are as follows (reference : Molecular Spectroscopy by Banwell). Important in the derivation is the non-zero dipole moment and the moment of inertia about the center of mass of the molecule.

- **Linear molecule :** For a linear molecule such as the diatomic molecule CO, the energy levels are given as :

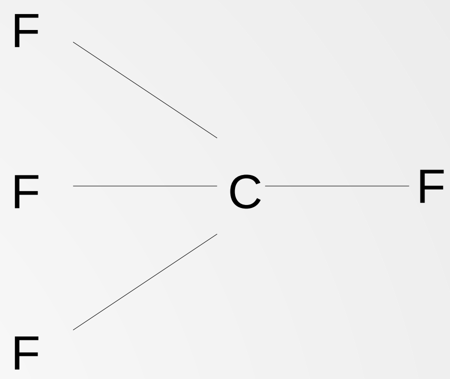
$$E = BJ(J+1)$$

where J= ± 1 and is the selection rule and $B=h^2/(8\pi^2 I)$

and I=moment of inertia of the molecule. For a linear diatomic moleculei it is given by $I=(m_1 m_2/m_1 + m_2)r_0^2$ where m_1 and m_2 are the masses of the atoms and r_0 is their separation. The rotational frequency is given by E/h.

Example : The CO molecule. The equilibrium separation of C and O atoms is 1.131 Angstrom. Show that the wavelength of the $J=2\rightarrow1$ line is at a wavelength of 1.3mm.

Vibrational Emission Lines



- **Symmetric top molecule** : If a polyatomic molecule has 2 axes of rotation and the 2 moments of inertia are equal, it is called a symmetric top molecule. An example is CF_4 which has a structure as shown below.
- Here $I_B = I_C \neq I_A$
- It can be a prolate of oblate symmetric top molecule, where $I_B = I_C > I_A$ or $I_B = I_C < I_A$
- The energy levels are given by

$$E = BJ(J+1) + (A-B)k^2$$

- Where J= ± 1 and K= -J, -J+1 to +J and $\Delta k = 0$

Electronic Transition Lines

Homo-nuclear molecules such as H_2 cannot have rotational emission lines. Instead they have electronic transitions of the molecule as a whole. Such transitions are often at high frequencies such as in the UV range.

Hence they are difficult to study as to study at UV wavelengths we have to use space telescopes.

The UV emission lines due to electronic transitions of H_2 were discovered using balloon experiments above the atmosphere of earth (earths atmosphere absorbs most UV radiation).

Continuum Radiation

There are 4 different types of continuum radiation:

- **Ionization** : There can be continuum emission or absorption in a spectrum due to bound-free and free-free transitions associated with ionization of an atom or molecule (see figure 2.10 in Dyson and Williams). An example is the UV photons that penetrate ISM molecular clouds, dissociating the H_2 molecules and creating a photodissociation region in the outer parts of the cloud.

  However, in general, ionization continuum is mainly important for stellar atmospheres, ionized regions around hot stars and for planetary nebulae. Not so much for ISM.

- **Bremsstrahlung radiation** : It is radiation emitted from charged particles that are accelerated during collisions. Arises from dense gas or plasma. The energy emitted depends on the energy of the colliding pair. For a Maxellian energy distribution the energy emitted between ν and ν+Δν, i.e. E(ν) is proportional to $T^{-1/2} n_e n_i \exp(-h\nu/kT)$ where n_e and n_i are the number densities of the electrons and ions. Hence, this radiation is important when $h\nu \ll kT$. Since the temperature of plasma in ISM is ~10^4 to 10^7K, this continuum is important for low frequencies.

Continuum Radiation …………….contd

The third and fourth type of continuum radiation

- **Synchroton radiation** : It is radiation emitted by relativistic electrons (i.e. moving close to the speed of light) in a magnetic field. Due to the acceleration the electrons will radiate energy, which is beamed in the forward direction.

  This radiation shows that there is magnetic field in the ISM. It is an important radiation from star forming regions, supernova remnants and also emitted when cosmic ray particles interact with the ISM magnetic field.

- **Cosmic Microwave Background radiation (CMBR)** : This radiation is remnant radiation from early epoch of the Universe. The CMBR peaks at wavelength of 1.9mm or 2.7 degrees K. There is a significant amount of energy in the CMBR, and it is comparable to stellar radiation, gas of hot gas and even cosmic rays. However, the coupling between ISM gas and CMBR is weak.

  For a few atoms/ions in the ISM, the interaction with CMBR is important. Like the rotational transitions of the CN radical and rotational transitions of formaldehyde seen in absorption.

Allowed and Forbidden Transitions

There are 2 types of emission lines depending on the whether electronic transitions or magnetic dipole/quadrupole transitions. The optical and NIR spectroscopy the two different types of lines are denoted differently.

- **Allowed Transitions :** They arise due to electronic transitions such as ionization lines (bound-free transitions) and electric dipole lines from rotational transitions of molecules. Good examples are the balmer lines Hα and Hβ which are common in the optical spectra of galaxies.

  Another good example is the CO molecule which has a dipole moment. Hence it shows rotational emission lines due to transition between E=BJ(J+1) energy levels where J=0,1,2….and ΔJ=±1. It is the next most abundant molecule after the H_2 molecule. The excited CO molecule relaxes quickly via J transitions, thus cooling the gas. The CO molecule is associated with dense H_2 clouds where $n(H_2)>10^4$ cm^{-3}, and $n(CO)\sim10^{-5}n(H_2)$.

  Allowed transitions are very important for cooling the ISM as many important coolants emit through allowed transitions. The allowed transitions occur faster than the forbidden ones.

Forbidden Transitions

- **Forbidden Transitions :** They arise from magnetic dipole or electric quadrupole transitions. The rate of decay is much slower than dipole transitions. These transitions are called forbidden because we cannot observe them on earth because before the atoms/molecules can decay, they will suffer collisions with other atoms in the atmosphere. But the ISM atmosphere is rarer than any vacuum on earth. Hence, these forbidden transitions can take place only in the ISM. We will discuss some examples.
  An important note : in astronomy a neutral atom has a "I" next to it and ionized atom has "II" rather than "+" next to it. Hence a neutral oxygen atom is OI, singly ionized atom is OII and so on. All forbidden transitions have square brackets around them.
  Example : transitions such as [OI], [OII], [SI], [NI], [OIII], all in optical range of λ.

- The H_2 molecule : The molecule is homo-nuclear and hence has no dipole moment. Only quadrupole transitions are allowed I.e. $\Delta J=\pm 2$. Hence the cooling process is very slow, timescale is $\sim 10^{10}$ seconds for J=2 level.

  However, collisions occur intervals of $\sim 10^{11}/n$ seconds or $10^{11}/10^4 \sim 10^7$ seconds. So the upper levels are populated faster than the relaxation from higher to lower levels. So upper levels are well populated and given by N(J) proportional to (2J+1)exp(-E(J)/kT). The radiation leak due to quadrupole transitions is minor perturbation.

Cooling of ISM Gas by Emission Lines

- The emission from gas in the ISM helps to cool it. Atoms/ions or molecules are excited via collisions in dense gas and often in shocks. The energy of the collisions excites the particle to higher levels and then photons are emitted. If they escape from the gas cloud this process will cool the gas.
- **For efficient cooling the following factors are important**
  1) frequent collisions, so abundant ions/atoms/molecules. 2) The excitation energy must be less or comparable to the thermal KE. 3) A high probability of excitation during collision. 4) Photon should be emitted before the next collision.

  Examples of important cooling processes in ISM by atoms/ions
- **(i) Singly ionized carbon or CII :** The most common atoms are C, N, O. Of these the CII has the transition $^2P_{1/2} \rightarrow {}^2P_{3/2}$ corresponding to the energy ΔE=92 K. The HI clouds in the ISM have temperatures of ~100K, whereas the denser H_2 clouds have T=20K. Hence, collisions with electrons in clouds of T=100K can excite the CII line, especially since the transition is an allowed line. The line lies in the infrared region and can be used to trace cold gas in the ISM

  The cooling rate is: $\Lambda(CII)=n(e)n(CII)x8x10^{-33}T^{-1/2}exp(-92/T)$ J $m^{-3}s^{-1}$

Cooling of ISM Gas …..Contd

Another example of cooling in ISM by atoms/ions

- **(ii) neutral hydrogen HI** : The HI atom is the most common atom in the Universe. But the transitions require large energies. For HI ionisation energy is 13.6eV. Minimum energy to take the HI above ground state is 10eV. This corresponds to $T \sim 10^4$ K. Hence, cooling by ionised H atoms (Hα, Hβ) requires high temperature gas ($10^4 – 10^6$ K).
- **(iii) other ions :** At intermediate temperatures ($T \sim 10^3$ K) there are ions such as FeII and SiII which can be exited by collisions to meta stable states which act as new ground states from which excitation and cooling occurs.

Cooling of ISM Gas ……...contd

Examples of important cooling processes in ISM by molecules

- **(i) Molecular Hydrogen H_2:** It is also one of the most common molecules but it does not have a dipole moment. Transitions occur via quadrupole transitions only $\Delta J=\pm2$. The least energetic transition $\Delta J=2$ corresponds to 510 K but the deacy time of the level is very large (see previous slides). Hence it is not an important coolant.
- **(ii) HD molecule :** If one atom is deuterium, then the molecule has a dipole moment. The lowest energy levels at ~100K corresponds to cooling rate of 3×10^{-33} Js^{-1}/molecule. But the abundance of HD is low $n(HD)<10^{-5}n(H2)$. Hence it is not an important coolant.
- **(iii) CO molecule :** It is the most important molecular coolant. As discussed earlier it has a dipole moment and hence rotational transitions. The $J=1\rightarrow0$ transition corresponds to T=5.5K. Hence for dense cold clouds it is the most important coolant. However, if the cloud is dense, the photons can be absorbed again by the CO molecules i.e. the cloud is optically thick to the radiation.

Cooling of ISM Gas ……...contd

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End of Third Lecture