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Origins

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Summary. The farthest of the galaxies that can be seen through the large ground-based telescopes of modern astronomy, such as those on La Palma in the Canary Islands, are so far away that they appear as they did close to the time of the origin of the universe, perhaps some 10 billion years ago. Much has been learned, and much has still to be learned, about the young universe from optical and radio telescopes, but these instruments cannot be used to look directly at the universe in its first few hundred thousand years. Instead, they are used to search the relatively recent past for relics of much earlier times. Together with experiments planned for the next generation of elementary particle accelerators, astronomical observations should continue to extend what is known about the universe backward in time to the Big Bang and may eventually help to reveal the origins of the physical laws that govern the universe.

The subject of "Origins" was suggested to me for this talk I suppose because this topic has always attracted the curiosity of scientists, and indeed of everyone else. It is an old dream of imaginative fiction that we might somehow be able to go back in time and be present at the origins of our own world. As an American attending the inaugural ceremonies for the new observatories in the Canary Islands, I naturally imagined how it would be to go back to September of 1492, to watch Columbus on La Gomera saying goodbye to Beatriz, or to see him a few days later on ship, looking back at Mt. Teide, his last glimpse of the old world, before he turned his face finally toward the new.

Alas, we cannot go back in time. However, because light travels at only a finite speed, we can in a sense look some way back into the past. If we glance at the sun, we see it not as it is now, but as it was 8 minutes ago, when the light that reaches us now left the sun's surface. True, we cannot with the naked eye see very far back toward our origins. The brightest stars we see in the sky are close enough so that we see them now as they were only a few years ago, within our own lifetimes. Even the most distant objects that can be seen with the naked eye we see as they were a mere million years or so ago, when the universe and even Earth's inhabitants were pretty much the same as they are now.

But matters are very different when we look at a photograph of the sky as revealed by the large telescopes of modern astronomy, such as those on the island of La Palma in the Canaries. One sees in the photographs millions of galaxies like our own Milky Way, each an archipelago of thousands of millions of stars. These galaxies extend in all directions to enormous distances, and they are rushing apart, the distance between any pair of typical galaxies presently doubling every 10 billion years or so (*1*). We can mathematically trace this expansion backward in time (*2*) and identify a moment in the past, roughly 7 to 20 billion years ago, when the density of the universe would have been infinite. This we call the origin of the universe, in at least its present phase. The farthest of the galaxies we see now in astronomical photographs are so far away that we are seeing them as they were at a time close to the origin of our universe.

The universe evidently was different at that time. Not only were the galaxies several times closer together than they are now, having been carried away from each other since then by the general expansion of the universe; the galaxies themselves were different. Many more of them had active nuclei, known as quasars, that pour out thousands of times more power than entire normal galaxies, from a region of space not much larger than our solar system. These quasars are enormously interesting, not least because the most plausible mechanism that has been proposed for producing all this energy is the gravitational collapse of matter into black holes (*3*). It is one of the great disappointments of astrophysics that today, more than 20 years after the discovery of the remarkable properties of quasars, we still have no direct observational confirmation that the quasars actually are powered by black holes—it is just that no one can think of any equally plausible possibilities. Perhaps further observations will be able to improve this situation.

The quasars are interesting not only in themselves but as beacons that tell us something about the matter that lies between them and us. When the light from these quasars is broken up by a spectroscope into its component colors, one finds that the spectra of individual quasars are crossed with a forest of dark lines, indicating that light from these quasars is being absorbed in specific atomic transitions in clouds of intergalactic matter, or in the halos of galaxies along the line of sight (*4*). These spectral lines are now being actively studied to learn about the evolution of extrastellar matter in the universe at very early times, relatively soon after the light we see now left the quasars.

Observations of this sort, requiring spectroscopic study of very faint ob-

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jects, are going to continue to require the use of large ground-based telescopes, even after the Space Telescope is launched by the United States. A 4-meter telescope has about three times the light-gathering power of the Space Telescope, and with a limited amount of light that must be spread out over many wavelengths, it is light-gathering power that counts most. The Space Telescope will be invaluable for studying fine details of spatial structure (and for studies at deep ultraviolet wavelengths), but many of the most important astronomical programs are not of this sort.

At the farthest limits of our vision we seem to reach a time in the past when the quasars had not yet begun to shine. It is difficult to be sure. As Edwin Hubble said when he summarized his own work just half a century ago (*5*):

> With increasing distance, our knowledge fades, and fades rapidly. Eventually, we reach the dim boundary—the utmost limits of our telescopes. There, we measure shadows, and we search among ghostly errors of measurement for landmarks that are scarcely more substantial.

Fortunately we can look even farther back toward the origin beyond the age of the quasars, but here we have to give up the use of visible light and operate at radio wavelengths.

The universe is filled with a faint radio whisper, emitted, we think, when the universe was only a few hundred thousand years old (*6*). It was produced by a hot gas that filled the universe at that time, with a temperature of about 3000 degrees, half that of the sun's surface. (This radio noise has been cooled since then by the expansion of the universe.) The intensity of the radio noise is amazingly uniform across the sky, indicating that at that time, when the universe was a few hundred thousand years old, there were no stars or galaxies or quasars (let alone astronomers). With microwave receivers, like one used recently on Mt. Teide on Tenerife, this radio noise is being carefully scanned to search for small fluctuations from point to point in the sky. Such fluctuations might reveal the beginning of a condensation of clumps of matter out of the hot vapor that filled the universe, clumps that would eventually condense further into galaxies and stars. Present observations are just on the edge of being able to detect the clumps that we believe should have been present when the radio waves we see now were emitted.

We cannot continue to use our optical and radio telescopes as time machines to look directly into the first few hundred thousand years of the history of the universe. At these early times, the hot gas that filled the universe was highly ionized, and light of any wavelength could travel only short distances through this gas before being scattered or absorbed. Our telescopes must here be used in an indirect mode: searching the relatively recent past for relics of much earlier times. That is, the telescope is used in this mode not as a time machine but as a geologist's hammer, chipping away at the surface appearance of the present world to gain clues as to its past.

Among the most important relics are the structures we see in the sky: many stars are grouped into clusters, the clusters themselves along with loose stars like our sun are grouped into galaxies, and the galaxies themselves are grouped into clusters of galaxies. A second great disappointment of modern astrophysics has been that we still do not have a clear and detailed understanding of how these structures were formed (*7*). We do not even know whether the smaller structures formed first and then coalesced into the larger ones, or whether the larger structures formed first and then broke up into the smaller ones.

Of all the structures that we see in the sky, perhaps the most revealing have been the globular clusters (*8*). These are gravitationally bound, nearly spherical systems containing hundreds of thousands or millions of stars. As a child I happened to see a photo of a globular cluster in the constellation Hercules, which I later learned is known as M13. It looked like a great luminous ball, but I could see, much more clearly than in photographs of galaxies, that it was composed of vast numbers of stars. Even though globular clusters are just parts of galaxies, nothing has ever given me such a powerful impression that we live in a very large universe.

The globular clusters are important to astronomy because each consists of a large number of stars, all we think formed at the same time, and all at about the same distance from us, a distance that can often be inferred from the apparent luminosities of certain variable stars that are found in such clusters. The theory of stellar evolution allows one to deduce the age and the initial composition of the stars in each cluster from the observed relation between these stars' colors and luminosities. The result is that these clusters are very old, much older than our own sun, indeed the oldest objects in our galaxy. In fact there seems to be a problem here—the oldest globular clusters appear to be about 15 to 20 billion years old, older than the most popular estimates for the age of the universe, which center on 10 billion years. Speaking as a friendly outsider, I would say that astronomers should feel very pleased that estimates of these two ages, based on such very different data and theories, agree as well as they do. But it is important to clear up this discrepancy.

From the study of globular clusters and other objects we can also infer that the initial chemical composition of the matter from which the first generation of stars began was three-quarters hydrogen and one-quarter helium. Perhaps the most satisfying triumph of modern cosmological theory is that it accounts convincingly for this recipe in terms of nuclear reactions that would have occurred in the early universe (*9*). Physicists are hard at work all over the world, trying to design thermonuclear reactors in which the temperature and density would be high enough to allow nuclear reactions to fuse isotopes of hydrogen into helium, releasing useful energy. At very early times, say in the first few seconds of the universe, the problem was just the opposite: the temperature and density of radiation were everywhere so high then that nuclear reactions were going on very rapidly, but in all directions; as soon as a nucleus formed from fusion of nuclear particles, it was broken up again into other particles. It is not hard to calculate that complex nuclei could begin to hold together only when the temperature of the universe dropped to about one billion degrees, which would have been when the universe was 3 minutes old. These reactions would have produced just the observed recipe of one-quarter helium and three-quarters hydrogen.

It is not certain that this happy agreement of theory and observation will persist. Theoretical predictions of the helium abundance go up as new species of neutrinos or similar particles are discovered, and observed values are occasionally reported to be going down (*10*). It is crucial to settle this.

It is also a bit disturbing that all these estimates of the ages and compositions of the stars rest on elaborate calculations of what is going on inside them, but all that we observe is the light emitted from their surfaces. There is only one star that in a sense we have been able to look at inside. It is of course the sun, whose insides are being explored both by the painfully difficult search for solar neutrinos (*11*) and also by a sort of solar seismology (*12*) based on observations of pulsations at the sun's surface, such as the observations made with the solar telescopes at the Teide Observatory. The sun is not the star one would have chosen first for detailed study if we had a choice; it is not a first-generation star, having formed a mere 5 billion years ago out of matter that had already been cooked by earlier stars. However, it is important to use the sun as a check on our general understanding of stellar structure and evolution, which we rely on for estimates of ages and elemental abundances.

It has so far not been possible to find and identify relics of the first few seconds of the universe. To look into this very early period, we have had to rely on theory alone. There is not much difficulty in extrapolating the expansion of the universe backward in time to when the temperature of the universe would have been about a million billion degrees, or 100 GeV, which would have been when the universe was nominally about one ten-billionth of a second old. At that time, the whole of the universe that astronomers can see today was contained in a sphere smaller than our present solar system. As a result of progress made in the last 20 years in understanding the interactions of elementary particles, we can work out the detailed evolution of the matter of the universe from this very early time through the first million years, but at even earlier times we run up against our ignorance of the behavior of matter at extremely high temperatures.

For example, we have every reason to believe that, a little before the time when the temperature dropped to a million billion degrees, the matter of the universe went through what is called a "phase transition," like the freezing of water into ice, in which the fundamental symmetry between different kinds of elementary particle forces became broken, just as the spatial uniformity of liquid water is broken by its freezing into ice. We do not know precisely at what temperature this important phase transition occurred, or which of several proposed mechanisms for the transition is the correct one. These are questions that will be explored with the next generation of elementary particle accelerators, such as the Tevatron Collider at Fermilab, the Stanford Linear Collider, TRISTRAN in Japan, HERA in Germany, and eventually the large electron-positron (LEP) collider being built at the Conseil European des Recherches Nucleaires (CERN) in Geneva, and the proposed superconducting super collider (SSC) accelerator in the United States. With these accelerators, we will be able to extend our understanding of the properties of matter upward in temperature a hundredfold and ten thousand times closer in time to the origin of the universe.

However, unless someone thinks of some ingenious new technique for accelerating particles, we are not going to be able to go much farther in this direction. The SSC accelerator would have a circumference of about 100 to 150 kilometers and would cost $3 billion. Perhaps the world economy will be able to afford even larger accelerators, but surely not much larger.

I refuse to believe that fundamental physics will stop at that point. Much more is at stake here than just extending our understanding of the universe backward in time. For there is a scientific problem even more fundamental than the origin of the universe. We want to know the origin of the rules that have governed the universe and everything in it. Physicists, or at least some of us, believe that there is a simple set of laws of nature, of which all our complicated present physical and chemical laws are just mathematical consequences. We do not know these underlying laws, but, as an act of faith if you like, we expect that eventually we will.

Perhaps it may be possible to go to much higher energies with accelerators of novel design, but if this is impossible, if indeed we are nearing the end of the age of artificial accelerators, then in our search for the laws of nature we may have to rely much more on the greatest accelerator of all, the heat of the very early universe. The more or less speculative theories that physicists have proposed in the last decade lead us to expect that the present universe should contain a number of relics of very early times. One such relic may be matter itself; it is plausible that the excess of matter over antimatter in the present universe is a consequence of certain interactions that operated effectively at temperatures of about a billion billion billion degrees (*13*) and, under the conditions of the present universe, would be detected only through a very slow decay of otherwise stable atomic nuclei, such as hydrogen or oxygen or iron. However, despite great efforts this nuclear decay has not been detected, and we really do not know how to calculate precisely what amount of matter would have been produced at very early times. Theorists have recently been giving great attention to this very very early time, when the universe was about a billion billion billion billionth of a second old (*14*). One reads in the physics literature of periods of cosmic inflation, in which the whole visible universe arose from an infinitesimal quantum fluctuation, or even of phase transitions in which the number of space dimensions effectively changed from nine dimensions to the observed three. These theories are of course very adventurous, but they do predict that various sorts of exotic relics should be left over from the early universe—strings, monopoles, photinos, axions—that could be detectable today.

Astronomy has already given us a hint that one or more of these relics may actually be present. In order to account for the gravitational forces that seem to be acting in galaxies and clusters of galaxies, there must be a good deal more mass in the universe than is accounted for by the visible stars (*15*). If we assume that gravitational forces are significant over cosmic distances (as seems to be required by various theories), then there must be about 100 times more mass in the universe than we see in the stars. Also, arguments based on cosmic nucleosynthesis (*9*) and observed abundances of light elements tell us that not more than 15 percent of this dark matter could take the form of ordinary atoms. So what is the dark matter? This question of the "missing mass" is one of the most exciting in astronomy today, and physicists are fervently hoping that the missing mass will turn out to be composed of one of the particles about which we have been speculating. My own favorite candidate right now is the particle called the photino. This particle may be responsible for some of the mysterious events seen recently in experiments at CERN, and if so, then it would have to have certain properties, from which one could calculate that photinos do indeed contribute a good part of the mass of the universe. But the CERN events may have other explanations.

So it goes. The current use of astronomical observations to learn about the laws of physics continues an old scientific tradition that goes back to Isaac Newton and before. The idea that the laws of nature are exemplified in the heavens was vividly expressed by George Meredith; in his poem, *Lucifer in Starlight*, the archfiend rebels and flies about the heavens doing great damage, until

> He reached a middle height, and at the stars
> Which are the brain of heaven, he look'd, and sank.
> Around the ancient track, marched rank on rank
> The army of unalterable law.

For one reason or another, the exploration of the universe plays a role for us today somewhat like that played by the exploration of the earth in the time of Columbus. In many nations throughout the world, these explorations awaken the imagination of the public, they gain the sometimes generous support of their governments, and they attract the most strenuous efforts of the men and women who undertake the explorations. One great difference is that, while the exploration of the world set the nations of Europe at each other's throats, the exploration of the universe has tended to bring them together. In my own area of subatomic physics, we have the example of CERN, the greatest international scientific collaboration of history. In the Canary Islands we see the productive cooperation of Denmark, Ireland, Germany, the Netherlands, Spain, Sweden, and the United Kingdom, all working together, as on a happy ship, to find new worlds.

In closing, I want to go back to one more point about cosmology. You may have noticed that, despite all these brave words, I have not explained the origin of the universe. The reason, of course, is that this is a matter about which scientists still have no clear idea. We can trace the history of the present period of expansion back to its first million years, or its first three minutes, or its first ten billionth of a second, but we still do not know if time really began just a little before then, or if so, then what started the clock. It may be that we shall never know, just as we may never learn the ultimate laws of nature. But I wouldn't bet on it.

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Cell Interactions in Myxobacterial Growth and Development

Martin Dworkin and Dale Kaiser

Cell interactions dominate the activity of the nervous, immune, and endocrine systems of animals. Ever since the seminal work of Hans Spemann (*1*), it has become increasingly evident that cells of animals and plants rely on interactions also to guide their proper development in embryos (*2, 3*).

Among the variety of known interactions, four distinct patterns have emerged (*4*):

1) Cells may secrete substances that are freely diffusible. Such substances may signal other cells that are near or far—depending on the anatomy, amounts secreted, and the stability of the secretions.

2) Cells may secrete nondiffusible substances, such as an extracellular matrix, that modify the behavior of adjacent cells.

3) Cells may bind other cells and influence a bound cell by direct contact.

4) Cells may join their cytoplasms by means of localized fusions or pores. Some junctions, thus formed, allow cytoplasmic mixing; others permit only certain substances to pass.

Although many cell interactions are known in animals and plants, it is less widely appreciated that bacteria also benefit from the advantages of cell interactions. One group of bacteria in particular, the myxobacteria, actually live as rudimentary multicellular organisms and engage in various cell interactions; both diffusible substances and cell contact interactions appear to have roles in the myxobacterial life cycle. In this article we delineate the facility with which molecular genetics, biochemistry, and cell biology can be applied to the study of bacteria.

The Myxobacteria

Myxobacteria move, feed, and lie dormant in organized multicellular masses. In fact, the structural complexity of myxobacterial fruiting bodies (Fig. 1) led to their mistaken identification as fungi (*5*), until Thaxter (*6*) recognized their prokaryotic nature. The fruiting bodies of myxobacteria are the products of multicellular development and cellular differentiation. The swarming motility of myxobacteria, their cooperative feeding, and their development of fruiting bodies are based on interactions between cells. The interactions are precise because, for example, the structure of the fruiting

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