CURVED SPACE, AND THE FATE OF THE COSMOS

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A QUESTION FOR DISCUSSION

• Using the tools and ideas you already know and/or you are all already familiar with, either from taking this course, or from external sources, come up with a hypothesis regarding the end of the universe (or, of only the earth if you have trouble coming up with something)
POSSIBLE OVERALL GEOMETRIES

- A Riemannian geometry: positive curvature (like a sphere/spheroid)
- Gauss-Lobachevsky hyperbolic: negative curvature (like a saddle or a funnel shape)
- Euclidean space: zero curvature (none, pancake)

\[ \Omega_0 = \Omega / \Omega_c \]

Image credit: NASA / WMAP science team / Gary Hinshaw.
FEATURES OF EACH POSSIBILITY

• **Positive**  Full extent of the universe unknown and likely unknowable in this case
  • Angles of a triangle add up to MORE THAN 180 degrees
  • Parallel lines CONVERGE eventually (but no “edge” exists)
  • The universe is UNBOUNDED but FINITE, circumnavigable

• **Negative**
  • Angles of a triangle add up to LESS THAN 180 degrees
  • Parallel lines DIVERGE
  • The universe is “more INFINITE” than it would be if flat (think how there are “more” real numbers than integers)

• **Zero**  Our very best data tell us that this one is most likely to be the correct answer
  • Angles add up to EXACTLY 180 degrees (old-school)
  • Parallel lines REMAIN PARALLEL forever
  • The universe is UNBOUNDED and INFINITE
If the universe is closed, light rays from opposite sides of a hot spot bend toward each other ...

If the universe is flat, light rays from opposite sides of a hot spot do not bend at all ...

If the universe is open, light rays from opposite sides of a hot spot bend away from each other ...

... and as a result, the hot spot appears to us to be larger than it actually is.

... and so the hot spot appears to us with its true size.

... and as a result, the hot spot appears to us to be smaller than it actually is.

Image credit: Smoot Cosmology Group / Lawrence Berkeley Labs.
THE CAUSES AND THE EFFECTS

• Positive
  • Cause: The average density $\Omega$ of matter/mass and energy in the universe is high, GREATER THAN a critical density $\Omega_c$, the value that makes space-time continuum perfectly flat
  • Effect: The universe is CLOSED. It can re-collapse

• Negative
  • Cause: The average density is low, LESS THAN critical
  • Effect: The universe is OPEN. It must keep expanding forever

• Zero
  • Cause: The density is PRESICELY EQUAL to critical
  • Effect: The universe is FLAT. It will keep expanding forever, but will slow down and stop after an “infinite time”

Density is the amount of stuff or number of things per unit of volume (3D space). For instance: 43 students per room, 100 bubbles per liter of soda
THROWING IN A MONKEY WRENCH

• All the previous points apply only if the universe is made solely of matter (atoms, neutrinos, etc.) and radiation (photons). Dark energy screws that up
  • Even a technically closed universe could expand eternally
• To understand why, we must first introduce the concept of the equation of state \( w = \frac{P}{\rho} \), where \( P \) is pressure (force per unit area) and \( \rho \) is the density
  • \( w = 0 \) for non-relativistic (cold, slow) matter (monopoles too), diluted as length cubed (volume) as universe expands
  • \( w = +\frac{1}{3} \) for relativistic (hot, fast) matter as well as radiation, which is diluted as length to the 4th power with expansion
  • \( w = -\frac{1}{3} \) for the intrinsic curvature of space-time (+ or -)
THE BEAST HATH MANY NAMES

• $w = -1$ for the “cosmological constant,” or the dark energy (energy of the vacuum of space itself). No dilution! Density remains the same during expansion.
  • Note it is the pressure (not density, impossibly) that is negative
  • Maybe same equation of state for the inflation after Big Bang
• $w > -1$ (but $< -1/3$) is weaker form of the dark energy (may be dynamic i.e. time-dependent: quintessence)
• $w < -1$ is speculative phantom dark energy, whose energy density counter-intuitively *grows* over time
  • The cosmic jerk: an accelerating acceleration! (3rd derivative)
• People will jokingly refer to it as the aether
• Repulsive, “anti-gravitational” in its behavior
POTENTIAL DOOMSDAY SCENARIOS

- Big Crunch (positive, closed), Big Chill (negative or zero, open or flat), and Big Rip (phantom energy)
- Dark energy or expanding universe in general can overcome local binding (matter held together with mutual attractive forces, gravity or others)
- If the universe expands too fast, the light horizon recedes (visible universe shrinks instead of growing)
  - Expansion of space is why spherical radius of visible universe is not directly related simply to the age of the universe
- If it contracts, there is no center of the collapse
OUR FUTURE HISTORY, IN BRIEF

• If we consider the Big Chill scenario (no official ‘end’)
  • 1 trillion ($10^{12}$) years from now: CMB too faint -- unobservable
  • 100 trillion ($10^{14}$): no more H, He for new stars to be born
  • $10^{24}$ years: end of stelliferous era. Only stellar remnants left (dwarfs, neutron stars, black holes). Degenerate era starts
  • $10^{36}$: proton decay (GUTs)
  • $10^{54}$: Only black holes are left
  • $10^{100}$: Even they “evaporate”
  • LATER: a quantum rebirth?

Should mention entropy: disorder keeps increasing
Image credit: NASA / Chandra X-ray observatory.
THE WEEKEND READING STACK

• Read essay “The Future of the Universe” by Hawking
• Beginning of book *Parallel Universes* by Fred Wolf (NOTE: Highly speculative. Take crazy ideas with salt)
• Cosmos - Carl Sagan - 4th Dimension – YouTube https://www.youtube.com/watch?v=xTL02N9EHzU
• Starting with “Living in Curved Space” p. 94 to end of http://www.albany.edu/physics/phy100/Chapter4TheSecretOfLight.pdf
• To clear up confusion: parallel universes and other dimensions are NOT the same thing; also, since we have come to know time as the 4th dimension, new spatial dimensions start being counted with the 5th