Gravity and Cosmology a Century after Einstein

Stacy McGaugh
Professor of Astronomy & Physics
Director, Warner & Swasey Observatory
Ptolemaic Cosmology

Most successful cosmology ever (in terms of life span)

Earth-centered
All planets, including the sun, orbit the Earth
That the Earth may be a Planet

That the seeming novelty and singularity of this opinion can be no sufficient reason to prove it erroneous.
Copernican Revolution placed the Sun at the center

Geocentric
Ptolemaic
Earth at center

Heliocentric
Copernican
Sun at center
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.

~ 350 years ago ~

Sir Isaac Newton (1642–1727)
Newton provided the first working, modern, scientific theory of gravity. It still suffices to this day for most practical purposes.

In his own time, Newton did have critics.

Huygens questioned how he explained action at a distance.

Leibniz accused Newton of regarding gravity as a kind of “occult quality”, with the quality of bodies somehow hidden within them and beyond the philosopher's understanding, being occult, imperceptible and unintelligible.
He said ... “as if” ... 

Twenty years later, he walked it back:

That gravity should be ... essential to matter, so that one body may act upon another at a distance through a vacuum, without the mediation of anything else, ... is to me so great an absurdity that I believe no man who has in philosophical matters a competent faculty of thinking can ever fall into it.
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.
~ 100 years ago ~

General Relativity
Geometric theory of space-time

Encompassed Newton’s Universal Law of Gravitation and predicts new phenomena

Albert Einstein (1879–1955)
Einstein’s explanation of action at a distance

Matter tells spacetime how to curve; curved spacetime tells matter how to move.

Newton’s action at a distance problem is solved by geometry: what we perceive as a gravitational force is the result of trying to move in a straight line through curved space.
Phenomena of General Relativity

Curved Space-Time
  Time Dilation
  Gravitational Lensing
  Gravitational Waves
  The Expanding Universe
Phenomena of General Relativity

Curved Space-Time
Time Dilation
Gravitational Lensing
Gravitational Waves
The Expanding Universe

Time passes slightly faster for Global Positioning Satellites - a General Relativistic effect that must be included for GPS to work.
Phenomena of General Relativity

Curved Space-Time
Time Dilation
**Gravitational Lensing**
Gravitational Waves
The Expanding Universe

Curved space bends light; can act like a magnifying glass
Phenomena of General Relativity

- Curved Space-Time
- Time Dilation
- Gravitational Lensing
- Gravitational Waves
- The Expanding Universe

Ripples in the fabric of space-time
Gravitational waves were inferred from the orbit of a binary pulsar - Hulse & Taylor awarded Nobel Prize in 1993.
Gravitational waves were inferred from the orbit of a binary pulsar - Hulse & Taylor awarded Nobel Prize in 1993.
The binary pulsar showed indirect evidence for gravitational waves. A binary black hole could show direct evidence...
LIGO gravitational wave observatories in Livingston, LA & Hanford, WA

Laser interferometers with 4km (2.5 mile) long arms in perfect vacuum
LIGO FIRST DIRECT GRAVITATIONAL WAVE DETECTION

Hanford, Washington (H1)  Livingston, Louisiana (L1)

DATA

H1 observed
H1 observed (shifted, inverted)

THEORY

Numerical relativity
Reconstructed (wavelet)
Reconstructed (template)

Residual

Observed 14 September 2015; announced 11 February 2016
A few numbers

- Bigger Black Hole mass
- Smaller Black Hole mass
- Separation at contact (event horizons “touch”)
- Speed at contact
- Time to merge
- Energy radiated (in gravitational waves)

\[
\begin{align*}
M_{\bullet,1} &= 36 \, M_{\odot} \\
M_{\bullet,2} &= 29 \, M_{\odot} \\
350 \text{ km} & \quad \text{(I drove 430 km to get here)} \\
\frac{1}{2} c & \quad \text{(half light speed)} \\
< 0.05 \text{ seconds} & \\
3 \, M_{\odot} c^2 &
\end{align*}
\]
Nobel Prizes all around!

Expect

Ray Weiss
Kip Thorne
Ronald Drever
to win in September
Phenomena of General Relativity

Curved Space-Time
Time Dilation
Gravitational Lensing
Gravity Waves
The Expanding Universe

The universe itself is dynamic in General Relativity. It must either expand or contract.
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 can not be static.

In 1915, an expanding universe was inconceivable. Surely the universe had been around forever!
Or a static one?

Einstein’s greatest blunder?

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

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

$$\mathbf{R}_{\mu\nu} - \frac{1}{2}g_{\mu\nu} = \frac{8\pi G}{c^4} \mathbf{T}_{\mu\nu} + \Lambda g_{\mu\nu}$$

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

$$\left( \frac{\dot{R}}{R} \right)^2 = \frac{8\pi G \rho}{3} - \frac{k c^2}{R^2} + \frac{\Lambda c^2}{3}$$
An expanding universe solves the stability problem that Newton & Bentley corresponded about.
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.
FLAT
CLOSED
OPEN
low density - infinite, expands forever
high density - finite, eventually re-collapses
critical density
Einstein’s General Relativity provides an elegant cosmology
that naturally explains many observations

- Expanding Universe
- redshift-distance relation
- geometry of space-time
- 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

There is also a dark side
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!
Need

- Dark Energy
  - to make the expansion accelerate

- Dark Matter
  - to gather the galaxies and in the darkness bind them
Ample evidence for dark matter

Spiral Galaxy

Rotation Curve

Flat when it should decline
Galaxy Cluster

Velocity dispersions (Zwicky); X-ray gas; gravitational lensing
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 = 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.

\[ t = 3.8 \times 10^5 \text{ yr} \]

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

\[ t = 1.4 \times 10^{10} \text{ yr} \]

very lumpy: \( \delta \rho / \rho \sim 1 \)

\[ \delta \rho / \rho \propto t^{2/3} \]
Many ongoing experimental searches for

Cold Dark Matter

Paging

Cold Dark Matter

Paging

Cold Dark Matter ... hello?
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

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

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

\[ a \ll a_0 \quad a \rightarrow \sqrt{g_N a_o} \]
MOND predictions

- The Tully-Fisher Relation
  - Slope = 4
  - Normalization = $1/(a_0 G)$
- 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 $\sim$ Surface Brightness
- Detailed Rotation Curve Fits
- Stellar Population Mass-to-Light Ratios

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

MOND predicts $a_0 GM = V^4$
$M_\star > M_g$ (MOND fits)
McGaugh (2005)
\( \text{McGaugh} (2005) \)

\( \text{Sakai} (2000); \, \text{Gurovich et al.} (2010) \)

\( \text{Begum et al.} (2008) \)

\( \sin(i_{\text{opt}}) < 1.12 \sin(i_{\text{HI}}) \)

\( \text{Gurovich et al.} (2010) \)

\( \text{Stark et al.} (2009) \)

\( \text{Trachternach et al.} (2008) \)

Position on BTFR independent of stellar \( M*/L \) for \( M* < M_g \)
The Tully-Fisher Relation

- **Slope = 4**
- **Normalization = 1/(a_0 G)**
- Fundamentally a relation between Disk Mass and \( V_{flat} \)
- 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

**MOND predictions**

- The Tully-Fisher Relation
- Slope = 4
- Normalization = 1/(a_0 G)
- Fundamentally a relation between Disk Mass and \( V_{flat} \)
- No Dependence on Surface Brightness
The Tully-Fisher Relation
Slope = 4
Normalization = 1/(a_0 G)
Fundamentally a relation between Disk Mass and $V_{flat}$
No Dependence on Surface Brightness
Dependence of conventional M/L on radius and surface brightness
Rotation Curve Shapes
Surface Density $\sim$ Surface Brightness
Detailed Rotation Curve Fits
Stellar Population Mass-to-Light Ratios

MOND predictions

- The Tully-Fisher Relation
- Slope = 4
- Normalization = 1/(a_0 G)
- Fundamentally a relation between Disk Mass and $V_{flat}$
- No Dependence on Surface Brightness
- Dependence of conventional M/L on radius and surface brightness
- Rotation Curve Shapes
- Surface Density $\sim$ Surface Brightness
- Detailed Rotation Curve Fits
- Stellar Population Mass-to-Light Ratios
The Tully-Fisher Relation
- Slope = 4
- Normalization = 1/(aoG)
- Fundamentally a relation between Disk Mass and Vflat
- 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

MOND predictions
- ✔ The Tully-Fisher Relation
- ✔ Slope = 4
- ✔ Normalization = 1/(aoG)
- ✔ Fundamentally a relation between Disk Mass and Vflat
- ✔ 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
The Tully-Fisher Relation

- Slope = 4
- Normalization = $1/(a_0 \cdot G)$
- Fundamentally a relation between Disk Mass and $V_{flat}$
- 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

MOND predictions

$\xi = \frac{V^2}{(Gh)}$

mass surface density

surface brightness

Not a fit
The Tully-Fisher Relation

- Slope = 4
- Normalization = $1/(a_0 G)$
- 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 $\sim$ Surface Brightness
- Detailed Rotation Curve Fits
- Stellar Population Mass-to-Light Ratios
A new test: the dwarf satellites of Andromeda

Use MOND to predict the velocity of stars within each dwarf
Velocity dispersions of the dwarf satellites of Andromeda
Pairs of photometrically identical dwarfs should have different velocity dispersion depending on whether they are isolated are dominated by the external field effect.

There is no EFE in dark matter - this is a unique signature of MOND.
Hubble Expansion
Primordial Nucleosynthesis
Cosmic Microwave Background

The Good

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*

We still have a lot to learn.