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A MILLENNIUM VIEW OF THE UNIVERSE

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We live in a universe that is amazingly beautiful, enormously large, and incredibly complex. Only during the 20th century have we had the tools and the technology to discover some of its secrets. Progress in understanding the universe has been one of the major intellectual achievements of this century. Yet our understanding is far from complete. I believe that there are deep mysteries that we have yet to uncover.

Due principally to the work of Kapteyn, De Sittter, Oort, Einstein, Lemaître, Hubble, Shapley, and others, 70 years ago we learned that we live in a Galaxy, that the universe is populated with billions of other galaxies, and that galaxies are moving away from each other. The best explanation is that the universe originated in an enormously hot, dense singularity, and has been expanding and cooling ever since. As the universe evolves, galaxies evolve, stars evolve, planets evolve, and life evolves. Only recently have we understood how interrelated are all the features of the universe. Almost a century ago, John Muir (1915) wrote, "When we try to pick out anything by itself, we find it hitched to everything else in the universe". It is these connections that I would like to identify today.

From observations of the nearby universe, we have learned:

(1) The universe is lumpy; stars form into galaxies, galaxies join into clusters, and clusters merge into superclusters.

(2) Gravity is the dominant force. Over large regions of space, whole streams of galaxies are being pulled toward regions of higher density.

(3) Most of the matter in the universe is dark. At least 90%, perhaps as much as 99%, has never been observed directly. Some of it may be conventional matter that is too faint to detect or for which radiation is not one of its properties. Some of it may be unconventional matter of a form predicted by some theories. It could be something we have not yet imagined.

(4) Almost all research questions that we have asked have yet to be finally answered. We do not know the age of the universe, the ages of the oldest stars, the density of the universe, how life originated on Earth, how soon galaxies originated following the big bang, and the ultimate fate of the universe. We do not know what the dark matter is.

These are the questions that will be answered in the future.

Let me start with a description of what we can see and what we know, by describing the geography of the universe around us. When you look at the sky on a dark night from the northern hemisphere, every star that you see is a member of our own spiral Galaxy. That means the stars are gravitationally bound, all orbiting in concert about the very distant center of our Galaxy. The stars are not distributed at random, but are flattened to a plane. The sun, our star, is located in the plane. And when we look through the plane we see on the sky a band of millions of stars, which we call the Milky Way.

Most ancient civilizations told stories to explain the Milky Way. It was not until 1609 that Galileo turned his newly perfected telescope to the sky and discovered that the Milky Way was composed of "congeries of stars". I like to say that Galileo advanced science when he took a cardboard tube, and placed a small lens at one end and a large brain at the other. Galileo's great genius was not only that he discovered things never before seen in the sky, but that he was able to understand and interpret what he saw.

Our Galaxy contains more than just stars. It contains clouds of gas and dust which may obscure more distant objects. From our position in the Galaxy we cannot see all the way to its center. When we use the telescope to look away from the plane of our Galaxy, we see external galaxies, each an independent agglomeration of billions of stars. In each galaxy, all the stars are gravitationally bound to that galaxy. Telescopic views of external galaxies convince us that we understand the structure of our Milky Way.

For the purposes of what I am going to be discussing today, there are two major facts to remember. In a galaxy, stars are very, very far apart. Relative to their diameters, the average distance between one star and the next is enormous. That is not true for galaxies. Virtually every galaxy has a companion galaxy within a few diameters. The second fact is that gravity is the force that controls stellar motions. Gravity is also the dominant force in the evolution of galaxies.

Figure 1 (see p. XIV) is a near-infrared photograph of the center and about 90 degrees on either side of the disk of our Galaxy. It was made by the orbiting COBE Satellite. This is the best picture I know of our Galaxy, and this is the photograph that should hang in schoolrooms around the world. Just as students should know about continents and oceans and polar caps and volcanoes, so they should also know about galaxies and the structure of the universe.

Seen face on, our Galaxy would look like the wide open spirals (Figure 2; see p. XIV) that we photograph with our telescopes; our sun is located far from the nucleus on the edge of a spiral arm. The sun, carrying the planets with it, has an orbit which carries it once around the galaxy in two hundred million years. Hence the sun has orbited about 20 or 30 times around the Galaxy since its formation.

The spiral arms of a galaxy are not fixed loci of stars, but regions in which the stellar density is high. A star will move into an arm and out of an arm, spending a longer period in the arm because of the higher gravity there. A fair analogy is a traffic jam on a road. If you look at a road where there is a bottleneck you will always see cars there, but from one time to the next they will not be the same cars.

As the universe cooled following the hot big bang, atoms of hydrogen and helium eventually formed, and from these elements the first generation of stars was made. It takes two things to form a star: gas, and gravity sufficient to cause the gas to contract to high density. As more gas particles are gravitationally attracted to the increasingly massive protostar, their infall energy is transformed to heat, raising the central temperature. Ultimately, the central temperature will be high enough that the star will start fusing atoms of hydrogen into helium, and helium atoms into heavier elements. During its lifetime, a star is a chemical factory for making elements more complex than the elements from which it formed. As it forms elements up to iron, energy is released, producing the starlight to which our eyes are sensitive. It is not a coincidence that human eyes have their peak sensitivity in the region of the spectrum which matches the peak of the visible solar radiation.

Ultimately, the star reaches an energy crisis, for it takes energy to produce chemical elements heavier than iron. The star reaches the end of its life, either gently, by shedding its outer atmosphere (Figure 3; see p. XV) or explosively by becoming a supernova (Figure 4). In either case, the star enriches the gas between the stars with heavier elements; these are the building blocks of future generations of stars. In some cases, it is the shock wave from the exploding supernova that compresses nearby gas, thus initiating a new generation of star formation. These stars are composed of atoms including carbon and nitrogen and oxygen, the elements necessary for life.

Star formation is a messy process, and the forming star is left with a residual disk of debris particles. Planets will ultimately form in this disk

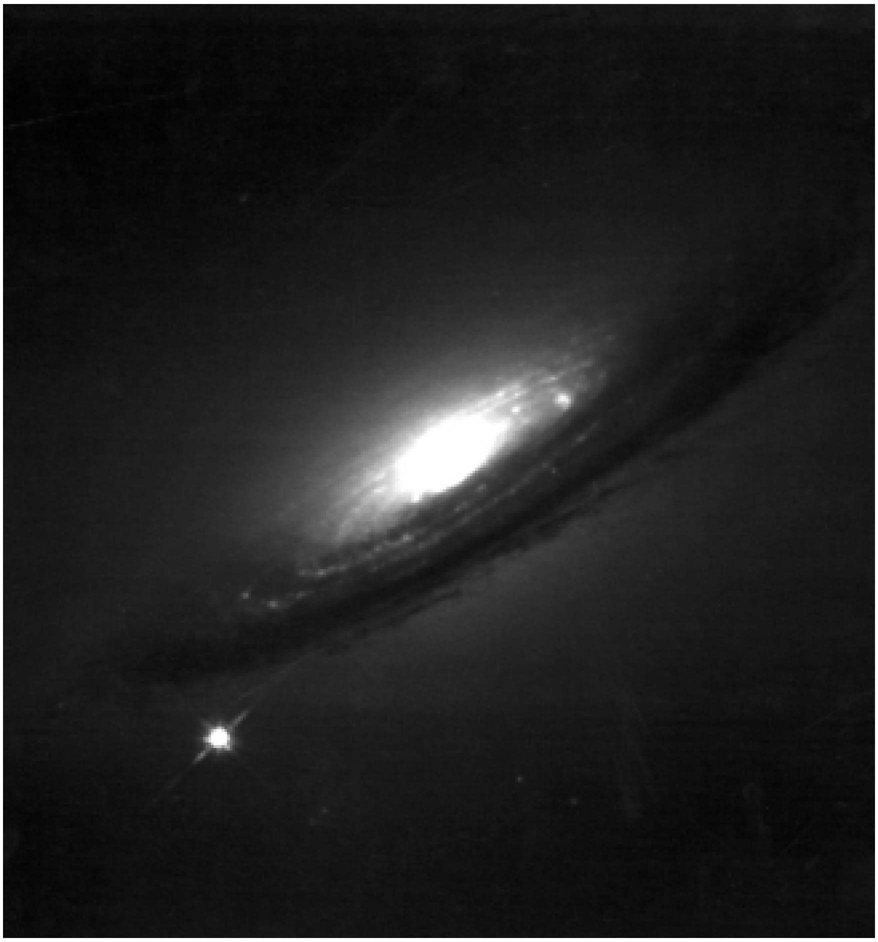

Figure 4. An image of NGC 4526, a galaxy in the Virgo cluster, taken with the Hubble orbiting telescope. The bright star is a supernova in that galaxy, SN 1994D. Credit: V.Rubin, STScI, and NASA.

from the merging of dust particles. From these particles will emerge the Earth with its iron core and its floating continents, and its biology and its living creatures. Without our Galaxy to gravitationally retain the gas atoms and molecules, without stars to make the heavy elements, and without the debris from our forming sun, the Earth and its living forms would not exist. John Muir would have liked to know this story.

Our Galaxy is not alone in space. We have two small nearby satellite galaxies, the Magellanic Clouds, visible in the sky with the naked eye from the southern hemisphere. The Magellanic Clouds orbit our Galaxy, and each orbit carries them through the gas layer of our disk. The gas between the stars is tidally disrupted as the Clouds move through. The Clouds lose energy, and their orbits diminish. Ultimately the Magellanic Clouds will cease to exist as separate galaxies. Instead, they will merge and become part of our Galaxy. A tidal tail of gas, pulled out of the Magellanic Clouds on a previous passage, is observed today by radio telescopes as a large arc of gas across the sky. The Sagittarius Dwarf, an even closer galaxy located beyond the nucleus on the other side of our Galaxy, is currently being pulled apart. Such smaller galaxies are gravitationally fragile, and hence at risk of capture by nearby, more massive galaxies.

Our Galaxy has another relatively close, but very large, companion, the Andromeda galaxy (M31). This nearest large galaxy to us has long been a favorite for study. M31 also has two bright satellite galaxies, and many fainter ones. The Andromeda galaxy and our own Galaxy are dominant members of the Local Group of galaxies. The Local Group consists of about twenty known galaxies, only a few of them large. Most are small irregular objects, each lacking a massive center. Hence they are gravitationally very fragile when they pass near larger galaxies. Ultimately, they will probably each merge with the more massive galaxy. The halo of our Galaxy contains sets of stars which were probably acquired in this fashion.

We live in an age when clusters of galaxies are forming. In some regions of space, the mutual gravity of the galaxies has overcome the expansion of the universe, and numerous galaxies gravitationally clump into one large system. Our Local Group is an outlying member of the Virgo Supercluster. Like clusters and superclusters, the Virgo Cluster contains many spheroidal galaxies. Many of these spheroidal galaxies probably formed from the merger of two or more disk galaxies, an occurrence expected frequently in the high galaxy density core of a cluster of galaxies. Spheroidal galaxies are a favorite laboratory for studying stellar motions.

This is the lumpy structure of the nearby universe is emphasized in Figure 5. We live in a spiral Galaxy that has one major companion in the Local Group. This group of galaxies is an outlying member of a large supercluster of thousands of galaxies centered on the Virgo Cluster. The gravitational attraction of the Virgo Cluster on our Galaxy is slowing down our expansion. We are expanding from Virgo due to the expansion of the universe, but at a lower speed than we would have if the Virgo galaxies were

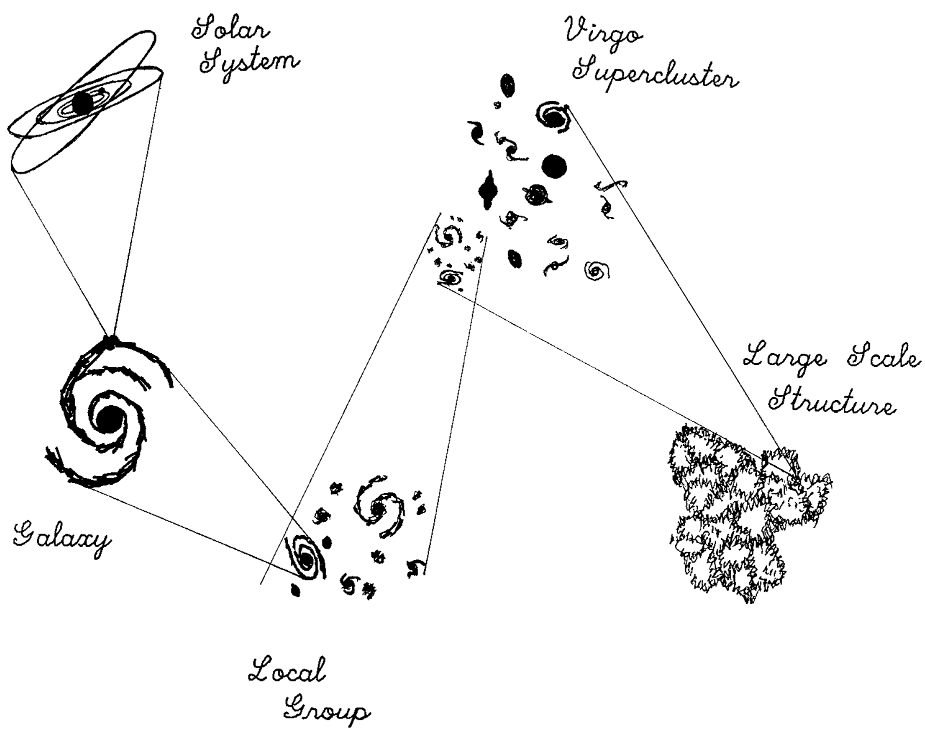

Figure 5. A sketch of the observed luminous universe, emphasizing the lumpy structure. We live on a planet orbiting a star; the star is located on the edge of a spiral arm of our Milky Way Galaxy, which is one galaxy in the Local Group of galaxies. The Local Group is an outlying member of the Virgo Supercluster, which forms one of the knots in the lumpy universe.

not there. At the center of the Virgo Cluster, the local gravitational field is so great that the expansion of the universe has been halted. The core of the cluster is not expanding, for the galaxies are all gravitationally bound to each other.

When we map the distribution of the bright galaxies on the sky, we find that their distribution is not uniform and not random. Instead, the galaxies are distributed in clusters, and the clusters form superclusters. There are galaxies in lace-like chains connecting the superclusters, as well as large regions in which no galaxies are seen. We do not know if these dark regions are void of all matter, or only void of bright matter.

I now want to turn to the evidence that there is very much dark matter in the universe. For many years I had been interested in the outer boundaries of galaxies, a subject relatively far from the mainstream of astronomy. I devised an observing program to take advantage of the new large telescopes, which would permit us to discover how stars in the outer disk orbit their galaxy center. Most of the observations were made at the Kitt Peak National Observatory outside of Tucson; others come from the Cerro Tololo Inter-American Observatory, and the cap. O of the Carnegie Institution of Washington in Chile.

By analogy with planets in the solar system, it was assumed that stars far from the galaxy center would orbit with velocities much slower than those near the galaxy center. Since before the time of Isaac Newton, scientists knew the orbital periods of the planets, Mercury, Venus, Earth, Mars, Jupiter, and Saturn, and their distances from the sun. The planet closest to the sun, Mercury, orbits very rapidly while Saturn, the planet distant from the sun, orbits very slowly. Newton taught us that gravitational forces fall off as the square of the distance from the sun, the source of the gravitational attraction in the solar system. And the planets, as all physics students know, are actually falling to the sun, but their forward motion is so great that they never reach the sun, but instead they describe an orbit. From their distances from the sun and their orbital periods, we can deduce the mass of the sun.

By similar reasoning, the mass within a galaxy can be determined from the orbital velocities of stars or gas at successive distances within that galaxy, until we reach the limit of the optical galaxy. My colleague Kent Ford and I would use at a telescope a spectrograph that splits the light from a galaxy into its component colors. Hydrogen atoms within the stars and gas produce spectral lines whose positions vary with the velocity of the source. Lines are shifted to the red for a source moving away from an observer, and shifted to the blue for sources moving toward the observer. The long slit of the spectrograph accepts light from each point along the major axis of that galaxy (Figure 6). The rotation of the galaxy carries the stars toward us on one side (therefore blue shifted), and away from us on the other side (red shifted).

By measuring the positions of the lines with great accuracy, I deduce the velocity for each observed position in the galaxy. I have obtained hundreds of spectra of galaxies, which I then study at my office. Now I record the observations and carry them via computer rather than photographic plates. In virtually all cases, the orbital velocities of stars far from the nucle-

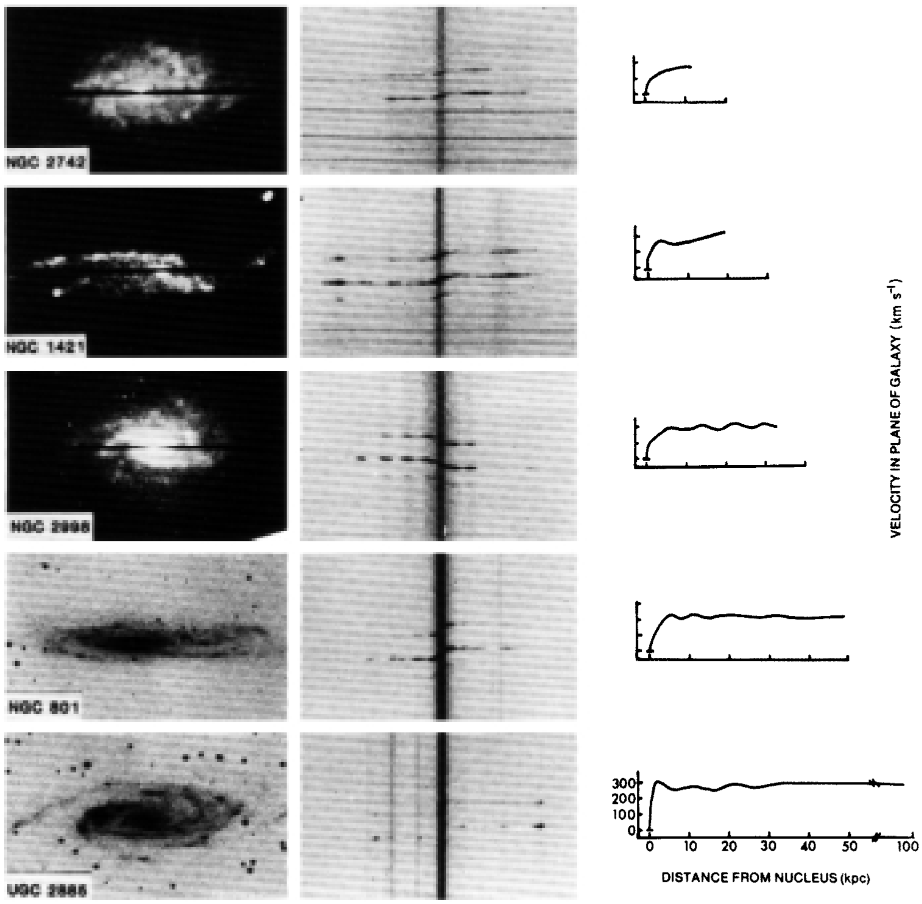

Figure 6. Images, spectra, and rotation velocities for 5 spiral galaxies. The dark line crossing the upper three galaxies is the slit of the spectrograph. The spectra show emission lines of hydrogen and nitrogen. The strongest step-shaped lines in each are from hydrogen and ionized nitrogen in the galaxy. The strong vertical line in each spectrum comes from stars in the nucleus. The undistorted horizontal lines are from the Earth's atmosphere. The curves at right show the rotation velocities as a function of nuclear distance, measured from emission lines in the spectra.

us are as high or even higher than orbital velocities of stars closer to the bright galaxy center.

Figure 6 shows five galaxies, their spectra, and their measured velocities. Whether the galaxies are intrinsically small, or intrinsically large, the rotation velocities remain high far from the nucleus. If you are a first year physics student, you know that in a system in equilibrium, a test particle orbiting a central mass M at a distance R moves with velocity V, such that the M is proportional to R times V (squared). The mass of the test particle does not enter. Thus the velocity of a gas cloud or a star (or any other test object) does not enter into the equation. This is what Galileo was trying to show when he dropped objects from the Tower of Pisa. It is not the mass of the falling (or orbiting) object which determines its velocity; it is the mass of the attractor, be it Earth or a galaxy.

As we see in Figure 6, orbital velocities are almost constant independent of distance. These tell us that the mass detected within the galaxy continues to rise with increasing distance from the center of the galaxy. Although the light in a galaxy is concentrated toward the center, the mass is less steeply concentrated. We do not know the total mass of a single galaxy; we know only the mass interior to the last measured velocity.

These high rotational velocities far out in a galaxy are one piece of evidence that most of the matter in a galaxy is dark, and that the dark matter extends beyond the optical galaxy. Stellar velocities remain high in response to the gravitational attraction of this extended distribution of dark matter. Some galaxies have hydrogen disks that extend well beyond the optical galaxy. Observations of velocities in these extended disks reveal that the rotation velocities remain high across the disks. The hydrogen gas is not the dark matter, but it too responds to the gravitational attraction of the extended dark matter. Astronomers call the distribution of dark matter a halo, but actually mean a spheroidal distribution in which the galaxy disk is embedded.

Questions concerning the dark matter remain; astronomers and physicists cannot yet supply the answers. Does it exist? Where is it? How much is there? What is it? I will briefly give the current thinking on each of these, from the view of an observer.

Does it exist? Most astronomers believe that it does. There are only two explanations that can explain these unexpectedly high orbital velocities in spiral galaxies. One possibility is that Newtonian gravitation theory does not apply over distances as great as galaxy disks, for this theory underlies our analysis. There are physicists who are attempting to devise cosmological models in which Newtonian gravitational theory is modified. But, if you accept Newton's laws, as most astronomers do at present, then the explanation is that the star velocities remain high in response to much matter that we cannot see.

Where is it? Fritz Zwicky, over sixty years ago, discovered that in a cluster of galaxies like the Virgo Cluster, many individual galaxies are moving with velocities so large that galaxies should be leaving the cluster. But evidence that clusters are not dissolving led Zwicky to suggest that there is more matter in the cluster than can be seen, and this unseen matter is gravitationally holding the cluster together. Zwicky called this “missing mass.” However, astronomers now prefer the term “dark matter,” for it is the light, not the mass that is missing.

We know now that dark matter dominates the mass of both individual galaxies and also clusters of galaxies. Direct evidence for the high dark matter mass in galaxy clusters comes from the discovery of gravitational lensing. Light from background galaxies, passing through the dense core of an intervening cluster, is gravitationally deflected, and the background galaxy images are warped into arcs and rings. A recent Hubble Space Telescope view of this effect is shown in Figure 7. Thus massive clusters act as natural telescope that enhance the intensity of the light. Nature made telescopes before Galileo did.

How much is there? Now the questions get harder to answer. The best answer is “We don’t know.” The amount of matter in the universe is fundamental to understand whether the universe will expand forever, or the

Figure 7. Galaxy cluster Abell 2218. The arcs are gravitationally lensed images of background galaxies, whose light is distorted by the mass of the foreground cluster. Credit: A. Fruchter and ERO team, STScI.

expansion will halt, and perhaps even recollapse. The galaxy and the cluster observations offer evidence that almost all the matter in a galaxy is dark. But even this high fraction of unseen matter describes a universe of low density, a universe that will continue to expand forever. However, theoretical cosmologists prefer a universe of higher density, so that the amount of matter is just sufficient to ultimately bring the expansion asymptotically to a halt. Such a high-density universe is the basis of the inflationary model of the Big Bang.

What is it? This is the question that really exposes our ignorance. Production of particles following the big bang puts a limit on the number of conventional particles in the universe. This limit suggests that only a small fraction of the dark matter can be baryonic, that is, conventional matter such as the familiar elementary particles and atoms known on Earth and in stars. Whatever constitutes the baryonic dark matter, it must be invisible: faint stars in enormous quantities, too faint to have been detected, mini-black holes, brown dwarfs, dark planets. All of these possible candidates have been looked for, and not found in significant numbers.

Some of the dark matter must be of an exotic nature unlike the atoms and molecules that compose the stars, the Earth, and our bodies. These might be neutrinos which are not massless, or those particles dreamed up but not yet detected; axions, monopoles, gravitinos, photinos. Physicists are currently devising laboratory experiments in an attempt to detect these still unknown particles. Maybe none of these ideas are correct. Observational cosmology has taught us that our imaginations are very limited. Most cosmological knowledge has come not from thinking about the cosmos, but from observing it.

This is the universe that we describe today. It would be a mistake to believe that we have solved the problems of cosmology. We have not. There are surely major features of the universe we have not yet imagined. Someday humans on Earth will know if the universe will expand forever, if the expansion is accelerating or decelerating, if life is ubiquitous throughout the universe. Most important, they will attempt to answer questions we do not now know enough to ask.

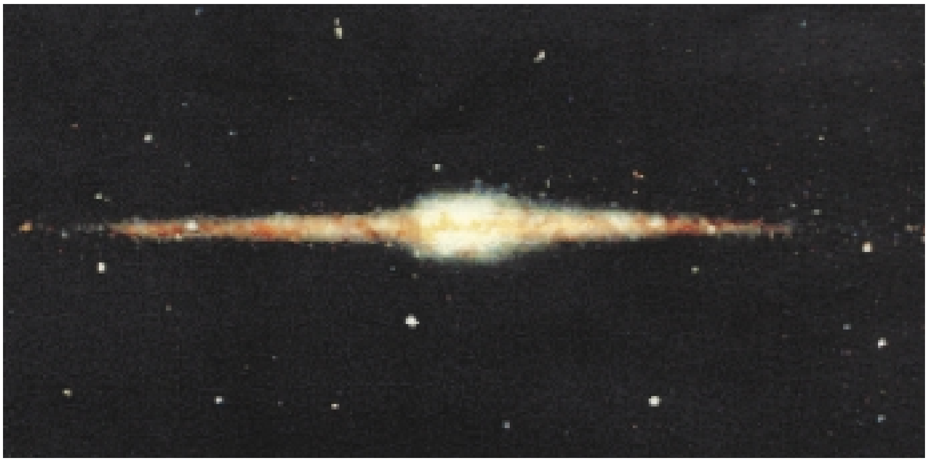

Figure 1. A near-infrared image of the Milky Way showing the central bulge and about 190 degrees of the galactic plane, taken by the COBE orbiting satellite. Most of the light in the disk and bulge comes from stars in the galactic plane. Credit: COBE/Goddard Space Flight Center/NASA.

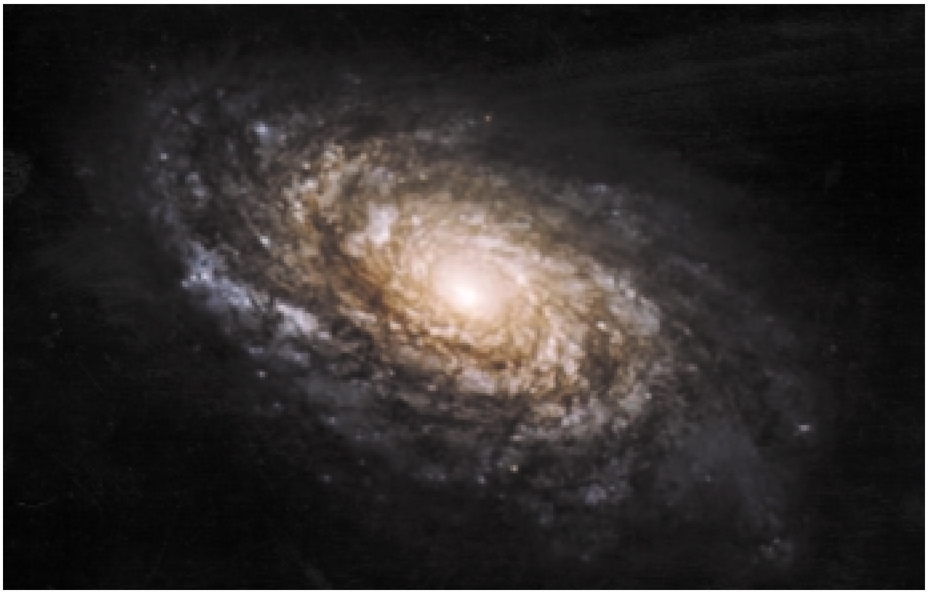

Figure 2. The spiral galaxy NGC 4414. We believe that our Galaxy, seen from outside, would resemble this spiral galaxy. Credit: Hubble Space Telescope Heritage Team (AURA/STScI/NASA).

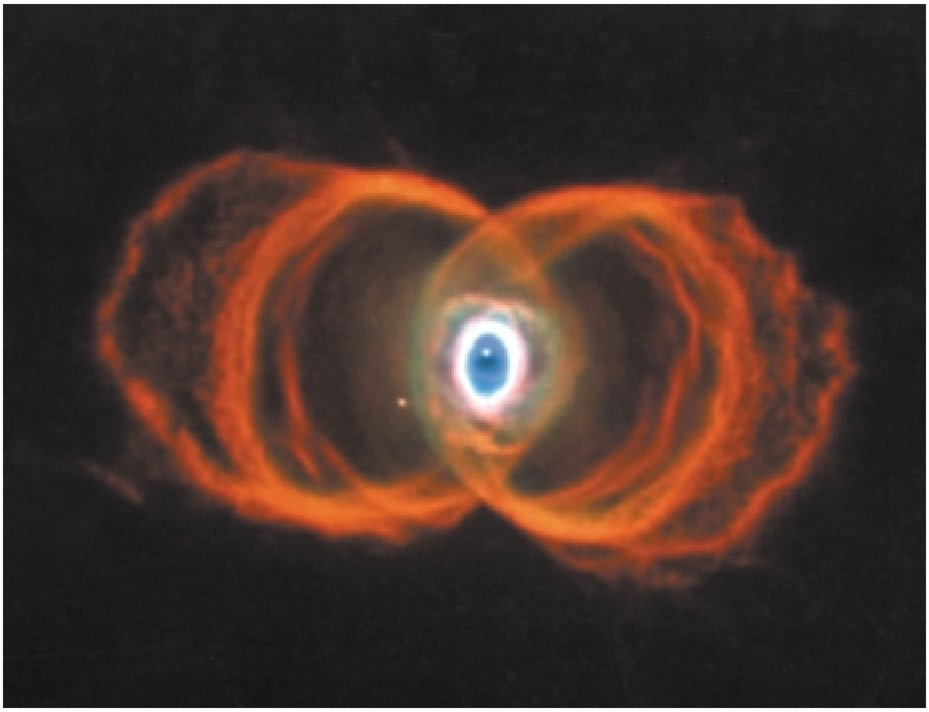

Figure 3. A Hubble Telescope image of the Hourglass Nebulae, a planetary nebula. The filaments are red because of the radiation from the hydrogen gas. Credit: R. Sahai and J. Trauger, the WFPC2 Science Team and NASA.