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The Hydrogen Atom Lyman Alpha-Line and the Expansion of the Universe

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Laboratory experiments show that all chemical elements emit photons only at characteristic wavelengths. These photons are manifest as emission or absorption lines in the spectrum of various astronomical objects such as galaxies. Performing spectral analysis of the light emitted by these objects astronomers found that for most of them, spectral lines are shifted to longer wavelengths. In other words, their light shows redshift. Redshift is denoted as z and is defined by the following equation

$$z = (\lambda - \lambda_E)/\lambda_E \quad \dots (1)$$

where λ_E is the wavelength of light emitted by an astronomical object and λ is the wavelength of this light measured by an Earth's observer.

If $z > 0$ then the galaxy has redshift; if $z < 0$ the galaxy has blueshift. In other words, blueshift is a negative redshift. In this communication, we will deal with only one type of astronomical object: galaxies.

Let us here clarify something. In the above definition of λ_E, we assume that this is the wavelength at which the light has been emitted as measured by a local observer in the galaxy (or by an observer comoving with the galaxy). This is not correct. λ_E represents the wavelength of light emitted by the assumed source type at rest in the laboratory.

All nearby and distant galaxies[1] (or extragalactic galaxies, i. e. the galaxies outside the Milky Way) show the redshift. According to standard cosmology, this so-called cosmological redshift (or more commonly just redshift) is due to the result of the Universe expansion (in fact of stretching of the space) during the flight of the light from these galaxies to the Earth. There are, however, only about a hundred known galaxies emitting the blueshifted light and most of them in the Local Group. One of these "local" galaxies is Andromeda having $z = -0.001$.

Alternatively, galaxies are moving through space, and the galaxy's redshift and blueshift can be interpreted as a result of the Doppler effect in light as Doppler shifts. According to this approach, the wavelength of the emitted light by a galaxy depends on its motion

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[1] We define nearby galaxies as those whose redshift z is from 0.001 to 0.1 (or $0.001 \leq z \leq 0.1$) and distant galaxies with $z > 0.1$. Of course, there is no sharp line between nearby and distant galaxies [1].

relative to Earth's observer. If the galaxy travels towards the Earth, the wavelength of its light is blueshifted, if this galaxy travels away from the Earth, its wavelength is redshifted.

Bohr's equation for energy levels of the hydrogen (H) atom is

$$E_n = 1/n^2(-2\pi^2e^4m/h^2) \dots (2)$$

where n (= 1, 2, 3,…) is the quantum number, m is the relativistic mass of the electron, e (= 1.6×10^{-19} C) is its charge and h (= 6.63×10^{-34} J sec) is Planck's constant.[2]

The spectrum of H atoms is dominated by a series of lines, the highest in energy being the Lyman series from 121.6 nm - 92.1 nm in the far-ultraviolet (UV) region. The hydrogen (Lyman) alpha-line or Ly-α at 121.6 nm is of utmost importance in many fields of astrophysics. This UV line is redshifted with distance to the visible and even near-infrared wavelength ranges. For the sake of simplicity, we will mainly deal in this communication with the Ly-α line.

The energy of the photon emitted by the H atom at rest, with electron's mass m_0 (= 9.1×10^{-31} kg), during its transition from the higher (excited) energy level with n = 2 to the ground level with n = 1 is

$$\Delta E = h\nu = E_2 - E_1 = (1 - 1/4)2\pi^2e^4m_0/h^2$$

or

$$h\nu_E = 3/2(\pi^2e^4m_0/h^2)$$

where ν_E is the frequency of the emitted photon. This is the equation for the energy of the Ly-α line. Dividing this equation with the speed of light c (≈ 3×10^8 m sec^{-1}) and after a bit of algebra we obtain

$$c/h\nu_E = 2/3(h^2c/\pi^2e^4m_0).$$

The wavelength of photon $\lambda_E = c/\nu_E$ and we arrive at

$$\lambda_E = 2/3(h^3c/\pi^2e^4m_0) \quad \dots (3).$$

EGSY8p7 is a distant galaxy, with a spectroscopic redshift of $z = 8.68$ [2], a light travel distance of 13.2 billion light-years from Earth, and observed as it existed about 600 million years after the Big Bang. EGSY8p7 is the most distant known detection of the Lyα emissions. This detection is surprising because the early Universe was full of atomic H clouds which should absorb these emissions.

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[2] It is often considered that the Schrödinger equation is superior to Bohr's equation in describing the H atom. In most cases, the results of both approaches coincide or are very close.

If the Ly-α line wavelength of galaxy EGSY8p7 depends only on the speed of this galaxy υ then one or more terms in eqn. (2) should depend on υ. However, except for the mass of electron m, universal constants h and e are invariant with Lorentz transformations. Of course, the electron's mass is Lorentz covariant. So

$$m = m_0/\sqrt{(1- \upsilon^2/c^2)} \quad \dots (4).$$

Therefore, the wavelength of the Ly-α line measured by Earth's observer is

$$\lambda_\upsilon = 2/3(h^3c/\pi^2e^4m) \dots (5).$$

Combining eqns. (3), (4) and (5) and after a bit of algebra, we arrive at

$$\lambda_\upsilon = \lambda_E\sqrt{(1- \upsilon^2/c^2)} \quad \dots (6).$$

Since $c > \upsilon$ and $m > m_0$ then $\lambda_\upsilon < \lambda_E$ Earth's observer would measure blueshift instead of redshift.

To explain the redshift of distant galaxies, such as EGSY8p7, most cosmologists refer to the relativistic Doppler effect in light, λ_D. According to this concept, the observed wavelength by the observer at rest is

$$\lambda_D = \lambda_E\sqrt{[(1 + \upsilon/c)/(1 - \upsilon/c)]} \quad \dots (7).$$

Combining eqns. (6) and (7), an after a bit of algebra, we get

$$\lambda_\upsilon = \lambda_D(1- \upsilon/c).$$

Having in mind that $c > \upsilon$, $\lambda_\upsilon < \lambda_D$.

The total wavelength λ_{tot} is a combination of λ_υ and λ_D or $\lambda_{tot} = \lambda_\upsilon + \lambda_D$. Therefore, Earth's observer would measure the redshift of the Ly-α line sourced by EGSY8p7. Moreover, as the speed of the galaxy υ approaches the speed of light c the contribution of υ, λ_υ, to the total wavelength λ_{tot} would be negligible compared to the contribution of the Doppler effect of light λ_D.

However, the above two concepts (the speed dependence wavelength and the Doppler effect in light for EGSY8p7) encounter a serious problem. The recessional speed of the expansion space is not equal to the "classical" speed υ. In other words, the redshift of EGSY8p7 is mainly due to the recessional speed but not due to the "classical" speed υ. In fact, υ is due to the peculiar motion of a galaxy and is negligible (< 300 km sec^{-1}) [3, and references therein). In general, the cosmological recessional motion of distant galaxies, such as EGSY8p7, far outweighs the peculiar motion. In other words, the redshift of EGSY8p7 is in line with the view of standard cosmology that the redshift of nearby and distant galaxies is due only to the Universe's expansion. Moreover, the recessional speed can be superluminal (higher than the speed of light c) and it is not expected to be uniform at all [4, and references therein] as the "classical" speed υ in eqns. (6) and (7).

The alternative to the cosmological recessional model for the redshift of EGSY8p7 is that the speed of light emitted by this galaxy is superluminal. Suppose that this redshift z is made of two parts: first one, z_u, which results from the expansion of the Universe, and second, z_E, from the superluminal speed of the light c_E coming from EGSY8p7. In equation form,

$$z = z_u + z_E.$$

There are three possible cases:
(a) the speed of light coming from EGSY8p7 is not superluminal then $z = z_u$ or its redshift is a result of the expanding Universe; (b) EGSY8p7 emits light of the superluminal speed c_E ($> c$) that is much higher than the recession speed υ_r (or $c_E >> \upsilon_r$). Then the redshift of EGSY8p7[3] is mainly a consequence of this speed; and, (c) both the expansion of the Universe and the superluminal speed of the light from EGSY8p7 contribute to its redshift.[4] For all three cases, we have to know the speed of light coming from EGSY8p7. However, this speed has not been measured so far for EGSY8p7 or any other nearby or distant galaxies [3].

References

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[3] T. M. Davis and M. I. Scrimgeour, *Deriving accurate peculiar velocities* (*even at high redshift*). MNRAS, 442, 1117–1122 (2014).
[4] D. Michel, *Analytical relationship between source-receiver distances, redshift, and luminosity, distances under pure modes of expansion.* Adv. Astroph., 2, November 2017.

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[3] In this case, the Principle of energy conservation requires that the light energy emitted by EGSY8p7 and measured by Earth’s observer is the same: hν. Since the wavelength of a photon is given by the ratio of its speed and frequency, it follows that the wavelength of the superluminal light of this galaxy (or in general, by nearby and distant galaxies), λ_E, is larger than the wavelength λ of the ordinary light with the speed c, or $\lambda_E > \lambda$.

[4] In this case, we cannot separate the redshift contributions of the Universe expansion z_u and the superluminal light z_E to the total redshift z: see the last equitation above. So, we do not know if the observable Universe expanding or not. In addition, we do not know whether the light coming from EGSY8p7 is superluminal or not.