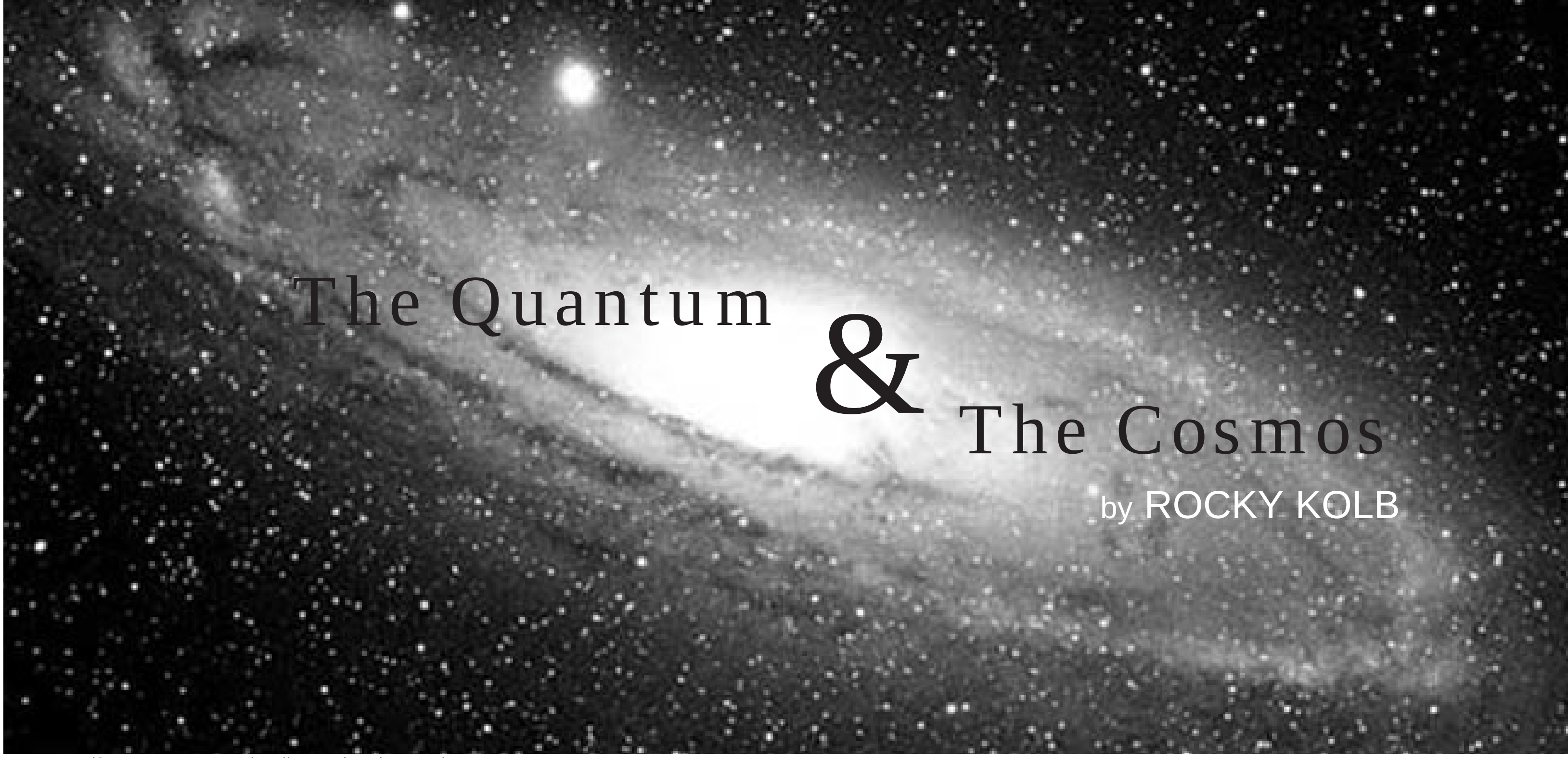


The Quantum & The Cosmos

by ROCKY KOLB

(Courtesy Jason Ware, http://www.galaxyphoto.com)

"When one tugs at a single thing in Nature, he finds it hitched to the rest of the Universe."

—John Muir

ONE NORMALLY THINKS that quantum mechanics is only relevant on submicroscopic scales, operating in the domain of atomic, nuclear, and particle physics. But if our most exciting ideas about the evolution of the early Universe are correct, then the imprint of the quantum world is visible on astronomical scales. The possibility that quantum mechanics shaped the largest structures in the Universe is one of the theories to come from the marriage of the quantum and the cosmos.

WHAT'S OUT THERE?

On a dark clear night the sky offers much to see. With the unaided eye one can see things in our solar system such as planets, as well as extrasolar objects like stars. Nearly everything visible by eye resides within our own Milky Way Galaxy. But with a little patience and skill it's possible to find a few extragalactic objects. The Andromeda Galaxy, 2.4 million light-years distant, is visible as a faint nebulous region, and from the Southern Hemisphere two small nearby galaxies (if 170,000 light-years can be considered nearby), the Magellanic Clouds, can also be seen with the unaided eye.

While the preponderance of objects seen by eye are galactic, the view through large telescopes reveals the universe beyond the Milky Way. Even with the telescopes of the nineteenth century, the great British astronomer Sir William Herschel discovered about 2,500 galaxies, and his son, Sir John Herschel, discovered an additional thousand (although neither of the Herschels knew that the objects they discovered were extragalactic). As

Galaxies fill the Hubble Deep Field, one of the most distant optical views of the Universe. The dimmest ones, some as faint as 30th magnitude (about four billion times fainter than stars visible to the unaided eye), are very distant and represent what the Universe looked ike in the extreme past, perhaps less than one billion years after the Big Bang. To make this Deep Field image, astronomers selected an uncluttered area of the sky in the constellation Ursa Major and pointed the Hubble Space Telescope at a single spot for 10 days accumulating and combining many separate exposures. With each additional exposure, fainter objects were revealed. The final result can be used to explore the mysteries of galaxy evolution and the early Universe. (Courtesy R. Williams, The HDF Team, STScI, and NASA)

astronomers built larger telescopes and looked deeper into space, the number of known galaxies grew. Although no one has ever bothered to count, astronomers have identified about four million galaxies. And there are a lot more out there!

Our deepest view into the Universe is the Hubble Deep Field. The result of a 10-day exposure of a very small region of the sky by NASA's Hubble Space Telescope, the Hubble Deep Field reveals a universe full of galaxies as far as Hubble's eye can see (photo above). If the Space Telescope could take the time to survey the entire sky to the depth of the Deep Field, it would find more than 50 billion galaxies.

Although large galaxies contain at least 100 billion stars and stretch across 100,000 light-years or more of space, they aren't the biggest things in the Universe. Just as stars are part of galaxies, galaxies are part of larger structures.

Many galaxies are members of groups containing a few dozen to a hundred galaxies, or even larger assemblages known as clusters, containing several thousand galaxies. Clusters of galaxies are part of even larger associations called superclusters, containing dozens of clusters spread out over 100 million light-years of space. Even superclusters may not be the largest things in the Universe. The largest surveys of the Universe suggest to some astronomers that galaxies are organized on two-dimensional sheet-like structures, while others believe that galaxies lie along extended one-dimensional filaments. The exact nature of how galaxies are arranged in the Universe is still a matter of debate among cosmologists. A picture of the arrangement of galaxies on the largest scales is only now emerging.

Not all of the Universe is visible to the eye. In addition to patterns in the arrangement of matter in the visible Universe, there is also a structure to the background radiation.

The Universe is awash in a thermal bath of radiation, with a temperature of three degrees above absolute zero (3 K or –270 C). Invisible to the human eye, the background radiation is a remnant of the hot primeval fireball. First discovered in 1965 by Arno Penzias and Robert Wilson, it is a fundamental prediction of the Big Bang theory.

Soon after Penzias and Wilson discovered the background radiation, the search began for variations in the temperature of the universe. For nearly 30 years, astrophysicists searched in vain for regions of the distant Universe that were hotter or colder than average. It was not until 1992 that a team of astronomers using the Cosmic Background Explorer Satellite (COBE) discovered an intrinsic pattern in the temperature of the Universe. Since the time of the COBE discovery, a pattern of temperature variations has been measured with increasing precision by dozens of balloon-borne and terrestrial observations. A new era of precision cosmological observations is starting. Sometime in 2001 NASA will launch a new satellite, the Microwave Anisotropy Probe (MAP), and sometime in 2007 the European Space Agency will launch an even more ambitious effort, the Planck Explorer, to study temperature variations in the cosmic background radiation.

Even if our eyes were sensitive to microwave radiation, we would have a hard time discerning a pattern of temperature fluctuations since the hottest and coldest regions of the background radiation are only about one-thousandth of a percent hotter and colder than average.

Although small in magnitude, the background temperature fluctuations are large in importance since they give us a snapshot of structure in the Universe when the background photons last scattered, about 300,000 years after the Bang.

WHY IS IT THERE?

A really good answer to a deep question usually leads to even deeper questions. Once we discover what's in the Universe, a deeper question arises: Why is it there? Why are stars arranged into galaxies, galaxies into clusters, clusters into superclusters, and so on? Why are there small variations in the temperature of the Universe?

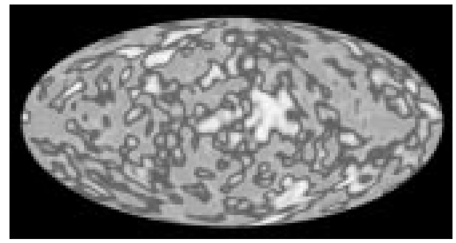
Part of the answer involves gravity. Everything we see in the Universe is the result of gravity. Every time you see a star the imprint of gravity is shining at you. Today we observe new stars forming within giant interstellar gas clouds, such as those found at the center of the Orion Nebula just 1,500 light-years away (see photo on next page).

Interstellar clouds are not smooth and uniform; they contain regions where the density of material is larger than in surrounding regions. The dense regions within the clouds are the seeds around which stars grow through the irresistible force of gravity. The dense regions pull in nearby material through the force of gravity, which compresses the material until it becomes hot and dense enough for nuclear reactions to commence and form stars.

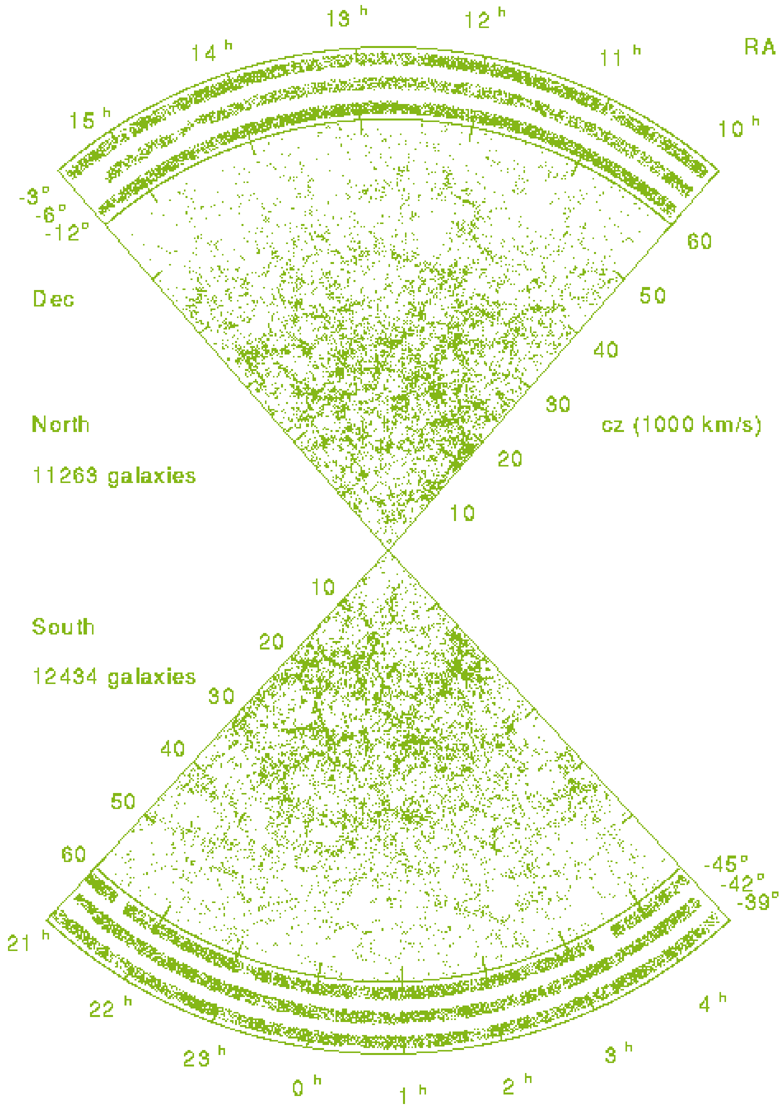
About five billion years ago in our little corner of the Milky Way, gravity started to pull together gas and dust to form our solar system. This fashioning of structure in our local neighborhood is just a small part of a process that started about 12 billion years ago on a grander scale throughout the Universe.

For the first 300 centuries after the Big Bang, the Universe expanded too rapidly for gravity to fashion structure. Finally, 30,000 years after the Bang (30,000 AB), the expansion had slowed enough for gravity to begin the long relentless process of pulling together matter to form the Universe we see today.

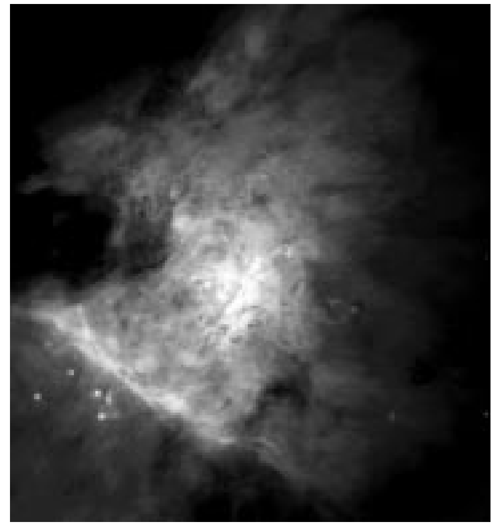
We are quite confident that gravity shaped the Universe because astrophysicists can simulate in a matter of days what Nature required 12 billion years to accomplish. Starting with the Universe as it existed 30,000 AB, large supercomputers can



The microwave radiation from the sky, as seen by COBE. The radiation has an average temperature of 2.73 degrees Centigrade above absolute zero. Here the dark and light spots are 1 part in 100,000 warmer or colder than the rest. They reveal gigantic structures stretching across enormous regions of space. The distinct regions of space are believed to be the primordial seeds produced during the Big Bang. Scientists believe these anomalous regions evolved into the galaxies and larger structures of the present-day Universe. (Courtesy Lawrence Berkeley Laboratory and NASA)



Galaxies and galaxy clusters are not evenly distributed throughout the Universe, instead they are arranged in clusters, filaments, bubbles, and vast sheet-like projections that stretch across hundreds of millions of light-years of space. The goal of the Las Campanas Redshift Survey is to provide a large galaxy sample which permits detailed and accurate analyses of the properties of galaxies in the local universe. This map shows a wedge through the Universe containing more than 20,000 galaxies (each dot is a galaxy). (Courtesy Las Campanas Redshift Survey)



The Orion nebula, one of the nearby star-forming regions in the Milky Way galaxy. (Courtesy StScI and NASA)

calculate how small primordial seeds grew to become the giant galaxies, clusters of galaxies, superclusters, walls, and filaments we see throughout the Universe.

Gravity alone cannot be the final answer to the question of why matter in the Universe has such a rich and varied arrangement. For the force of gravity to pull things together requires small initial seeds where the density is larger than the surrounding regions. In a very real sense, the fact there is anything in the Universe at all is because there were primordial seeds in the Universe. While the force of gravity is inexorable, structure cannot grow without the seeds to cultivate. Just as though there wouldn't be any seeds to trigger star formation within the Orion Nebula if the gas and dust were perfectly uniform, structure would never have formed if the entire Universe was completely uniform. Without primordial seeds in the Universe 30,000 AB, gravity would be unable to shape the Universe into the form we now see. A seedless universe would be a pretty boring place to live, because matter would remain perfectly uniform rather than assembling into discrete structures.

The pattern of structure we see in the Universe today reflects the pattern of initial seeds. Seeds have to be inserted by hand into the computer simulations of the formation of structure. Since the aim of cosmology is to understand the structure of the Universe on the basis of physical laws, we just can't end the story by saying structure exists because there were primordial seeds. For a complete answer to the questions of why are there things in the Universe, we have to know what planted the primordial seeds.

In the microworld of subatomic physics, there is an inherent uncertainty about the positions and energies of particles. According to the uncertainty principle, energy isn't always conserved—it can be violated for a brief period of time. Because quantum mechanics applies to the microworld, only tiny amounts of energy are involved, and the time during which energy is out of balance is exceedingly short.

One of the consequences of the uncertainty principle is that a region of seemingly empty space is not really empty, but is a seething froth in which every sort of fundamental particle pops out of empty space for a brief instant before annihilating with its antiparticle and disappearing.

Empty space only looks like a quiet, calm place because we can't see Nature operating on submicroscopic scales. In order to see these quantum fluctuations we would have to take a small region of space and blow it up in size. Of course that is not possible in any terrestrial laboratory, so to observe the quantum fluctuations we have to use a laboratory as large as the entire Universe.

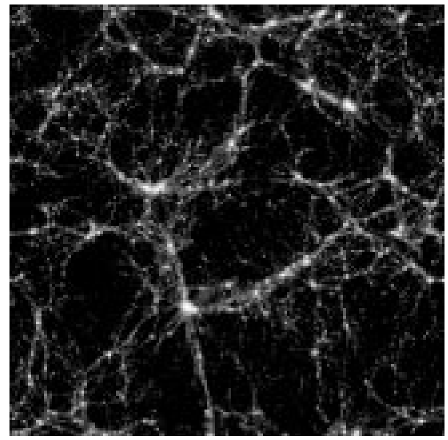
In the early-Universe theory known as inflation, space once exploded so rapidly that the pattern of microscopic vacuum quantum fluctuations became frozen into the fabric of space. The expansion of the Universe stretched the microscopic pattern of quantum fluctuations to astronomical size.

Much later, the pattern of what once were quantum fluctuations of the vacuum appear as small fluctuations in the mass density of the Universe and variations in the temperature of the background radiation.

If this theory is correct, then seeds of structure are nothing more than patterns of quantum fluctuations from the inflationary era. In a very real sense, quantum fluctuations would be the origin of everything we see in the Universe.

When viewing assemblages of stars in galaxies or galaxies in galactic clusters, or when viewing the pattern of fluctuations in the background radiation, you are actually *seeing* quantum fluctuations. Without the quantum world, the Universe would be a boring place, devoid of structures like galaxies, stars, planets, people, poodles, or petunias.

This deep connection between the quantum and the cosmos may be the ultimate expression of the true unity of science. The study of the very large leads to the study of the very small. Or as the great American naturalist John Muir stated, "When one tugs at a single thing in Nature, he finds it hitched to the rest of the Universe."



One of several computer simulations of the large-scale structure of the Universe (spatial distribution of galaxies) carried out by the VIRGO collaboration. These simulations attempt to understand the observed large-scale structure by testing various physics models. (Courtesy VIRGO Collaboration)

For Additional Information on the Internet

Rocky Kolb. http://www-astro-theory.fnal.gov/Personal/rocky/welcome.html

Jason Ware. http://www.galaxyphoto.com

Hubble Space Telescope Public Pictures. http://oposite.stsci.edu/pubinfo/Pictures.html

NASA Image eXchange. http://nix.nasa.gov/

VIRGO Consortium. http://star-www.dur.ac.uk/~frazerp/virgo/virgo.html

COBE Sky Map. http://www.lbl.gov/LBL-PID/George-Smoot.html

Las Campanas Redshift Survey. http://manaslu.astro.utoronto.ca/~lin/lcrs.html

Sloan Digital Sky Survey. http://www.sdss.org