The Cosmic Microwave Background:

Ringing in the New Cosmology

Wayne Hu
Planetarium Short Course
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In the Beginning...
There was light.

- CMB
- γ
- e
- p
- n
- He

Recombination
Turn on, Tune in, Drop out

- CMB photons have dropped out of the visible spectrum into the microwaves; a temperature 3 degrees above absolute zero
- Wavelengths in the mm-cm regime, comparable to radio and TV wavelengths

- Tune a TV between channels and about 1% of the static is from the CMB
- Tune a microwave receiver to the peak frequency of CMB photons and they dominate the night sky and come from everywhere at a rate of 10 trillion photons per second per square cm.
The Microwave Sky

Uniform Emission

Penzias & Wilson 1965
The Microwave Sky

Nigel: but it goes up to 11
no make that 100,000

http://map.gsfc.nasa.gov
Seeing Spots

- 1 part in 100000 variations in temperature
- Spot sizes ranging from a fraction of a degree to 180 degrees

Selecting only spots of a given range of sizes gives a power spectrum or frequency spectrum of the variations much like a graphic equalizer for sound.
Seeing Spots
Sounding Out Origins
Darkness from Light: Recombination

- Reversing the expansion, CMB photons got hotter and hotter into the past
- When the universe was 1000 times smaller and the CMB photons were at 3000K they were energetic enough disintegrate atoms into electrons and protons.
Seeing Sound

- Colliding electrons, protons and photons forms a plasma
- Acts as gas just like molecules in the air
- Compressional disturbance propagates in the gas through particle collisions
- In the air we experience this as sound hitting the eardrum

- Unlike sound in the air, we see the sound in the CMB
- Compression heats the gas resulting in a hot spot in the CMB
Gravitational Formation of Structure

- After recombination, CMB photons stop interacting with matter.
- Matter fluctuation collapses due to gravitational self-attraction.
- Grows into the large scale structure of the universe in 14 billion yrs.

A. Kravtsov
Prime Mover

Horizon 3x10^5 yrs
Prime Mover

Horizon

3x10^5 yrs

Time

Inflation

Horizon

Diagram showing the relationship between inflation and the time horizon.
Inflation as Prime Mover

- Searching backwards in time for the origin of structure, eventually the size of a given structure becomes larger than the horizon.
- Since information cannot travel faster than light, no causal process can then originate the structure under a normal expansion.

- Inflation is a period of superluminal expansion that takes microphysical scales into cosmological scales.
- Driven by a hypothetical form of matter called the inflaton.
- Quantum mechanical fluctuations due to the uncertainty principle become the seeds of structure today.

- Can structure originate at intermediate times and provide a loophole?
Piper at the Gates of Dawn

- Blow into a flute or an open pipe
- Spectrum of sound contains a fundamental frequency and harmonic overtones
Inflation is the source of sound waves at the beginning of time.

Sound waves are frozen at recombination, yielding a harmonic spectrum of frequencies that reach maximum displacement.
Harmonic Signature

• Much like a musical instrument, identify construction through the pattern of overtones on the fundamental frequency

• Without inflation, fluctuations must be generated at intermediate times

• Like drilling holes in the pipe and blowing in random places, harmonic structure of peaks destroyed

• Observed frequency spectrum consistent with inflationary origin

• Detailed examination of the overtones, reveals the composition of the universe

• But first...
In Space No One Can Hear You Scream

- Inflation predicts equal amplitude initial fluctuations on all scales since universe looks the same as it expands.
- Observed fluctuations bear the imprint of sonic processing.
- Most dramatically: fluctuations beyond the third peak or 10 arcminutes are exponentially damped.
- Sound propagates through the collision of particles.
- In air, molecules can only travel $10^{-5}$ cm before colliding.
- In the "empty space" before recombination photons travel $10^4$ light years before colliding!
- Sound waves of shorter wavelength cannot propagate and are damped.
- Accounting for this, variation in the initial fluctuations over a decade in scale no more than $\sim4\%$.
Observed Power Spectrum

$\Delta T$ ($\mu$K)

$D_T (mK)$

$l$

$l = 10$, $100$, $1000$

0x159

W. Hu 02/03

W. Hu 05/00

W. Hu 04/01

W. Hu 06/02

W. Hu 11/02

W. Hu 04/01

W. Hu 05/02

W. Hu 12/02

W. Hu 12/02

W. Hu 12/95

W. Hu 12/98

Tegmark Compilation

BOOM

BOOM

BOOM

BOOM

ACBAR

ACBAR

VSA

MAP

MAP

DASI

DASI

BIMA

BIMA

Pyth

Pyth

RING

RING

SuZIE

SuZIE

ARGO

ARGO

Viper

Viper

BAM

BAM

ATCA

ATCA

OVRO

OVRO

IAB

IAB

SP

SP

MAX

MAX

FIRS

FIRS
Harmonic Composition
Fundamental: Weighing the Universe

- Measuring the angular extent of the fundamental wavelength (spot size) yields the curvature - universe is spatially flat
- Einstein says matter-energy density curves space: universe is at the critical density
Sound Spectrum

- Spectrum of sound shows harmonics at integer ratios of the fundamental.
- Other models that generate structure causally at intermediate times would not have these harmonics.
Harmonics: Ordinary Matter

- Competition between gravity and pressure depends on phase of oscillation
- At the fundamental (and odd frequency multiples) gravity assists sonic motion; at second peak (and even multiples) gravity fights sonic motion

**Fundamental**

**2nd Peak**

- gravitational potential

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**inflation**

**recombination**

**space**

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**inflation**

**recombination**
• A low second peak indicates baryon or ordinary matter density comparable to photon density

• Ordinary matter consists of $\sim5\%$ of the critical density today
Harmonics: Dark Matter

- What maintains the gravitational potential if the ordinary matter oscillates as a stable sound wave?
- Without matter that does not interact with photons/light or dark matter, gravitational potentials decay once ordinary matter enters into oscillation.
- Gravitational enhancement destroyed soon after 1st peak.

Recombination:

- dark matter
- no dark matter
Dark Matter

- A third peak comparable to second peak indicates a dark matter density $\sim 5\times$ that of ordinary matter
- Dark matter $\sim 25\%$ of the critical density
Missing Energy

- Ordinary matter and dark matter comprise ~30% of the total density as measured by the first peak
- ~70% of the universe unaccounted for
- Must have negligible contribution at recombination else seen in the peaks
- New form of energy whose energy density decreases more slowly than matter as the universe expands

- Dub this new form of energy density:

  Dark Energy
Concord (and Discord?)
Yeah, Right...

• An improbable conclusion? new forms of matter: inflaton, dark matter, dark energy

• Dark matter and dark energy densities must scale differently with the expansion and yet coincidentally have comparable densities today

• More than just a fanciful story

• Concordance with previously known cosmological facts

• Predicts phenomena that have now been observed

• Predictions will be sharply tested by new observations
CMB Chauvanist Anacronisms

- **Dark matter** originally introduced by Zwicky in 1930’s to explain the mass density in clusters of galaxies
- **Dark energy** originally introduced by Einstein in 1917 to change the expansion rate; observational support from distant supernovae which show the universe is accelerating
- **Inflation** introduced to explain the lack of relics from the early universe
- **Density of ordinary matter** originally set to explain the observed abundance of light elements with big-bang nucleosynthesis
- **CMB determinations** beautifully consistent with these disparate observations
- Simplicity of the **acoustic physics** allows for the cleanest, most precise probes of these phenomena to date
Predictive Power

- Model predicts the precise form of the damping of sound waves: observed
- Model predicts that associated with the damping, the CMB becomes polarized: observed
- Model predicts that temperature fluctuations correlated with local structure due to the dark energy: observed
Why Polarization?

- Polarization arises from scattering of CMB photons just like reflection of sunlight off of a surface.

- Heuristically, photon electric field shakes the electron which emits light polarized in the direction of the shaking.

- Polarization requires a preferred or special direction – absent if photon directions randomly changing because of rapid scattering.

- Only on scales where the photons are streaming relatively unimpeded can a preferred direction arise and impart a polarization.
Polarization on the Sky

- **Polarization retains directional information on temperature variations** at recombination.
- Distinguish between temperature variations from sound waves vs. gravitational waves (from anisotropic stretching of photon wavelengths).
(Re)Scattering

- Polarization requires an **difference** in the **intensity** of photons at 90 degree angles.
- **Rapid collisions** randomize the directions of photons leading to **no polarization**.
- Polarization only occurs on **scales comparable** to the **distance between collisions**.
- During **recombination** this is the **damping scale**.
- After **recombination**, this scale increases to the whole **observable universe**.
- **Large scale polarization** of the CMB measures the amount of scattering after recombination.
- **WMAP Surprise:** 20% of the photons have **rescattered** during a period of **reionization**.
Reionization and Inflationary Spectrum

- **Reionization** of the universe is a natural outcome of the gravitational instability model for structure formation.

- Inflationary fluctuations on small scales collapse and eventually form the first **stars**; starlight then **ionizes** hydrogen.

- Surprise is this event occurred **relatively early**: challenge for **star formation models** and may perhaps require larger fluctuations on small scales than **simple inflationary models** predict.

- Conversely, hints of a **deficit of power** at intermediate scales (**large scale structure**) and the **largest scales** (**CMB**) increasing tension on theory.

- Discord?
Dark Energy & Gravitational Redshifts

- Accelerated expansion halts the growth of structure
- Gravitational potential decays - blueshift correlated with galaxies and the large scale structure of the universe
Requiem? Not!

- **CMB observations** have helped establish a **standard cosmological model** based on
  - Inflationary Origin of Structure
  - Dark Matter
  - Dark Energy

  which has **predictive and explanatory power**

- A **phenomenological model** that fails to answer deeper questions: what is the **inflation, dark matter and dark energy**

- **Inflationary physics** from spectrum of initial fluctuations and gravitational waves in the polarization of the CMB

- **Dark matter and energy** from using the CMB to backlight structure in the universe: scattering in clusters of galaxies and gravitational lensing
The Emperor of the South Sea was Fast, the Emperor of the North Sea Furious, the Emperor of the center was Primordial Blob. Fast and Furious were discussing how to repay Primordial Blob's bounty.

All men have seven holes through which they look, listen, eat, breathe; he alone doesn't have any. Let's try boring them.

Every day they bored one hole, and on the seventh day Primordial Blob died.

– Chuang-tzu (c. 350 BC)
Lecture based on Scientific American article in collaboration with Martin White (UC Berkeley) to appear 2004.

Animations require the free Acrobat 6 (or higher) and a computer with multimedia capabilities; best viewed on a Macintosh.