# Relativistic universe: expansion *in* the space or *of* the space?

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The relativistic universe is the universe described by Albert Einstein's General Relativity Theory (GRT) (see [1]). In the majority of the relativistic models, the universe is expanding. And it is here that the title's question makes sense: are galaxies expanding *in* space, i.e., it is a kinematic expansion, or are galaxies, in a way, "carried along" by the expansion *of* space? This has been discussed elsewhere [2] and, as it can be seen, the answer to this question is not simple.

But the most common formulation of relativistic models is the one in which the space itself is expanding, and the galaxies are moving away from each other due to the increase of the existing space amongst them. On the other hand, I will show that, for the local universe, that is, for distances smaller than about 500 Mpc ($\approx$ 1.5 billion light-years), the expansion of space is *mathematically* indistinguishable from the expansion in space.

Before that, however, we will discuss some topics that will help on achieving that goal.

Superimposed upon the expansion of space, the galaxies, and the stars in the galaxies, also realize motions, which are independent of the expansion of the universe. These motions — these kinematic effects — can be measured through the analysis of the light emitted by those objects. We will discuss the foundation of such analysis, which is the *Doppler effect.* After that we will treat the expansion of the local universe using as guides the critical Friedmann relativistic model and the observational work of the astronomer

Edwin Hubble. I will use, then, a very clarifying image, devised by the cosmologist Edward Harrison [3], in order to show the inherent complications of the observation of redshifts in cosmology, namely, a ballet. I will finish with some general remarks.

## Doppler shift

The Doppler shift, or displacement, is an effect that happens when a source of radiation and the observer move one with respect to the other. The observed wavelength will be different from the emitted wavelength of the — sound or electromagnetic — radiation.

The case we are interested in is of a source of electromagnetic radiation — a star or a galaxy — that moves with velocity $v$, approaching or moving away from the observer. In this case, if the source emits a radiation whose wavelength as measured at the laboratory, i.e., with $v = 0$, is $\lambda_\circ$, then the observer will detect a wavelength $\lambda$. If the source is moving away ($v > 0$), $\lambda$ will be *larger* than $\lambda_\circ$, that is, $\lambda_\circ$, will be shifted, or displaced, in the direction of the red, in the case of a visible spectrum. In the opposite case ($v < 0$, source approaching), $\lambda_\circ$ will be observed with a smaller wavelength, therefore, shifted in the direction of the blue. The relative spectral shift $(\lambda - \lambda_\circ)/\lambda_\circ$ is given by:

$$\Delta\lambda/\lambda_\circ = v/c,$$

where $\Delta\lambda = \lambda - \lambda_\circ$, $v$ is the source velocity and $c$ is the speed of light in vacuum. In general, especially in cosmology, the relative spectral shift $\Delta\lambda/\lambda_\circ$ is represented by the letter $z$. The Doppler effect may be then written simply as $z = v/c$, or

$$v = zc.$$

Next I will present two examples of application of the Doppler effect.

The first one is a binary star system. In the figure below, just paying attention to one of the stars, we see that while it moves, the light it emits shifts either to the blue or to the red, thereby exposing its orbital motion.

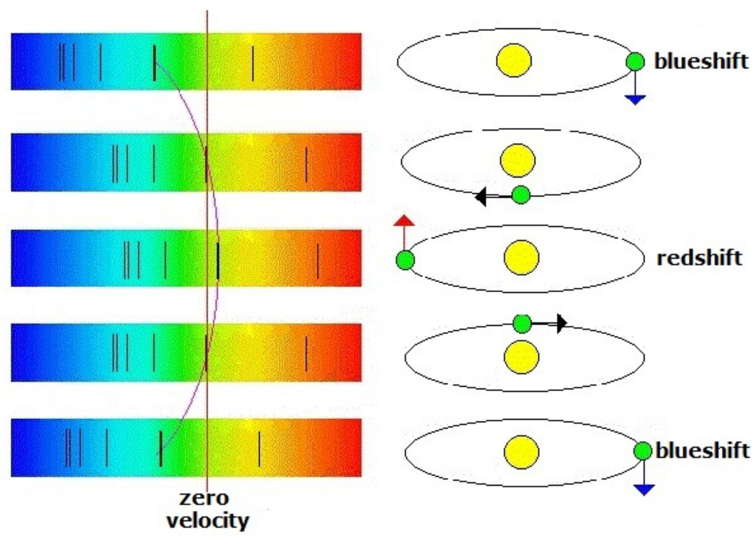


Figure 1: Schematic binary star system where the orbital motion of the secondary star (the smaller star) is highlighted. The side bar represents the visible spectrum, from blue ($\lambda$=400 nm, outermost left) to red ($\lambda$=700 nm, outermost right). The vertical black segments represent the absorption spectral lines produced in the secondary atmosphere. When the secondary approaches the observer, the spectral lines shift towards the blue. When its motion crosses the line of sight, the spectrum does not exhibit Doppler shift, and when it moves away the spectrum shifts to the red region of wavelengths.

But attention, there is a detail that needs to be corrected in the figure. Actually, the *separations* between the lines of the absorption spectrum displaced to the red or to the blue do not stay the same as in the zero velocity spectrum. This happens because the *absolute* Doppler shift $\Delta\lambda$ is proportional to the laboratory wavelength $\lambda_\circ$, i.e., $\Delta\lambda = \lambda_\circ v/c$. The line with the smaller $\lambda_\circ$ will have a smaller $\Delta\lambda$ and the one with the larger $\lambda_\circ$ will have a larger $\Delta\lambda$.

The second example is the rotation of a spiral galaxy. The Triangulum galaxy, so called because it is located on the Triangulum constellation, is one of the largest of the Local Group. The figure below shows the emission of radio waves by the atomic hydrogen that exists spread all over the galaxy and even beyond its optical limits. Spiral galaxies are galaxies with disc symmetry and spin around their centers. When spinning, one part of the galaxy approach us and the other moves away. The atomic hydrogen is observed through a spectral line, with wavelength of 21 cm, in the frequency of 1420.4 MHz. This line shifts to the red in the regions of the galaxy that move away from us, and to the blue in the regions that approach us. Note that the terms "red" and "blue" are used here, even if we are not dealing with visible light, and that is so by convention, for any spectral range in investigation.

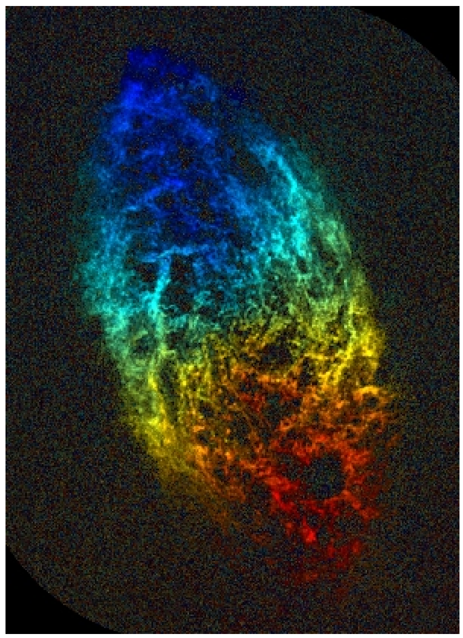

Figure 2: Atomic hydrogen emission in M33, the Triangulum galaxy, the 3$^{\text{rd}}$ largest galaxy in the Local Group (cf. [4]). The emission is coded in blue for blueshift and in red for redshift, in order to show the velocity field of the galaxy. Thus, the Doppler shifts indicate the rotation of the galaxy about its center (National Radio Astronomy Observatory, United States, 1998).

**Expansion of the local universe**

To the study of the local universe I will use the most simple Friedmann relativistic model, namely, the critical model. This model is also known as the *Einstein-de Sitter model*. The Friedmann critical model has a matter density exactly equal to the critical cosmological density. The universe has flat spatial geometry — the space on large scale is Euclidean — and is, as the other Friedmann models, in decelerated expansion (some aspects of Friedmann models are discussed by me and Arthur Viglioni in [5]).

The expansion of space in the critical Friedmann model is given by [3, eq. 15.30]:

$$v = 2c\left[1 - (1+z)^{-1/2}\right],$$

where $z \equiv \Delta\lambda/\lambda_\circ$ is called, in this case, *cosmological* redshift, since it is not related to the motion of the source, that is, it is not the result of a Doppler effect. This velocity is the expansion velocity, at the position of the emitting galaxy, at the time that the light is detected by the observer on Earth. In the expression, the larger the $z$, the larger the expansion velocity. Note that $v$ can be larger than $c$, reaching a maximum equal to $2c$ (see more details in [6], especially its Fig. 2). It is worthwhile point out also that the expansion velocity at the time that the light is emitted [3, eq. 15.31] is different from the velocity of expansion *at the time of detection*. Both, however, converge to the same $v(z)$ in the local universe. And more, the velocity of expansion of space on a *given* cosmic time is different on different points of space; in the local universe the velocity of expansion is given by Hubble's law.

The increase of $z$ happens because of the increase in $\lambda$. The wavelength, by its turn, increases because, during the time of travel of the radiation from the galaxy to the observer, the space between the galaxy and the observer increases resulting in a corresponding increase in $\lambda$. That is, the more distant the galaxy, the light travels during more time, and $z$ will be larger. The distant universe will be characterized, then, by large values of $z$ and the local universe by very small values of $z$, i.e., by $z \ll 1$.

We can use an approximation for $(1+z)^{-1/2}$, that appears in $v(z)$ above, with the help of the binomial expansion:

$$(1+z)^n = 1 + nz/1! + n(n-1)z^2/2! + ...$$

For $z \ll 1$, it suffices to take the two first terms of the series, with $n = -1/2$, and we have

$$v \cong 2c\left[1 - (1 - z/2)\right],$$

$$v = zc,$$

which is the same expression for the Doppler shift seen before, in first order approximation. In other words, *the expansion of the local space is mathematically indistinguishable from the motion of the galaxies in this same space.*

The next figure is based on a illustration made by Edwin Hubble himself. The galaxy velocities are calculated with $v = cz (z \equiv \Delta\lambda/\lambda_\circ)$, which can be interpreted both as the result of a *space* cosmological expansion and as the result of a local *kinematic* cosmological expansion.

Paradoxically, Hubble did not believe in neither of the two possibilities, but that the existence of $z$, for distant galaxies, was the indication of a new phenomenon of nature (further details on this in [6, 7]). The data of the figure result in a linear relation between velocity and distance, the famous *Hubble's law* for the local universe.

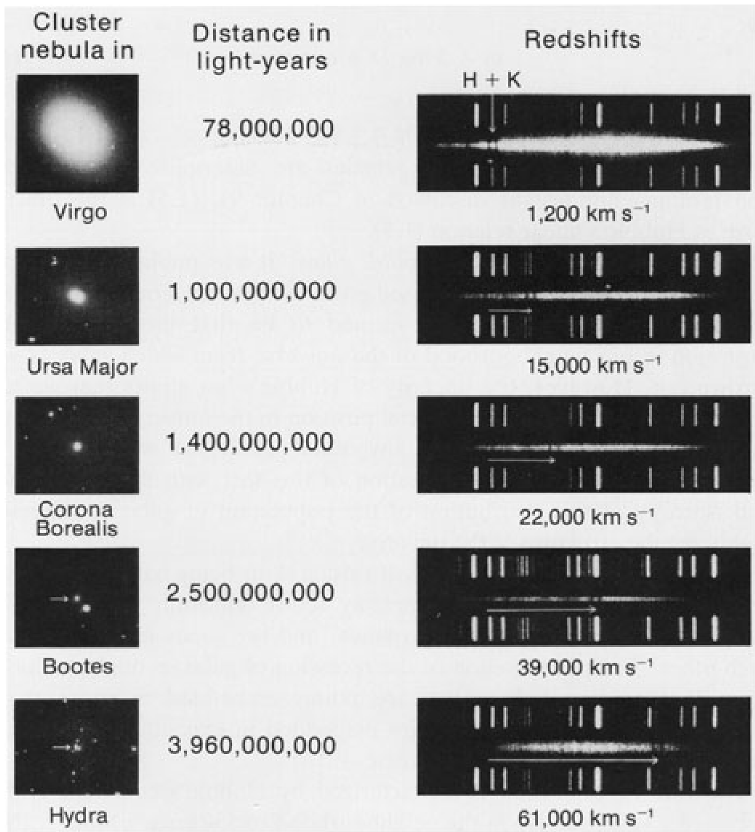


Figure 3: Redshifts and distances for the brightest galaxies in clusters. The white arrows on the central parts of the spectra indicate the redshifts of the H (396,8 nm) and K (393,4 nm) absorption lines of the atomic element calcium. Distances based in a Hubble constant $H_\circ = 50$ km $s^{-1}$ $Mpc^{-1}$ (Palomar Observatory, United States, 1983).

### Harrison's *ballet of redshifts*

There are additional complications, which must be considered when analyzing the spectra of distant galaxies. On page 308 of his *Cosmology* [3], Edward Harrison creates a very interesting picture for the redshifts observed in modern astrophysics. The light detected by our telescopes is affected by three types of redshifts, which realize an actual dance of $\Delta\lambda$s to complicate the analysis of the observations. They are:

- cosmological redshift: presumably caused, in relativistic cosmologies, by the expansion of cosmic space. There are relativistic models in contraction, and in this case the shift is to the blue; this can happen, for example, in the closed Friedmann model. Alternatively, the cosmological shift may be caused by a new phenomenon of nature.

- Doppler redshift: caused by the intrinsic motions of the galaxies. It can be a blueshift as well. Here, both the motions of the radiation emitter and of the detector must be considered. For example, the Earth — where the detector is located — has an intrinsic rotation and moves around the Sun; the Sun moves around the galactic center; the Milky Way moves in the Local Group and the latter moves in the Virgo cluster of galaxies; the Virgo cluster of galaxies moves, by its turn, in the Local Supercluster (see [8]). All of these motions of the observer must be removed in order to get the cosmological shift.

- gravitational redshift: relativistic effect discovered by Einstein, which occurs when the light runs across a variable gravitational field, or, in the GRT language, a curved space-time. This is, in general, the smaller of the three. It can be a blueshift as well. The radiation suffers a redshift when it leaves the emitting galaxy and a blueshift when it enters the Milky Way and reaches the observer on Earth. These shifts are, usually, negligible against the other two. According to Harrison, the light that enters the Milky Way and reaches the Earth surface has a blueshift equal to 0.001 ($\Delta\lambda/\lambda_\circ = -0.001$).

The separation of the three effects in the observed light is a complex task, and considerations about the physical details of the problem must be carefully used. For the local universe, the contamination by the other shifts is more severe because, as we saw, the cosmological shift is small.

According to what was described above about the three shifts, it may be reasonable to generalize Harrison's ballet, and talk about a "ballet of spectral shifts", because the shifts may be both to the red and to the blue.

## Final remarks

The expansion of the relativistic universe must be seen with caution. In the local universe, it can be described by the phenomenology of the Doppler effect. For large redshifts, i.e., $z$ larger than approximately 0.1, this does not work anymore, and the expressions for $v(z)$ of each specific relativistic model must be used.

In the context of the discussion about the expanding universe, we have a great paradox. Hubble, considered as the discoverer of the expanding universe, did not believe in this hypothesis. The reason for that highlights the great scientist he was. Hubble did not believe it especially because, in his time, the hypothesis of the expansion led to an age of the universe much smaller than the geological age of the Earth. The Hubble constant was yet ill-determined and, as we know, the age of the relativistic universe is proportional to the inverse of this parameter. That is, to Hubble the theory must pass the confirmation — which is definitive — of the observational evidences.

Nowadays there are problems much greater than the age problem. That is to say, the age problem was "solved" at the expenses of the introduction of innumerable new unknowns (dark baryonic matter, dark non baryonic matter, dark energy, etc.). Certainly Hubble would not accept so many unproved hypothesis and still would prefer to believe that the effect observed on galaxy spectra could be due to a new phenomenon of nature yet to be uncovered.

We must, now, answer the question posed in the title: expansion *in* or *of* the space? Two "ifs". If the expansion exists and if it is described by the relativistic models, the expansion is of the space in the majority of the relativistic formulations. However, appropriate choice of cosmological coordinate systems can substitute expansion of the space by expansion in the space (cf. [2]). In the local universe, the expansion of the space is *mathematically* indistinguishable of the expansion in the space, described by the simple Doppler effect. But, *physically*, it is still an expansion of the space.

And in conclusion, another very relevant question: *why simply do not accept the spectral shifts of the distant galaxies as the results of Doppler shifts, and therefore, as indicators of a generalized motion of recession, i.e., of expansion in the space?*

The answer is simple. Because there are no real and convincing subsidiary observational indications that such spectral shifts be Doppler. Let us see the example of the binary stars. With them, the spectral shifts are Doppler, that is, indicators of motion, because there are physical evidences for that; it is known indeed that pairs of stars exist in mutual orbits, inclusive proved by visual observations; the symmetry of the temporal variation of the spectral shifts clearly points to an orbital motion. In another example, of the rotation of disc galaxies, there are also subsidiary physical evidences. The symmetry of the spatial distribution of the spectral shifts conforms to a simple model of rotation of the disc; the rotation so obtained serves to the calculation of the masses of the galaxies leading to results that are consistent with other methods.

Now, the fundamental subsidiary physical evidences for the spectral shifts of distant galaxies are mere unproved *ad hoc* hypotheses, such as the existence of dark — i.e., unobservable — components of baryonic and non baryonic matter and the existence of a diffuse component of dark *energy*, just to mention two of the main ones. These hypotheses are necessary for the interpretation of the spectral shifts as originating from the motion of expansion in the space be viable. The putative expansion and the theoretical age of the universe are not compatible without these dark components, because one gets a universe that is younger than its constituents, namely, the stars and the planets.

In other words, we have strong reasons to doubt the expansion of the universe, be *in*, be *of* the space.

Furthermore, *data venia*, it is rather insignificant — esthetically and philosophically — the very idea of a cosmic expansion. But we should not leave that aesthetics and philosophy or our personal preferences be above Science and its behavioral prescriptions. Let us remain with the greatest scientist of mankind, Isaac Newton, that somewhere in Book III of the *Principia* writes: *"We are certainly not to relinquish the evidence of experiments for the sake of dreams and vain fictions of our own devising"*.

# References

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