A short answer to critics
of our article “Eppur si esplode”

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Abstract

Recently we presented a formal mathematical proof that, contrary to a widespread misconception, cosmological expansion cannot be understood as the motion of galaxies in non-expanding space. We showed that the cosmological redshift must be physically interpreted as the expansion of space. Although our proof was generally accepted, a few authors disagreed. We rebut their criticism in this Note.

1 The essence of our proof

Our claim:

(A) We remark that the concept of “space” (in the sense of a 3D submanifold) is not a well-defined (invariant) concept in Einstein’s general relativity. Therefore the meaning of “expansion of space” is indeed ambiguous. However, one can define “non-expanding space”: as hypersurface in stationary spacetime, i.e. spacetime equipped with a timelike Killing vector.

(B) The question of whether the observed cosmological redshift (given by the Friedmann-Lemaître-Robertson-Walker metric; hereafter FLRW) can be distinguished from a purely kinematic Doppler effect resulting from the motion of particles (galaxies) in stationary spacetime, has an invariant answer. This answer is therefore independent of observers, coordinates, or conformal factors.

(C) Combined measurements of redshift and radar distance uniquely distinguish between real cosmological expansion and the hypothetical motion of galaxies in stationary spacetime. The reason for this is illustrated in Figure 1.
Figure 1: Radar measurement of distance. The light trajectories reveal different spacetime structures in the case of non-expanding and expanding space. Obviously, this difference will show up in simultaneous measurements of the redshift and distance. Thus measuring the redshift and distance allows to establish whether or not space is really expanding.
2 The criticism and its rebuttal

The criticism of our arguments is best summarized by Lewis et al. in [6]. We quote them here in their original wording, and then present our rebuttal.

2.1 Rebuttal of the 1st point raised by Lewis et al.

“Recently, Abramowicz et al. considered in [1] radar ranging of a distant galaxy in expanding cosmologies and concluded that the fact that the radar and Hubble distance, from \( d = \frac{v}{H_0} \), differ in all but an empty universe, that space must really expand. In a counter argument, [3] again considers radar ranging in open cosmological models. Instead of examining distances, he focuses upon the transit time of light in usual cosmological coordinates and its conformal representation. With this he reveals that in the former coordinates the paths are asymmetrical in transit time, taking longer on the return journey, whereas in conformal coordinates, the light travel times to and from the distant galaxy are equal. Hence, he concludes that the expansion of space is a coordinate dependent effect which can be made to disappear with the correct coordinate transform, and therefore the expansion of space is not a physical phenomenon.”

Rebuttal: The argument by Chodorowski in [3] unfortunately misses the whole point. Our invariant statement is based on a gedanken experiment, in which a fundamental observer measures the interval of his proper time between two events and a redshift. These measurements are independent of coordinate or conformal representations. Chodorowski instead discusses a different problem: of “the transit time of light in usual cosmological coordinates and its conformal representation”. Here the answer is obviously coordinate-dependent, but the problem is by no means equivalent to our invariantly defined gedanken experiment.

2.2 Rebuttal of the 2nd point raised by Lewis et al.

“In their recent work, Abramowicz et al. showed that, in all but an empty universe, distances derived from the Hubble law and radar ranging differ and hence one must conclude that space is expanding. But how is this difference occurring? Is the expansion of space acting on a light ray (or even a rocketeer) as they travel through the universe? We can think of space as a rubber sheet that stretches to wash out peculiar motions and drives everything back into the Hubble flow (see [2]). However, it is the presence of matter that necessitates the inclusion of gravitational forces upon the motion of the rocketeers and it is this - the changing gravitational influence of matter in the universe on the rocketeers - that causes the increasing asymmetry moving down the panels in Figure 1 not that space physically expands.”

Rebuttal: The measurements of redshift and proper time interval for receiving the radar echo that we discussed in [1] depend directly on the spacetime geometry. We considered in [1] two reference metrics: the standard FLRW
cosmological metric (1) and the Minkowski metric (2),

\[
\begin{align*}
\text{(1)} & \quad ds^2 = dt^2 - R^2(t) \left[ dr^2 + r^2(d\theta^2 + \sin^2 \theta d\phi^2) \right], \\
\text{(2)} & \quad ds^2 = dt^2 - \left[ dr^2 + r^2(d\theta^2 + \sin^2 \theta d\phi^2) \right].
\end{align*}
\]

Because the geometry in (1) and (2) is fixed, the measurements that we consider depend neither on field equations nor on matter distribution.

Ellis and collaborators [4, 5], playing devil’s advocates, considered a model of a non-expanding Universe, assuming a static spherically–symmetric (SSS) metric,

\[
\text{(3)} \quad ds^2 = G^2(r) dt^2 - \left[ dr^2 + F^2(r)(d\theta^2 + \sin^2 \theta d\phi^2) \right].
\]

There is obviously no expansion of space in the SSS Universe. The observed cosmological redshift-magnitude \((z, m)\) relation is explained as a purely gravitational effect. The price to pay is high: not only is the SSS Universe spatially inhomogenous, but in addition one must assume that we live near its center, and that at the antipodal location there should be a static fireball that mimics the Big Bang.

Notice that the gedanken experiment we consider in [1] would immediately rebut the SSS model, since it shows that radar-measured distances to galaxies do not increase with time.

Some people might perhaps be willing to pay the high price mentioned above in order to avoid the “expansion of space” alternative (the hostility to which eludes our understanding), and consider the motion of galaxies in the non-expanding space described by the metric (3). Even in this case, a coordinate–independent experiment can distinguish between the true expansion (also of space) that is consistent with the FLRW metric (1) and its kinematic imitation consistent with the non-expanding space in (3).

Following [4], we leave demonstrating this as an exercise for the reader.

2.3 Rebuttal of the 3rd point raised by Lewis et al.

“In closing, we state that it is a fools errand to search for the truth of the existance of expanding space; not only because it is dependant upon a choice of coordinates, but also because general relativity is represented by Newtonian physics in the weak field limit and the global behaviour of the FLRW metric always reduces to Newtonian gravity in the limit of the local universe with no need for expanding space. While the expansion of space is a valid (but dangerous picture when working with the equations of relativity), any attempts to obtain observations to address the question of whether galaxies are moving through static space or are carried away by the expansion of space are doomed to failure.”

Rebuttal: The above statement that “general relativity is represented by Newtonian physics in the weak field limit and the global behaviour of the FLRW metric always reduces to Newtonian gravity in the limit of the local universe with no need for expanding space” is not an argument against the expansion of space. Newton’s gravity is a mathematical approximation to Einstein’s theory.
but is *conceptually* totally different. Indeed, the consistent and coherent description of the situation here is this: according to Einstein’s theory, cosmological space expands. As we argued in [1], the expansion of space implies a non-zero curvature of spacetime. At small distances, Newtonian theory should give a correct description of the physical situation. The only way to describe non-zero curvature in Newton’s theory is through gravitational potential. Thus gravitational potential should also provide a way of describing the physical effects of the expansion of space in Newton’s theory, with non–expanding space. Indeed, as explained by Bondi (see e.g. [7]), to second order, it is indeed correct to think of the cosmological redshift as a combination of Doppler and gravitational redshifts in Newton’s physics.

3 Final statement

Although the concept of space is not well defined in Einstein’s relativity, one can prove, as we did in [1], that the statement that the cosmological redshift may be described as a Doppler effect in non-expanding space is *false*. Eppur si espande.

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