In Search of Dark Matter

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THE UNIVERSE’S MATTER BUDGET

Dark Matter: 86.09%

Hydrogen: 10.33%

Helium: 3.44%

All Heavier Elements: Carbon, Oxygen, Silicon, Iron, Uranium ... 0.14%
• Eighty Years of Evidence for Dark Matter: Five Big Reasons
• Efforts to Detect Dark Matter
• The Next Ten Years
Evidence Part I: Motions of Galaxies (1933)
Early Evidence

• Swiss Astronomer Fritz Zwicky is usually credited with providing the first indications of a large component of dark matter in the universe in two papers in 1933 and 1937.

• Zwicky studied the velocities of galaxies in the nearby Coma Cluster of galaxies.
The Coma Cluster

**Distance:** 300 Million light-years

**Diameter:** 12 Million light-years

**Apparent Size:** 10 times bigger than the full moon on the sky
Dark Matter in the Coma Cluster of Galaxies
The Coma cluster contains about one thousand nebulae. The average mass of one of these nebulae is therefore

\[ \overline{M} > 9 \times 10^{43} \text{ gr} = 4.5 \times 10^{10} M_\odot. \]  \hspace{1cm} (36)

Inasmuch as we have introduced at every step of our argument inequalities which tend to depress the final value of the mass \( M \), the foregoing value (36) should be considered as the lowest estimate for the average mass of nebulae in the Coma cluster. This result is somewhat unexpected, in view of the fact that the luminosity of an average nebula is equal to that of about 8.5 \( \times \) 10\(^7\) suns. According
“If this result is confirmed, we would arrive at the astonishing conclusion that dark matter is present in Coma with a much greater density than luminous matter.”

-Zwicky 1933
Evidence Part II: Motions Within Galaxies (1970)
Rubin & Ford (1970) reported on the "rotation curve" of the Andromeda galaxy.
Andromeda

• about 750 kpc (2.4 Million lightyears) distant
• About the size of the Milky Way
• Rubin & Ford’s Rotation Curve
Velocities: Observed vs. Expected from Light
The material in galaxies moves too \textbf{Fast} to be explained only by the mass contained in stars and interstellar gas.
Evidence Part III: Light Element Nucleosynthesis (1964-2001)
<table>
<thead>
<tr>
<th>Element/Isotope</th>
<th>Abundance</th>
<th>Made in...</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>73%</td>
<td>Early Universe</td>
</tr>
<tr>
<td>Helium</td>
<td>24.5%</td>
<td>Early Universe</td>
</tr>
<tr>
<td>Oxygen</td>
<td>1%</td>
<td>Stars</td>
</tr>
<tr>
<td>Carbon</td>
<td>0.4%</td>
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</tr>
<tr>
<td>Iron</td>
<td>0.1%</td>
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</tr>
<tr>
<td>Silicon</td>
<td>0.06%</td>
<td>Stars</td>
</tr>
<tr>
<td>Deuterium</td>
<td>0.002%</td>
<td>Early Universe</td>
</tr>
<tr>
<td>Lithium</td>
<td>0.0000001%</td>
<td>Early Universe</td>
</tr>
</tbody>
</table>
Hydrogen and Helium

• The Universe is 75% Hydrogen, 24% Helium, and 1% other stuff.

Hydrogen (H): 1 proton

Helium ($^4$He): 2 protons, 2 neutrons, very strongly held together
Deuterium (D): Hydrogen Isotope with one Proton and one Neutron, loosely bound together

Lithium (⁷Li): 3 protons, 4 neutrons, loosely bound together

• The Universe contains trace amounts of Deuterium and Lithium, which are destroyed rather than produced within stars
Cosmic Rewind

1 sec. to 20 min: Light Element synthesis

400,000 yr: CMB Produced

200 Million Years: First Stars

13.7 Billion Years: Today
In the very early universe (t < 1 second):

- Densities are very high & interactions happen very quickly because interaction rates increase with temperature and density
- The weak interactions interconvert protons and neutrons
- Equilibrium is maintained while interactions are rapid
Neutrinos

- Neutron
- Electron
- Proton
- Neutrons
- Xenon-142
- Strontium-90
- Uranium
- Yttrium
- Neutrino
Neutrinos

• Electrically neutral, therefore:
  • they do not interact with or emit light
  • they are unnoticed by us under most circumstances

• Interact via the Weak Nuclear Force only, so
  • four light-years of solid lead (24 trillion miles) would be required to have a 50% chance of “catching” a neutrino.

• Much lighter than protons, neutrons, or electrons so they move fast when produced
Fusion processes like the above, allow larger nuclei to form from the constituent protons and neutrons.
Synthesis of the Light Nuclei

- The Universe expands, cools, and interactions “freeze out”
- Equilibrium is lost and residual neutrons are incorporated into Deuterium, Helium, & Lithium by $t=20$ minutes
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For Helium ($^4\text{He}$), the convention is to use the fraction by mass $Y_p$.

Abundance of Element Compared to Hydrogen

Fractional Density of the Universe in normal baryonic matter, $\Omega_{\text{BARYONS}}$
For Helium ($^4\text{He}$), the convention is to use the fraction by mass $Y_P$.

Dashed lines show range of observed values.

Abundance of Element Compared to Hydrogen

Fractional Density of the Universe in normal baryonic matter, $\Omega_{\text{BARYONS}}$
Production of light elements in the Early Universe is consistent with observations, only if 4% of the entire Universe is in the form of normal “baryonic” matter!
Note: This is also astounding because it says that we know how all of the elements in the Universe were produced!
Evidence Part IV:
Why do we see surfaces of clouds, the Sun, or anything?
Cosmic Rewind

1 sec. to 20 min: Light Element synthesis

400,000 yr: CMB Produced

200 Million Years: First Stars

13.7 Billion Years: Today
OUR MILKY WAY Galaxy, And Us

OUR VIEW OF
THE Big Bang
The Universe’s Baby Picture

• Measured by the Wilkinson Microwave Anisotropy Probe
The Universe’s Baby Picture

- Measured by the Wilkinson Microwave Anisotropy Probe
Galaxies in Our Universe
Dark Matter is Necessary to Grow Structure

Contemporary Distribution of Galaxies

Microwave Background Image of the Universe 13 Billion Years Ago
Evidence Part V: Gravitational Lensing
Dark Matter Candidates
Neutrinos

• Electrically neutral, therefore:
  • they do not interact with or emit light
  • they are unnoticed by us under most circumstances

• Interact via the Weak Nuclear Force only, so
• Much lighter than protons, neutrons, or electrons so they move fast when produced
• Like dark matter in that they are, dark, but they are much too light to be the dark matter!
Top Two Candidates

• Weakly-Interacting, Massive Particles (WIMPs):
  • Analogous to very heavy neutrinos
  • Can be produced in the Early Universe in processes analogous to light element nucleosynthesis
  • Are natural parts of theories that were developed to explain other phenomena
Top Two Candidates

• Axions:
  • New particle invented to explain other aspects of the strong nuclear force.
  • Very difficult to detect.
Detecting Dark Matter Without Gravity
Detecting WIMPs
WIMPs Hit The Earth
Directly On the Earth

Depositing Heat on a Cold, Semiconductor Crystal
COUPP Detector
Annihilation
products

Gamma rays

dark matter particles

Gamma Rays

US
Annihilation Products
Annihilation Products
Accumulation of Dark Matter in the Sun
Accumulation of Dark Matter in the Sun

DARK MATTER ACCUMULATION

ν
Ice Cube Neutrino Detector
Ice Cube Neutrino Detector
Status Report

• To Date, there are no unambiguous detections of signal attributable to dark matter; however, ...

• We are just achieving the technologies that should be capable of seeing WIMP candidate particles

• The WIMP hypothesis could well be excluded or confirmed within the next decade.

• If dark matter is not a WIMP (an axion, say), the search could continue for quite some time