The light from beyond the stars
presented by

Hael Collins
“I’m astounded by people who want to ‘know’ the universe when it's hard enough to find your way around Chinatown”

Woody Allen
Why is the night sky dark?
Is it perfectly dark?
Heinrich Wilhelm Olbers
(1758–1840)
Oblers’ Paradox
(or “Why is the night sky dark?”)

\[ \frac{\text{Light}}{\text{Star}} \propto \frac{1}{r^2} \]

\[ \frac{\text{Stars}}{\text{Slice}} \propto r^2 \]
Oblers’ Paradox
(or “Why is the night sky dark?”)

\[
\left( \frac{\text{Light}}{\text{Star}} \propto \frac{1}{r^2} \right) \times \left( \frac{\text{Stars}}{\text{Slice}} \propto r^2 \right) = \left( \frac{\text{Light}}{\text{Slice}} \propto \text{constant} \right)
\]

**Resolution:**

1. Finite size?
   (the average density of stars far away falls off faster than \(1/r^2\))

2. Finite time?
   (the universe had a beginning)

3. Dilution?
   (some additional effect weakens the light at great distances)
“[I] chucked the law for astronomy, and I knew that even if I were second-rate or third-rate it was astronomy that mattered.”

Edwin Hubble
Edwin Powell Hubble
(1889–1953)
Hubble’s Discovery
(1929)

The farther away something is from us,
the faster it is moving away
Do we live in a special part of the universe?

(and what about the Copernican Principle?)
Two possibilities:

1. Space is fixed, and the galaxies move

2. Space itself is expanding and the galaxies are more or less fixed
“I think and think for months and years. Ninety-nine times, the conclusion is false. The hundredth time I am right.”

Albert Einstein
Albert Einstein
(1879–1955)
General Relativity

“Die Grundlage der allgemeinen Relativitätstheorie”
A. Einstein (1916)

Gravity = Geometry of space-time

Gravity (energy/momentum of the stuff in the universe)
Given an initial impulse, space-time could expand.
A. Friedmann (1922) – H.-G. Lemaître (1927)

- Matter or radiation ⇒ act to retard expansion
A Mysterious Ingredient

General Relativity also allows a self-repulsive material

W. de Sitter (1917)

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average distance between galaxies

**vacuum energy**

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time
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matter or radiation ⇒ act to retard expansion
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"vacuum energy" (Λ) ⇒ acts to heighten expansion
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If the universe is expanding now, then it must have been smaller in the past.

But space is not perfectly empty.
The scale factor: \( a(t) \)

Later

\[ a(t_3) \]

\[ a(t_2) \]

\[ a(t_1) \]

Time

Earlier

\( a(t) = \) how much lengths change with time

What happens to the number of hydrogen atoms per unit volume as the universe evolves?
hydrogen atoms per unit volume \( \propto \frac{1}{a^3(t)} \)
What happens when you adiabatically compress a gas?

It gets denser and hotter
What happens when you adiabatically compress a gas?

It gets denser and hotter

neutral hydrogen (hotter)
What happens when you adiabatically compress a gas?

It gets denser and hotter

neutral hydrogen (still hotter)
What happens when you adiabatically compress a gas?

It gets denser and hotter

a hydrogen plasma
What happens when you adiabatically compress a gas?

So at some early stage, the universe should have been filled with a hot, opaque gas.

Where did the light go?
Oblers’ Paradox Redux
(or “Why isn’t the night sky purple?”)

Resolution:

1. Finite size?
   (the average density of stars far away falls off faster than $1/r^2$)

2. Finite time?
   (the universe had a beginning)

3. Dilution?
   (some additional effect weakens the light at great distances)

What happens to light in an expanding universe?
Gravitational redshifting

The wavelength ($\lambda$) of light is stretched by the expansion of space

\[
\text{Energy}(t) = \frac{h}{\lambda(t)} = \frac{h}{\lambda(t_0)} \frac{a(t_0)}{a(t)} = \frac{a(t_0)}{a(t)} \text{Energy}(t_0)
\]

\[
\text{temperature}(t_0) = \frac{a(t)}{a(t_0)} \text{temperature}(t)
\]
Prediction!

Lemaître (1931), Tolman (1934), Alpher & Gamow

1. If general relativity is correct and

2. If the universe has been expanding since its “beginning”

The universe should be filled with a cold, faint relic glow left when the early plasma cooled and became transparent —

The Cosmic Microwave Background (CMB) Radiation
“There is nothing like looking, if you want to find something. You certainly usually find something, if you look, but it is not always quite the something you were after.”

J. R. R. Tolkien
Penzias and Wilson's Discovery (1965)

The universe is filled with the faint radiation of a 2.7 K (nearly) perfect blackbody.

Where does this radiation originate?
Our own galaxy

Columbia University

50,000 light-years
The local clusters of galaxies

100 million light-years
The neighboring superclusters

1 billion light-years
The visible universe

13.7 billion light-years
The visible universe

13.7 billion light-years

The cosmic microwave background radiation originates on the inner surface of this sphere.
Penzias and Wilson’s Discovery (1965)

The universe is filled with the faint radiation of a 2.7 K (nearly) perfect blackbody.
A Homemade CMB Detector

About 1% of the noise on an old television set is due to that cosmic radiation
Where did it all come from?
“Faultily faultless, icily regular, splendidly null,
Dead perfection, no more. . .”

Alfred Tennyson
(from Maud)
Too much symmetry is a bad thing
But little asymmetry can be good
But little asymmetry can be good
But little asymmetry can be good
But little asymmetry can be good
Gravity causes little asymmetries to become big asymmetries.
Gravity causes little asymmetries to become big asymmetries.
How uniform is the Cosmic Background?

From 1965 to the beginning of the 1990’s, the faint relic radiation looked perfectly uniform.

But the asymmetries that grew into stars and galaxies and clusters of galaxies had to be there in the microwave background.

With gravity and time, the tiniest of asymmetries (a part in 100,000) would have been enough.
Prediction!

1. If general relativity is correct and
2. If the stars and galaxies formed from tiny asymmetries

The cold, faint relic glow left when the early plasma cooled and became transparent should not be perfectly uniform

Measure the temperature of the cosmic background very carefully
The COsmic Background Explorer (COBE)  
launched November 18, 1989
COBE’s Discovery
(ca. 1992 – launched in 1989)

Saw small variations of the temperature of the CMB in different parts of the sky

COBE’s temperature map of the sky (only 7° resolution)
What makes the hot and cold spots?

Two competing effects —

1. A more (less) dense region is hotter (colder)
2. But light cools (warms) as it emerges from a more (less) dense region

gravitational redshifting
Beyond COBE
(1990’s)

COBE told us that our basic picture of the universe was right

complicated structures growing gravitationally from a very uniform early plasma
Beyond COBE (1990’s)

Can we do better?

1. how did the asymmetries arise?
2. what is the shape of the universe?
3. what composes the universe?
4. are we missing something?

COBE’s temperature map of the sky (only 7° resolution)
“Anything you can do, I can do better. I can do anything better than you.”

Irving Berlin

(from Annie Get Your Gun)
Wilkinson Microwave Anisotropy Probe (WMAP)
lunched June 30, 2001
WMAP’s Discovery
(2003 – ongoing)

Precisely measured the temperature and polarization of the earliest relic light

COBE’s temperature map of the sky (only a 7° resolution)
WMAP’s Discovery  
(2003 – ongoing)  
Precisely measured the temperature and polarization of the earliest relic light

WMAP’s temperature map of the sky (about a 0.2° resolution)
WMAP’s Discovery
(2003 – ongoing)

Precisely measured the temperature and polarization of the earliest relic light

WMAP’s temperature map of the sky (about a 0.2° resolution)
WMAP’s Discoveries
(2003 – ongoing)

1. The universe is $13.73^{+0.13}_{-0.17}$ billion years old
2. The first stars formed 13.3 billion years ago
3. The universe is flat (just enough ± 2 %)
4. The universe is made of
   a) dark energy: 72 %
   b) dark matter: 24 %
   c) ordinary matter: 4 %
5. The entire universe is filled with distortions of space (nearly featureless noise)
6. Many further discoveries
“‘And – and – what comes next?’
‘Oh, yes, yes, what the dickens does come next? C’est la question, ma très chère demoiselle!’”

Thomas Mann
(from Buddenbrooks)
Open Questions

1. What is the dark matter?
2. What is the dark energy?
3. What made those primordial distortions of space? (inflation?)
4. What produced that initial impulse that caused the universe to expand?
5. How far ultimately can we peer behind the cosmic background radiation? (nucleosynthesis)
6. and many, many more
The End