Dark Universe – Part II

- Is the universe "open" or "closed"?
- How does dark energy change our view of the history and future of the universe?
Old view: Density of the Universe determines its destiny

\[ \Omega_{\text{total}} = \Omega_M \]

where

\[ \Omega_M = \text{matter density (including regular and dark matter)} \]

\[ \Omega_{\text{tot}} = \text{density/critical density} \]

If \( \Omega_{\text{tot}} = 1 \), Universe is flat, expansion coasts to a halt as Universe is critically balanced.

If \( \Omega_{\text{tot}} > 1 \), Universe is closed, collapses on itself.

If \( \Omega_{\text{tot}} < 1 \), Universe is open, expands forever.
Cosmological curvature

\[ \Omega = \frac{\text{density of the universe}}{\text{critical density}} \]

- \( \Omega < 1 \) hyperbolic geometry
- \( \Omega = 1 \) flat or Euclidean geometry
- \( \Omega > 1 \) spherical geometry
After inflation ends,

\[ \Omega_{\text{total}} = \Omega_M + \Omega_\Lambda = 1.0 \]

where

\[ \Omega_{\text{total}} = \text{density/critical density} \]
\[ \Omega_M = \text{matter density (including regular and dark matter)} = 0.27 \]

So therefore.....

\[ \Omega_\Lambda = \text{cosmological constant or dark energy density} = 0.73 \]
Today’s Cosmology

- $\Omega_{\text{TOT}} = 1.0$ from CMB measurements (WMAP). We live in a flat Universe.
- $\Omega_M < 0.3$ from extensive observations at various wavelengths. Includes dark matter as well as normal matter and light.
- $\Omega_{\Lambda} \sim 0.7$ derived from Type Ia SN data combined with WMAP and other measurements.
- Hubble constant $= 70$ km/sec/Mpc from HST observations. Age of Universe $= 13.7$ billion years.
- Universe *accelerates and is open, even though it is geometrically flat.*
In the (old) standard picture, a flat Universe would expand more slowly with time, eventually coasting to a stop.

However, the SN data (and other data e.g., from clusters of galaxies) show that the expansion of the universe is actually accelerating.

This supports the existence of mass-energy with a strong negative pressure, such as the cosmological constant \((\Lambda)\) originated by Einstein.
Dark Energy History

- Dark Energy must have been insignificant at early times, otherwise its gravitational influence would have made it almost impossible for ordinary matter to form stars, galaxies and large-scale structure.

- In the early Universe, gravity dominated and various structures formed.

- However as the Universe expanded, and self-gravitating structures (such as clusters of galaxies, etc.) grew further apart, the space between them expanded, and dark energy began to dominate gravity.
Expansion History of the Universe

- HST (Riess et al.) found most distant Type 1a
- It was so far away that it occurred during the period when the expansion was still slowing down due to gravity from the galaxies in a smaller Universe

Ann Feild (STScI)
Expansion history of the Universe

- Other dimensions

Ann Feild (STScI)
History and fate of the Universe

Data from Supernova Cosmology Project (LBL)

Graphic by Barnett, Linder, Perlmutter & Smoot

Blue region:
The expansion of the universe slowed down for a long time and then, with dark energy, sped up.

Gold region:
The expansion of the universe always slowed down after the first fraction of a second.
Resources

- Inflationary Universe by Alan Guth (Perseus)
- A Short History of the Universe by Joseph Silk (Scientific American Library)
- Before the Beginning by Martin Rees (Perseus)
- Inflation for Beginners (John Gribbin)
  http://www.biols.susx.ac.uk/Home/John_Gribbin/cosmo.htm
- Ned Wright’s Cosmology Tutorial
  http://www.astro.ucla.edu/~wright/cosmolog.htm
Resources

- Physics Web quintessence
  http://physicsweb.org/article/world/13/11/8

- Big Bang Cosmology Primer
  http://cosmology.berkeley.edu/Education/IUP/Big_Bang_Primer.html

- Martin White’s Cosmology Pages
  http://astron.berkeley.edu/~mwhite/darkmatter/bbn.html

- Lindsay Clark’s Curvature of Space
  http://www.astro.princeton.edu/~clark/teacherguide.html

- Before the Beginning by Martin Rees
  (Perseus)
Backups follow
Multiverses

- Universe was originally defined to include everything
- However, the possibility exists that our “bubble universe” is only one of many such regions that could have formed, with the parameters arranged as in the concordance model so that we can be here having this discussion
- Other universes could have very different physical conditions and we will never see them – they may be on different “branes” or in other dimensions that we cannot measure
A Humbling Thought

- Not only do we not occupy a preferred place in our Universe, we may not occupy any preferred universe in the Multiverse!
COMPOSITION OF THE COSMOS

- Heavy Elements: 0.03%
- Neutrinos: 0.3%
- Stars: 0.5%
- Free Hydrogen and Helium: 4%
- Dark Matter: 25%
- Dark Energy: 70%
Recall the Uncertainty Principle

- The uncertainty principle states that you cannot know both the position $x$ and the momentum $p$ of a particle more precisely than Planck’s constant $\frac{h}{2\pi} \rightarrow \text{“h-bar”}$
- When dimensions are small, particles must therefore move in order to satisfy the uncertainty principle
- This motion creates a “zero point energy” $> 0$

\[ \text{Uncertainty Principle} \quad \Delta x \Delta p \geq \frac{\hbar}{2} \]
Uncertainty Principle

- Another version of the uncertainty principle relates the energy of a particle pair to lifetime.
- This version explains the “virtual particles” that appear as quantum fluctuations.
- They do not violate the uncertainty principle as long as their lifetimes are very short, and they are created in pairs which conserve charge, spin, and other quantum properties.
Quantum fluctuations?

- Virtual particle pairs continually emerge and disappear into the quantum vacuum.
- If you observe the particles (hit them with a photon), you give them enough energy to become real.
- The particles can also get energy from any nearby force field (like a BH).
The shape of the Universe

- The shape of the Universe is determined by a struggle between the momentum of expansion and the pull of gravity.
- The rate of expansion is determined by the Hubble Constant, $\text{H}_0$.
- The strength of gravity depends on the density and pressure of the matter in the Universe.
  - $G$ is proportional to $\rho + 3P$
  - $\rho$ is the density and $P$ is the pressure.
- For normal matter, $P$ is negligible, so the fate of a universe filled with normal matter is governed by the density $\rho$. 
The fate of the Universe

- As the universe expands, the matter spreads out, with its density decreasing in inverse proportion to the volume. \( V = \frac{4\pi r^3}{3} \) for a sphere
- The strength of the curvature effect decreases less rapidly, as the inverse of the surface area. \( A = 4\pi r^2 \) for a sphere
- So, in the (pre-1998) standard picture of cosmology, geometry (curvature) ultimately gains control of the expansion of the universe.
Properties of Dark Energy

- Einstein’s cosmological constant $\Lambda$ has the property that $P = -\rho = -1$. Significant quantities of matter-energy with “negative pressure” will cause the expansion of the universe to accelerate.

- The quantity $P/\rho = w$ is known as the “equation of state” parameter. Best measurements right now (WMAP and others) find that $w = -1$, consistent with the value expected for the “concordance model” aka $\Lambda$–CDM (cosmological constant + cold dark matter)
## Concordance Model

From Spergel et al. 2006

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Basic parameters</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$H_0$</td>
<td>$70.9^{+2.4}_{-3.2}$ km s$^{-1}$ Mpc$^{-1}$</td>
<td>Hubble parameter</td>
</tr>
<tr>
<td>$\Omega_b$</td>
<td>$0.0444^{+0.0042}_{-0.0035}$</td>
<td>Baryon density</td>
</tr>
<tr>
<td>$\Omega_m$</td>
<td>$0.266^{+0.025}_{-0.040}$</td>
<td>Total matter density</td>
</tr>
<tr>
<td><strong>Derived parameters</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\rho_0$</td>
<td>$10.5^{+2.6}_{-2.9}$ kg/m$^3$</td>
<td>Critical density</td>
</tr>
<tr>
<td>$\Omega_\Lambda$</td>
<td>$0.772^{+0.036}_{-0.048}$</td>
<td>Dark energy density</td>
</tr>
<tr>
<td>$t_0$</td>
<td>$13.73^{+0.13}_{-0.17} \times 10^9$ years</td>
<td>Age of the universe</td>
</tr>
</tbody>
</table>
Vacuum Energy = Dark Energy?

- The cosmological constant $\Lambda$ may be related to the "zero-point energy" of the Universe which comes from the quantum fluctuations of the vacuum.

- However, the vacuum energy density is $10^{120}$ too high to allow structure formation to occur.

- Something must be canceling almost all of the vacuum energy in order for us to be here.

- And that something must have arranged for the $\sim 73\%$ of critical density to be left over at our current time, 13.7 billion years later.
Quintessence

- Quintessence is another theory for dark energy that involves a dynamic, time-evolving and spatially dependent form of energy.
- It makes slightly different predictions for the acceleration.
- It’s name refers to a “fifth essence” or force.
Gravity and pressure

Relativistic
\[ G = \rho + 3P \]
\[ P = \rho/3 \]
\[ G = 4\rho > 0 \]

Non-relativistic
\[ G = \rho + 3P \]
\[ P = 0 \]
\[ G = \rho > 0 \]

\[ \Lambda \]
\[ G = \rho + 3P \]
\[ P = -\rho < 0 \]
\[ G = -2\rho < 0 \]

Quintessence
\[ G = \rho + 3P \]
\[ P = -2\rho/3 < 0 \]
\[ G = -\rho < 0 \]