Cracking the Cosmic Code

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Ancient Cosmology: A Flat Earth

Here there be dragons!

Old Map of Hecataeus of Miletus (c. 500 BC)
Nuit, the goddess of the night, was in a tight embrace with her husband Sibû, the earth god. Then one day, the god Shû grabbed her and elevated her to [become] the sky despite the protests and painful squirming of Sibû. But Shû has no sympathy for him and freezes Sibû even as he is thrashing about. And so he remains to this day, his twisted pose generating the irregularities we see on the Earth's surface. Nuit is supported by her arms and legs which become the columns holding the sky.

The ancient Egyptians conceived the sky as a roof placed over the world supported by columns placed at the four cardinal points. The Earth was a flat rectangle, longer from north to south, whose surface bulges slightly and having the Nile as its center. On the south there was a river in the sky supported by mountains and on this river the sun god made his daily trip (this river was wide enough to allow the sun to vary its path as it is seen to do). The stars were suspended from the heavens by strong cables, but no apparent explanation was given for their movements.
The Ancient Hebrew Conception of the Universe

To Illustrate the Account of Creation and the Flood
Incan Cosmology
The Ancient Greeks recognized that the earth is round
Eratosthenes measures the Earth (c. 240 B.C.)

Measurements:
Syene to Alexandria
- distance ≈ 500 miles
- angle = 7°
i.e, 7/360 of the circumference
- circumference of the Earth: ≈ 25,000 miles

It was known long before Columbus that the Earth is not flat!
Antikythera mechanism (c. 90 BC)

(improved lunar cycle)

(months/year)

(Improved eclipse with location info)
Schools of thought

Aristotle: Earth at the center of a finite universe

Stoics: Earth at the center of an indefinite universe

Epicurus: Earth just one of many planets in an infinite universe

Aristarchus: recognized that the sun was larger than the earth, and that the earth orbited the sun. His original work does not survive and is only known from the criticism of others.
Stoic universe

Earth at the center surrounded by a finite volume of stars that trails off into an indefinite void.

OLBER's PARADOX
Aristotle argued that the universe had to be finite so that the dome of the sky could rise and set every day - it couldn’t go infinitely fast around the fixed earth.
Aristotle's picture of a central earth surrounded by a finite heavenly sphere was adapted by medieval theology.
Geocentric Cosmology

The most successful cosmology ever in terms of life span
Competing Cosmologies - the Copernican Revolution

**Geocentric**
- Ptolemaic
- Earth at center

**Heliocentric**
- Copernican
- Sun at center
Geocentric Cosmology

The most sophisticated geocentric model was that of Ptolemy (A.D. 100–170) — the Ptolemaic model:

- Sufficiently accurate to remain in use for 1,500 years
  - i.e., predicted correct positions of planets for many centuries
- Ptolemy sought but did not observe parallax, reasonably concluding that the earth did not move
Geocentric Cosmology

Inferior planets arbitrarily tied to earth-sun line

Movement of small circles upon larger circles explained retrograde motion.
Heliocentric Cosmology
Heliocentric Cosmology

Copernicus (1473–1543):

• He proposed the Sun-centered model (published 1543).
• He used the model to determine the layout of the solar system (planetary distances in AU).

But . . .

• The model was no more accurate than Ptolemaic model in predicting planetary positions, because it still used perfect circles.
Geocentric
Ptolemaic
Earth at center

Heliocentric
Copernican
Sun at center

The sun is the source of light in both models

**Explain**
- Motion of Sun
- Motion of Moon
- Solar and Lunar Eclipses
- Phases of Moon

**Predicts**
- No parallax
- Venus: crescent phase only

**Retrograde Motion**
Needs epicycles
Inferiority of Mercury & Venus
Must tie to sun

**Consequence of Lapping**
Interior to Earth’s Orbit
Phases of Venus

Geocentric

Only crescent phase
Size roughly constant

Heliocentric

All phases
Size varies
Phases of Venus first observed by Galileo

Phase and angular size of Venus depend on viewing angle as expected in the heliocentric cosmology.

\[ \alpha = 58^\circ \]

\[ \alpha = 42^\circ \]

\[ \alpha = 24^\circ \]

\[ \alpha = 15^\circ \]

\[ \alpha = 10^\circ \]
Kepler abandons purely circular orbits

“If I had believed that we could ignore these eight minutes [of arc], I would have patched up my hypothesis accordingly. But, since it was not permissible to ignore, those eight minutes pointed the road to a complete reformation in astronomy.”

Johannes Kepler (1571–1630)
Formulated the Universal Law of Gravity

Everything happens ... as if the force between two bodies is directly proportional to the product of their masses and inversely proportional to the square of the distance between them.
Bentley-Newton correspondence

Bentley: would not a finite assemblage of stars collapse from their mutual gravity?

Newton: if the matter was evenly diffused through an infinite space, it would never convene into one mass.

Bentley: can such a system remain stable?

Newton: such an assemblage, even if infinite, is like an array of needles standing upright on their points, ready to fall one way or another.

Newton: this frame of things could not always subsist without divine power to conserve it.

God actively intervenes to keep things in order.
Victorian Universe
Stoic-like with a vast Milky Way embedded in an indefinite void
“No competent thinker, with the whole of the available evidence before him, can now, it is safe to say, maintain any single nebula to be a star system of coordinate rank with the Milky Way. A practical certainty has been attained that the entire contents, stellar and nebular, of the sphere belong to one mighty aggregation...”

- Agnes Clerke (1890)

i.e., a Stoic picture: the universe might extend indefinitely to infinity, but the contents (though enormous) were finite.
Curtis-Shapley Debate
(the “Great Debate” - 1920)

Curtis

Shapley

The Milky Way is big; we are not near the center

The Milky Way is small; we happen to be near the center

Other nebulae are clouds of gas within the Milky Way

The spiral nebulae are “island universes” comparable to the Milky Way

Michigan Man
An Expanding Universe?

\[ R_{\mu\nu} - \frac{1}{2}g_{\mu\nu} = 8\pi GT_{\mu\nu} \]

A homogenous, isotropic universe evolving according to Einstein’s field equation must either expand or contract. It can not be static.
Or a static one?

Einstein’s greatest blunder?

\[ R_{\mu\nu} - \frac{1}{2}g_{\mu\nu} = 8\pi G T_{\mu\nu} + \Lambda g_{\mu\nu} \]

Einstein’s intention was to keep the universe static. But it this solution is unstable!
Or a static one?

Einstein’s greatest blunder?

\[ R_{\mu \nu} - \frac{1}{2} g_{\mu \nu} = 8\pi G T_{\mu \nu} + \Lambda g_{\mu \nu} \]

Einstein’s intention was to keep the universe static. But it does expand!

“If there is no quasi-static world, then away with the cosmological term”

- Einstein
Now we believe in an expanding universe
governed by

Einstein field equation

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

Roberston-Walker metric

$$c^2 ds^2 = -c^2 dt^2 + R^2(t) \left( \frac{dr^2}{1 - kr^2} + r^2 d\psi^2 \right)$$

Friedmann equation

$$\left( \frac{\dot{R}}{R} \right)^2 = \frac{8\pi G \rho}{3} - \frac{kc^2}{R^2} + \frac{\Lambda c^2}{3}$$

expansion rate

gravitating mass

anti-gravity/dark energy

geometry
An expanding universe solves the stability problem that Newton & Bentley corresponded about.
low density - infinite, expands forever

high density - finite, eventually re-collapses

critical density

OPEN

FLAT

CLOSED
Einstein’s General Relativity provides an elegant cosmology that naturally explains many observations.

- Expanding Universe
- Finite Age (~ 14 Billion years)
- Early hot phase (Big Bang)
  - Nucleosynthesis of the light elements (H, He, Li)
- Cosmic Microwave Background
Hubble Expansion

Big Bang Nucleosynthesis

Origin of the light elements in the first few minutes

Cosmic Microwave Background (~ 380,000 years)
Modern cosmology only works with

- dark matter
- dark energy

We don’t know what dark matter is and we don’t understand what dark energy means.

Unseen mass that provides more gravity

Something that acts like antigravity
Not only does the universe expand, but this expansion is accelerating!

Need “Dark Energy” to do that!
2011 Nobel Prize in Physics

After inflation, the expansion either...

first decelerated, then accelerated

...or always decelerated

past, today, future

Redshift

Billions of Years Before and After Today

Scale of Time Relative
Spiral Galaxy

Rotation Curve

Longer arrows represent larger orbital velocities.
Galaxy Cluster
Large Scale Structure
What is the Dark Matter?

Baryonic Dark Matter
Normal things:
- very faint stars, brown dwarfs
- other hard-to-see objects (planets, gas)

Hot Dark Matter
- neutrinos - got mass, but not enough

Cold Dark Matter
- Some new fundamental particle
  - doesn’t interact with light, so quite invisible.
Two big motivations:
1) total mass outweighs normal mass from BBN
2) needed to grow cosmic structure
(1)

Normal baryonic mass = 5% of critical density
from Primordial Nucleosynthesis

Total mass density = 30% of critical density
from gravity

gravitating mass >> normal mass

Most of the mass needs to be in some brand new form!
There isn’t enough time to form the observed cosmic structures from the smooth initial conditions unless there is a component of mass independent of photons.

very smooth: $\delta\rho/\rho \sim 10^{-5}$

very lumpy: $\delta\rho/\rho \sim 1$

$\delta\rho/\rho \propto t^{2/3}$
Particle physicists’ best guess is that the **Cold Dark Matter** needed in cosmology is a new form of fundamental particle called the **WIMP** (Weakly Interacting Massive Particle). There are ambitious projects to detect WIMPS in underground laboratories.
“Cosmologists are often wrong, but never in doubt”
- Lev Landau
What gets us into trouble is not what we don’t know.

It’s what we know for sure that just aint so.

- Mark Twain
As yet, we have no quantum theory of gravity. We do not understand it at a fundamental level.

Might that matter to cosmology? Could dark matter and/or dark energy really be a sign of new gravitational phenomena?
MOND

Modify gravity at an acceleration scale

\[ a_0 \approx 10^{-10} \text{ m s}^{-2} \sim cH_0 \sim c\Lambda^{1/2} \]

\[ a \gg a_0 \quad a \to g_N \]

\[ a \ll a_0 \quad a \to \sqrt{g_N a_o} \]
The Tully-Fisher Relation

- Slope = 4
- Normalization = \( \frac{1}{a_0 G} \)

- Fundamentally a relation between Disk Mass and \( V_{\text{flat}} \)
- No Dependence on Surface Brightness

- Dependence of conventional M/L on radius and surface brightness
- Rotation Curve Shapes
- Surface Density ~ Surface Brightness
- Detailed Rotation Curve Fits
- Stellar Population Mass-to-Light Ratios

“Disk Galaxies with low surface brightness provide particularly strong tests”

MOND predictions
Rotation curves

MOND predicts $a_0 G M = V^4$
$M_* > M_g$ (MOND fits)
McGaugh (2005)
\[ M^* > M_g \] (MOND fits)
McGaugh (2005)

\[ M^* > M_g \] (H-band popsynth)
Sakai (2000); Gurovich et al. (2010)

\[ M^* < M_g \] \((V_c = W_{20}/2)\)
Gurovich et al. (2010)

\[ M^* < M_g \sin(i_{opt}) < 1.12 \sin(i_{HI}) \]
Begum et al. (2008)

\[ M^* < M_g \]
Stark et al. (2009)

\[ M^* < M_g \]
Trachternach et al. (2008)

Position on BTFR independent of stellar \(M^*/L\) for \(M^* < M_g\)
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**MOND predictions**

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A new test: the dwarf satellites of Andromeda

Use MOND to predict the velocity of stars within each dwarf
The Good

- Hubble Expansion
- Primordial Nucleosynthesis
- Cosmic Microwave Background

The Ugly

The Bad

Dark Matter

Dark Energy

MOND
“We find ourselves, in the company of multitudes of others in the past, speaking of the Universe as if it were at last discovered and revealed. Our ancestors made this mistake continually and most likely our descendants will look back and see us repeating the same mistake.”

- Edward Harrison, *Cosmology*