The Driving Role of Gravity in Cosmology

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Ancient Cosmology: A Flat Earth

Here there be dragons!

Old Map of Hecataeus of Miletus (c. 500 BC)
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.

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.
Greek Map in 3D
Incan Cosmology
THE ANCIENT HEBREW CONCEPTION OF THE UNIVERSE
TO ILLUSTRATE THE ACCOUNT OF CREATION AND THE FLOOD
Chinese myth:
The world rests on the back of a great turtle. And what does the turtle stand on? Why, it's turtles all the way down!
well, maybe the earth is round

and the center of creation.
Geocentric Cosmology
Competing Cosmologies

Geocentric
Ptolemaic
Earth at center

Heliocentric
Copernican
Sun at center
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
- Arabic translation of Ptolemy’s work named *Almagest* ("the greatest compilation")
Geocentric Cosmology

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.
Competing Cosmologies

Geocentric  
Ptolemaic  
Earth at center

Heliocentric  
Copernican  
Sun at center

The sun is the source of light in both models

<table>
<thead>
<tr>
<th>Geocentric</th>
<th>Heliocentric</th>
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<td>Explains:</td>
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<td>- Motion of Sun</td>
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<td>- Motion of Moon</td>
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<td>- Solar and Lunar Eclipses</td>
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<td>- Phases of Moon</td>
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Retrograde Motion

Needs epicycles  
Inferiority of Mercury & Venus

Must tie to sun

Consequence of Lapping

Interior to Earth’s Orbit

Predicts

- No parallax  
- Venus: crescent phase only

- Parallax  
- Venus: all phases
“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)
Sir Isaac Newton (1642–1727)

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.
But what if the universe isn’t **static**?
If the universe is **expanding**, Newton’s gravity gives the right equation of motion just by considering a point on the surface of a sphere that feels the gravity of a uniform density within that sphere (Milne & McCrea).
The Cosmological Principle

- The Universe is
  - Homogeneous
  - Isotropic

A philosophical assertion that there should be nothing special about where we are, so the universe should look much the same to an distant alien observer as to us.
The Perfect Cosmological Principle

• The universe looks the same from everywhere at all times.

This is a logical extension of the Cosmological Principle in time as well as space. Trouble is, it is not true.
An Expanding Universe?

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

A homogenous, isotropic universe evolving according to Einstein’s field equation must either expand or contract. It cannot 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 does expand!
Einstein’s geometrical theory of gravity forms the basis of modern cosmology. The expansion history and the geometry of the universe depend on its mass density.
Gravity makes all the difference

- Low density: expands forever
- High density: eventually re-collapses

Types of universes:
- **OPEN**
- **FLAT**
- **CLOSED**
(a) Spherical space
\[ \rho_0 > \rho_c, \Omega_0 > 1 \]
Parallel light beams converge

(b) Flat space
\[ \rho_0 = \rho_c, \Omega_0 = 1 \]
Parallel light beams remain parallel

OPEN

Parallel light beams diverge
Not only does the universe expand, but this expansion is accelerating!

Need “Dark Energy” to do that!
A mathematical blunder: Einstein’s cosmological constant $\Lambda$ makes the expansion *accelerate*!
In addition to Dark Energy, there is lots of evidence for Dark Matter.
Spiral Galaxy

Rotation Curve

Longer arrows represent larger orbital velocities.
Galaxy Cluster
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
Normal baryonic mass = 4% of total from Primordial Nucleosynthesis

Total mass density = 27% of total 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: $\frac{\delta \rho}{\rho} \sim 10^{-5}$
- Very lumpy: $\frac{\delta \rho}{\rho} \sim 1$

$$\frac{\delta \rho}{\rho} \propto t^{2/3}$$

$t = 3.8 \times 10^5$ yr

$t = 1.4 \times 10^{10}$ yr
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.
Cosmological Mass-Energy Budget

THE ANSWER:

- Dark Energy: 73%
- Dark Matter: 23%
- Baryons: 4%

Hot Big Bang + Dark Energy + Dark Matter is now called “ΛCDM”
“Cosmologists are often wrong, but never in doubt”

- Lev Landau
“Cosmologists are often wrong, but never in doubt”  
- Lev Laundau

Things we know for sure in cosmology:

1990:  
\[ \Omega_m = 1.00 \]  
\[ \Omega_\Lambda = 0.00 \]  
\[ \Omega_b h^2 = 0.0125 \]  
\[ H_0 = 50 \text{ km/s/Mpc} \]  

Dark Matter = Cold Dark Matter
“Cosmologists are often wrong, but never in doubt”  
- Lev Laundau

Things we know for sure in cosmology:

2010: $\Omega_m = 0.27$  
$\Omega_\Lambda = 0.73$  
$\Omega_b h^2 = 0.0224$  
$H_o = 72$ km/s/Mpc  

Dark Matter = Cold Dark Matter  
... or maybe Warm Dark Matter  
... or Self-Interacting Dark Matter
Things are getting a bit complicated!

CDM

age

reionization

σ_8

nonlinear scale dependent bias

feedback

tilt

Rotation curves

CMB

BBN

Hubble Expansion

Large Scale Structure

CDM

Λ

Λ
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
Can gravity be unified with the other fundamental forces?
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?
Extended gravity theories

- DGP gravity
- MoG
- Weyl gravity
- MOND
• DGP gravity

• Dvali, Gabadadze, Porrati

• introduced to provide for an accelerating expansion without dark energy

• adds a 5th dimension - the usual 4D GR holds at short distances, with 5D dominating at large distances.
MoG

\[ \ddot{r} = -\frac{GM}{r^2} + \frac{G - G_N}{r^2} \left(1 + \frac{r}{r_0}\right)e^{-r/r_0} \]

Moffat

- adds massive vector field to the tensor already present in GR
- net result is a locally repulsive term that makes “normal” gravity weaker than it is at large scales
- fits all data all the time
- couples with rolling constants (fudge factors?)
• Conformal Weyl gravity

• Mannheim & Kazanas

• Raises gravity to 4th order conformally invariant theory (Einstein stopped at simplest 2nd order generally covariant theory)

• Theoretically appealing, but can it fit data?
- MOND

- Milgrom; Bekenstein

- Fits data well, but can it be a viable relativistic theory?

- TeVeS (tensor-vector-scalar)

- bimetric MOND

\[ \ddot{r} = \sqrt{a_0 \left( \frac{GM}{r^2} \right)} \text{ for } \ddot{r} \ll a_0 \]

\[ a_0 \approx 1 \text{ Å s}^{-2} \]
Rotation curves

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

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

Stellar M*/L independent of theory.
SAKA (2000); GUROVICH ET AL. (2010)

\[ M^* > M_g (\text{MOND fits}) \]
McGaugh (2005)

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

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

Position on BTFR independent of stellar \( M^*/L \) for \( M^* < M_g \)
M* > M_g (MOND fits)
McGaugh (2005)

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

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

Position on BTFR independent of stellar M*/L for M* < M_g
\(M^* > M_g\) (MOND fits)  
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\(M^* > M_g\) (H-band popsynth)  
Sakai (2000); Gurovich et al. (2010)

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

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

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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
Position on BTFR independent of stellar $M^*/L$ for $M^* < M_g$

prediction confirmed
Planck mission (ESA) to report early 2011

What about cosmology?
We still have a lot to learn.