

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Physics 8.224 Exploring Black Holes
General Relativity and Astrophysics
Spring 2005

QUOTE OF THE WEEK

The Royal Swedish Academy has at its meeting on November 10, 1922, according to the directions of Alfred Nobel's will from November 27, 1895, decided to – independent of the value, which after possible confirmation may be attributed to the theories of relativity and gravitation – present the prize, which for 1921 is awarded to the person who within the study of physics has made the most important discovery or invention to Albert Einstein for his services to theoretical physics, and especially for his discovery of the photoelectric effect.

– from the Nobel Prize citation for 1922 (translated by Helena Reinstad)

ASSIGNMENT: WEEK 8

For the week of 3/30 through 4/5/05

INTRODUCTION

Modern cosmology began in 1917 with the publication by Einstein of the first mathematical model for the universe as a whole based on general relativity. Einstein assumed that on large scales the universe is homogeneous and isotropic *and static*, unchanging in time. In order to make a static model, Einstein was forced to add a new term, called the **cosmological constant**, to his field equations. This term provided a uniform gravitational repulsion that balanced the gravitational attraction of ordinary matter.

In 1929, the astronomer Edwin Hubble showed that the universe is not static – the galaxies today are rushing apart as if expelled by a gigantic explosion which we now believe occurred 13.7 billion years ago. However – and this is one of the most difficult concepts for beginning students – the explosion took place everywhere, without a center. This explosion is called the Big Bang. After Hubble's discovery, Einstein disavowed his cosmological constant.

After Hubble's work, cosmology made few great advances until 1965, when a faint microwave glow filling the universe was discovered by the radio astronomers Penzias and Wilson. One of the best popular science books ever written, *The First Three Minutes* by physicist Steven Weinberg (Basic Books, 1993, ISBN 0465024378), discusses the discovery of the cosmic microwave background radiation and its implications.

Cosmology entered a third golden era in the 1980s when particle physicists began contributing ideas about the mysterious **dark matter** surrounding galaxies discovered by astronomers through its gravitational effect. Another important idea was contributed by particle physicist (now MIT

professor) Alan Guth, who proposed that during the earliest moments of the Big Bang the universe was driven into a state of exponential or near-exponential expansion by an exotic substance called **vacuum energy**. Interestingly, vacuum energy behaves just like Einstein's discredited cosmological constant. Why did Guth's model inflate while Einstein's was static? Simply because Guth made the cosmological constant so large that its gravitational repulsion overwhelmed the gravitational attraction of ordinary matter. However, Guth required that this repulsive gravitational substance would quickly decay away, leaving the universe spatially flat ($K = 0$) and in a state of rapid expansion that, 13.7 billion years later, has slowed down to the leisurely pace we see today.

A fourth revolution in cosmology began in the mid-1990s, thanks to two crucial new observations. The first made in 1998 through the optical light from distance supernova explosions and now confirmed by other observations, implies that the expansion of the universe is currently accelerating instead of decelerating as would be expected due to the gravitational attraction of matter. Once again, vacuum energy - or some other substance called **dark energy** - can explain this by its repulsive gravitational effect. The nature of dark energy is one of the most profound mysteries of science today.

The second recent observation is the discovery and measurement of fluctuations in the cosmic microwave background radiation. The most recent measurements by the WMAP satellite indicates that these fluctuations fit the predictions of Guth's cosmic inflation theory. They are the seed fluctuations that changed the homogeneous and isotropic universe into a richly textured cosmos full of galaxies, stars, and planets.

These observations are so recent that few books have been written about them. Moreover, Thorne's book excludes cosmology. Thus, in this last week of regular assignments, we provide an updated Cosmology project that replaces Project G in EBH.

If you are interested in a very broad overview of modern cosmology ranging from black holes to the big bang and other universes, you may read a popular article entitled "Piecing Together the Biggest Puzzle of All" written by distinguished astrophysicist Martin Rees for Science magazine, volume 290 (2000), pages 1919-1925. The Rees article is available online at <http://arXiv.org/abs/astro-ph/0103391> . It is optional for our class.

READING

Notes: "Project G: Cosmology"

AND

THORNE: Chapter 9 Serendipity

EVENING SEMINAR

Professor Alan Guth will discuss the Cosmological Models on Wednesday evening, March 30, from 7 to 8:30pm in Room 37-187. Feel free to come early for cookies and conversation!

RECITATION

At the usual hour 2:30 to 4pm in Room 2-131

At least one of the following questions will appear on the section quiz this week:

1. Explain BRIEFLY how radio astronomers create a radio antenna with resolving power comparable to that of a single dish many kilometers in diameter.
2. Radio signals often come from "lobes" that are far from the galaxy that is the source of the energy which they emit. Describe a physical mechanism that might result in radio emission from these lobes.
3. Make a physical argument that justifies the following variation of the density of different components of the universe as a function of the scale factor R
density of matter goes as $1/R^3$
density of radiation goes as $1/R^4$
density of dark energy is independent of R
4. When the Universe is twice as old as it is now, one of your descendents (who is living elsewhere than near our long-gone Sun!) looks at the heavens by eye. According to the cosmological model and current densities discussed in the cosmology project, what will he or she (or it) see?

PROJECTS

By 4 PM on Thursday, 4/7 post on the website for your project an abstract and outline of your project.

PROBLEM SET

By 4 PM Thursday, 4/7, submit answers to the following Queries from the Cosmology project. NOTE that you are asked to solve only parts of some Queries.

QUERY 2. Measuring Distance. Solve all parts.

QUERY 5. Contributions to the Density. Solve all parts

QUERY 6. The Friedmann-Robertson-Walker Universe. Solve all parts.

QUERY 7. Various Kinds of Universes. Solve parts A and C.

QUERY 8. Acceleration of the Scale Factor. Solve all parts.

QUERY 9. Pressure from Different Sources. Solve parts A, B, and C.