

Today in Astronomy 142: the new flat Universe

The cosmic background and the structure of the Universe:

- ❑ Acoustic oscillations in the early expansion: a new standard ruler.
- ❑ A flat Universe? A nonzero cosmological constant?



Image: Deployment of the balloon-borne BOOMERANG cosmic-background anisotropy experiment in Antarctica, with Mt. Erebus in the distance (Caltech/UCSB/U. Rome/NASA).

23 April 2009

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Acoustic oscillations in the early Universe, and a new standard ruler

Naturally, some inhomogeneities – peaks and troughs in the density – are to be expected in an expanding gas like that of the Big Bang, even if the contrast of the inhomogeneities is small.

These inhomogeneities **oscillate** acoustically – ring like a bell, driving sound **waves** into their surroundings:

- ❑ Gravity tends to collapse the density peaks, heating them up and increasing the temperature of the radiation (light) therein.
- ❑ This increases the radiation pressure, which pushes it back the other way, then gravity pulls it in again, then...
- ❑ And exactly the opposite happens in the density troughs.

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Acoustic oscillations in the early Universe, and a new standard ruler (continued)

This proceeds until decoupling, when the radiation can escape from the matter.

- ❑ Thus a last snapshot of the Universe in the act of this “ringing” is preserved in images of the cosmic background.

Can the oscillations be as large in wavelength as they want?

- ❑ Yes, but any that have wavelengths much larger than twice the size of the Universe at decoupling won't show up in the cosmic background. Think of the Universe before decoupling as a **resonant cavity** (like the pulsating stars we considered [earlier](#)): there would be a **fundamental mode** evident in the spectrum of sound.

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Acoustic oscillations in the early Universe, and a new standard ruler (continued)

□ Thus the cosmic background should have anisotropies on the scale of the longest wavelength that would resonate in the universe, plus wavelengths that represent harmonics of this longest-wavelength resonance.

Figure by Wayne Hu, U. Chicago

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Acoustic oscillations in the early Universe, and a new standard ruler (continued)

Figure by Wayne Hu, U. Chicago.

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Acoustic oscillations in the early Universe, and a new standard ruler (continued)

Importance: we can calculate what the longest wavelength is, and we can measure the angular size of the oscillations in images of the cosmic background.

This combination gives us a rather direct measure of the **curvature** of the Universe. A given length would subtend a smaller angle in a negatively-curved universe and a larger one in a positively-curved universe. It turns out that a flat universe would have its fundamental at about 1 degree.

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Acoustic oscillations in the early Universe, and a new standard ruler (continued)



Animation courtesy of the WMAP Science Team (NASA/GSFC). See map.gsfc.nasa.gov.

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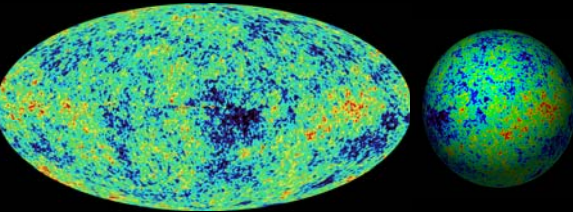
Acoustic oscillations in the early Universe, and a new standard ruler (continued)

The angular resolution of COBE was 7 degrees, so different experiments were necessary to see the oscillations.

- ❑ Very hard to do from the ground! People tried for decades, though. (Atmospheric absorption and interference are the main problems.)
- ❑ First successful measurements were a series of radio telescope/receiver instruments borne on long-duration balloons, such as MAXIMA and BOOMERANG.
- ❑ But the definitive measurement was made by satellite in 2002: NASA's Wilkinson Microwave Anisotropy Probe (WMAP) imaged the whole sky and detected all the bubbles from the two lowest acoustic resonances.

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Acoustic oscillations in the early Universe, and a new standard ruler (continued)



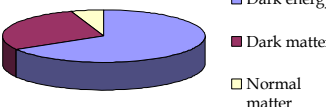
Full-sky map (plane of Milky Way along the equator) and animated globe of WMAP results, courtesy of NASA and the WMAP Science Team; see map.gsfc.nasa.gov.

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Dark energy

So about 70% of the mass-energy in the Universe seems to act gravitationally like a cosmological constant does - that is, "anti-gravitationally."

- ❑ And, yes, that's the same way [exotic matter](#) works.
- ❑ We call this stuff **dark energy**, to distinguish it from dark matter.
- ❑ We have no idea what it is made of. It's not vacuum fluctuations, though, like exotic matter is.
- ❑ Dark energy is overwhelmingly outweighed by matter in the local part of the Universe, but outweighs matter on the largest scales.



- Dark energy
- Dark matter
- Normal matter

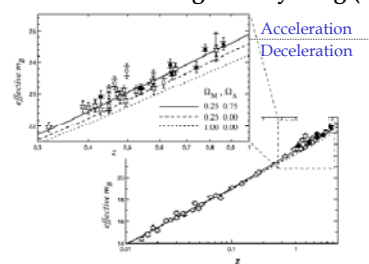
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This changes everything.

- ❑ **If the cosmological constant is nonzero, then there is no longer a one-to-one correspondence between curvature, boundedness and fate.** For example:
 - If the value of Ω_Λ were negative, the universe would collapse and end in a singularity no matter what its curvature.
 - If the value of Ω_Λ were positive and large, even a positively-curved, closed universe would expand forever.
- ❑ If $\Omega_\Lambda = 0.7$, **distant galaxies should be seen to accelerate.** This may have been pre-confirmed in observations of distant galaxies in which supernovae of type Ia have been seen to be a bit faint considering their redshifts.

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This changes everything (continued).



Acceleration
Deceleration

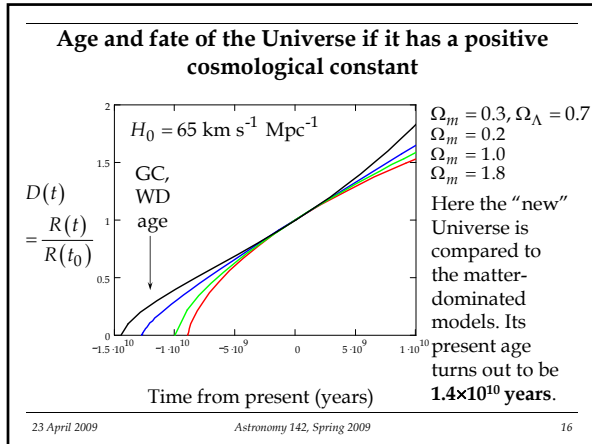
Ω_M, Ω_Λ

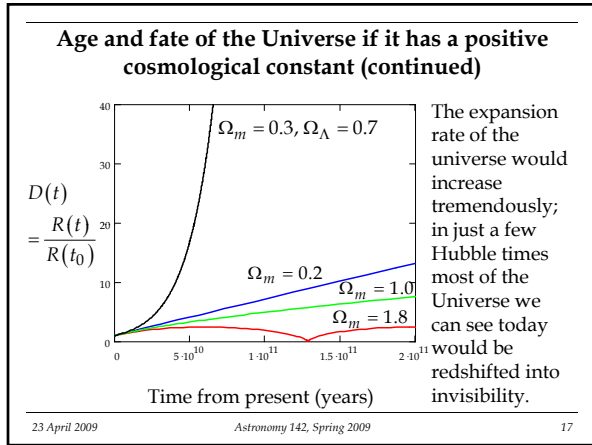
- 0.25 0.75
- - - 0.25 0.00
- ... 1.00 0.00

R.A. Knop et al. 2003

Astrophysicists are still arguing about whether they're faint because they're further away than expected (i.e. acceleration), or because supernovae of this type are just less luminous earlier in the Universe's history. If it's acceleration, it's consistent with the WMAP flatness measurement.

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Summary: best (experimental) determination of the state of the Universe

- ❑ The Universe has a present-day relative mass density of $\Omega_m \cong 0.3$ (dark plus luminous).
- ❑ If matter dominates its energy, the Universe is negatively-curved and **open**, the presently-observed expansion will continue forever, and about 1.3×10^{10} years have elapsed since the Big Bang.
- ❑ But the WMAP experiment shows definitively that the Universe is **flat** between here/now and recombination.
- ❑ The **simplest** explanation is a substantial, positive cosmological constant and associated dark energy, which dominates the present energy of the Universe: $\Omega_\Lambda = 0.7$.
- ❑ If this is true, the Universe is **open**, the present expansion will continue and will increase dramatically over time, and the Universe is about 1.4×10^{10} years old.

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