AQM Term paper : Hα line and its significance in astrophysics

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Abstract : The background to understand the origin and properties of the Hα line is built by discussing, in chronological order, developments like the observation of line spectra in the visible region, Balmer's empirical relation for visible spectrum, discovery of UV and IR spectra, Rydberg's empirical relation and how the Bohr model explains these by looking at a simple dimensional derivation of Rydberg's formula with the Bohr Model as the starting point. The properties of the Hα line are listed and its importance in astrophysical observations is looked at. Finally, a basic idea of the construction and working of Hα filters is given.

I. LINE SPECTRA

In the beginning of the nineteenth century, Wollaston observed that sunlight did not have a continuous spectrum but, instead, had some colours missing [1]. Building on his work, Frauhofer systematically observed and reported missing wavelengths from the absorbtion spectrum of the sun [2]. Further, it was observed that different metals have different emission spectra and hence metals could be identified by the colour of their sparks or flames. Soon the emission spectra of gases were being observed and it was Angström who first observed the visible spectrum of Hydrogen in 1855 [3].

Up until almost the end of the nineteenth century, only the visible spectra of atoms were observed. In the late nineteenth century and early twentieth century, with the invention of better techniques, the UV and the IR spectra were also seen. Lyman discovered the UV spectrum of Hydrogen during 1906-1914 [4, 5] and the IR spectrum was seen by Paschen in 1908 [6].

II. BALMER'S RELATION

Angström had measured the wavelengths of the first four lines in the visible spectrum of hydrogen spectrum as 656.21 nm, 486.07 nm, 434.01 nm and 410.12 nm. In 1885, Balmer noticed that these wavelengths can be given by a simple formula with an integer parameter, n [7]. He found that the wavelengths could be expressed as

$$\lambda = B\frac{n^2}{n^2-4} \tag{1}$$

with $B = 364.56$ nm and $2 < n \in N$.

Rydberg extended this idea for the IR and UV spectrum in 1890 and gave his famous equation [8]:

$$\frac{1}{\lambda} = R\left(\frac{1}{n_1^2} - \frac{1}{n_2^2}\right) \tag{2}$$

where R is the Rydberg's constant and $n_1, n_2 \in N$. Setting $n_1 = 2$, we can recover Balmer's Formula (Equation 1) and identify $R = \frac{4}{B} = 10973731.57\ \mathrm{m}^{-1}$.

III. ATOMIC MODELS

In 1911, Rutherford proposed the nuclear model for the atom [9] on the basis of observations by Geiger and Marsden. Even though this model was very successful in explaining the mass distribution inside atoms, it could neither explain the stability of atoms nor the existence of a discrete line spectrum.

To explain the stability and spectra, in 1913, Bohr put forward his model of the atom [10] postulating the existence of stable electron orbits with discrete energy levels and quantized angular momenta, the only interaction between electrons and the nucleus being Coulomb interaction. The spectral lines arise due to transition of electrons between energy levels resulting in the difference in energy being radiated out as light.

IV. FROM BOHR TO RYDBERG

Consider the following derivation of Rydberg's formula (Equation 2) using the Bohr model and purely dimensional arguments.

The angular momentum, L, of electrons in an atom was postulated to be an integral multiple of the reduced Planck's Constant, $\hbar$.

$$\implies L \sim vr \sim n \tag{3}$$

where v is the velocity of the electron, r is the radius of its orbit and $n \in N$.The orbital centripetal force is provided by the Coulomb force:

$$\implies \frac{v^2}{r} \sim \frac{1}{r^2} \tag{4}$$

This means $r \sim \frac{1}{v^2}$. Substituting this in Equation 3,

$$v \sim \frac{1}{n} \tag{5}$$

and hence, the energy,

$$E \sim v^2 \sim \frac{1}{n^2} \tag{6}$$

So the n^{th} energy level of a Bohr atom has energy $E \sim \frac{1}{n^2}$. The energy of emitted radiation due to transition of an electron between these levels is given by the difference in the energies of these levels, $\Delta E = \left(\frac{1}{n_1^2} - \frac{1}{n_2^2}\right)$. The wavelength of radiation is given by the inverse of its energy.

$$\implies \frac{1}{\lambda} \sim \left(\frac{1}{n_1^2} - \frac{1}{n_2^2}\right) \tag{7}$$

This has the same form as Equation 2 and hence the Bohr model explains the origin of line spectra of atoms.

V. H-ALPHA LINE

The longest wavelength radiation emitted by Hydrogen in the visible region corresponds to the transition of an electron from $n = 3$ to $n = 2$ level. It has a wavelength of 656.21 nm as can be calculated from Rydberg's Formula (Equation 2). This line is called the Hα line. It has a deep red colour. Among all lines in the visible spectrum of Hydrogen, this line has the highest intensity. This is beacuse the probability that the $n = 3$ to $n = 2$ transition is part of a typical cascade of an electron as it combines with ionized hydrogen is about half. So Hα line indicates presence of ionized Hydrogen.

VI. ASTROPHYSICAL SIGNIFICANCE

Hydrogen is the most abundant element in the Universe [11]. Since Hα indicates presence of Hydrogen, it is very useful to observe the Universe in this wavelength. It can be used to observe nebulae, stars, galaxies, astronomical clouds, accretion disks and many features of the Sun like its chromosphere, spicules, prominences, flares, filaments and many more [12].

Even though the Lyman-α line is more intense than the Hα line, Lyman-α gets blocked by the atmosphere because it is in the UV region. As a result, Hα was very important for early astronomers and still is for ground based observatories. The position and velocities of various astronomical sources can also be determined by comparing the wavelength of the incoming Doppler shifted Hα line with the actual wavelength.

VII. FILTERS

An Hα filter blocks all other wavelengths of light and allows only a narrow band (˜1 Å) centred around Hα to pass through it - it acts as a band-pass filter. It is used in front of telescopes to view astronomical objects in the Hα wavelength. To block the unwanted radiation and let only a small band pass, it uses the principle of destructive interference to block everything except Hα and constructive interference to enhance the intensity of Hα in the direction of the objective lens of the telescope.

A typical Hα filter for astronomical use has three parts to it. Light first falls on a piece of red glass which removes the smaller wavelengths and lets only red light to pass through. This red light then passes through a Fabry-Perot etalon which is an optical cavity designed essentially by placing two partially reflecting wedges in succession at a suitable distance which lets only the resonant frequencies, Hα in this case, to pass. The final piece is a dichoric filter which is a collection of thin films that further reduce the bandwidth of the passing radiation. In this way, a very thin band passes through the entire filter.

To incorporate Doppler shifts, the centre of the allowed wavelength band can be changed by changing the temperature of the filter or tilting it by particular angles.

VIII. SUMMARY AND SCOPE FOR FURTHER STUDY

The origin of spectra of atoms was discussed and explained on the basis of the Bohr model of the atom. The properties of Hα line were seen and their role in making Hα an ideal wavelength to observe astronomical objects was studied. The construction and working of filters used to filter Hα from incoming radiation was also described.

With further advancements in spectroscopic techniques, it was observed that the seemingly single Hα line splits into two very closely spaced lines. This splitting is explained by the hyperfine structure of the Hydrogen atom on the basis of the interactions between the spins of the electron and the proton. How this splitting can be used to differentiate between Hydrogen and Deuterium can be explored further.

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APPENDIX: IMAGES

Figure 1: The Hydrogen spectrum in the visible region. The bright red line on the far right is the Hα line [13].

Figure 2: The pelican nebula photographed in Hα wavelength [14].

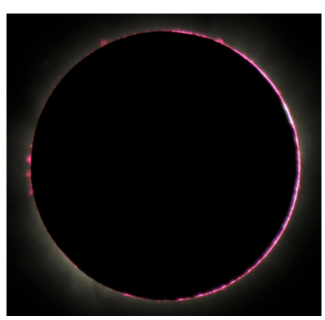

Figure 3: The chromosphere of the sun during a solar eclipse as seen in Hα [12].

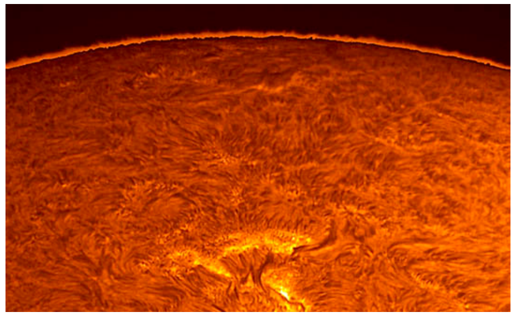

Figure 4: The spicules - “orange fur” of the sun in Hα [12].

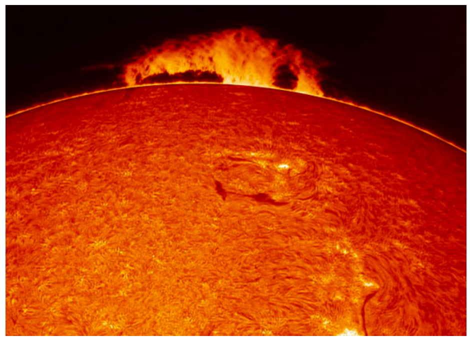

Figure 5: A large prominence on the sun in Hα [12].

Figure 6: A filament on the surface of the sun in Hα [12].

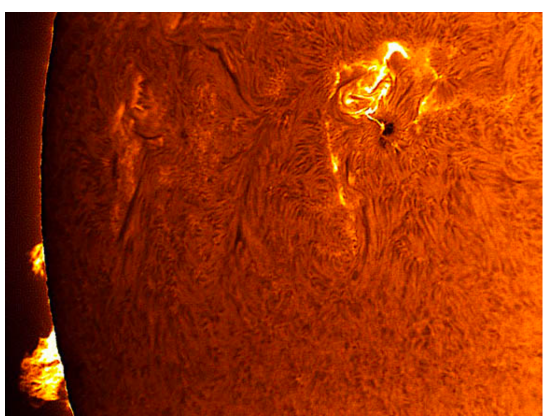

Figure 7: A large solar flare in Hα [12].