The Universe as a Laboratory: Fundamental Physics

The universe serves as an unparalleled laboratory for frontier physics, providing extreme conditions and unique opportunities to test theoretical models. Astronomical observations can yield invaluable information for physicists across the entire spectrum of the science, studying everything from the smallest constituents of matter to the largest known structures.

Astronomy is the principal player in the quest to uncover the full story about the origin, evolution and ultimate fate of the universe. The earliest “baby picture” of the universe is the map of the cosmic microwave background (CMB) radiation, predicted in 1948 and discovered in 1964. For years, physicists insisted that this radiation, seen coming from all directions in space, had to have irregularities in order for the universe as we know it to exist. These irregularities were not discovered until the COBE satellite mapped the radiation in 1992. Later, the WMAP satellite refined the measurement, allowing cosmologists to pinpoint the age of the universe at 13.7 billion years.

Continued studies, including ground-based observations, seek to glean clues from the CMB about the basic nature of the universe and of its fundamental constituents.

New telescopes and new technology promise to give astronomers better information about extremely distant objects—objects seen as they were in the early history of the universe. This, in turn, will provide valuable clues about how the first stars and galaxies developed and evolved into the objects we see in the universe today.

The biggest mysteries in physics—and the biggest challenges for cosmologists—are the nature of dark matter and dark energy, which together constitute 95 percent of the universe. Dark matter was discovered by astronomers who measured its gravitational effect on “ordinary” matter in galaxies, but what it is remains unknown. Dark energy was discovered in 1998 when astronomers found that the expansion of the universe actually is accelerating, rather than slowing or progressing at a steady pace. Dark energy is the term for whatever force is counteracting gravity to cause the acceleration. Extremely precise measurements of great distances in the universe are considered a prime means of narrowing down the details of theoretical models for the nature of dark energy.

Pulsars, spinning neutron stars that pack the mass of the sun into roughly the space of a medium-sized city, offer great opportunities for a variety of physics experiments in fields ranging from gravitational waves and relativity to particle physics. These capabilities arise from pulsars’ extreme densities, intense magnetic fields and highly regular rotation periods.

Fast-rotating millisecond pulsars can serve as a natural “detector array” for making the first direct detection of gravitational waves. Albert Einstein predicted the existence of gravitational waves nearly one hundred years ago, but they have not yet been confirmed by direct evidence. Study of the first known binary pulsar, discovered in 1974, produced indirect evidence that the system was radiating gravitational waves. Now, scientists hope to see evidence of gravitational waves by precisely measuring “glitches” in the rotation of millisecond pulsars. Timing the glitches in a number of widely separated millisecond pulsars could reveal the passage of a gravitational wave, which would cause the glitch by briefly distorting spacetime.

Measuring the masses of pulsars with radio and X-ray telescopes promises to yield valuable data about the characteristics of neutron stars themselves. A neutron star approaches the density of an atomic nucleus.

Precise measurement of the neutron star's mass can put strong constraints on the exact nature of the matter in the star, and possibly make a definitive determination of what physicists call the "equation of state" of that matter. (Boyle's Law, which relates temperature, pressure, and volume, is an equation of state for gases.)

The very strong gravitational field near the super-dense neutron stars offers the ability to test predictions of Einstein's theory of general relativity in conditions unobtainable anywhere else in the universe. Einstein's theory has competitors whose predictions differ, and such strong gravitational fields provide conditions that can discriminate between the models.

In the next few years, current and planned astronomical instruments will play a vital role in answering numerous, important and outstanding questions in fundamental physics.