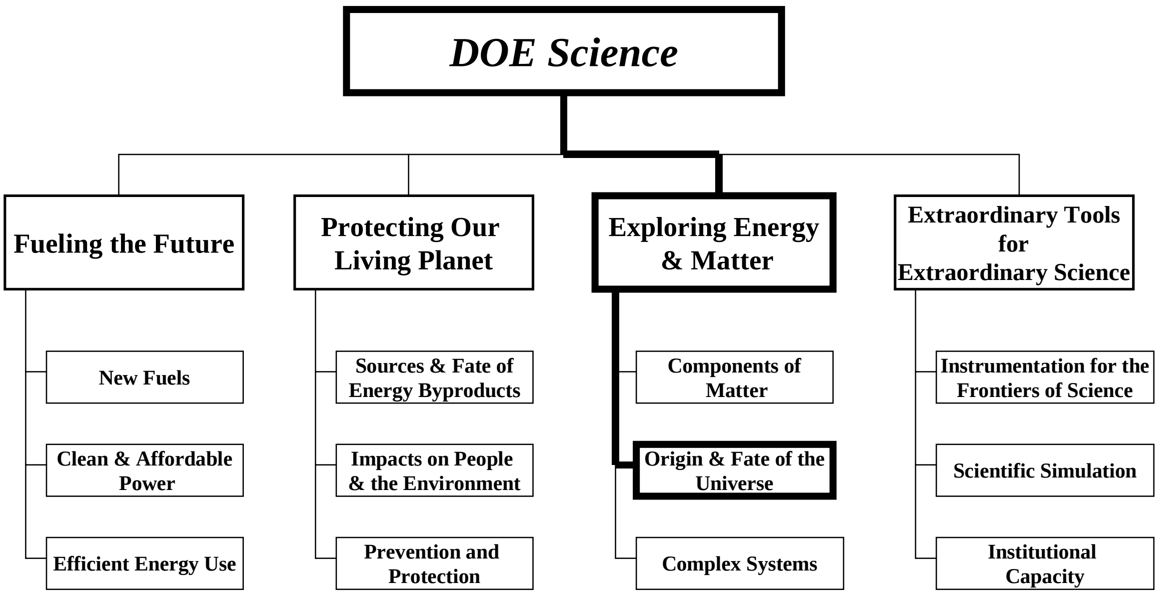
Chapter 9

Origin and Fate of the Universe

Scientific Challenge: ***To understand the evolution of the universe from fundamental laws.***



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Understanding the origin and fate of the universe seeks to answer the eternal questions: Where did we come from? Where are we going? What is the ultimate fate of the universe? The expansion of the universe, originally observed by Edwin Hubble in the 1920s, and the Cosmic Microwave Background Radiation (CMBR), discovered by Penzias and Wilson in 1962, gave rise to the Big Bang Cosmology, which theorizes that the universe began with an enormous concentration of radiant energy in an extremely small volume at an extremely high temperature (a singularity), which then expanded and cooled. After an inflationary era in which the expansion was very rapid, the expansion settled down to the steady rate observed by Hubble; the radiant energy condensed to form matter as it cooled, leaving behind the 2.7 degree CMBR that we observe today. Neutrinos also cooled to form a similar background, which has yet to be detected.

The original discovery by Hubble indicated that the velocity of recession of distant galaxies is proportional to the distance from Earth. It is as though we are on the surface of a large balloon, which is expanding at a constant rate. Very recently, observations of distant supernova suggest that there is an additional term in the expansion rate originating from a cosmological constant ("dark energy"), which can be effectively regarded as a universal repulsive force.

Modern theories of the basic building blocks of matter and the fundamental forces between them tell us a great deal about the stages of matter formation. In the earliest few seconds, the cooling radiation, consisting of photons and gluons, condenses to form pairs of fundamental particles, quarks and leptons, and their corresponding anti-particles. This is the so-called quark-gluon plasma, which the RHIC facility hopes to detect in collisions of heavy nuclei with one another. At a later stage, quarks and gluons condense to form nuclei, which then form galaxies and stars; our knowledge of high energy and nuclear physics enables us to gain insight into these processes. One in particular, the evolution of a world dominated by matter, rather than an equal mixture of matter and anti-matter, as it must have been in the beginning, is intimately related to the issues to be studied in DOE-sponsored research. Another, the question of whether the Universe will continue expanding or will slow down and start to contract, is closely related to the problem of Dark Matter and its connection with new families of particles.

In the beginning of the Big Bang, pure energy was confined to a tiny space. And the energy expanded and cooled and condensed into matter, so that it was a thick soup of photons, leptons, quarks, their anti-particles, and gluons forming a plasma. Then space inflated rapidly and, because the laws of physics did not respect the symmetry between particles and anti-particles in a mirror, photons, leptons, quarks began to predominate over anti-particles, and the universe became a universe of matter. Then it expanded more slowly, and the quarks condensed to form protons and the protons to form light nuclei in a sea of photons.

As the sea of photons cooled, it became a universal background, detectable today as the Cosmic Microwave Background, first detected by Penzias and Wilson in 1962. Photons do, however play an important role in the synthesis of light nuclei, such as helium and lithium, from primordial hydrogen. Because of tiny directional asymmetries in the photon and lepton background that arose in the inflationary era, matter began to cluster into clouds of hydrogen gas under the influence of mutual gravitational attraction. Further expansion and cooling led to separation of the gas into galaxies and stars.

The actual process of galaxy formation is a problem ideally suited to computational physics. The basic law of gravitational attraction is well understood and so can be applied to the large-scale situation in which vast numbers of particles, predominantly hydrogen atoms, interact with one another and clump together. This clumping is thought to reflect the universe's small matter asymmetries, asymmetries that have indeed been observed by the COBE satellite, and amplifies them to form the galaxies. From observing rotation curves, scientists know the universe contains a great deal of dark matter, which does not shine like the stars, but which makes its presence known through its gravitational interactions. The nature of this matter—brown dwarfs, unknown elementary particles, or massive neutrinos—is not known, and its role in galaxy formation is not fully understood. This dark matter problem is one of the principal problems of astrophysics and particle physics.

Within the stars, gravity produced further condensation which caused the temperatures in the stars to rise until they were hot enough to make the hydrogen fuse to form heavier elements. Because of the Curve of Binding Energy—a major property of the strong nuclear force—the fusion process in stars went all the way to iron and then stopped.

Stars with heavy iron cores tend to collapse under their own weight and explode, blowing off their excess material in a gigantic supernova explosion and leaving behind a dense neutron star or black hole. The explosion of some supernovae becomes visible to the naked eye over a short period of time, but neutrinos carry off most of the gravitational energy released in these explosions. Such neutrinos were detected in 1987 by large water Cerenkov detectors originally built to search for proton decay. Stellar fusion and explosions are responsible for the production and distribution of elements heavier than helium and lithium throughout the universe.

The precise mechanism of supernova explosions has been a subject of investigation for many years and is still not completely understood. While neutrinos are important, it is not entirely understood how they help to blow off the outer layers of the exploding star. Understanding this phenomenon represents a major computational challenge.

Elements heavier than iron are much harder to produce in stellar processes and are therefore relatively rare. Generally speaking they are made by neutron capture processes on iron and heavier elements, followed by beta-minus decay, which turns a neutron into a proton and thereby changes the chemical properties of the final nucleus. Some neutron capture processes (r-processes) proceed rapidly, and others (s-processes) tend to be slow. Scientists can learn a great deal about these naturally occurring processes by bombarding the parent nuclei in the laboratory with neutrons and with heavier, radioactive species.

The cosmic dust blown off by supernovae begins to accumulate in gravitationally bound orbits around stars and will, from time to time, coalesce into planets like those of the Earth's solar system. Planetary structures are too small to generate nuclear reactions, as stars do, so they can remain stable and absorb energy from the radiation emitted by the star. Under the right conditions, a planet may acquire an atmosphere of light gaseous elements, like that of the Earth, which shields it from the most harmful effects of stellar radiation, and even traps energy carried by it.

As the starlight is absorbed it can, through the process of photosynthesis, lead to the creation of biological molecules combining carbon and hydrogen and rarer elements. Much remains to be learned through laboratory experimentation regarding the formation and evolution of life on the Earth, and about the possibility of life in other planetary systems.

Beginning of the Cosmos

Description, Objectives, and Research Performers

During recent years, a close connection has developed among the research areas of high energy and nuclear physics, cosmology, astrophysics and gravity. Pertinent interdisciplinary questions concern the early moments of the Big Bang expansion of the universe as it flowered into existence, the microscopic origin of the observed cosmic asymmetry between matter and antimatter, the nature of dark matter which is thought to dominate the matter content of the universe, the possibility of “dark energy”, the formation of structure in the universe, and the ultimate fate of the Universe (whether it will expand indefinitely, and at what rate, or ultimately contract, and whether there might be multiple universes). This research is carried out at universities and national laboratories.

Research Challenges and Opportunities

A major goal is to determine the fundamental parameters of the universe itself, in the context of Einstein’s Theory of General Relativity. During the past few years there has been substantial theoretical progress in constructing candidate theories of quantum gravity (so-called super-string theories). These promise deeper understanding of black holes and even of the Big Bang itself. Many important questions remain unanswered. How did the universe evolve in its earliest moments of existence? Does the universe have curvature? Is there a cosmological constant (“dark energy”)? Recent experiments on Supernova redshifts, utilizing techniques from High Energy Physics, seem to have some indications for “dark energy.” This has led to reformulations of the early universe scenarios. Other challenges include understanding the origin of the observed baryon asymmetry in the universe (matter over anti-matter), and the origins of galaxies.

The search for dark matter provides a clear example of the deep connections between High Energy Physics and cosmology. The inflationary theory of the early universe together with astronomical measurements, favor a total density of the universe that is nearly critical. Observations tell us that most of the critical density cannot be luminous matter. Direct observation of galactic rotations indicate significant amounts, perhaps half of the galactic mass, consists of non-luminous matter. Collectively, this is called dark matter. Candidates for dark matter include massive neutrinos, and/or stable relics of the Big Bang. Such relics are predicted in theories of CP violation, supersymmetric theories and strong-interaction theories. The discovery of any one of these particles would indicate physics beyond the Standard Model, and would represent a significant advance in understanding the origin and evolution of the universe.

Research Activities

Experiments search for particle dark matter, survey large redshift supernovas and galaxies, seek to understand the small anisotropy of the cosmic microwave background, study the highest-energy cosmic rays, and search for proton decay, magnetic monopoles and neutrino masses. These experiments are conducted mostly far away from accelerators—at remote sites on mountain tops, deep mines, deep ice, high plains, or in space.

Accomplishments

- Scientists have established connections that show how the early universe evolved from a dense plasma of quarks and gluons to the vast regions of empty space in the universe. The relative amounts of hydrogen, helium and other light elements can be calculated on the basis of known nuclear properties together with observed properties of neutrinos.

- Scientists have measured in deep underground laboratories neutrinos produced by cosmic rays bombarding the atmosphere and have deduced that neutrinos may have mass. More direct accelerator-based measurements are being mounted to verify this major discovery. This was rated one of the two top discoveries of 1998 by *Science* magazine.

- Researchers formulated the theory of inflation, according to which the universe in its earliest moments went through a period of rapid expansion, enabling quarks and gluons to condense into neutrons and protons, forming the basis of atomic matter.

- Val Fitch and James Cronin were awarded the Nobel Prize for the discovery of CP violation, or the lack of symmetry between particles and anti-particles. This lack of symmetry leads to a present-day universe which is dominated by matter, rather than one equally populated by matter and anti-matter.

- High energy physics techniques for detecting photons have been used by astronomers and astrophysicists at Lawrence Berkeley National Laboratory to perform a survey of distant supernovae, one as far as ten billion light years away, to determine their distance and speed of recession from Earth. The further away the supernovae are, the longer it takes the light to reach the earth; thus the distant supernovae enable us to look at the universe at an earlier time, billions of years before the present era. The startling result of this research, confirmed by an independent survey in Australia, is that the universe appears to be expanding at an increasing rate as time goes by, that it will go on expanding forever, and that there is a “dark energy” component of the universe. This research has just been rated the top discovery of 1998 by *Science* magazine.

- According to modern theories of particle physics, the evolution of a matter-dominated universe from the Big Bang requires that the proton not be an absolutely stable particle, but must be able to eventually decay into lighter particles after a very, very long time. Present day experiments are searching directly for proton decay, but have failed to detect it thus far, indicating that a proton must live more than one hundred thousand billion billion billion years!

- The techniques of nuclear physics and high energy physics are being used today to search for other relics of the Big Bang, including relic neutrinos, magnetic monopoles, and other particles. Some of these may be related to the problem of dark matter, matter that we detect by its gravitational properties, but does not emit light or any other electromagnetic radiation

- The observational and computational techniques of high energy and nuclear physics have been used by the Sloan Digital Sky Survey to observe the most distant quasar, several billion light years away.

Creation of Nuclei and Matter

Description, Objectives, and Research Performers

Understanding the evolution of the universe beyond the first moment of the Big Bang is a matter of reconstructing events on the basis of the known laws of physics. After the initial singularity, a sequence of events had to take place as the universe cooled, in order that the universe came to be as it is today. Exactly what happened is the subject of intense theoretical speculation. In particular, scientists theorize that, very quickly after the Big Bang, the hot, dense matter (of quarks, antiquarks, leptons, antileptons, and other particles) created in the initial disturbance of the vacuum underwent a phase transition to normal matter, the stuff that makes up today's universe. In the sequence of events almost all of the antimatter was annihilated, leaving only a small excess of matter. This process requires CP violation, observed in high energy physics experiments, violation of baryon number, e.g., proton decay (not observed as yet), and/or lepton number (also not observed), and thermodynamic non-equilibrium. Protons and electrons are among the most abundant particles in the universe, numbering approximately 10^{80}. They are also extremely stable and may not decay.

Neutrinos left over from the initial annihilation are also in principle detectable, but in practice they have eluded detection. The light atoms left over represent all of the normal matter in the universe, and some of these gradually coalesced into galaxies even as the universe was expanding. The relative abundance of the light atoms is determined by the interaction dynamics. For example, the synthesis of nuclei in the early cosmos and the relative abundance of the elements D, ^{4}He, and ^{7}Li depend on the number of species of light neutrinos, and astronomical observations limits their number to be about 3. This is exactly the number observed in high energy physics experiments, and exactly the number of neutrino species in the Standard Model. This research is carried out at universities and national laboratories.

Research Challenges and Opportunities

The challenge is to find and measure the relevant entities that shed light on the early creation of matter in the universe. This includes recreating and studying in the laboratory the behavior of nuclear matter at temperatures and densities comparable to those that existed after the Big Bang. Understanding the origins of CP violation and baryon asymmetry is central to this activity. Understanding the relative abundance of the light atoms is also very important. For example, almost all the hydrogen and deuterium in the universe today was produced in the Big Bang.

Research Activities

Using relativistic heavy ion collisions, nuclear physics experiments study the behavior of hot, dense nuclear matter and search for evidence of a “quark-gluon plasma” and the phase transition to normal hadronic matter. High energy physics experiments have measured the proton lifetime to be more than 10^{32} years, for the most probable modes of decay. Theories that unify the electroweak and strong forces predict that protons decay with a lifetime in a range perhaps just beyond the reach of current experiments. Along with proton decay, these theories predict the possible existence of magnetic monopoles, relic particles created in the Big Bang carrying units of magnetic charge, analogous to electric charge. Magnetic monopoles have been sought in high energy physics experiments, so far without success. Finally, these theories predict the possible existence of even stranger objects, among them cosmic strings, of enormous length and mass. These may have existed since the Big Bang, and if so would have been instrumental in the formation of galaxies. Other experiments in high energy and nuclear physics have searched for violation of lepton number, and have set stringent limits on such processes. Other experiments are proposed to search for antimatter in cosmic radiation.

Accomplishment

- Knowledge of nuclear physics and high energy physics has enabled scientists to explain the abundances of light elements in the early universe, and to calculate the ratio of the number of hydrogen atoms to the number of photons in the universe, roughly one to one billion. These ratios are influenced by the number of different kinds of neutrino and indicate that no more than three different kinds exist. This result is consistent with the direct measurement of the number of neutrino types made by studying the Z bosons at the LEP electron-positron collider at CERN.

- Experiments have established the properties of dense “normal” nuclear matter at temperatures below that expected for the production of a “quark-gluon plasma.” This knowledge is essential for the discovery and observation of the quark-gluon plasma state of nuclear matter at higher energies and temperature at the RHIC facility.

- Radioactive beams of ^{18}F have been produced at the ATLAS facility at ANL to measure proton capture and reaction cross sections, which provide very stringent constraints to nuclear astrophysicists trying to understand the production of nuclei heavier than oxygen.

- Developing methods necessary to perform experiments at energies that correspond to the conditions in the core of a star, neutron capture in ^{7}Li has been carefully measured at the Oak Ridge Electron Accelerator (ORELA). The results of this important experiment resolved a significant discrepancy in the data needed for the understanding of the formation of heavy elements like carbon, nitrogen, and oxygen in the evolution of the universe.

Evolution of Astrophysical Structures

Description, Objectives, and Research Performers

Even as the universe expanded from its first moments, the radiation remaining from the matter-antimatter annihilation was not completely uniform and isotropic. Tiny anisotropies in those moments, a few parts per million, are evident today in observations of the anisotropy of the microwave background. These tiny imperfections could have become the seeds of galaxies according to current theories. Further, neutrinos, being part of this radiation, could also participate in the seeding, particularly if they themselves carry mass. High energy and nuclear physics experiments are currently showing some indications that neutrinos might carry a tiny mass. These anomalous regions of higher radiation density created gravitational potential wells that gradually attracted matter, which in turn caused a gravitational attraction for more matter.

As the clouds of light atoms flowed into galactic and super-galactic clusters of matter, some regions of self-gravitating matter coalesced and heated up through mutual interactions, and the first stars were born. This process was repeated hundreds of millions of times in each galaxy, for billions of galaxies. Understanding this process is a major objective of astrophysics, and understanding the underlying seeding from the early cosmos is a central goal of cosmology.

The evolution of stars and galaxies is the focus of astrophysics, aided by astronomical observations. The life cycle of a star is a fascinating subject in itself. In falling (mostly hydrogen) gas contracts and heats up under the influence of gravity, and is ignited by nuclear interactions. Protons, the nuclei of hydrogen atoms, fuse to produce deuterium nuclei that further interact with protons to produce helium. Helium cooks in the inferno, and through interactions with other nuclei, synthesis of heavier elements up to carbon occurs. Then carbon nuclei interact with other nuclei producing even heavier elements, all of the elements in the Periodic Table. Energy is produced in many of these interactions, which heats up the star and produces light and other radiation, such as neutrinos and cosmic rays. Understanding these processes, and the critical nuclear reaction rates which drive them, is a major focus of the nuclear physics program.

The end of the life cycle of a star can be spectacular, as a dying star goes through the red giant phase, and as the nuclear fires start to burn out, contracts under gravity, and in the case of larger stars, explodes into a supernova. This process results in the core of the star contracting to nuclear densities, a neutron star or pulsar as it is known from its radio wavelength radiation. In even heavier stars, the core will contract to a black hole. The latter is a meeting place and testing ground for quantum gravity, as black holes can radiate particles through a quantum process. Thus the ultimate description of a black hole must properly combine gravity and quantum mechanics. Recent work by super-string theorists has resulted in a calculation of the entropy of a black hole from a microscopic quantum theory. There are, however, many unanswered questions about the dynamics of supernovas and black holes. Understanding the explosion of a supernova will require detailed calculations of the transport of neutrinos through dense nuclear matter. Some interesting current experiments attempt to detect high energy gamma rays, and to detect the very highest energy cosmic rays, both of which may come from astrophysical sources powered by black holes. Other experiments have detected the neutrino radiation from a nearby supernova (SN1987A). Furthermore, our present understanding of element formation has the elements heavier than iron formed during the brief period of supernova explosions. Models for these processes requires knowledge of nuclear reaction rates at relevant stellar energies and with nuclear species far from the region of stable nuclei. Research in these areas is conducted at universities and national laboratories.

Research Challenges and Opportunities

The challenge is to understand the origin and evolution of stars and galaxies from first principles, and to understand the production rates of the elements observed in nature. Researchers seek to identify relevant experiments and theories. For example, determining whether neutrinos have mass not only relates to the understanding of the Standard Model, but also to the formation of galaxies. Likewise, dark matter may relate to extensions of the Standard Model (e.g., supersymmetry, grand unified theories, super-strings), and also to galactic rotations. The observed elemental abundances relate directly to a number of critical nuclear reaction rates.

Research Activities

Experiments and theoretical investigations that bear on the understanding of the formation and evolution of astrophysical structures are ongoing. Direct searches are underway for dark matter, neutrino mass, magnetic monopoles, supernovas, and high energy cosmic. The calculations relating to Black Holes, supernova dynamics, and the seeding of galaxies comprise much of the current theoretical activities. New accelerator facilities and instrumentation are being developed to measure critical nuclear reaction rates for element formation. In particular, the concept is being developed for a new accelerator, the Rare Isotope Accelerator, that will produce intense radioactive beams far from stability.

Accomplishments

- William Fowler was awarded the Nobel Prize for his theoretical and experimental studies of nuclear reactions of importance in the formation of the chemical elements. His work, together with experimental and theoretical efforts in recent years, has resulted in the basic framework for understanding the production of the chemical elements of the universe.

- The SuperKamiokande detector has found strong evidence for neutrino mass—a result just rated as one of the top ten scientific discoveries of 1998 by Science Magazine—and this may provide part of the missing mass, or dark matter of the universe. New experiments are being mounted at accelerators to determine the mass parameters. Also, a new detector, KamLAND, is being constructed by a Japanese-American collaboration to measure the mass parameters of reactor-generated neutrinos. The Big Bang has left behind a sea of relic photons that have been measured with great accuracy by COBE satellite. Tiny inhomogeneities, at the level of one part in ten thousand have been detected, and these appear to be responsible for the formation of the galaxies we see today.

- The Sloan Digital Sky Survey has revealed the most distant quasar ever discovered.

- Precision measurements of giant resonance excitation in nuclei using the Texas A&M Cyclotron have led to an accurate determination of the compressibility of nuclear matter at the density of ground state nuclei. This information is an important experimental ingredient in developing the equation of state of nuclear matter, which is needed in models of supernova evolution.

Formation of Life

Description, Objectives, and Research Performers

As the universe evolved, so too did life, from a collection of complex biomolecular structures to simple organisms capable of replication. With the discussion just a few years ago of possible simple life on Mars, our view of the universe, and of our own uniqueness on planet Earth, continues to change. Similarly, exploration of our own planet, aided by science and technologies developed at the Department of Energy, are radically changing our view of the formation of life and the possibilities of life in extreme environments. For example, science that began as an initial outgrowth of the atomic era—an era challenged with understanding the effects of radiation on living organisms—recently culminated in the identification of a new form of life on Earth, a third kingdom of living organisms known as Archaea (from the Greek word for ancient). Archaea are distinct from other microbes in that they lack a cell nucleus. DOE's Microbial Genome Program performed the genomic sequencing of the first Archea, *Methanococcus jannaschii*, a methane-producer that dwells in the extremely harsh conditions of "white smokers" on the sea floor. This genomic sequencing confirmed for the first time the emerging belief that the organism was part of a new, third kingdom. This information, coupled with similar information from sequencing of other organisms within Archaea, shows promise and may lead to several commercial products, such as heat-stable enzymes for the textile, paper, and chemical industries; systems that produce methane for chemical feedstock and renewable fuels; and tailor-made proteins that can be used to clean toxic contaminants from the environment.

Further research into the details of key microbes will enable insights into the workings of these minimal forms of life, some of which inhabit environments notable for extremes of temperature, pressure, acidity, and salinity, as well as high concentrations of toxic chemicals and even high fluxes of radiation. Beyond improvements in our understanding of evolution and the origins of life, benefits will undoubtedly extend to medicine, agriculture, industrial processes, and not least, environmental bioremediation—the latter an important issue at some Department of Energy facilities. Research is carried out at national laboratories and universities.

Research Challenges and Opportunities

Research on this topic reveals many challenges and opportunities, but understanding the structure, function, and regulation of genes at a genomic scale will be one of the great challenges in biology for the next several decades.

In addition, the identification and understanding of new organisms with interesting and useful properties will provide many new opportunities. Often nature is truly one of the best and most creative inventors. A particular challenge is to understand simple living organisms that are capable of seemingly incredible feats of self-preservation in the face of extremely harsh conditions, and to synthesize and harness these processes for various applications. One such organism is *Deinococcus radiodurans*. It prospers even when exposed to doses of radiation that would kill the typical microbe many times over. The secret is not avoidance of damage, but rather a remarkably efficient DNA repair mechanism—one that might be engineered to allow bioremediation of dangerous radioactive wastes. Another challenge is to expand and convert our scientific knowledge of *Methanococcus jannaschii* into useful expressions, such as medical, industrial, and energy applications.

Overall, advances in genomics, structural biology, instrumentation and automation, as well as the use of model organisms, pose both research challenges and opportunities in science.

Research Activities

Research activities include the identification of primitive microorganisms with potentially useful properties for bioremediation, as well as industrial, medical, and agricultural applications, with particular attention devoted to simple organisms capable of surviving in extreme environments; continued examination of intracellular processes (including life cycle and repair mechanisms, and enzymes) that regulate the life control of simple organisms; potential evolutionary aspects of simple organisms; and development of methods to accelerate genetic sequencing and structural biology research leading to high throughput technologies for providing information on gene structure.

Accomplishments

- Scientists confirmed the existence of a third form of life, the Archae, a branch at the root of life on Earth, with the complete genomic sequencing of the DNA from *Methanococcus janaschii*.

- Complete genomic sequencing of *Mycoplasma genitalium*, the smallest known free-living organism—a key to understanding the minimum requirements for life.

- Complete genomic sequencing of Archae from different families on this branch of the tree of life. These include *Archaeoglobus fulgidis* (involved in oil well souring), *Methanobacterium thermoautotropicum* (another methane producer), and an Archae that can survive at extremely high temperatures, *Pyrobaculum aerophilum*.

- Complete genomic sequencing of Deinococcus radiodurans, dubbed Conan the bacterium by the media, with potential uses in the cleanup of DOE waste sites.

Portfolio Summary

This portfolio area, “Origin and Fate of the Universe,” encompasses research from many programs and supporting activities that crosscut the research topics covered above. The table below summarizes specific core research activities that strongly support or moderately support Origin and Fate of the Universe, including beginning of the cosmos, creation of nuclei and matter, evolution of astrophysical structures, and formation of life. The funding totals for these areas are an analytic tool reflecting the highly crosscutting, leveraged aspects and implications for individual research areas within DOE's science portfolio. **Because research areas may appear in multiple chapters, there will be significant instances of multiple counting, and the chapter totals will not sum to the overall science budget.** Additional details on these research areas are presented in the Research Summary Matrix and the corresponding Research Summary Profiles.

Strongly Supportive Core Research Activities Advanced Computing and Communications Facility Operations Applied Mathematics Computer Science to Enable Scientific Computing CP Violation - B-Meson System CP Violation - K-Meson System General Plasma Science Heavy Ion Facility Ops. & Constr. Low Energy Facility Ops. & Constr. Microbial Genomics Neutrino Mass and Mixing Nuclear Structure & Astrophysics - Low Energy Nuclear Physics Nuclear Structure/Dynamics ... Phase Trans. - Heavy Ion Nuclear Physics Particle Astrophysics & Cosmology Plasma Theory and Computation Scientific Computing Application Testbeds Theoretical Nuclear Physics
Moderately Supportive Core Research Activities Atomic, Molecular, and Optical Science" Electroweak Interactions General Purpose Plant & Equipment (GPP/GPE) Hadron Spectroscopy High Energy Physics Theory High Performance Computer Networks Medium Energy Facility Ops. & Constr. Multiprogram Energy Lab Facilities Support (MELFS) Oak Ridge Landlord Quark/Gluon Substructure of Nuclei - Medium Energy Nuclear Physics Science Education Support Search for Higgs & Supersymmetry Spin Structure of Nucleons Strong Interactions, Supersymmetry & Particles
NOTE: Please see Appendix A for more information on the budgets, the research performers, and other related information for each Core Research Activity.