FEATURE

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Research Area: Astrophysics

How Did the Universe Begin?

The universe is filled with CMBR, the leftover heat from the Big Bang

How did the universe begin? What happened in its first moments? How did the rich structure of galaxies, stars and planets emerge out of nothingness? While humans have been asking these questions for millennia, we can now directly observe physical processes that occurred in the first moments of the universe.

Because light travels at a finite speed, when we look out in space, we look back in time. Since it takes light eight minutes to travel from the Sun to the Earth, we observe the Sun as it was eight minutes ago. We see Jupiter as it was 30 minutes ago and see nearby stars as they were 5 or 100 years ago. When the Subaru telescope observes a distant galaxy, it sees light that left the galaxy 12 billion years ago.

Einstein's theory of General Relativity (together with our observations of the properties of the universe) implies that our current universe began 13.7 Billion years ago. Today, the universe is filled with *cosmic microwave background radiation (CMBR)*, the leftover heat from the "Big Bang." Today, the temperature of the CMBR is only 3 degrees above absolute zero. However, when the universe was younger, the CMBR was much hotter.

Three hundred and eighty thousand years after the big bang, the temperature of the CMBR was 3000 degrees above absolute zero, roughly half the temperature of the surface of the Sun. At this temperature, the CMBR was hot enough to ionize most of the hydrogen in the universe, so space was filled with a dense plasma of electrons and protons. The CMBR cannot penetrate this thick fog, so when we look out in space, this is as far as we can see back in time.

Over the past 15 years, most of my research has focused on interpretation of tiny fluctuations in the temperature of the CMBR measured by the Wilkinson Microwave Anisotropy Probe (WMAP). WMAP is a NASA satellite that orbits the Earth and Sun at four times the distance of the moon where it characterizes the CMBR.

A simple model explains cosmological observations

Our observations have found a pattern of CMBR temperature fluctuations consistent with a very simple cosmological model characterized by only five basic numbers: the age of the universe, the mean density of atoms in the universe, the mean density of matter in the universe, the amplitude of fluctuations in the density of the universe and the scale-dependence of these fluctuations (see Figure 2). Not only does this model fit our data, but

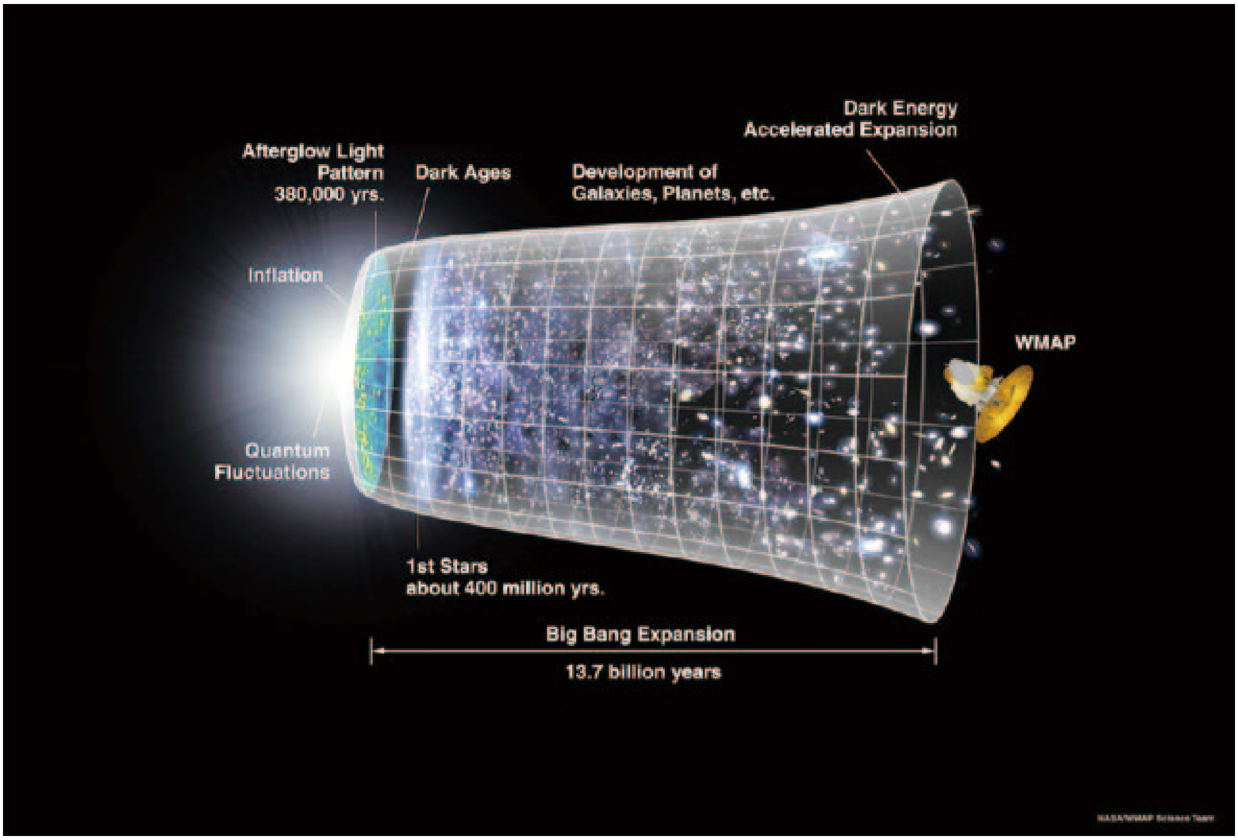

Figure 1: This image (from the WMAP science Team) shows the history of the expanding universe.

with the same parameters, this simple model also fits a host of astronomical observations including measurements of the Sloan Digital Sky Survey's measurements of the large-scale distribution of galaxies, the Subaru telescope's measurements of galaxy lensing and the Hubble Space Telescope's measurements of the expansion rate of the universe using both supernovae and Cepheid variables.

This simple cosmological model not only provides a quantitative description of the evolution of our universe to its current rich structure, but also provides insights into the first moments of the universe by testing the *theory of inflation*, a theory that grew out of ideas in particle physics that describes the first moments of the universe.

During the early 1980s, physicists studying the unification of nuclear interactions with electromagnetism recognized that any unified theory would make a startling cosmological prediction: the very hot early universe would have produced copious number of massive particles called monopoles. These monopoles would today completely dominate the universe, a prediction that is in obvious violation of the observed properties of the universe. Katsuhiko Sato, Alan Guth, Andrei Linde, Paul Steinhardt, and Andrew Albrecht identified a solution to this monopole problem: if the early universe underwent a phase transition, then it would experience a rapid period of expansion that we now call inflation driven by the energy of the

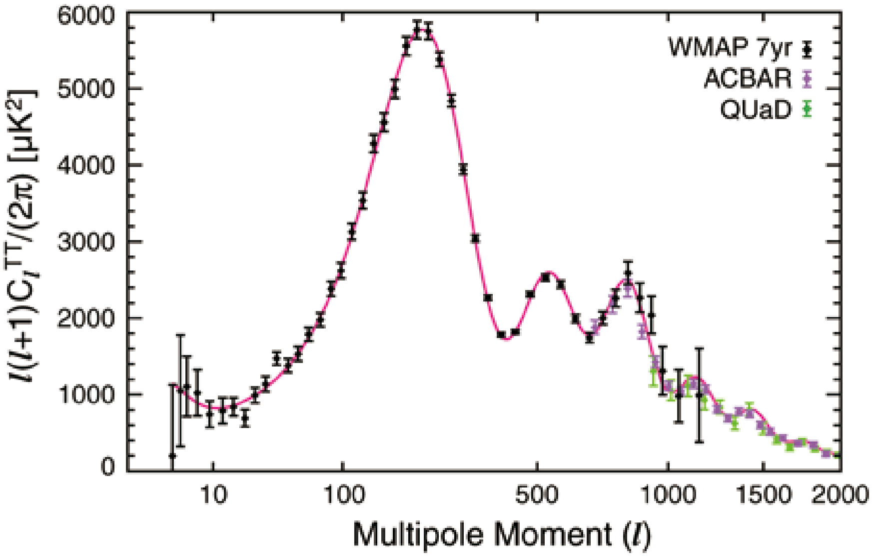

Figure 2: This plot (from Komatsu et al. 2010) shows the amplitude of temperature fluctuations as a function of angular scale. The red line shows our best fit cosmological model and the points show results from the WMAP, QUAD and ACBAR experiments.

vacuum. This vacuum energy-driven inflationary expansion would dilute the density of monopoles and reconcile unified theory with observations.

In 1980s, inflation was a speculative theory, not the subject of experiment

The inflationary model not only solved the particle physicists' monopole problem but also solved a host of cosmological problems: this rapid expansion could explain why different regions of space had similar physical properties and could explain the universe's large size.

The inflationary model also made a number of generic predictions about the properties of the universe:

- Because inflation stretched the size of the universe, *the geometry of the universe would be close to flat* (i.e., the geometry of spacetime would be the familiar Euclidian geometry that we all learned as teenagers).
- Because different regions of space experienced slightly different amounts of inflation, there would be variations in the density of the universe. The inflationary model predicted that the fluctuations would be *nearly scale invariant*. In the simplest inflationary models, these fluctuations are *Gaussian random phase fluctuations*.
- Because all regions of space experienced inflation, these variations would be *adiabatic*: regions with excess numbers of electrons and protons would also have excess numbers of photons.
- The expansion of the universe could not only decelerate due to the gravitational pull of matter, but could also accelerate due to the effects of the vacuum energy.

When physicists made these predictions in the 1980s, they seemed far removed from the observed world.

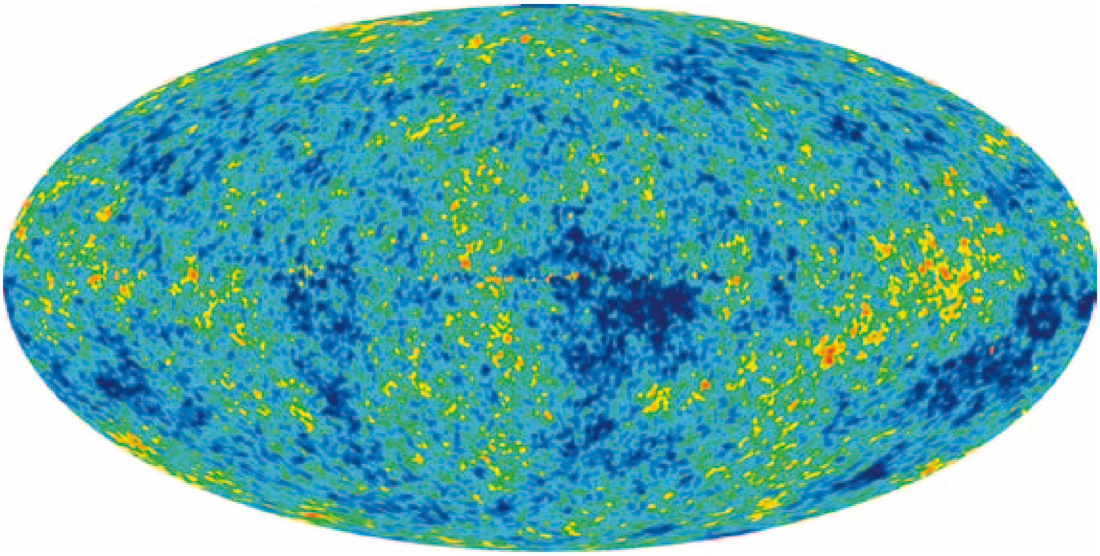

Figure 3: WMAP's image of CMBR temperature fluctuations. The red spots are 1/10,000 of a degree hotter than the blue regions.

WMAP measurements directly tested the inflationary model predictions

The WMAP measurements have directly tested these essential predictions of the simplest inflationary model. The WMAP data implies that the geometry of the universe is remarkably close to flat and supports the astronomical evidence (primarily from supernovae observations) that the universe today is again undergoing a vacuum energy-driven period of accelerating expansion. The basic CMBR fluctuations are remarkably well fit by a Gaussian (top-hat) distribution and appear to be statistically random. The pattern of temperature and polarization fluctuations also reveal that the variations in density were adiabatic, another dramatic confirmation of the predictions of the inflationary model. The WMAP data also confirmed that the expansion rate of the universe is accelerating today.

What more can we learn about inflation? Inflationary models also predict the production of gravitational waves that have distinctive signature in the pattern of microwave polarization fluctuations. The Planck satellite and several ground and balloon-based experiments are currently trying to detect this signal.

Does inflation predict other signatures? *Is there more information hidden in our image of the CMBR (Figure 3)*? Some inflationary models including many of the string theory-inspired models, predict subtle correlations in the maps. Since Eiichiro Komatsu came to Princeton to work with me on a JSPS graduate fellowship over a decade ago, I have been interested in looking for these "non-Gaussian" signals. Some of my work at IPMU is an effort to look for new ways of observing these signatures. With its rich mix of physicists, astronomers and mathematicians, IPMU is an ideal environment to contemplate and identify novel signatures of early universe physics and to continue our quest of studying the universe's first moments.