Neutrinos in Cosmology and Astrophysics

by Edward W. Kolb, Jr.

It has been over 15 years since Penzias and Wilson discovered the 3 K microwave background radiation. Interpretation of this background as a remnant of the hot Big Bang is the cornerstone of modern theories of the beginning, the present, and the future evolution of the large-scale structure of the universe. Despite the appearance of the clear night sky as viewed from the mountains of northern New Mexico, most of the photons in the universe do not originate in stars, but are present in the invisible 3 K background. Fifteen years of observation have confirmed the thermal nature of the background spectrum. A universe at a temperature of 3 K has about 400 photons per cubic centimeter, or about 10^{88} photons in the visible universe. By comparison, neutrons and protons, which number only about 10^{80}, are but a small contaminant in a vast sea of photons, (Luckily, the nucleons, unlike the photons, are not uniformly distributed.) By observing the background photons, we directly probe the state of the universe when the photons were last scattered, which occurred when the universe was at a temperature of 10^{s} K, or about 10^{6} years after the Big Bang.

In addition to the background photons, there should also be a sea of neutrinos left over from the Big Bang. There should be about as many neutrinos as photons, about 10^{88}. Confirmation of this neutrino background would be in some sense even more fundamental than the discovery of Penzias and Wilson, since the background neutrinos last scattered when the temperature of the universe was 10^{10} K, or about one second after the Big Bang. Thus, the background neutrinos are a much older relic of the origin of the universe than are the background photons.

Although direct detection of the background neutrinos seems remote, they may nevertheless play a crucial role in cosmology, and may even dominate the mass of the universe. Since the average energy of a nucleon (rest mass energy of 10^9 eV) is about 10^{13} times larger than the average energy of a background photon (10^{-4} eV), the nucleons contribute a factor of 10^5 more mass-energy to the universe than do the more numerous photons. However, if there exists a neutrino with mass greater than about 10 eV, the larger mass of the nucleon would be compensated by the sheer number of neutrinos, and the neutrinos would provide the bulk of the energy density. Although "weighing" the universe is not an easy task (where does one put the scale?), there are observational limits on its total mass. These observations require any neutrinos that survived the Big Bang and contribute to the present energy density of the universe to have a mass less than about 50 eV. If there are neutrinos with mass greater than about 20 eV, they would provide enough mass to gravitationally bind the universe, halt its expansion, and eventually cause it to recontract. It is fascinating to imagine the minuscule neutrino determining the fate of the universe.

A neutrino with a mass of a few eV may also account for the "dark mass" in galaxies. Astronomers can determine the mass of a galaxy by measuring its gravitational potential or by measuring the emitted light. However, these two methods disagree. Galaxies should be much brighter if all their mass is contained in stars. This so-called missing mass problem can be viewed as a missing light problem. Neutrinos with mass of a few eV would be expected to cluster gravitationally with the galaxies and could thus account for the dark mass.

Neutrinos may be important in astrophysics not only because of their mass, but also because of the possibility of neutrino decay, If one species of neutrino has a mass, all species of neutrinos would be expected to be massive. Most theories predict that the heaviest neutrino would be unstable. One possible decay mode would be the decay of a heavy neutrino to a light neutrino and a photon. Although the lifetime of the neutrino would be expected to be extraordinarily long, if it is less than about 10^{18} years, it may be possible to detect the ultraviolet radiation from the decay of 10-eV background neutrinos. There have even been exotic suggestions that the decay of short-lived ($\sim 10^{-14}$ s), heavy (-1 MeV) neutrinos can provide enough energy to power supernovae.

Finally, neutrino oscillation could solve the puzzle of the missing solar neutrinos. We know that a large number of electron neutrinos are produced by the reactions that power the sun. However, experiments measure a much lower solar neutrino intensity than predicted by theory. But if the electron neutrinos oscillate, they could arrive at the earth as muon or tau neutrinos, escape detection, and account for the missing neutrinos.

Because massive neutrinos offer such attractive solutions to a wide variety of astrophysical and cosmological problems, it has been suggested that massive neutrinos *must* exist. Even if one does not subscribe to such an extreme viewpoint, it is easy to understand the importance of determining the properties of the neutrino ■