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Ask the Universe:
cosmic questions at the frontiers of gravity

The study of cosmology presents today's physicists with the biggest challenges to their understanding of gravity and of fundamental physics in general. Both on theoretical and on observational grounds, it seems that we will not be able to understand cosmology well until we understand physics better than we do today. But it also seems that cosmology could provide us with the keys to that deeper understanding of physics.

In this chapter: we confront the limits of modern physics with puzzles and clues from cosmology. They have to do with the large-scale properties of the Universe, the formation of galaxies, and event the formation of life. The next big step in theoretical physics will be the unification of gravity with the other forces. The resulting theory should be able to address the questions we ask here, and go beyond them. It should clarify quantum theory, and even tell us something new about time itself.

The biggest gap in physics is quantum gravity: we do not yet possess a consistent way of representing gravity as a quantum theory. There is no uncertainty principle in general relativity, no quantization of gravitational effects, no need to use probabilities in making predictions about the outcome of gravitational experiments. This seems inconsistent with the fact that all material systems that create gravity are quantum systems: if we can't say exactly where an electron is, how can we say exactly where its gravitational field is?

Many physicists believe that the way to quantize gravity is to unify it with the other forces of nature in a single theory in which electromagnetism and gravity are just different members of a single family of forces, and in which the unity among these forces only becomes apparent at very high energies, near the Planck energy. One would expect such a theory to predict new phenomena at these high energies. The only places where we know such energies have been met in the history of the Universe are (1) inside black holes, and (2) at the Big Bang. Phenomena inside black holes are hidden, but the Big Bang is very visible.

▷The unified theory could also predict new phenomena at lower energies, but none have been noticed in experiments. Some physicists have recently suggested that they might modify Newtonian gravity, making it stronger on distance-scales shorter than some characteristic length, which could be as large as 1 mm!

> By a combination of theory, experiment, and observation, physicists and astronomers hope to use the Universe as a laboratory to make big advances in physics. Cosmology is a hunting ground for clues to the ultimate unification of the physical forces.

Fortunately, there are many clues. We have met a number of them in passing during earlier discussions. Here is my personal list of cosmic puzzles whose solutions have the potential to revolutionize our understanding of physics.

▷The image under the text on this page is a *simulation* of the kind of data expected from NASA's MAP satellite, which began observation of the cosmic microwave background shortly before the completion of this chapter (2002). It will provide the most detailed map to date of the microwave background's irregularities. (Compare with Figure 25.4 on page 381.) These in turn will give physicists their best measures so far of the conditions in the very early Universe. Even higher-resolution data should come from the Planck mission, planned for launch by ESA by 2007. Courtesy MAP Science Team and NASA/GSFC.

- *Clue.* The Universe on the large scale is *homogeneous* and *isotropic*. Regions that, in the conventional Big Bang model, have not yet had enough time to have communicated with each other (see Figure 27.1 on page 393) are nevertheless very similar. They have the same density of matter, the same numbers and types of galaxies, the same degree of clustering; the microwave background radiation has the same temperature in all directions around us to a few parts in 10^6! How was this arranged?

- *Clue.* Galaxies could not have formed without *dark matter* seeds. Experimental searches for the dark matter may soon show what the cold component is. If it turns out to be a new elementary particle, then its identity will be a clue to new kinds of physics. There are plenty of candidates for this new physics already, but scientists need experimental or observational data to tell them which ideas are right.

- *Clue.* When astronomers make their best estimate of the total mass density of the Universe, adding in the dark matter and dark energy densities, they find it *equals the critical density* as defined in Equation 24.10 on page 361. This is a very special value, because if the Universe is critical at one time, it remains critical for all time. Many physicists feel that this should have an explanation.
- *Clue.* Observations of the cosmic microwave background strongly support the idea of *inflation*, that the Universe underwent a very early phase of enormously rapid expansion, which was driven by dark energy with a negative pressure, like a temporarily large cosmological constant. The cause of inflation is shrouded in our ignorance about physics at the highest energies, but it is already clear that many fundamental processes can mimic a cosmological constant.
- *Clue.* Observations of the expansion of the Universe seem to show that the Universe has again entered a phase of *accelerated expansion* with a much smaller dark energy. This could be a remnant of the earlier inflationary phase, or a new physical field, or a permanent cosmological constant (or all three!).
- *Clue.* Theories of high-energy physics suggest that the Universe may contain *cosmic strings*, long concentrations of dark energy, thinner than any elementary particle. Cosmic strings do not curve time but they do curve space, and they could be detected by gravitational lensing.
- *Clue.* Observations of the *highest-energy cosmic rays* have shown that the Earth is struck by about one cosmic ray with an energy larger than 10^{20} eV each second. This is a tiny flux of particles that have incredibly energy, some 10^8 times greater than physicists can produce in particle accelerators. The origin, and even the nature, of these cosmic-ray particles is a complete mystery. Maybe their sources are dark and represent new physics, or maybe the particles themselves are new.

▷For comparison with the flux of these cosmic rays, recall that in Chapter 11 we saw that in each second ten billion neutrinos of much lower energy pass through your body alone!

- *Clue.* The Universe would not have produced human beings if the laws of physics did not have some very special properties, including some apparent *coincidences among the fundamental constants of nature.* Some scientists see in these accidents a role for God, as the creator of the improbable machinery that led to life. But many others look for explanations within physics. We will discuss several mystifying coincidences below.

▷Could the coincidences be explained by selection from a large set? For example, does the Universe have many Big Bangs in different places, each beginning with a different set of randomly chosen constants, so that some are guaranteed to allow people to evolve and ask these questions? (The British astrophysicist Martin Rees (b. 1942) has called such a universe a "multiverse".) Many physicists treat such speculations seriously, and they hope that quantum gravity will provide serious answers.

We will go through this list of puzzles in this chapter, weaving these challenges into a larger discussion of quantum gravity and the prospects for a unified theory of all the forces of Nature.

Unlike in previous chapters, here we are at the frontiers. Physicists' perspectives on what is puzzling, important, or fundamental change rapidly here. Even by the time you read this, some of the puzzles on our list may have been resolved; others may have been rendered irrelevant to fundamental physics; new ones might join the list. Progress, stimulated by new observations and new theoretical speculations, is sure to be rapid but unpredictable. But don't underestimate the difficulty of arriving at a full understanding of the physics of the Universe. It is work for a generation of physicists. Or more.