Expanding Confusion: common misconceptions of cosmological horizons and the superluminal expansion of the universe

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Abstract

- They use standard GR to illustrate and clarify common misconceptions about the expansion of the universe.
- They point out confusions regarding: the particle horizon, the event horizon, the "observable universe" and the Hubble sphere.
- They show that we can observe galaxies that have recession velocities greater than c.
- Recession velocity, from Hubbles law: $v_{rec} = H \times D$, H = Hubble constant, D = distance.
- They rule out the special relativistic Doppler interpretation of cosmological redshifts by studying supernovae.

1 Introduction

- GR interpretation of redshift of galaxies → expansion of universe, widely accepted.
- Many texts addressing the expansion of the universe contain misleading statements concerning recession velocities, horizons and the "observable universe."
- Most common misconception: expansion of universe at distances where Hubble's law predict recession velocities $> c$.

2 Standard GR description of expansion

- This paper: standard GR of expanding homogeneous, isotropic (same in all directions) universe. ΛCDM with $(\Omega_M, \Omega_\Lambda) = (0.3, 0.7)$, $H_0 = 70\,\mathrm{km\,s^{-1}Mpc^{-1}}$.
- Figure: Spacetime diagrams
- Particle horizon: the distance light can have travelled from $t = 0$ to a given time t. Marks the size of our observable universe = the distance to the most distant object we can see at any particular time. The particle horizon can be larger than the event horizon (we cannot se events that occur beyond our event horizon, but we can see galaxies that are beyond our current event horizon by light they emitted long ago). The photons we receive with infinite redshift were emitted by objects on our particle horizon.
- Event horizon: the distance light can travel from a given time t to $t = \infty$. Galaxies with $z \sim 1.8$ are currently crossing our event horizon = the most distant objects from which we will ever be able to receive information about the present day. All galaxies become increasingly redshifted as we watch them approach the cosmical event horizon. As the end of the universe approaches, all objects that are not gravitationally bound to us will be redshifted out of detectability.

- Hubble sphere: the distance beyond which the recession velocity exceeds the speed of light. The Hubble sphere is NOT a horizon → redshift does not to infinity at sphere, for many models we can see beyond it: ΛCDM concordance model, all objects with $z > 1.46$ are receding faster than c.

3 Misconceptions

3.1 Misconceptions #1: Recession velocities cannot exceed the speed of light

- Common misconception: the expansion of the universe can not exceed the speed of light.
- Sometimes stated that Hubble's law therefore need special relativistic corrections at large distances ($v_{rec} \rightarrow c$).
- We need GR in general to describe cosmological observations, not SR.
- No contradiction in SR when $v > c$ occurs outside the observer's inertial frame. A galaxy moving away from us with $v > c$ are at rest locally, so that is fine. The galaxies are not catching up with photons! Both the galaxies and photons are receding with $v > c$.
- The velocity is due to the rate of expansion of space, not movement through space: it can NOT be calculated with the SR Doppler shift formula. We can not just apply SR corrections to redshift.
- GR redshift is a function of time. We must decide at which epoch we wish to calculate the recession velocity of the object we are observing.
- SR incorrectly describes cosmological redshifts, but has been been used for a long time. It has the low redshift approcimation $v = cz$. GR has that too, but it is only recently that observations have been deep enough that it makes a difference.
- Recession velocities exceed c in all viable cosmological models for $z > 1.5$.
- Figure 2: velocity as a function of redshift for SR, low redshift approx and a range of Friedmann-Robertson-Walker models. Same for small z, but is quite different for larger z!

3.2 Misconceptions #2: Inflation causes superluminal expansion of the universe, but the normal expansion of the universe does not

- Inflation is often described as the time of superluminal expansion, indicating that that time is now over. That is not true, as space still expands faster than the speed of light outside the Hubble sphere.
- During inflation, objects inside the Hubble sphere did not recede with a velocity larger than c, the thing is just that the Hubble constant during that time was so large that the distance to the Hubble sphere was really small.
- When we say that objects leave the horizon during inflation, it means that they became larger than the Hubble sphere. Later the objects may reenter the horizon, once inflation is over.
- If the Hubble constant was so large that space was expanding faster than c at distances down to the Planck length, it would be more appropriate to address the time of inflation as superluminal expansion.

3.3 Misconceptions #3: Galaxies with recession velocities exceeding the speed of light exist, but we cannot see them

- Misconception: objects with a recession velocity larger that c can not be observed.

- Objects outside the hubble horizon recede with $v > c$, photons travel towards us with c, and the total velocity of the photons is then away from us.
- However, the Hubble sphere also recedes. As long as it recedes faster that the photons immediately outside it, the photons end up in a subluminal region and will approach us.
- galaxies beyond z=1.46 are receding faster than the speed of light, and many of these have been observed, so obviously we can see them.
- It is the particle horizon, not the Hubble sphere, that determines the size of our observable universe.
- When the expansion of space is exponential, we can not observe anything outside the Hubble sphere (it becomes our event horizon.)

3.4 Ambiguity: The depiction of particle horizons on space-time diagrams

- Particle horizon at any particular time: sphere around us with r = distance to the most distant object we can see.
- Traditionally: the particle horizon is depicted as the worldline of the most distant particle we have ever been able to see. This only gives the radius to the particle horizon, and the rest of the worldline can be misleading and does not represent a boundary between events we can and cannot see, or the distance to the particle horizon at different times.
- they propose: plot the distance to the particle horizon as a function of time in spacetime diagrams: Figure 3.

4 Observational evidence for the general relativistic interpretation of cosmological redshifts

4.1 Duration-redshift relation for type Ia supernovae

- They show that a specific observational test using type Ia supernovae can not distinguish between SR and GR expansion of the universe.
- In GR, events occurring on a receding emitter will be time dilated by a factor $\gamma_{GR}(z) = 1+z$. For emitter: Δt_0, for observer: $\Delta t = \gamma_{GR}\Delta t_0$.
- Since supernovae type Ia are convenient standard clocks, it can be used to test cosmological time dilation, and it can again be determined if cosmological redshifts are a result of the expanding universe. A bunch of people did this, and it is clear that a $\gamma = (1+z)$ time dilation is preferred to no time dilation.
- BUT does this test show that GR time dilation is preferred over SR time dilation as an explanation of cosmological redshifts? This is what they want to check (spoler alert, the answer is no).
- In SR they have the time dilation factor: $\gamma_{SR} \approx 1 + z^2/2$, which is different from the one in GR. However, this does not take into account that the distance to the emitter is increasing during the time that we measure the duration of the event. So, this requires an extra time dilation factor, which is 1+v/c, and in total we then again end up with the same dilation factor as in GR, $\Delta t = \Delta t_0(1+z)$. Figure 4.
- Conclusion: this kind of time dilation can not be used to distinguish between SR and GR expansion, even though it gives great evidence for expansion being a good explanation of cosmological redshifts.

4.2 Magnitude-redshift relationship for SNe Ia

- One observation that can distinguish between SR and GR expansion is the magnitude-redshift relation, where SNe Ia are used as standard candles. Figure 5.
- The section has some details telling how they calculated magnitudes and distances, but the actual results are shown in figure 5.
- SR is 23σ from the GR ΛCDM model, and the simple linear relation $v = cz$ is actually closer to the data points, but still 12σ away. The different lines matching better with the data points are GR with different cosmological parameters.

4.3 Future teste

- redshift of distant galaxies will change over time, as shown in equation (11). This variation is, however, small over human timescales, and will vary only $\Delta z \sim 10^{-8}$ in 100 years. At the time of the article the best redshift measurements are down to $\Delta z \sim 10^{-5}$. We need better technology to measure this, but this could help us directly measure the cosmological parameters.

5 Discussion

- They discuss the significance of actually understanding velocity and distance of objects, vs. just ignoring it and only focusing on redshift. However, they argue that the understanding of cosmological redshift itself is dependent upon the definition of expansion, which again means nothing if we choose to ignore distance and velocity.
- They then discuss why they have chosen proper distance and time to be the fundamental radial distance and time in their paper.
- Proper distance is chosen because it is the spatial geodesic measured along a hypersurface of constant cosmic time, while luminosity and angular-size distances parametrize radial distances, but are not geodesic distances along the 3D spatial manifold, and thus not relevant for calculating recession velocity.
- Proper time is chosen because it is the proper time of a comoving observer and the homogeneity of the universe is dependent on that choice of time coordinate. Time can be defined differently, but then we had to sacrifice the homogeneity of the universe and the synchronous proper time of comoving objects.

6 Conclusion

- Superluminal recession is a feature of all expanding cosmological models that are homogeneous and isotropic and does not contradict SR.
- The superluminal recession that occurred during inflation is the same as any other time period, the only difference is the size of the Hubble parameter.
- The Hubble sphere is not a horizon, and we observe galaxies with superluminal recession all the time.
- It is more informative to plot the particle horizon as a function of time in spacetime diagrams.
- They ruled out the SR interpretation of cosmological redshift by using magnitude-redshift data.
- All in all, the GR interpretation of the cosmological redshift is preferred over the SR one.

Appendix A: Standard general relativistic definitions of expansion and horizons

Gives all the definitions and standard calculations of a homogeneous, isotropic universe (Robertson-Walker metric).

Appendix B: Examples of misconceptions or early misinterpreted statements in the literature

A list of people getting it wrong.