From the Big Bang to the Nobel Prize: Cosmic Background Explorer (COBE) and Beyond

Goddard Space Flight Center Lecture
John Mather
Nov. 21, 2006
Astronomical Search For Origins

First Galaxies

Big Bang

Galaxies Evolve

Life

Stars

Planets
Looking Back in Time

Hand: 1 m, 0.000 000 003 sec
Earth: 7000 km, 0.02 sec
Sun: 150,000,000 km, 500 sec
Star: 4 yrs
Galaxy: 25,000 yrs
Big Bang: 15,000,000,000,000 y
Measuring Distance

1. **TRIANGLES**

   ![Diagram of triangle with known angles and distances]

   - Earth Now
   - 1 AU
   - Sun
   - 6 Months Later
   - p = parallax (angle)
   - d = distance

2. **STANDARD CANDLES**

   - ![Diagram of standard candles with distance measurements]

   - \[ \frac{\text{Brightness}_1}{\text{Brightness}_2} = \frac{r_2^2}{r_1^2} \]

This technique enables measurement of enormous distances.
Atoms emit light at discrete wavelengths that can be seen with a spectroscope. This “line spectrum” identifies the atom and its velocity.
Galaxies attract each other, so the expansion should be slowing down -- Right??

To tell, we need to compare the velocity we measure on nearby galaxies to ones at very high redshift.

In other words, we need to extend Hubble’s velocity vs distance plot to much greater distances.
The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2006 jointly to John C. Mather, NASA Goddard Space Flight Center, Greenbelt, MD, USA, and George F. Smoot, University of California, Berkeley, CA, USA "for their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation".
The Power of Thought

Georges Lemaitre & Albert Einstein

George Gamow

Robert Herman & Ralph Alpher

Rashid Sunyaev

Jim Peebles
Power of Hardware - CMB Spectrum

Paul Richards
Mike Werner
David Woody
Frank Low
Herb Gush
Rai Weiss
Brief COBE History

• 1965, CMB announced - Penzias & Wilson; Dicke, Peebles, Roll, & Wilkinson
• 1974, NASA AO for Explorers: ~ 150 proposals, including:
  – JPL anisotropy proposal (Gulkis, Janssen…)
  – Berkeley anisotropy proposal (Alvarez, Smoot…)
  – Goddard/MIT/Princeton COBE proposal (Hauser, Mather, Muehlner, Silverberg, Thaddeus, Weiss, Wilkinson)
COBE History (2)

- 1976, Mission Definition Science Team selected by HQ (Nancy Boggess, Program Scientist); PI’s chosen
- ~ 1979, decision to build COBE in-house at GSFC
- 1982, approval to construct for flight
- 1986, Challenger explosion, start COBE redesign for Delta launch
- 1989, Nov. 18, launch
- 1990, first spectrum results; helium ends in 10 mo
- 1992, first anisotropy results
- 1994, end operations
- 1998, major cosmic IR background results
Starting COBE

Pat Thaddeus

John & Jane Mather

Dave & Eunice Wilkinson

Mike & Deanna Hauser

Rai & Becky Weiss

George Smoot

Sam & Margie Gulkis, Mike & Sandie Janssen
COBE Science Team

Chuck & Renee Bennett

Nancy & Al Boggess

Ed & Tammy Cheng

Eli & Florence Dwek

Tom & Ann Kelsall

Philip & Georganne Lubin
COBE Science Team

Steve & Sharon Meyer

Harvey & Sarah Moseley

Tom & Jeanne Murdock

Rick & Gwen Shafer

Bob & Beverly Silverberg

Ned & Pat Wright
COBE Engineering Leadership

Back row: Bill Hoggard, Herb Mittelman, Joe Turtil, Bob Sanford
Middle row: Don Crosby, Roger Mattson, Irene Ferber, Maureen Menton
Front row: Jeff Greenwell, Ernie Doutrich, Bob Schools, Mike Roberto
Back row: Dennis McCarthy, Bob Maichle, Loren Linstrom, Jack Peddicord
Middle row: Lee Smith, Dave Gilman, Steve Leete, Tony Fragomeni
Front row: Earle Young, Chuck Katz, Bernie Klein, John Wolfgang
COBE Satellite, 1989-1994

Deployable Sun, Earth, RF/Thermal Shield

DIRBE

FIRAS

DMR Antennas

Helium Dewar

Deployable Solar Panels

Spacecraft

Deployable Mast

Earth Sensors

TDRSS Omni Antenna

WFF Omni Antenna
Far Infrared Absolute Spectrophotometer

John Mather
Rick Shafer
Bob Maichle
Mike Roberto
Calibrator (Eccosorb) on arm, before insulation, attached to parabolic concentrator
Cosmic Background Spectrum at the North Galactic Pole

The smooth curve is the best fit blackbody spectrum

Based on 9 minutes of data
Presented at AAS, January 1990
Current estimate: $T = 2.725 \pm 0.001$ K

New technology could reduce residuals 2 orders of magnitude?
Confirming the Big Bang Theory

I wish He wouldn't keep that darn thermostat at 3 K!

- Hot Big Bang theory is right
- No extra energy released after the first year
- No exotic events like turbulent motion
“Scientists confirmed today that everything we know about the structure of the universe is wrongedy–wrong–wrong.”
Differential Microwave Radiometers

DMR Signal Flow Diagram

Differential Microwave Radiometers

Corrugated Antennas

Calibrator

Switch

Frequency Converter

Amplifier

Diode Detector

Synchronous Demodulator Switch

Output Proportional to Brightness Difference

George Smoot
Chuck Bennett
Bernie Klein
Steve Leete
Sky map from DMR, 2.7 K +/- 0.003 K

Doppler Effect of Earth’s motion removed (v/c = 0.001)

Cosmic temperature/density variations at 389,000 years, +/- 0.00003 K
COBE Map of CMB Fluctuations
2.725 K +/- \sim 30 \mu K \text{ rms}, 7^\circ \text{ beam}
DIRBE (Diffuse Infrared Background Experiment)

- Map entire sky in 10 bands from 1.2 to 240 µm
- Measure, understand, and subtract for zodiacal and galactic foregrounds
- Determine small residual from early universe, primeval galaxies, etc.
- Requires absolute calibration
DIRBE far IR
(100, 140, 240 µm) Sky Modeling
COBE Cosmology

• CMB has blackbody spectrum, $\delta F/F_{\text{max}} < 50$ ppm. Strong limits, about 0.01%, on energy conversion (from turbulence, unstable particles, etc.) after $t = 1$ year. No good explanation besides Hot Big Bang.

• CMB has spatial structure, 0.001% on scales $> 7^o$, consistent with scale-invariant predictions and inflation, dark matter and dark energy or $\Lambda$ constant, and formation of galaxies and clusters by gravity.

• CIBR has 2 parts, near (few microns) and far (few hundred microns), each with brightness comparable to the known luminosity of visible & near IR galaxies: $L$ of universe is $\sim$ double expected value.
WMAP

Wilkinson Microwave Anisotropy Probe

Chuck Bennett, PI

Goddard & Princeton team

Launched in 2001
The Universe at age 389,000 years

Temperature (µK) relative to average of 2.725 K

Galactic Plane
Cosmic Parameters to ~ percent accuracy

\[ \Omega_{\text{tot}} = \Omega_b + \Omega_c + \Omega_\Lambda = 100\% \]

\[ \Omega_m = \Omega_b + \Omega_c = 27 \pm 4\% \]
CMB Angular Power Spectrum

Angular scale

$\ell(l+1)C_{\ell}/2\pi$ [\(\mu K^2\)]

Multipole moment $\ell$

WMAP
Acbar
Boomerang
CBI
VSA
Planck Mission - ESA-led with NASA contributions, for 2008 launch

Higher spatial resolution and sensitivity than WMAP, with shorter wavelengths
James Webb Space Telescope (JWST)
Summary of JWST

- Deployable infrared telescope with 6.5 meter diameter segmented adjustable primary mirror
- Cryogenic temperature telescope and 4 instruments for infrared performance, covering 0.6 to 29 μm
- Launch June 2013 on an ESA-supplied Ariane 5 rocket to Sun-Earth L2: 1.5 million km away in deep space (needed for cooling)
- 5-year science mission (10-year goal)
James Webb Space Telescope

- Mission Lead: Goddard Space Flight Center
- International collaboration with ESA & CSA
- Prime Contractor: Northrop Grumman Space Technology
- Instruments:
  - Near Infrared Camera (NIRCam) – Univ. of Arizona
  - Near Infrared Spectrograph (NIRSpec) – ESA
  - Mid-Infrared Instrument (MIRI) – JPL/ESA
  - Fine Guidance Sensor (FGS) – CSA
- Operations: Space Telescope Science Institute
Four Scientific Themes

• First objects formed after Big Bang
  – Super-stars?
  – Super-supernovae?
  – Black holes?
• Assembly of galaxies (from small pieces?)
• Formation of stars and planetary systems
  – Hidden in dust clouds
• Planetary systems and conditions for life
JWST Science Objectives versus Cosmic History

- Big Bang: 3 minutes
- Particle Physics: 389,000 years
- Atoms & Radiation: 200 million years
- Star & Planet Formation: 1 billion years
- Now: 13.7 billion years

NASA
End of the dark ages: first light?
The Eagle Nebula as seen with Hubble
The Eagle Nebula as seen in the infrared
Birth of stars and protoplanetary systems

Stars in dust disks in Orion
Planetary systems and the origins of life

- **The star Fomalhaut**
- **Center of offset dust ring**
- **Hypothetical planet** (estimated to be orbiting between 4.6 and 6.5 billion miles from the star)
- **Offset dust ring**
HST characterizes transiting planets; so will JWST
Chemistry of Transiting Planets

Additional absorption due to planetary atmosphere

Normal absorption spike depth from star
What happened before the Big Bang?
What’s at the center of a black hole?
How did we get here?
What is our cosmic destiny?
What are space and time?

... Big Questions, Ripe to Answer