A Verification of the Expansion of Space

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Andromeda: A Galaxy Like Ours
Galaxies in the Universe
• “Redshift” describes the stretching of electromagnetic wavelengths from receding sources
• We measure the redshifts of objects via characteristic patterns in electromagnetic spectra
• The amount of redshift gives the object’s speed, in this case, 47 million miles per hour
A colleague of Edwin Hubble’s, Vesto Slipher, measured the redshifts of many galaxies, and found something surprising...

Almost all galaxies (Andromeda is an exception), appear to have REDSHIFTs, or shifts to longer wavelengths (in contrast to blueshifts)

This was startling because the implication is that most galaxies are moving away from ours!
Edwin Hubble made a plot of the distance to galaxies against the velocities that galaxies were receding.

Galaxies recede at a speed proportional to their distance.

Today the Hubble expansion rate is 22 (km/s) for every million light years of distance.
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OUR MILKY WAY
The Expanding Universe
The Expanding Universe

- Einstein’s theory of describes an expanding Universe
The Expanding Universe

earlier time

later time

- Einstein’s theory predicts that perceived recession speed is proportional to distance
The Expanding Universe

- Wavelengths of light are stretched by the expansion, giving rise to the redshift
The amount of stretching, or redshift, gives the amount of cosmic expansion
Cosmic Raisin Bread

- The expansion and measured redshifts require no notion of a "center"
1. Predicts the correct abundances of light elements in the Universe: Hydrogen (75%), Helium (24%), Deuterium (0.01%), Lithium (0.00001%)
Big Bang Successes

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2. Predicts the abundances and clustering patterns of galaxies correctly
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3. Predicts a nearly uniform “background” of radiation from the early Universe: the 3 K, Cosmic Microwave Background (CMB)
CMB Discoverers: Arno Penzias & Robert Wilson
We deeply appreciate the helpfulness of Drs. Penzias and Wilson of the Bell Telephone Laboratories, Crawford Hill, Holmdel, New Jersey, in discussing with us the result of their measurements and in showing us their receiving system. We are also grateful for several helpful suggestions of Professor J. A. Wheeler.

May 7, 1965

PALMER PHYSICAL LABORATORY
PRINCETON, NEW JERSEY

REFERENCES


A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE
AT 4080 Mc/s

Measurements of the effective zenith noise temperature of the 20-foot horn-reflector antenna (Crawford, Hogg, and Hunt 1961) at the Crawford Hill Laboratory, Holmdel, New Jersey, at 4080 Mc/s have yielded a value about 3.5° K higher than expected. This excess temperature is, within the limits of our observations, isotropic, unpolarized, and
Fig. 18.2. Spectral intensity distribution of Planck’s black-body radiation as a function of wavelength for different temperatures. The maximum of the intensity shifts to shorter wavelengths as the black-body temperature increases.
Intensity, Wavelength, and Frequency

- A Hot “O STAR”
INTENSITY, WAVELENGTH, AND FREQUENCY

- A Cool Star
INTENSITY, WAVELENGTH, AND FREQUENCY

- The Sun
The Wilkinson Microwave Anisotropy Probe

http://map.gsfc.nasa.gov
The Cosmic Microwave Background

- A Map of the CMB on the sky is extremely smooth
- The CMB has a thermal spectrum with $T=2.726 \text{ K} = -454.7 \text{ °F}$
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The Cosmic Microwave Background

- Turning up the contrast on the map reveals fluctuations of 1 part in 100,000 or temperature changes of ~ 0.00003 K
The Cosmic Microwave Background

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OUR MILKY WAY

OUR VIEW

OUR MILKY WAY
Everyone’s View!

Some Other Galaxy
Intervening Galaxy Cluster

CMB Light, Distorted by Cluster

Our Milky Way
1. Much of the light we get from galaxy clusters is from X-ray emission from gaseous hydrogen and electrons between the galaxies.
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2. The hydrogen and electron gas is extremely hot (180 Million Degrees!)
Galaxy Clusters

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3. The CMB photons that interact with the hot cluster gas, acquire energy
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3. The CMB photons that interact with the hot cluster gas, acquire energy

4. Acquiring energy means boosting frequencies, or increasing wavelengths
Intervening Galaxy Cluster

CMB Light, Distorted by Cluster

Our Milky Way
The Sunyaev-Zeldovich Effect

The Sunyaev-Zeldovich effect is caused by the hot thermal distribution of electrons provided by the ICM of galaxy clusters. CMB photons passing through the center of a massive cluster have only a ≈1% probability of interacting with an energetic ICM electron. The resulting inverse Compton scattering preferentially boosts the energy of the CMB photon by roughly $k_BT_e/m_ec^2$, causing a small (∝1 mK) distortion in the CMB spectrum.

Figure 1 shows the SZE spectral distortion for a fictional cluster that is 1000 times more massive than a typical cluster to illustrate the small effect. The SZE appears as a decrease in the intensity of the CMB at frequencies ≲218 GHz and as an increase at higher frequencies.

This review discusses the basic features of the SZE that make it a useful cosmological tool.

Dashed: “Normal” 
CMB Spectrum 

Solid: “Distorted” 
CMB Spectrum From Behind A Cluster

Yakov Zeldovich

Rashid Sunyaev
The Sunyaev-Zeldovich Effect

At Low Frequency, one sees....

angle coordinate

cluster of galaxies

Yakov Zeldovich

Rashid Sunyaev
Fast-Moving Galaxy Cluster

CMB Light, Distorted by Cluster

Our Milky Way
The Sunyaev-Zeldovich Effect

The Sunyaev-Zeldovich Effect (SZE) is caused by the hot thermal distribution of electrons provided by the ICM of galaxy clusters. CMB photons passing through the center of a massive galaxy cluster have only a \( \approx 1\% \) probability of interacting with an energetic ICM electron. The resulting inverse Compton scattering preferentially boosts the energy of the CMB photon by roughly \( k_B T_e / m_e c^2 \), causing a small (\( \lesssim 1 \) mK) distortion in the CMB spectrum.

Figure 1 shows the SZE spectral distortion for a fictional cluster that is 1000 times more massive than a typical cluster to illustrate the small effect. The SZE appears as a decrease in the intensity of the CMB at frequencies \( \lesssim 218 \) GHz and as an increase at higher frequencies. The derivation of the SZE can be found in the original papers of Sunyaev & Zeldovich (Sunyaev & Zeldovich 1970, 1972), several reviews (Sunyaev & Zeldovich 1980a, Rephaeli 1995, Birkinshaw 1999), and in a number of more recent contributions that include relativistic corrections (see below for references).

This review discusses the basic features of the SZE that make it a useful cosmological tool.
The Sunyaev-Zeldovich Effect

![Graph showing the Sunyaev-Zeldovich Effect]

- **Intensity Change** vs. **Frequency in GHz**
- **Change Due to a Cluster**
- **No Shift**
The Sunyaev-Zeldovich Effect

![Diagram showing frequency in GHz vs. intensity change. The graph illustrates three scenarios:

- **No Shift**: A horizontal line at zero intensity change.
- **Change Due to a Cluster**: A blue curve indicating a significant intensity change.
- **Change Due to Cluster Motion**: A red curve showing another intensity change pattern.]

Frequency in GHz

Intensity Change
The Sunyaev-Zeldovich Effect

Change due to a Cluster

Change due to Cluster Motion

Change required if the speed of the Cluster is to explain its redshift!
If Galaxy Cluster Velocities explain redshifts, rather than the stretching of space, then there should be a large decrease in the CMB intensity at ALL FREQUENCIES!
Measured Sunyaev-Zeldovich Effect

Decrement Frequency, 150 GHZ

Null Signal Frequency, 220 GHZ
**Measured Sunyaev-Zeldovich Effect**

Decrement Frequency, 150 GHZ

Null Signal Frequency, 220 GHZ
SUMMARY
1. We perceive a cosmic microwave background with respect to which we appear to be stationary.
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2. We see a “thermal” Sunyaev-Zeldovich distortion of the CMB, so the CMB must be coming from great distances behind the galaxy clusters.
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3. We see no “kinetic” Sunyaev-Zeldovich distortion, so clusters are also stationary!
1. We perceive a cosmic microwave background with respect to which we appear to be stationary.

2. We see a “thermal” Sunyaev-Zeldovich distortion of the CMB, so the CMB must be coming from great distances behind the galaxy clusters.

3. We see no “kinetic” Sunyaev-Zeldovich distortion, so clusters are also stationary!

4. Space expands, in order to explain high redshift (Doppler shifted) clusters that do not move!