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Artist's impression of the Big Bang (Choi, 2017)

The World in Colour: Examining the Significance of the Redshift Effect

ABSTRACT

The scientific method of studying objects and materials based on colour is known as Spectroscopy. Colour is constituted by the electromagnetic radiation of wavelengths between 380nm -700nm, which make up the visible spectrum. The discovery of the cosmological *Redshift Effect* has allowed the scientific community to gain a broader understanding of even the farthest cosmic objects in the universe. It has also allowed a more meaningful discourse on the origins of the universe.

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The World in Colour:
Examining the Significance of the Redshift Effect

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"The story of the Universe is written in the light that fills it. Stranded on the surface of our tiny rock, we can look up and try to read that story."
(Geach, 2018, p. 31)

Introduction

As far back as around 1000BCE, the Assyro-Babylonians who lived in Mesopotamia had attempted to read the story of our Universe, not with the objective of understanding what the Universe was but rather as a tool for timekeeping to help with their agricultural practices and religious rituals. The Assyro-Babylonians did this by charting the sky with the naked eye and recording the periodicity of cosmic objects on clay tablets (European Space Agency 2019). In the centuries since this celestial gazing by the Mesopotamian civilisation, humans have used increasing degrees of knowledge of cosmic objects and their movements for such purposes as timekeeping and navigation, but our ability to truly read the story of the Universe did not begin until we were able to understand the light that fills it.

The scientific method of studying objects and materials based on colour is known as Spectroscopy (NASA 2022). It involves analysing the detailed patterns of colours that materials emit, absorb, transmit, or reflect. Colour is defined as the "electromagnetic radiation of a certain range of wavelengths visible to the human eye" (Nassau, 2019). Known as the visible spectrum, it consists of electromagnetic radiation with wavelengths between 380 to 700 nanometres (NASA, 2010) (see fig.1).

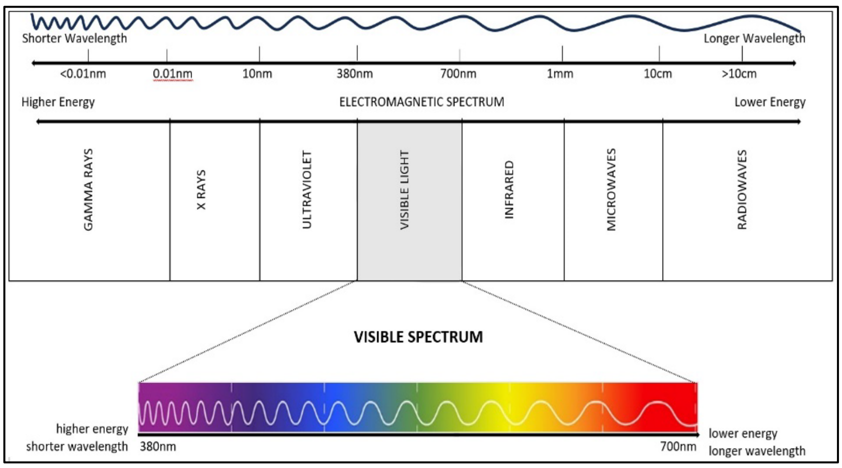

Figure 1: Electromagnetic spectrum indicating the visible spectrum (Ismail 2024)

Observation of changes, or 'shifts' in the wavelengths of visible spectrum reaching the earth from cosmic objects are especially important in understanding our Universe. The shift towards the red region of the spectrum or the *Redshift Effect* continues to play an especially significant role in furthering this understanding.

In this paper the concept of the redshift effect will be introduced in Part I. Part II presents briefly the discovery of the cosmological redshift and Part III discusses how knowledge of redshift effect has led to a more advanced understanding of our Universe and its origins.

I- The Concept of Redshift

The redshift effect is similar to that of the Doppler effect. In 1842, Christian Andreas Doppler observed that sound waves from a passing car creates a marked shift in the pitch as the vehicle speeds towards (Observer B in **Figure 2**) or away from the observer (Observer A in **Figure 2**). Most often applied to sound waves, the Doppler effect can tell whether an object is moving towards or away from the observer.

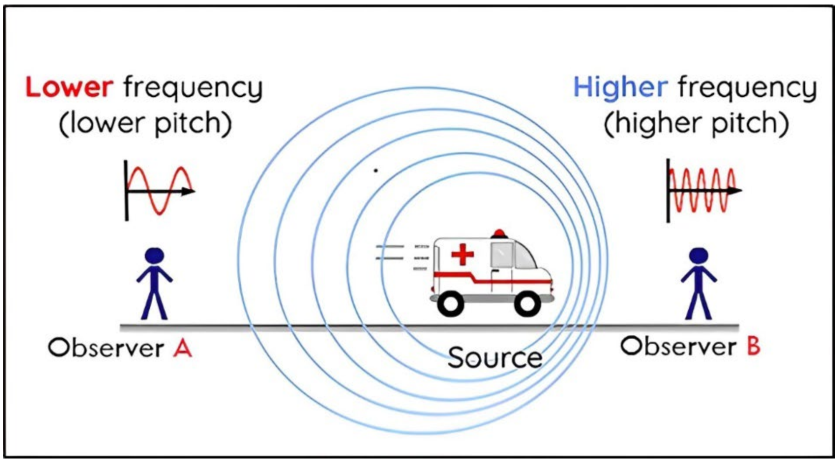

Figure 2: Illustration of Doppler effect (Science Ready 2024)

In the case of the Doppler effect on sound waves, a stretched, lower pitch is noted when an object is moving away from the observer. Similarly, as light can also be represented in wave form, when the source of a light appears to be moving away from the observer, its wave frequency becomes longer and more stretched (Las Cumbres Observatory 2023). This is observed as a red light, due to light wavelengths of lower frequencies appearing as red to the eye and this phenomenon is referred to as a 'doppler shift'. A cosmological redshift occurs when the light emitted by a cosmic object is stretched because the space between the light and the observer is expanding. A distinguishing feature between a 'doppler shift' and a 'cosmological redshift' is that in the case of cosmological redshift, the observed red shift is not due to the movement of the object or observer, but rather due to the stretching or expansion of space between the observer and the cosmological object (see fig. 3).

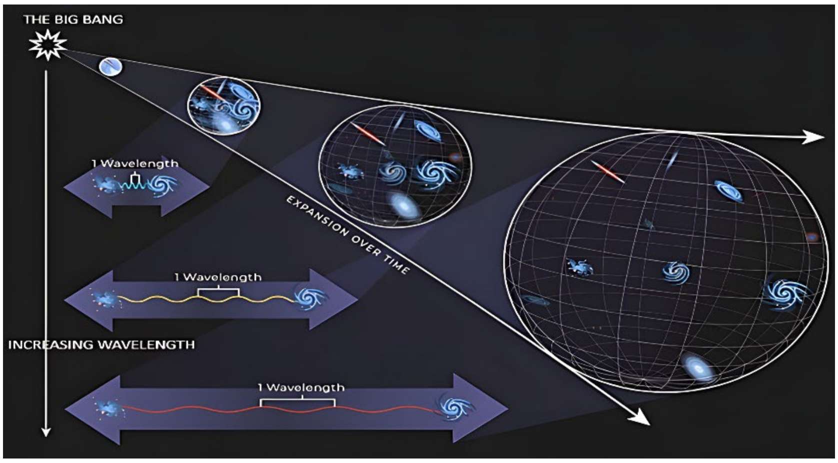

Figure 3: Expansion of space leading to a stretching of light - wavelength (Hustack, 2022)

The measurements of redshifts are discussed in terms of the redshift parameter z. This is calculated using the below equation (Eq. 1).

$$z = \frac{(\lambda_{observed} - \lambda_{rest})}{\lambda_{rest}}$$

$\lambda_{observed}$ is the observed wavelength of the line on the spectrum

λ_{rest} is the wavelength that line would have if its source was not in motion

Equation 1: Equation to find parameter **z** (Las Cumbres Observatory, n.d.)

In the above equation, z defines the number of years the light from the object has moved to reach the observer. However, this is not the distance to the object in light years, because as the light from the object travelled to reach the observer, the universe has also been expanding and due to this reason, the object is now much farther away from the observer (Las Cumbres Observatory, n.d.).

II- Discovery of the Cosmological Redshift Effect

The cosmological redshift was discovered in 1912 by the American astronomer, Vesto Slipher whilst investigating a spiral nebula - the Andromeda Galaxy (PBS, 2019). Slipher used a spectroscopy to measure the light emitted by this spiral nebula. In spectroscopy, dark lines called 'absorption lines' appear on the spectrum in different patterns highlighting the different elements in the light source. Slipher noticed the light captured on the spectrum from the spiral nebula had absorption lines that were shifted to the red region of the spectrum. From this observation Slipher was able to deduce the spiral nebula was moving away from the observer, and at rapid speeds, but he was not able to measure the distances to these cosmological objects (PBS, 2019).

In 1923, with Edwin Hubble's discovery of Cepheids within the Andromeda, and with the help of Henrietta Leavitt's period luminosity relation for Cepheids, Hubble determined that the ratio of distance to cosmological objects producing redshifts was 170 kilometres/second per light year of distance. This is now known as *Hubble's constant* (Lowell, 2012). The scientific works produced by both Slipher and Hubble, along with the contributions of Henrietta Leavitt are the founding contributions in the discovery of cosmological redshift.

Like Slipher and Hubble, many other scientists also observed galaxies that were redshifted, and deduced that these cosmological objects were moving away from Earth, thus leading to an understanding that the universe was expanding. The *expanding Universe* theory was solidified by Lemaitre and Friedmann in 1927 when they used Einstein's field equation (see Eq. 2) to provide theoretical evidence of the expansion of the universe.

$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4}\, T_{\mu\nu}$$

Equation 2: Einstein's field equation with cosmological constant

In 1929, Lemaitre and Friedmann's findings were confirmed by Hubble's observational evidence (Space Telescope Science Institute, 2020). Hubble's observations confirmed that the universe is constantly in a state of expansion and that light from the more distant galaxies appeared to be stretched to longer wavelengths or to have undergone a redshift effect.

III- Significance of Cosmological Redshift

The expansion of the Universe is often explained in terms of a spacetime 'fabric' that is stretched and where the light waves within this fabric are also stretched. By measuring the redshifts of galaxies using spectroscopy, scientists can determine its distance and therefore, its rate of recessions, allowing a mapping of the expansion of the universe and thus providing further evidence in support of the Big Bang theory (Lohar, 2023).

The presence of redshifted galaxies and the ever-expanding nature of the Universe are crucial evidence supporting the Big Bang theory. As galaxies move further away from each other, tracing back in time, there would be a point at which all matter in the universe was in one spot (see fig. 4).

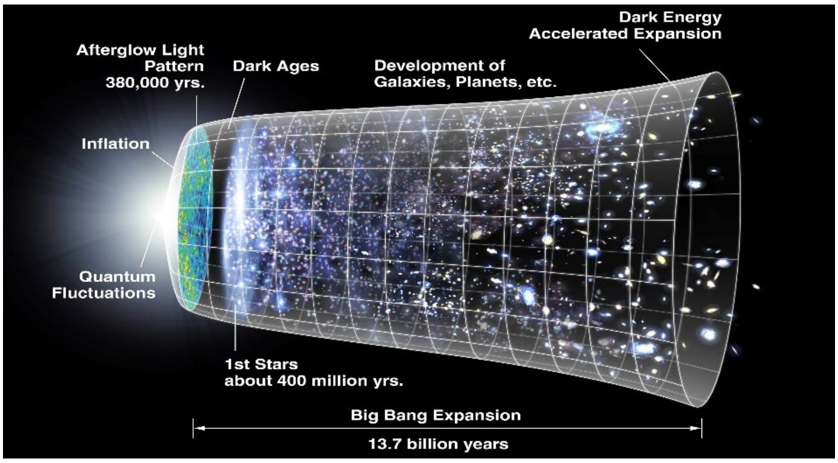

Figure 4: Expansion of Universe from point of the Big Bang (NASA n.d.)

Hubble's Law (see Eq. 3) allows scientists to estimate the distance to faraway galaxies and explain a fundamental relationship in the expansion of the universe. Hubble’s Law states that the recessional velocity (that is, the speed at which two galaxies are moving away from each other) is equivalent to the distance between those two galaxies (Lohar, 2023). In other words, the farther away two distant galaxies are, the faster they move away from each other. This linear relationship is expressed as an equation (see Eq. 3) and diagrammatically (see fig. 5) below.

$$v = H_0 d$$

$\boldsymbol{v}$ *is the recessional velocity, measured in kilometres per second* $(Km\ s^{-1})$
$\boldsymbol{H_0}$ *is Hubble's constant and is* $70\ (km\ s^{-1})/(Mpc^{-1})$
$\boldsymbol{d}$ *is the distance between the galaxies, measured in megaparsec* (Mpc)

Equation 3: Hubble’s Law (Lohar, 2023)

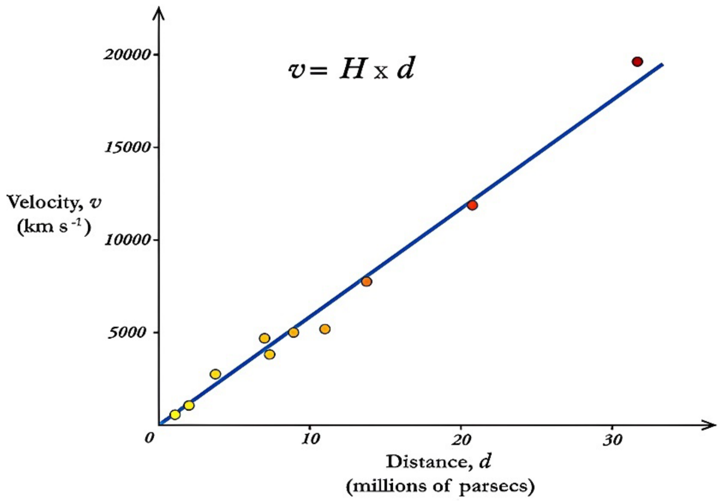

Figure 5: The velocity – distance relation or Hubble law diagram (Pixels, 2018)

By using Hubble's constant, one can directly trace the reciprocal to acquire the approximate age of the Universe or the birth of the Universe. At the birth of the Universe, or at the moment of the 'Big Bang', as the universe expanded, it left traces of radiation which filled the universe. The 'Big Bang' theory predicted that this microwave radiation should still exist. Scientists have now detected this Cosmic Microwave Background Radiation (CMBR) using highly accurate orbiting detectors (School Observatory, 2023). This radiation is living evidence of the expansion of the universe, because of the uniform temperature, which was a characteristic expected of radiation created in the early universe.

Conclusion

This paper introduced the concept of the redshift effect, distinguishing it from the Doppler effect and the Doppler shift. It then presented how distances to distant galaxies can be measured using redshift. Redshift is used to determine distances to the furthest cosmic objects in our Universe. Until the discovery of the redshift effect, scientists were only able to observe and study our own Milky Way. The cosmological redshift enabled the discovery of new galaxies and exoplanets that are not visible to the naked eye. It has also supported a new understanding of the universe as an ever-expanding domain, supporting many of the propositions of the Big Bang theory and stretching the very fabric of our Universe. Our understanding of the cosmological redshift has allowed scientists to boldly make assumptions about the origin of the Universe and then go out looking for evidence supporting these assumptions. The discovery of CMBR was one such moment when developments in science and technology proved one such assumption right– further supporting the notion of an expanding Universe.

We still stand on the surface of our tiny rock but now possess knowledge of not just the furthest celestial objects, but also of a Universe less foreign – thanks to the discovery of the redshift effect.

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Bibliography

1. Canetti, L, Drewes, M & Shaposhnikov, M 2012, ‘Matter and antimatter in the universe’, *New Journal of Physics*, vol. 14, no. 9, p. 095012.

2. Choi, CQ & Harvey, A 2017, *Our Expanding Universe: Age, History & Other Facts*, Space.com, Space.com, viewed 12 June 2024, <https://www.space.com/52-the-expanding-universe-from-the-big-bang-to-today.html>.

3. Cox, L 2021, *Who Invented the Telescope?*, Space.com, viewed 12 June 2024, <https://www.space.com/21950-who-invented-the-telescope.html#section-exploring-the-cosmos.>.

4. European Space Agency 2022, Astronomy & Astrophysics 101: *What Is ‘Redshift?’*, SciTechDaily, viewed 12 June 2024, <https://scitechdaily.com/astronomy-astrophysics-101-what-is-redshift/>.

5. Geach, J 2020, *Five Photons*, Reaktion Books.

6. Hirshfeld, A 2020, *Introduction to Stars and Planets*, *IOP Publishing Ltd eBooks*, IOP Publishing.

7. Hustak, L 2021, *Relationship Between Color, Wavelength, and Energy*, WebbTelescope.org, viewed 12 June 2024, <https://webbtelescope.org/contents/media/images/01F8GF6NH5PTXGBVNVHR2TSQRB>

8. Las Cumbres Observatory 2023, *Redshift | Las Cumbres Observatory*, lco.global, viewed 12 June 2024, <https://lco.global/spacebook/light/redshift/>.

9. Lohar, D 2023, *Expansion of the Universe | What is the relationship between the Doppler effect, Hubble’s law, redshift, and cosmic microwave background radiation in supporting the Big Bang Theory?*, Elucidate Education, viewed 12 June 2024, <https://www.elucidate.org.au/content/expansion-of-the-universe>.

10. Lowell 2012, *Origins of the Expanding Universe 1912-1932*, www2.lowell.edu, viewed 12 June 2024, <http://www2.lowell.edu/workshops/slipher/>.

11. NASA 2022, *Spectroscopy 101 – Introduction*, WebbTelescope.org, www.webbtelescope.org, viewed 29 June 2024, <https://webbtelescope.org/contents/articles/spectroscopy-101--introduction>.

12. NASA 2010, *Visible Light - NASA Science*, science.nasa.gov, NASA, viewed 12 June 2024, <https://science.nasa.gov/ems/09_visiblelight/>.

13. NASA 2020, *Measuring the Universe’s Expansion Rate*, HubbleSite, viewed 12 June 2024, <https://hubblesite.org/mission-and-telescope/hubble-30th-anniversary/hubbles-exciting-universe/measuring-the-universes-expansion-rate>.

14. NASA 2022, *Roman Space Telescope Redshift Infographic*, NASA Scientific Visualization Studio, viewed 12 June 2024, <https://svs.gsfc.nasa.gov/14107/>.

15. NASA n.d., *Why the Roman Space Telescope,* science.nasa.gov, viewed 12 June 2024, <https://science.nasa.gov/mission/roman-space-telescope/why-the-roman-space-telescope/>.

16. Nassau, K 2019, *Color: Definition, Perception, Types, & Facts*, *Encyclopædia Britannica*, viewed 12 June 2024, <https://www.britannica.com/science/color>.

17. National Schools' Observatory 2019, *Evidence for the Big Bang*, Schoolsobservatory.org, viewed 12 June 2024, <https://www.schoolsobservatory.org/learn/astro/cosmos/bigbang/bb_evid>.

18. Nordica, S 2019, *Einstein's Field Equations of General Relativity*, Stellan Kinberg, viewed 12 June 2024, <http://www.kinberg.net/wordpress/stellan/einsteins-field-equations-of-general-relativity/>.

19. PBS 2019, *A Science Odyssey: People and Discoveries: Hubble finds proof that the universe is expanding*, Pbs.org, viewed 12 June 2024, <https://www.pbs.org/wgbh/aso/databank/entries/dp29hu.html>.

20. Science Photo Library 2018, *Hubble's Law Graph by Science Photo Library*, Pixels, viewed 12 June 2024, <https://pixels.com/featured/hubbles-law-graph-science-photo-library.html>.

21. The Editors of Encyclopedia Britannica 2017, *Expanding universe*, *Encyclopædia Britannica*, viewed 12 June 2024, <https://www.britannica.com/science/expanding-universe>.