From the Atom to the Universe: Recent Astronomical Discoveries

Jeremiah P. Ostriker

JEREMIAH P. OSTRIKER, a Fellow of the American Academy since 1975, is the Charles A. Young Professor Emeritus of Astrophysics at Princeton University and Professor of Astronomy at Columbia University. His research interests concern dark matter and dark energy, galaxy formation, and quasars. His publications include *Heart of Darkness: Unraveling the Mysteries of the Invisible Universe* (with Simon Mitton, 2013) and the volumes *Formation of Structure in the Universe* (edited with Avishai Dekel, 1990) and *Unsolved Problems in Astrophysics* (edited with John Bahcall, 1997). He was the recipient of the U.S. National Medal of Science in 2000.

Astronomy starts at the point to which chemistry has brought us: atoms. The basic stuff of which the planets and stars are made is the same as the terrestrial material discussed and analyzed in the first set of essays in this volume. These are the chemical elements, from hydrogen to uranium. Hydrogen, found with oxygen in our plentiful oceanic water, is by far the most abundant element in the universe; iron is the most common of the heavier elements. All the combinations of atoms in the complex chemical compounds studied by chemists on Earth are also possible components of the objects that we see in the cosmos. Although almost all of the regions that we astronomers study are so hot that the more complicated compounds would be torn apart by the heat, some surprisingly unstable organic molecules, such as cyanopolyynes, have been detected in cold regions of space with very low density of matter. Nevertheless, the astronomical world is simpler than the chemical world of the laboratory or the real biological world.

But the enormous spatial and temporal extent of the cosmos allows us – and in fact forces us – to ask questions that would seem offbeat to a chemist. Where do the chemical elements come from? Precisely how, where, and when were they made? Do the abundances of the elements change with time? Does alternative "matter" that is not made of the ordinary chemical elements exist and exert gravity in the universe? We in the trades of astronomy and astrophysics *must* ask ourselves these questions – and they are only the beginning.

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In our first essay, "Reconstructing the Cosmic Evolution of the Chemical Elements," Anna Frebel asks precisely the first of these questions. A discoverer of some of the oldest and most metal-poor stars, she tells us how we have found out where and when the nuclear cooking of the elements occurred and precisely which cosmic explosions spewed out which of our familiar elements, from the sodium in salt to the gold in our jewelry. She also introduces some of the remaining mysteries of element creation in the early universe: what do we *not* know?

Let us move beyond standard units of ordinary matter to some larger objects in the universe. The Earth, our beloved planet, is but a grain of sand on the scale of the cosmos; however, it is a respectable body in our solar system of eight normal planets. For literally thousands of years the brighter of these "wanderers" (the meaning of the Greek word "πλανεται," or "planētai") puzzled our ancestors, who believed that their motions among the fixed stars foretold events on earth. The revolutionary discoveries of Tycho, Kepler, Galileo, and Newton identified our position as the third orbiter of the sun, following, along with our companion planets, precisely the paths predicted by Newton's laws of gravity and motion. But are there other planets outside of our solar system? Are the stars that we see in the night sky orbited by their own planets? When I was a graduate student, this was a subject of speculation; there was no factual knowledge. But in the last decades several independent techniques have been developed that tell us without equivocation that extrasolar planets are common! In fact, most stars probably have planets orbiting them. In "Exoplanets, 2003–2013," Gáspár Bakos lays out the dramatic tale of how we have recently found a startling variety of new planets: fat and thin, in round and in elliptical orbits, massive and lightweight. Amazingly, much of the discovery work has been done with relatively small telescopes, using the astronomical equivalent of crowdsourcing (a movement that Bakos has helped lead). The search may soon reach the point where we will be able to use large telescopes to analyze the spectra from the most interesting newly discovered planets to tell if any of them have atmospheres like ours on Earth; and then the question of "life on other worlds" will become the province of science rather than science fiction.

Next up the scale from planets is, of course, the domain of the stars – those fixed points of light in the sky that the ancients cataloged and arranged into houses or constellations. By the eighteenth century it was known that they were not, in fact, fixed, but varied in brightness and moved (albeit slowly) on their own paths across the sky, their current positions by then being significantly different from those recorded by the classical astronomers. By the twentieth century, the enigmatic "nebulae," including the common spiral nebula, were found to be simply giant assemblages of stars and galaxies – "billions and billions of stars," as incanted by the wonderful popularizer of science of the last century, Carl Sagan. We live in such a galaxy – the Milky Way – and our neighbor Andromeda, seen in the northern hemisphere in the winter sky, is another fine example of a typical spiral galaxy. The greatest classical astronomer, Hipparchus, constructed a catalog of fixed stars that had fewer than one thousand entries. By the early twentieth century, the standard HD catalog of bright stars (named for the American astronomer Henry Draper) contained over two hundred thousand entries. The Messier catalog of nebulae published in 1775 contained slightly more than one hundred objects; by the end of the nineteenth century, the similar NGC catalog contained nearly ten thousand galaxies and clusters. But now we live in the age of electronic detectors, huge telescopes, giant computers, and enormous databases. A gigantic explosion of information has occurred in our age of "big data," as outlined in the essay by Michael Strauss, "Mapping the Universe: Surveys of the Sky as Discovery Engines in Astronomy." Strauss, a leader of the Sloan Digital Sky Survey (the largest such survey completed to date), notes that catalogs now contain over a billion stars and galaxies; and they are growing – if the reader will forgive the pun – at an astronomical rate! Couple this with the new tools available for querying databases (such as Google) and one can imagine the rate of discovery.

Massive black holes are much heavier (and stranger) than any star. The first solution indicating the possibility of the existence of black holes was obtained shortly after Einstein invented general relativity in 1915, but it was decades before their character was understood and still longer before black holes were found in nature. Given their common name by the visionary physicist John Wheeler in 1967, they can form when massive stars collapse to such a small size that gravity overwhelms any pressure or nuclear forces, crushing the star into a singularity from which nothing, not even light, can escape. But gaseous matter falling into black holes is heated as it is compressed and will copiously emit light before it disappears into the abyss. This makes black holes visible to astronomers, and many have been found in our galaxy in binary star systems, each one with a mass roughly ten times that of the sun. When quasars – enormously luminous objects at the centers of distant galaxies – were discovered, their variability and incredible luminosity immediately led to speculations that they were much more massive black holes. We now know that the centers of most massive galaxies in fact harbor these enigmatic beasts whose individual masses typically range from four million solar masses at the center of our own galaxy to six billion solar masses at the center of the giant elliptical galaxy M87. The processes by which these megamonsters were formed are under intense investigation and are still quite uncertain. But the saga of how we discovered these extraordinary objects and what we now know about them can be told; and we are fortunate to have had one of the discoverers of quasars, Scott Tremaine, author the essay "The Odd Couple: Quasars and Black Holes." We are just learning that there appear to be close relations between galaxies and their resident central massive black holes, but how and why these relations were formed remains a total mystery.

Moving farther up the cosmic scale, we find galaxies, which are typically a thousand times the mass of the black holes that they harbor at their centers. Galaxies are the basic building blocks of the universe. While it is true that they are collections of stars, they also seem to be embedded in massive halos of mysterious "dark matter," the total weighing in typically at roughly a trillion solar masses with most of it in the mysterious dark component. The visible galaxies were taken for granted by Hubble and the early twentieth-century astronomers as being simply "there," but by the 1960s, the realization had spread that they must be evolving with time, and in fact their formation itself was a subject that must be addressed. Luckily, our increasingly powerful telescopes can see farther and farther out and consequently look back to earlier and earlier times due to the finite speed of light. The most distant galaxies that we can find are thus seen as they existed several billion years ago. With major telescopes, we can use the universe as a time machine and directly study the evolution – and perhaps even the formation – of galaxies in the distant past. Pieter van Dokkum has done just that; in his essay, "The Formation and Evolution of Galaxies," he will limn out what we have learned through the use of powerful telescopes and giant computers that simulate the physics of galaxy evolution. The discoveries are piling up at a great rate in the last decade and we now know that for the most massive galaxies, a two-phase evolution seems to occur: when the galaxy first forms, cold streams of gas converge, flowing into deep wells where the cosmic gravity is greatest due to dark matter accumulations, and huge numbers of stars are formed in relatively small regions. Then, at a later epoch, these monster systems eat their neighboring smaller galaxies (massive black holes and all) and grow further – perhaps by a factor of two in mass and four in size without much additional star formation. Cannibalism among the galaxies! The evolution for lower-mass galaxies like the Milky Way and our companion Andromeda is less well understood. Stay tuned.

Finally, climbing up the ladder of distance and time, we approach the largest known scale: the universe itself. During the last two decades, the knowledge of the universe accumulated over the last century has been synthesized into a well-defined global model that fits all cosmic observations to an uncanny degree. While the nature of the two chief ingredients in this model – dark matter and dark energy – remains a mystery to us, the model has passed all tests given to it so far. The existence of dark matter has been confirmed by both gravitational lensing and the growth patterns of various cosmic structures. Similarly, dark energy seems to have produced the amply observed acceleration of the universe (it is expanding faster and faster rather than slower and slower, as had been expected). But the primary tool for refining and precisely testing the new model has been the analysis of the microwave background (Cosmic Background Radiation, or CBR): the relic radiation left over from the Big Bang. The angular fluctuations seen in the sky by ever more sensitive and precise satellites studying the CBR ("COBE," launched in 1989; "WMAP," launched in 2001; and now "Planck," launched in 2009) have essentially banished doubt about the essential correctness of the standard model of cosmology. David Spergel, a leader of the WMAP satellite team, authors the final essay in this volume, "Cosmology Today," which tells the story of how these results came about, what they tell us about the universe, and what (large) puzzles still remain.

These six essays lay out for the interested reader the extraordinary renaissance that astronomy has undergone in the last decades. We are fortunate indeed to have firsthand discoverers' tales of these adventures to entertain and inform us.