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"Planetary Exploration (Lecture One)"

Carl Sagan

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Portland State University

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CARL DITTMER: [recording begins mid-sentence] …Condon lectures. These lectures are significant to me for three very important reasons. The first is, they were named after Thomas Condon and thereby recognized his outstanding scholarly activities, which started with him as a congregational missionary, and in 1876, when the University of Oregon was formed, he was named professor of natural sciences and later became the first head of the Geology department. Throughout his life, he enjoyed the science of the earth, and he was always able to make the study of natural sciences exciting to his students and to his lay audiences. The second reason I believe these lectures have a special significance is because it keeps reminding us of the efforts of John C. Mariani, the past president of the Carnegie Institution of Washington, D.C., who prevailed on the members of the State Board of Higher Education of Oregon that they should establish an annual lectureship on human values of science and nature. And finally, the most important significance is the fact that the Oregon board of higher education actually did establish the lectureship, and in 1943 they did this, and since 1945, outstanding scholars, scientists, humanists, and philosophers have come into the state to give this distinguished set of lectures. The lecturers include such names as Robert Oppenheimer, George Beadle, Paul Sears, Rene Dubos, and last year, Jacob Bronowski.

The lectures each year are selected by a committee representing the University of Oregon—from there is Dr. Wattles; Oregon State University, Dr. Wilkinson; from the Chancellor's Office, Dr. Steedle; and from Portland State College, myself, and I'm Carl Dittmer. The lectures are given annually at the University of Oregon, Oregon State University, and Portland State College. The committee on the Condon lectures is particularly appreciative for the excellent local arrangements that were made at Portland State College by Don Schaffroth of our department of Earth Sciences. We appreciate everything you've done, Don.

To the distinguished list of lecturers, the last 22, we now add the name of Carl Sagan, who takes the credit by far of being the youngest scientist to ever have spoken from this lectureship podium. This particular fact reminds me of something that happened to a friend of mine, Dave Brown, who is a youthful provost or dean of the faculties at Drake University, when he issued an edict last fall that all parking ordinarily held by faculty, students, and staff would not be permitted, so to make it possible for friends of the university and alumni to park there because they had big festivities connected with Homecoming. At nine o'clock this particular Saturday morning, Dean Brown decided he had to pick up something at the office, and he pulled into his usual parking area, when the campus police came and said, "You can't park here, because the dean has so ordered." He said, "But I'm the dean!" And he looked at him and he said, "Boy, you graduate students try to pull everything, don't you." [laughter]

Dr. Sagan is a native of New York City; he was born there in 1934, not many years before this Condon lecture series started. He earned his A.B., his B.S., and M.S. and Ph.D. degree from the University of Chicago, receiving the Ph.D. degree in 1960 in astronomy and astrophysics. He became a Miller research fellow at the University of California in Berkeley, and since 1962 has held the chair of lectureship or assistant professor at Harvard University and a staff appointment at the Smithsonian astronomical observatory in Cambridge, Massachusetts. During this time of the appointment, he also served as assistant professor of genetics at Stanford University. This fall, he tells us, and it's been announced, that he is leaving Harvard University to take a position in the astronomy department at Cornell University in Ithaca. He is the author of many scientific papers and co-author of the following books: *The Atmosphere of Mars and Venus,* which came out in 1961; *Planets* in 1966; and *Intelligent Life in the Universe* in 1966. His major interests are in the physics and chemistry of the planetary atmospheres and surfaces; also in the origin of life on Earth and in exobiology.

I am pleased at this time to present to you the 1968 Condon lecturer, Dr. Carl Sagan, who will speak to you tonight and give you the first part of a two-part lecture on Planetary Exploration. Dr. Sagan. [applause]

CARL SAGAN: Thank you very much, Dean Dittmer; I am very pleased to be here with you. I want these two lectures to talk about planetary exploration: how it's done, what we know, what we don't know—by far the largest part is what we don't know—and also something about the "so what" of planetary exploration. Why it is important both in scientific terms and in social and political terms.

I'd like to begin by briefly reviewing for you the evolution in the past one or two thousand years of our view that we are in the universe. The first small slide… will be visible if the lights go out… This is an artist's impression of the kind of universe that we lived in two thousand years ago, or at least that they thought we lived in. Here is primitive man right here. You can barely see him, looking up. He lived, so we thought, on a sort of very large disc. It was pretty big, but it wasn't all that big; maybe it was, oh, a thousand or two thousand miles across. It was at the center of an enormous… one or several inverted bowls which was the sky. In the daytime, the sun rose and set, and in the evening, the moon went through a rising and setting process, and over the period of a month it went through phases. There were stars which had relatively fixed positions; if you observed over the period of some months there were some stars which appeared to move in a not quite erratic pattern, but certainly moved with respect to the so-called fixed stars. These wandering stars were called planets, which means "wanderers" in Greek. The word simply refers to the apparent motion over a period of months of years of the planets against the background of stars.

Now, the explanations which were forthcoming for this—there were several, but the one which prevailed, from about the time of Aristotle to the Renaissance—was the idea that the Earth was obviously at the center of the universe—what else?—that the moon and planets went around the Earth, but went around the Earth because they were attached to sort of crystal spheres which articulated smoothly. And beyond was an enormous crystal sphere in which all the fixed stars were fixed. Lights please… lights, please. Thank you. We can have the slide off. Thank you.

Well. This was a perfectly adequate view; in fact it was obviously true: a flat Earth surrounded by lots of crystal spheres. And then, at the time of the Renaissance, starting with the Polish astronomer Nicholas Copernicus, an alternative view was suggested. It was suggested that the apparent motions of the moon and planets could just as well be understood if the sun was at the center, and the Earth and moon and planets went around the sun. Then, due to the fundamental discoveries in the laws of motion and the laws of gravitation by Isaac Newton, it was even understood why, in some sense why, the planets ought to go around the sun. We now know not only that it's a better idea, that is, it explains the observations with a simpler investment of hypothesis, but also it makes certain predictions, such as that Venus ought to go through phases like the moon does, which have been confirmed; they were confirmed by Galileo when he first peered through a telescope and could make out a sensible disc of Venus instead of just a point of light. If there are any Ptolomaicists still in the audience, I can show you that there aren't any crystal spheres very simply. We have sent space vehicles past the moon and Mars and Venus, and all these space vehicles were equipped with tiny microphones which were designed to listen for micro-meteorites. Well, as these space vehicles passed through the position of these crystal spheres, there was no sound of tinkling crystal… [laughter] and so that's sort of direct evidence that the idea of crystal spheres at least was mistaken.

Well, OK. So we were not at the center of the universe; we were only one planet of, as it now turns out, nine going around the sun. But still, if this was the only place, that would be kind of all right. But we're not the only place. In fact, an amazing discovery made, oh, shortly after the… such things as I was just mentioning, was that the sun was a star, and stars were suns, and they just seemed so dim because they were so far away. They're enormously far away, and that all of those thousands of stars that you can see on a clear night—those of you who live where there are clear nights—all of those stars are suns, and if you were as far from them as you are from our sun, they would appear more or less as bright. Well, it turns out that we are sitting in a collection of stars, a collection of about two hundred billion stars, called our galaxy. I'll show you in a moment some illustrations of that. These two hundred billion stars are all, to some extent, more or less like our own. The next small slide shows you an artist's impression of some other place. My goodness. That was a good trick; can we get closer? I'd like to see what… some of the things in detail, I've never… [laughter] Well, this is, needless to say, an artist's impression, but of a very real place. This is a double star—here's an enormous red giant star, and here's a small and very hot white dwarf—it sounds like something out of the Brothers Grimm, doesn't it? And these two stars go around each other as a double star, and in the foreground is a hypothetical but perfectly possible planet which orbits the two of them. So here's a planet with two suns in the sky. The idea of having simply one paltry sun in the sky is not the only possibility. Similarly, there are many planets in our solar system which have many moons in their sky. So the sort of essential idea that we all grow up with that there's one moon and one sun and what else is a sort of provincial idea. Elsewhere, there's lots of suns, lots of moons.

Well, not only are we not at the center of the solar system, but the solar system isn't even situated in some central position in the galaxy. It was once thought that we were at the center of the galaxy and people took considerable pride in that fact: well, we're only the third planet, but we're at the exact center of the galaxy. Well, we now know through the work of Harlow Shapley on globular clusters that this is not the case; in fact, we are far off from the center, we're about 30,000 light years from the center, far in the galactic boondocks. There's nothing in any sense special about where we are. The next small slide is a perfectly typical photograph of the region towards, but not directly at, the center of our galaxy. Every one of those small white spots is a sun. This is a small fraction of the 200,000,000,000 suns in our galaxy. By the way, this red coloration is due to the emission lines of hydrogen. Hydrogen is far and away the most abundant atom in the universe.

The next small slide is a rather interesting one. This stuff in the foreground, all this, is stars in our galaxy. Behind all these stars is this nebulous, hazy, diffuse something-or-other. This is, in fact, the nearest spiral galaxy like our own. It's called M31, it's in the constellation of Andromeda. This is very similar to our own galaxy. It also has one or two hundred billion stars in it. If this were our galaxy, we would be somewhere about here. See? Here's where the action is; here's where we are. [laughter] Now, these two little things are satellite galaxies, which in fact orbit M31, suggesting to us that there are other galaxies. In fact, there are enormous numbers of other galaxies; some similar and some, like these two satellite galaxies, different from our own.

The first large slide… can you do that zoom thing? This is a typical photograph of what happens when you point a large telescope, in this case the two-hundred-inch telescope at Mt. Palomar, in some direction other than the center of our galaxy. There are some stars, see? These are sort of a diffuse scattering of stars in our own galaxy, and then through it we suddenly start seeing thousands of other galaxies. This is a spiral galaxy seen head-on; this is an irregular galaxy seen face-on; this is a globular or ellipsoidal galaxy. In fact, there's a whole question of the evolution of galaxies. How do they form, and does one of these somehow evolve into another, and so on? Well, the number of galaxies which are known by typical source counts is in the billions. And that means that the number of stars is in the hundreds of billions of billions. Lights, please. Lights, please? It's just the delay time. I have a theory that sound travels at a finite velocity and the fellow who hears me is at a very great distance away, although he can hear very well, and so there's a time delay.

Now, what about planets? How likely are planets? Is it possible that planets are extremely rare and infrequent, and that we just happen to be in one of those lucky places that has planets going around stars? Or, is it possible that planets are frequent or an invariable accompaniment of stars? Well, what can we do to learn about this? First of all, there is our own solar system. You might say that's just one example, but it's more than one example, because in addition to the planets which go around the sun, there are satellite systems which go around the planets. So that Jupiter, for example, has eleven moons which go around it, and Saturn now has ten—two years ago it only had nine, but we've found one since. Now, these are very much like miniature solar systems. See, they're all in a common plane, the same as the plane of rotation as the primary. Whatever the process was that formed planets in this solar system, it formed miniature planetary systems, the moons of the major planets. That immediately suggests that planetary formation may be common.

In addition, however, there are more direct observations. It is possible by measuring the slight gravitational perturbation due to a dark companion to detect its existence in the motion of the parent star. Now, this is a very delicate operation; such measurements are only possible for the most massive of planets, and only possible for the nearest of stars. Well, something like half of the ten or twelve nearest stars seem to have dark companions of approximately planetary mass, determined by this isometric method. That is, of course, still a small sample, but unless we believe there's something quite extraordinary about star formation in our stellar neighborhood, we are really forced to the conclusion that planets are common. That means, if we can use these numbers at all, that there are hundreds of billions of billions of planets. We live on one.

Well? How typical is our one? Is it a very common sort of planet? Are the things that happen here things that happen everywhere else, or is this an extraordinary planet in some respect? We'll never know if we don't look at other planets. Fortunately, there are eight other planets and thirty-three natural satellites in our solar system, and so it's possible to make a close scrutiny of a lot of other objects. To find out something about the uniqueness of our place, something about the generality of various sciences concerning the planets. Well, how can you go about finding out what other planets are like? You can, of course, go there and look around, and that will turn out to be not only the best but in many senses the only reliable way of doing it. But still, it's possible to garner a great amount of information indirectly, by looking at the light that is reflected or emitted from a planet and appropriately analyzing its light by the full armory of physics and chemistry. In this way it is possible to determine a great deal about planets.

I think the best way to visualize this process is to imagine it in reverse. Imagine yourself living on Mars, and there's this planet that you sometimes see in the morning sky and sometimes see in the evening sky, and it's called Earth. You probably wouldn't call it Earth; I'm just telling you which planet it is. And the question is, what about Earth? What kind of place is it? What sort of environment do they have there? Is there any possibility of life on Earth? How would you find out? Well, you might try photographing Earth. You could photograph it from the ground of Mars with a large telescope; you could get pretty good resolution. You could photograph it from a space vehicle put into orbit around Mars but still looking at the Earth; you could do it from space vehicles which fly near to Earth or go into orbit around the Earth. Well, a very good ground-based photograph of the Earth from Mars would look something like the next slide.

This is, in fact, a photograph of the Earth that's taken by a satellite which is in stationary orbit above the Pacific Ocean, and most of the photographs I'll be showing you in the next few slides are taken from other meteorological satellites. As you'd examine this photograph from your vantage point on Mars, you would, in typical astronomical tradition, divide the planet into bright areas and dark areas… [laughter] That would be safe; there's no commitment yet as to what anything is. And you would note, after some prolonged scrutiny, that these bright patterns—in fact this kind of thing here would certainly suggest turbulence to you—that the bright patterns would change. And as you would look for a long period of time, you would notice that there are some underlying faint details visible—here, for example—you can see here's dark stuff, and here's slightly brighter stuff. This is, in fact, Mexico; this is the Gulf of California, that's Baja California, that's California, and peeking in here through the clouds is Oregon. [laughter] It's cloud-covered, as you can see. Now, you would, in time, as the Earth rotated, be able to construct maps of the surface of the Earth, and these would be pretty good, or be the reasonably good topography that you'd get out of that; you would be able to determine what the period of rotation of the Earth is from the apparent time for one characteristic feature to disappear over one limn or edge of the Earth and to reappear at the other limn or edge. You would be able, in the same way, to determine what the inclination of the axis of rotation was to the plane of orbital motion, and from this information, you would be able to say something about temperature because you know how far the Earth is from the sun; from the tilt of the axis you know something about the seasons, and from the period of rotation you know how long the sunlight falls on the surface before night occurred. In this way, you would be able to calculate through physics what the temperatures on the Earth were, and your answers would be roughly right. They would, in fact, be low by about twenty or thirty degrees centigrade, because you would not have allowed for the greenhouse effect, which heats the Earth's surface somewhat above the equilibrium temperature. But still, you would be very close.

Now, how could you check this calculation? How could you determine whether you had gotten the right temperature for the Earth? Well, it's possible to measure temperature directly. You would put a thermocouple or belometer at the focus of a large telescope and measure, as the Earth swam into your field of view, just how much infrared radiation you were getting from the Earth, and you would know how far away it is—you would know about the inverse square law—you could then calculate what the average temperature of the Earth was, or, if you had resolution, if you could discriminate one part of the Earth from another, you could see what the temperatures were on different parts of the Earth. You could do just the same thing in the radio or microwave spectrum and here you'd be getting radiation not quite from the surface but from slightly sub-surface because microwaves are somewhat penetrating into matter.

The next slide is a photograph of the Earth taken not in reflective visible light, as was the last photograph, but in emitted infrared light. This is, in fact, a negative in the sense that the cold stuff is bright—the clouds here which are very bright are cold—this is a night-time emission photograph. So Italy here, which you can make out quite clearly though it is a somewhat unusual projection, is colder than the surrounding waters, and that has to do with the fact that the high specific heat of the water prevents it from heating and cooling too rapidly. So the water you would discover in this way… Well. You would discover in this way that this stuff, whatever it is, tends to be colder than the land in the daytime and warmer than the land in the evening, and that would then give you some information on its properties. In fact, from this sort of reasoning, you would be able to deduce that this stuff was very likely something like water. Incidentally, we've looked at this photograph in order to—and similar ones like it—in order to determine whether there's any way of detecting cities by the thermal emission that they have. Cities should be somewhat hotter than the countryside, but it turns out that Rome is only a few degrees hotter than the countryside and so is Vesuvius, so it's hard to distinguish cities from volcanoes. There may be a moral in that.

So, this sort of thing can be indefinitely extended. We can look at a given wavelength, at images of the Earth, with varying degrees of resolution. The next slide is back now to an ordinary photograph taken in visible light. Incidentally, this thing here—this big "X" is of course a fiducial marking on the television system, it's not on the surface of the Earth… [laughter] Actually, Captain Kidd's treasure is buried right there. Well, so now this is a resolution of the Earth of about a tenth of a kilometer. That is, anything smaller than that would, regardless of its contrast, be indetectible on this picture. Things larger than that, if they have some fair contrast with their surroundings, would be detectible. Well, if you take a close look at this, you'll find, for example, no sign of life intelligent or otherwise in Washington D.C. [laughter; applause] The same is true for New York, Moscow, Peking, Canberra, Bombay, Calcutta, Montevideo, and so on. We have looked for life on Earth in pictures such as this and the answer is negative. There's no sign of life on Earth. Now, this is quite remarkable, because… look, the eastern seaboard of the United States: this is an area with, you know, large cities and bridges and highways which are straight and you'd imagine they'd stand out, canals; there is even still some timberland, and none of this is in any way visible. Of course, there are contrasting features in here, but it's not the least bit obvious just from looking what they are.

Now, we have photographs of Mars. The best photographs we have of Mars were taken by the Mariner IV spacecraft on Bastille Day 1965, and those best photographs are somewhat poorer in resolution than this photograph of the eastern seaboard of the United States. Well, you will perhaps remember that when Mariner IV flew by Mars and these pictures were released, eager journalists scanning the pictures deduced there was no life on Mars, and newspapers were all full of how lifeless Mars was. Well, nothing could have been detected on those pictures which was smaller than about a mile across. So what was excluded was like Martian elephants a mile across. [laughter] There are some people understandably distressed about the fact that there were no Martian elephants a few miles across, but that is very different from saying that there isn't any life on Mars. But of course that doesn't say that there *is* any life on Mars. The point is that the activities of even a civilization, a life as well-developed as ours, are not readily visible photographically at this sort of resolution. In order to get some sign of life, and also, in order to get a much better set of information about other non-biological aspects of the Earth, it's necessary to improve the resolution. I mean, look how much is going on in this area that there is not the slightest sign of by this sort of photography, which is better than the best photograph we now have of any other planet. Not just biological things, but geological things, small-scale meteorological things… they're all totally invisible.

We've attempted to find some sign of life on Earth by a fairly large-scale search of these meteorological satellite photographs of the Earth, and the kind of thing we're looking for were straight lines. The idea is that large numbers of quite straight lines are generally not produced by geological processes; they are produced by technical civilizations through reasons of geometry and economy, and therefore, the discovery of lots of straight lines on the Earth might be taken as some sign of life. The next slide shows the first straight line we found. Here it is: this is in fact the northern coast of Morocco—this is the Mediterranean here; here are clouds up above—and this thing you see seems to stretch from this peninsula to the main body over here. It seems perfectly straight, a clear sign of life. In fact, it's not perfectly straight. It doesn't even continue from here to here; there's a break of some five miles right over here that isn't visible; it's irregular in outline, and it's no sign of life at all. It's an irregular natural peninsula and it wasn't even built by the Carthaginians. So that suggests that there might be things which with limited resolution look straight but aren't, and therefore this is a caution in the search for intelligent life elsewhere by straight lines. And this caution I'll come back to in the next lecture tomorrow when we talk about canals on Mars.

The next slide shows another set of straight lines—I don't know how well those of you in the back can make them out, but—here is a set of rather straight lines, here's a set… in fact this whole picture is, except for places like here and here, full of straight lines. What are these? Are these signs of life, perhaps a hundred highways all in parallel here, for, I don't know, some kind of discrimination scheme among different varieties of automobile or something? What's that about? Well, it's no sign of life at all. These are, in fact, seif dunes on the Arabian peninsula and you can even calculate that rather straight dunes will be produced by winds of a certain velocity picking up particles of a certain particle size. Therefore, this sort of thing is not any sort of evidence for intelligence.

The next slide is our first success in finding—at this resolution, about a tenth of a kilometer—signs of life on Earth. I'm talking about this kind of giant tic-tac-toe board on the face of the Earth right here, see, there's more than half a dozen straight lines that way, and then about the same number at right angles. What's the origin of this rectangular grid? This is in fact lumber country near Cochrane, Ontario, in Canada, and what's happened is that the lumberers have cut swaths about a mile across, something like that, through the forest, in cutting down trees; then have moved parallel about a mile or so and cut a parallel swath, leaving the intermediate trees standing for reforestation and other reasons. After they cut a set of parallel swaths, then they turned at right angles and cut a perpendicular set of swaths, and then the snow fell, heightening the contrast. Now suppose you had a photograph of Mars returned by some satellite and you found a rectangular grid of this sort. Would you immediately deduce this whole story about forests and lumberers and reforestation and snowfalls? You certainly wouldn't, or it would certainly be a mistake if you did. Instead, you'd say this is a set of straight lines; they seem quite unusual; they may be a sign of life; we'll have to investigate that locale more closely some other time… and then some other time you'd send some landing vehicle down there right in the middle of the lumbering camp, you know… [laughter] and you'd find a sign of life on Earth.

Well, we find that it takes about a thousand photographs of the Earth at this resolution to find one sign of life, and of these signs of life only about fifty percent of them actually are reliable, like this one, as compared with, say, the peninsula in Morocco. It's clear that to get improved discrimination about what's due to life and what's not, we have to have improved resolution. The next slide.

This is the first photograph I've shown taken by a manned satellite; this is in fact the manned satellite over here in the left-hand corner, this is the Gemini satellite. There is in fact an astronaut who is standing behind this taking this picture of the Earth with his Hasselblad camera. This is the Imperial Valley, California; this is the Salton Sea; it in fact is itself a sign of life if we only knew how to interpret it—it's due to an error in rerouting a river once. [laughter] And here, you can *not* make out, but you can *almost* make out, the chopping up the land into various individual farms in contour farming. You're just at the limit of resolution. Were we to increase the resolution even slightly, we would be able to make out a very clear geometrical pattern.

The next slide shows the result of such an increase in resolution. This is a typical area of the United States; it happens to be between Sacramento and San Francisco, and you can make out the characteristic pattern of farmland here, an airport up here, a railroad here, and the kind of regular and monotonous and boring patterns of housing developments… [laughter] in here, and here. Now suppose you had no previous experience with farms and airports and railroads and housing developments, and you were presented with this picture. Would you deduce life on Earth? You sure would. This is *so* heavily geometrized, this has so much order in it compared to what you'd expect in a typical aerial photograph of a region where only geological forces have operated that you would be instantly led, on quite sound grounds I believe, to deduce intelligent life on Earth. But this is, after all, superb resolution, much better than we have of any other place. Now, it's remarkable that if you took a photograph with this resolution of this exact spot, but only, say, 100,000 years ago, none of this stuff would be visible. Because all of these things are due to recent technological advances—I mean recent in a geological sense—recent technological advances of man. And for four and a half billion years previously, the Earth was around, and for most of that time there was life here, and yet there was no way of detecting such life by such photographs. In order to detect individual organisms, you have to improve your resolution by about a factor of ten more, and then, if you're lucky, you occasionally will get photographs like the next one.

This is, in fact, a field somewhere in California, and all these things in the field are in fact cows. What they're doing in a furrowed field I don't, myself, know. But notice that you can't quite make out the cows. They are just a little something or other, but they're casting long shadows, and in fact the sun is quite low, quite close to the horizon—that's why the shadows are long—by examining these shadows, you would get a good idea what a cow is like. Well, I mean, we are very used to the idea of quadrupeds being a sign of life and so on, and of course we would immediately deduce life on Earth from this picture and say that we've found a sign of life. But suppose you weren't familiar with quadrupeds. Suppose you were sort of like a jellyfish, and squamous, and you had nineteen tentacles or something, so four legs didn't immediately say "life" to you. I maintain that you could still deduce life on Earth from this photograph. Lights, please.

The argument that you would use is the following. You would say, from the length and shape of these shadows, and from the angle of the sun and the resolution of the photograph, I can deduce what these objects on this field are. They're about so long and about so high off the ground, something like that, and these main body things, these lumps, are connected to the ground by four stilts. OK? [laughter] There's a perfectly unambiguous conclusion from the photograph. Then, you would argue as follows. You would say, this is a dynamically unstable configuration. Right, there are these little thin narrow stilts connecting this big lump to the ground. If you just give it a little push it should fall over. Well? In fact, there are things giving it pushes. You would know by this time in your exploration of the Earth about erosion. You would know that there is wind erosion; you would know that there is water erosion. You could calculate that these erosional forces would erode away the stilts in periods of, let's say, a few thousand years. OK? Therefore, there is some mechanism for the regeneration of stilted lumps on Earth. [laughter]

Moreover, this regeneration mechanism must work on geologically very short time scales. There's a stilted lump regeneration mechanism that does it in thousands of years or less, and does it all over this field. [laughter] Now, it seems unlikely that this field is the only place on Earth that has stilted lumps. There's a large-scale process which rapidly makes stilted lumps on the Earth. And now, using only geological processes, you have to understand what that regeneration process is, you're in trouble. You're not going to be able to make a geological explanation of this, and you will be forced toward biology.

Well, this is an example of the idea behind a search for life. Searches for life on other planets—at least remote searches, that is without actually going down there and picking up an animal—are based upon disequilibrium. We've just talked about a dynamical disequilibrium; there are other kinds of disequilibrium. Let me give you two examples. You might have a thermodynamic disequilibrium. The atmosphere of the Earth is about 20% oxygen. Oxygen is, of course, a very reactive gas. The Earth also contains about a part per million of methane, CH_4. Now, methane is oxidized by oxygen to carbon dioxide. This is a relatively rapid process. Therefore, you could calculate what the equilibrium, what the thermodynamic equilibrium abundance of CH_4 ought to be in the Earth's atmosphere. That amount would be something like 10^{-36}. Well, that's a discrepancy with observations of thirty orders of magnitude. So even in this sort of problem you would say that's a significant discrepancy. Now, what is the source of this discrepancy? Well, you might think about maybe sequestered organic matter made early in the history of the planet and slowly dissociating and producing the methane, but as soon as you made a quantitative calculation, you would realize that that doesn't work. And you would again be forced to a biological alternative. In fact, the methane in the Earth's atmosphere is almost exclusively of biological origin, and a lot of it—some of it is due to microorganisms called methane bacteria, which live in swamps; hence the phrase "swamp gas," and similar methane bacteria live in the intestinal tracts of cows, where they gleefully metabolize, producing the methane. The methane is then released to the atmosphere by bovine flatulence. Now… [laughter] now there is a debate as to whether the ungulate source is larger than or smaller than the marsh source, but at least the ungulate source is large. You see, that means that you could deduce, if you were only clever enough, from the vantage point of Mars, not only the existence of ungulates but some rather intimate metabolic processes about the ungulates. Now of course you would not be able to deduce cows on Earth merely from finding the methane in the Earth's atmosphere. The methane would be, by the way, very easy to detect; there's an enormous absorption band at 3.33 microns and it would be completely easy to see from Mars in infrared spectroscopy. But you would certainly be led, by this disequilibrium, to the conclusion that there was probably life on Earth.

A final sort of disequilibrium that I'll mention is a kind of radiation or a spectral disequilibrium. The Earth is at some average temperature of about 280 Kelvin, something like that, and this means that it puts out a black body spectrum that is peaked in the middle infrared at about 10 microns and continues falling slowly toward longer and longer wavelengths. In fact, the amount of radiation put out by the Earth at microwave or radio wavelengths is very small. As on Mars, you would continue to scan across the radio spectrum of the Earth. As you got to longer and longer wavelengths you would suddenly see an enormous peak, absolutely stunning, and if you believed that that peak were due to thermal emission from the Earth, that is because the Earth was hot, you would deduce that the temperature of the Earth was about 400,000,000 degrees. OK? Obviously that's a mistake. There's some other non-thermal source of radio emission from the Earth.

As the North American continent would turn towards Mars, if you had by accident found the right frequency, there would be an absolutely stunning blast of radio emission that would knock you right off the air, and that would be due to domestic television transmission from North America. [laughter] In fact, over very large distances, there are only three signs of intelligent life on Earth or any other kind of life on Earth. One is domestic television transmission, you know, the housewives' daytime serials; two is the high-frequency end of the AM broadcast band; and three is the radar defense networks of the United States and the Soviet Union. These are the only signs of life on Earth detectable over large distances. This is our image to the cosmos. [laughter] You know, you sometimes have this argument that says if there's intelligent life elsewhere, how come there haven't been any clear-cut signs of them coming here and visiting us? Now you know.

Well, if you wanted to have a thoroughgoing exploration of the Earth, you would clearly do it in this sort of nested steps of photographs and other images at a variety of wavelengths that would increasingly improve resolution; you would make spectral scans of the atmosphere; you would look for thermal emission at various wavelengths, look for non-thermal emission, but also look at the range of thermal emission over the surface; and by the time you were done you would have an excellent characterization of the chemistry of our atmosphere and something about the chemistry of our surface. You would know about land and oceans, you would know the pressures at the surface of the Earth, what the temperatures were, and if you made a few right observations, you would even have deduced life.

There is another way of looking for life on Earth, and that is simply going to Earth, landing let's say an instrument package somewhere, and picking up things and bringing it into the space vehicle and closely examining it for signs of life and then radioing back the information to Mars. In fact, there's a very good cartoon I once saw which showed a lecturer lecturing to an audience, kind of like here except the lecturer and the audience all had little pointy ears and little antennae—otherwise they looked perfectly human—and the lecturer was pointing to a slide on the screen as I have been. And the slide shows a picture taken from above, and it shows a guy at an outdoor cookout with a big hat on saying "I am the chef" and stuff, and you can see the little hamburgers on the stove. And he's looking over his shoulder, and running as fast as he can, and the caption is, "This was the last photograph before impact." [laughter]

Well, after an impact, you see, you might land anywhere. You might land in the Gobi Desert, in the middle of the Atlantic Ocean, or… the chance of coming upon something large and obviously alive as a person or a kangaroo rat would be kind of small. Instead, if you made a search for microorganisms, they're everywhere. That's a perfectly reliable, in the case of the Earth, method of looking for life. Except it's not all that reliable. I'd like to just say another word about this kind of problem.

Suppose you had a genuine sample of extraterrestrial material and you examined it for some sign of life. What would happen? Well, in fact we *do* have genuine samples of extraterrestrial material; they're called meteorites, and they come most likely from somewhere out in the asteroid belt, which are hunks of rocks and iron which circle the sun between the orbits of Mars and Jupiter. A piece occasionally comes into our atmosphere and lands, and people pick it up and take it to laboratories and look at it. Well, there are three claims made about the metereorites, particularly about a certain kind of meteorite called a carbonaceous chondrite, which has a very high content of organic matter. The first claim is that there's organic matter—there's organic molecules not necessarily produced by life; an organic molecule, I simply mean one based on carbon—and that turns out to be right. These things are loaded with organic molecules; this kind of meteorite is about 1% made of organic molecules. It's just absolutely full of them. The question is, what is the source of this organic matter? Could it have been produced by non-biological processes, the kind of things that led to the origin of life on the Earth some billions of years ago, or were these things produced by life somewhere out in the asteroid belt? This is a hotly debated question and there still is no generally resolved answer for that. So that gives us some caution about the argument about a returned sample from somewhere else.

The second claim made about these is that if you look closely, you can see in them little inclusions which are so highly structured, so non-random in geometry, that they must be the fossil remnants of some organism that lived out in the asteroid belt. Furthermore, it is claimed that some of these things are so different from any known terrestrial microorganism that the contamination possibility is remote. The next slide shows a photograph of one such inclusion. This thing up here is hexagonal in shape; it has three sleeves: that's one, that's two, there's a third behind; through these sleeves are hundreds of fine hairs; it's about ten or twenty microns across. This was called organized element type 5—typical scientific jargon—and this was claimed to be an example of an extraterrestrial organism. Nobody had ever seen anything like it before. All sorts of microbiologists and palynologists looked at this and said, "Hm. That's nothing I ever saw before." [laughter] Well, it turns out that in the preparation of this sample a kind of unusual stain was used called a Gridley stain. And some scientists at the University of Chicago thought they would see if the Gridley stain happened to perhaps make some common microorganisms look different than their usual form. If you'll remember what this thing looks like, let's compare it with what's on the next slide: OK, practically identical. This is what happens when you Gridley stain ragweed pollen. [laughter] That then leaves two possibilities. One is that there's ragweed out in the asteroid belt… [laughter] you know, like in the illustrations of Antoine de Saint Exupéry's book

The Little Prince where there's a guy out in the asteroid belt and there are little flowers all around. And the other possibility is that this sample, this porous sample that fell through the Earth's atmosphere and lay around a French field for months and then was put in a museum, might have been contaminated by accident. As interesting as the former possibility is, the latter possibility is clearly more to be favored.

So the conclusion from this is that even if you have a bona fide sample of extraterrestrial material, you have to be mighty careful that you're not contaminating it with some form of terrestrial organism, and even then there may be debates on whether the organic matter you find is of biological origin or not. Still, the existence of organic matter in this stuff is of great interest in itself, because it means—suppose it's not of biological origin—it still means that there are processes for the large-scale production of organic molecules out in the asteroid belt. And that is not a favorable environment for life by our standards. It means that organic molecules must be produced all over the solar system, and it suggests that the origin of life is a very likely thing.

Well, I'd like to briefly go—very briefly, now—through the moon and maybe one or two planets about which we know very little, so I'll dwell very little on, and try to give you a brief summary of what we know based on the kinds of techniques I've been talking about. The next slide is a typical lunar orbiter photograph of the moon. These parallel streaks are just the places where adjacent strips of the photograph have been joined. You'll here see things which wind and have a sinuous shape, and yet they stick up; they are elevations. There are similar features which are depressions, and look for all the world like some river valley on the Earth. Now, in fact, there is no water, no liquid water on the moon; there is no atmosphere on the moon; there certainly could not be a river valley produced today, but it is possible that in the earlier history the moon contained an atmosphere, contained running water, and therefore the possibility has been raised that life may have arisen on the moon earlier in its history and there may be remnants of it awaiting lunar exploration, or there may be fossil forms. This is not necessarily a strong possibility, but we don't know enough to exclude it. The average temperature on the lunar surface is the same as it is here, but the variations in temperature are extreme. The noontime temperature is above the boiling point of water, the temperature before sunrise is about 180 centigrade degrees below zero.

The next slide shows a typical cratered—look at all these enormous numbers of craters, big ones and tiny ones—when you look at the moon with a variety of resolution you find craters of all sizes, down to things a few millimeters across, as observed when space vehicles like Surveyor looked at their feet and they found all these little tiny craters pockmarked all around them. These things are almost surely largely due to the impact of debris which is floating around the solar system and occasionally accidentally impacts the moon in the same way that a meteorite impacts the Earth. We know that there's a lot of this stuff around; we know that it has a certain probability of impacting the Earth. In fact, all the craters in this picture *in toto* are about the number of craters you'd expect over geological time from such impacts. There are also some craters on the moon which are clearly of volcanic origin. So there are both craters of impact and of volcanic origin.

The next slide is just for fun; it shows the interior of an enormous lunar crater, Copernicus. You can see where a whole enormous wall of the thing has slumped down; right here there are signs of mass wasting; there are signs of erosional processes on the moon. You can see those nice hills at the horizon. The next slide shows us a Ranger 9 photograph of the lunar crater Alphonsus. There was outgassing observed from here; apparently some gases were emitted. Also, this crater, this crater, and these two craters have these dark halos around them which you can clearly see, and these are apparently due to some stuff that was outgassed from the craters. This is the sort of evidence—this is one kind, there are lots of other kinds—of evidence for outgassing events on the moon suggesting that there is stuff of interest beneath the lunar surface which occasionally comes out. There's some reason to believe there is subsurface water; there is some reason to think that there are other molecules beneath the surface which occasionally penetrate the surface and escape into space. Digging a hole on the moon, if it's a deep hole, is going to be mighty interesting.

The next slide is the last having to do with the moon, and it's a remarkable picture because it shows one space vehicle photographed by another. The first United States space vehicle to land on the moon and send back useful data after landing was Surveyor 1. This bright spot in the middle of the circle is the reflection of sunlight from Surveyor 1. This kind of dark streak coming out from it is in fact the shadow of Surveyor 1; we're looking at low sun. This… all of these round things are craters and not mounds. It's occasionally an optical illusion, particularly if you're looking at the thing for the first time, which suggests that things are sticking out at you instead of away. They are, in fact, depressions. Lights, please.

Well, that's the moon. I think I will not go on to the other planets tonight, but save them for the next lecture. The kinds of information that we have extracted from lunar observation has been varied; it is a kind of precursor to the sorts of investigations that it's possible to make of the other planets. Not only have we observed the moon from the distance of the Earth and mapped its near side—it, of course, always keeps the same face to the Earth—but now we have sent—by "we" I mean the Soviet Union and the United States—have sent space vehicles around the moon, so we have photographs of the hidden side of the moon which no man has ever before in history ever looked upon. There have been space vehicles which have landed on the lunar surface, actually plopped down on the surface, photographed the environment, sent out an arm, picked up a little rock, held it up to be photographed, squeezed it to see if it would fall apart—some rocks fell apart, some rocks didn't fall apart—which told you whether there are dust clods on the moon or hard rocks, that has its own importance. It looked down very carefully at all the little craters at its feet. It looked out at the horizon and saw where there were big rocks; there were occasionally the tops of what looked like enormous boulders, most of which were buried down below. It got enough of the surrounding hills that it was then possible to say exactly where the thing had landed by comparing with photographs taken from above. You could say, "Gee, I know that hill, that's in this picture," and it turns out everything is just what you expected.

The chemical composition of the lunar surface has been determined by an alpha ray scattering experiment in which the spacecraft looked at stuff it was sitting on and determined its chemical composition, rather similar to rocks on Earth. In this hand experiment, there was feedback between the moon and the Earth. It was possible to say to that hand, "Look, leave that rock alone, but go over to that rock, pick it up, hold in it up in the air.” There were all kinds of things you could tell it; it was a robot on the moon obeying human commands. There will be others.

There will also, of course, very shortly be human beings on the moon. They will land on the moon—the first ones will—and then they will prepare to take off again, and they’ll take off. But after a while, there will actually be guys landing on the moon who are interested in the moon, and they’ll go out for long walks and examine another world. It’s a whole other place. No one’s ever been there before; there’s no telling what’s there. I mean, the sense of adventure involved in this, I think, is absolutely compelling. There is really no telling what’s up there. And this sort of adventuresome spirit, I think, applies much more stringently to exploration of the other planets, as I’ll talk about in the next lecture.

[applause]

SAGAN: Thank you. It’s been customary to be… for the Condon lecturer to be responsive to questions from the audience, and I’ll be delighted to try to respond to your questions, if you have any. Yes, sir.

[audience member speaks in background]

SAGAN: The question is, would I say something about the quasi-stellar objects? Well… that’s the source of… that’s the subject of a whole lecture. In a couple of sentences, it’s kind of like this. There are objects in the sky which look very much like stars, at least superficially, but which are sources of radio emission. When their spectra are taken, it’s observed that the spectral lines are all shifted to the red by an amount which is proportional to the wavelength of the line, and this is the typical situation for a Doppler shift where the thing you’re looking at is running away from you and in fact, from the amount of Doppler shift, it has to be running away at very great velocities. In fact, velocities approaching the speed of light. Nothing can travel faster than light, but some of these things seem to be very close to the speed of light. Now, the only other things that we know about that are running away from us at very high speeds are the most distant galaxies, and that’s due to the general expansion of the universe. So the first suggestion was that these were extremely distance objects, billions of light years away, and that means that we are seeing them billions of years ago in time, the same idea as the hypothetical reason I invented for the delay in the lights turning on. It takes… light travels at the speed of light—what else—and even at that speed, it takes billions of years to come here from some distant objects. OK, so we are looking at them as though they were billions of years ago in the past. Now, if they are really that far away, then there’s a fundamental problem, because how come they look just like stars? Stars are near; stars are bright. How come they are so bright in the radio part of the spectrum? There’s all this huge amount of emission. In fact, it turns out there’s no known way of explaining all of the energy that could come from that far away. So maybe you’ll say, “OK. They’re not far away; they’re nearby.” OK, terrific. Then you don’t have to worry about all that great energy in the optical and radial part of the spectrum, but then how come they are going close to the speed of light? Something must have shot them out at great speed. Well, that takes a lot of energy. And again, you’re back in the same energy box. So, the answer is, nobody knows what quasars are; nobody even knows if they are near or far, but they certainly represent an extremely exciting puzzle, and they will tell us something absolutely fundamental about the universe, but nobody knows what! Yes, sir. Yes.

[audience member speaks in background]

SAGAN: The question is, from an astronomer's point of view, what about the origin of the Earth? Well, it's something like this. The sun has a certain lifetime which… we know enough about the nuclear processes in the interior of the sun to know how long it's been around, and the answer is it's been around about 5,000,000,000 years. The Earth, from radioactive dating of rocks, is about 4,500,000,000 years old; pretty close to the age of the sun. Meteorites, which I explained come from the asteroid belt, are again, from radioactive dating of rocks, about 4,500,000,000 years old. So, everything is around four and a half or five billion years old around here. So, four and a half or five billion years ago, all this stuff was made somehow. So how? Well, nobody knows for sure how. There are a variety of theories. None of them is completely generally accepted, but the general view—I'm not going to give you a theory now, I'm going to give you the framework of most of the theories—goes something like this. You start out with the interstellar medium, which is an extremely under-dense medium full of gas and an occasional little dust grain. In fact the amount is about one atom every cubic centimeter. To put into more—I once calculated it—to put it into more familiar terms, it's like having a building which is sixty miles long, sixty miles wide, and sixty miles high in which there is a single grain of dust. OK? That's how empty space is. Now, those of who are concerned with the origin of the solar system make solar systems out of stuff that under-dense.

Now, the interstellar medium is not perfectly uniform. There are places where stuff is denser, places where stuff is more rarefied. There are statistical fluctuations of density. Where there are denser places they will gravitationally attract neighboring gas atoms and dust grains and so they'll grow bigger and more massive, and then of course they'll attract more stuff, and they'll grow bigger and bigger and bigger. So, you must now imagine this enormous gas cloud, absolutely huge interstellar dimensions, light years across, which is growing and growing and growing, and it starts collapsing because of the gravitational attraction of the different parts of it for each other. As it collapses, the interior temperatures build up; as the interior temperatures go above several millions of degrees, thermonuclear reactions begin, and one can say that the star has turned on. [laughter] You like that, huh? I might add that that turn-on lasts thirteen billion years. In the course of this condensation of stars, there are smaller condensations in the vicinity of it which are gravitationally attracted to it which become planets. That's the general framework. Now, the actual details of how it goes physically and chemically is open to all sorts of debate. That's the general picture. Yes.

[audience member speaks in background]

SAGAN: The question is about the origin of the moon. Right. There are three views—again, nobody knows which is right—here's the three views. One, the moon was torn out of the Earth some billion years ago by a tidal instability. The gaping hole left is the Pacific Ocean. Two, the moon was captured from somewhere else. It was minding its own business going through space and the Earth grabbed it with gravitational attraction, and here it is trapped. Homesick, lonely… [laughter] Third, that the moon and the Earth is a kind of double planet formed at the same moment, back four and a half or five billion years ago, where—by accident the moon and the planet are pretty close in mass, it's about 80:1—different from most of the other planet-satellite situations. Well, there are serious proponents of each of these views today, and nobody knows which it is. But it turns out, by more direct exploration of the moon, it's possible to decide among these. For example, the idea that it's torn out of the Pacific Ocean: there should be signs on the moon of that event, and there are ways of distinguishing between the other two also. So, as fundamental a question as the origin of the moon can be studied by exploration of the moon. Yes, sir.

[audience member speaks in background]

SAGAN: Erosion processes on the moon, right. There's no air, there's no water. How could there possibly be any erosion? There are several sources of erosion. One is, someone comes in and makes a crater. OK? Whatever happened to be at that spot isn't there anymore. That's a source of erosion. [laughter] A second source of erosion: an object comes in and makes a hole, blasting out material. Fine-grained stuff, some of which escapes to space, some of which stays on the moon. OK? So there's a fine dust cover which lands and covers things over; that's a source of erosion. Thirdly, there is reason to believe that—there are several mechanisms—but there is reason to believe that dust tends to move downhill on the moon. So dust produced high winds up low, and that's a source of erosion. Also, it's perhaps barely possible that there were wind and water erosion sources early in the history of the moon. As I say, that's a controversial point. Yes?

[audience member speaks in background]

SAGAN: OK, two questions, one easy, one hard. First question… well, I mean, it's well known that both the United States and the Soviet Union have military reconnaissance satellites. You know, a satellite was launched from Vandenburg Air Force today—no further details were given by the Air Force—now, I know what that's about, right? As to how efficient military reconnaissance satellites are as far as resolution goes, there are several approaches. One, you can make a calculation. A 36-inch telescope over a hundred miles, you can calculate what the resolution is and it's good enough to see an individual human being at low sun. It's absolutely terrific resolution. And then we have the statement of Fidel Castro, who I believe is an accurate reporter on this particular problem; he said that United States military reconnaissance satellites were getting so efficient that it became hazardous for Cuban ladies to sunbathe nude. [laughter]

Now, the hard question: Can life be explained in terms of physics and chemistry? Well, um… there's no evidence that there is anything else in life other than the operations of the laws of physics and chemistry. That's not quite an answer to your question. Certainly, in the history of biology, the idea that there is something else besides physics and chemistry has been notably poor in producing any understandings of life. Historically, the way things went were that the great advances in celestial mechanics due to Isaac Newton and his successors, the idea grew up that the solar system was a kind of clockwork with all the planets going around in preordained orbits by very simple laws explaining them. The biologists caught this spirit and said, OK, let's find out what the clockwork is in biology. So they cut things open and so and and found that the clockwork was terribly complicated. So they said that there doesn't seem to be any clockwork… so they invented a kind of ghostly mainspring called the "vital force." They said that the vital force explains all those things that we are too stupid to understand. OK? Why does a flower open up? Ah, it's the vital force. Well… I mean, that's just words. There's no… there's never been an advance in biology from that.

On the other hand, the idea that it's just physics and chemistry has been remarkably productive in achieving results. I'm thinking in particular about the advances in the last fifteen years in molecular biology. Absolutely stunning set of discoveries, all of which are based upon quite straightforward physics and chemistry, things like x-ray crystallography, and which have given a fundamental understanding of the basis of heredity, the chemical basis of heredity: what happens in the hereditary process? How does genetic material influence the operation of the cell? How does evolution occur? So, while it's impossible to give a definitive answer to your question, certainly all of the progress has been based upon the idea that it's physics and chemistry and nothing else, and that we are an extremely complex example of what matter is capable of. I mean, some people feel upset about the idea that it's just physics and chemistry; they have the idea that it means that they don't have free will and so on, but obviously, some of us have free will. Others don't, so much. And I don't think there's anything appalling about it being just matter. Because that means that there's almost awesome possibilities in matter. It means that matter could be put together in sufficiently intricate a way to produce you. And so don't knock matter!

It also means that there's a kind of fundamental kinship between us and everything else in the universe. We are made out of exactly the same stuff and it's just been put together slightly differently here than elsewhere. Yes?

[audience member speaks in background]

SAGAN: Gee. I know a lot. What are you thinking of? An 18-centimeter emission?

[audience member continues]

SAGAN: Yeah. There are a lot of sources of highly polarized radio emission. The Crab Nebula is polarized; Jupiter is polarized. Polarization is interesting. It often is a sign of […] emission. It's nothing absolutely terrific. It's interesting. Yes?

AUDIENCE MEMBER: [in background] How was the Earth formed?

SAGAN: I answered that. Yes?

[audience member continues]

SAGAN: Origin of the asteroid belt. [aside] You're tired, huh? [laughter; applause] I'll tell you the reason that I said that; it's because this lecture that you heard I've heard before, and… I only get so much kicks out of it, but… answering the questions is more fun, it's some audience interaction. Well, how did the asteroid belt get formed? That's OK, now? Yeah. Well, like a lot of the other things I said, there's two views. One view is that it was a planet that never formed, and the other view is that it's a planet that exploded. Nobody knows how to explode a planet, so that idea is probably wrong. [laughter] I'm not making fun; that's right. There is no physical process known which will blow up a planet, never mind intentionally. No collision process, nothing. Therefore, it's most likely a set of debris which never actually formed a planet but just stayed in little pieces. Yes?

[audience member speaks in background]

SAGAN: About what?

[audience member continues]

SAGAN: Yes? …Yeah. I'll try to repeat the question; it has to do with anti-matter. Well, anti-matter. A hydrogen atom has a positively charged proton around which goes a negatively charged electron. An anti-hydrogen atom has a negatively charged proton around which goes a positively charged electron. And such things exist; they are made in a laboratory. Now, there is no reason why matter ought to be any more fundamental than anti-matter. So you might expect, offhand, that you should find as much matter as anti-matter in the universe. There may be one person who is made of matter and the other is made of anti-matter or something like that. There's a problem with that, though, and that's when matter and anti-matter come in contact, there is a violent explosion and what's called annihilation radiation is produced; it's gamma rays, and matter is converted totally into energy. So that's why it's not likely that you would have both matter and anti-matter in close contact.

Now, why can't you have very distant galaxies made of anti-matter? Well, maybe you can, but then there's a problem even of the intergalactic medium. Is that matter or anti-matter? Has contact with these other galaxies—there should be gamma rays produced—you know what the gamma ray spectrum is, you should be able to fly a space vehicle into the upper atmosphere, look at the gamma ray spectrum, see the stuff; it's not there. So at least out to as far as we can see there is some objection, some reason, why matter is fashionable and anti-matter isn't fashionable, and nobody knows what the answer to that is. It may go back to the times of origin. There's a nice little example of this whole point which given by Richard Feynman, a distinguished physicist at Cal Tech, who imagines that contact is established by radio between two civilizations, us and another advanced civilization. We find some mutually acceptable language and have all sorts of nice discussions; we tell them that our planet is nice and they say, "That's terrific, and what are you guys like?" And we tell them, you know, through our pictures, and they say, "Hmm, you're really lovely fellows. What are you like on the inside?" and we send back various descriptions; we say our heart is on the left side, and then comes back the response, "The left side? What's the left side?" So now you've got to explain to them which is left. It's just radio, and there's no reference. Well, Feynman says there is a reference. It turns out there is a particular experiment in the non-conservation of parity. You can tell them, "Do this experiment," and there's a certain beam of charged particles which will be deflected in a certain direction and you can define "left." Except if they're made out of anti-matter, in which case it'll go right. So Feynman says that after you've had a nice exchange by radio and so on and then you arrange for a kind of interstellar journey to some neutral territory and the two spacecraft dock near each other, and the guys get out and you've taught them your social customs, and you extend your right hand to shake his hand… if he extends his left hand, watch out! [laughter; applause] Yes?

[audience member speaks in background]

SAGAN: Will I say something about the origin of the universe? All right. Why not? Um… here's one possibility: there was no origin to the universe. Perfectly acceptable possibility. Matter has always been here, the universe has always been here, therefore the idea of origins is a false problem. This is consistent with several general relativistic cosomologies, and as far as we know is perfectly possible. Other possibilities are that one, the universe was made from nothing about thirteen billion years ago by some process which I don't happen to know about, and two, that the universe is infinitely old, but matter is being made from nothing all the time at a slow rate. The first of these is called the "big bang" hypothesis and the second is called the "steady state" hypothesis. Well, enough information is in now on the space density of very distant objects, particularly observed at radio frequencies, to be able to exclude the steady state theory. So as far as we know it's either an infinitely old universe which pulsates, and so thirteen billion years ago or whatever it is was the last time all the matter was very close together, or everything was made from nothing thirteen billion years ago by some very interesting process. Yes.

[audience member speaks in background]

SAGAN: The moon has no magnetic field. It should, of course, have some induced radioactivity due to cosmic rays striking it; according to an experiment done by a Soviet fly-by vehicle, it has some natural radioactivity due to potassium, thorium, and uranium, as we do here. No fantastically high levels of radioactivity. Yes?

[audience member speaks in background]

SAGAN: Is it feasible to project holograms by lasers across space? Yeah, if you've got guys who know what they're doing at both ends. [laughter; audience member continues] The future of the solar system? Sure. Remember one of the slides I showed, that hypothetical planet and there was a red giant and a white dwarf? That's the future of the solar system. The sun, in about six or eight billion years from now, is going to have exhausted its hydrogen thermonuclear fuel supply and it will start collapsing on the inside, therefore heating up and therefore expanding on the outside, and the sun will swell and grow and become what's called a red giant. In fact, it can be calculated that it will get to be so enormous that it will engulf the orbits of Mercury and Venus—probably not the orbit of Earth—but it will be an absolutely enormous thing in the sky. And you can calculate what the temperatures will be on the Earth, and it'll be enough to boil the oceans and evaporate the atmosphere and fry everybody on Earth. On the other hand, it may make Uranus or Neptune the garden spots of the solar system. [laughter] The sun will go through a series of pulsations, matter will be lost, and it will then collapse into a white dwarf and end out its days as a degenerate black dwarf. That really does sound like the Brothers Grimm, doesn't it? That is the fate of all stars, so far as we know, and that would be the fate of the sun. There are more immediate problems; this is only eight billion years away. I think there are more immediate threats to life on earth. Yes.

[audience member speaks in background]

SAGAN: Is there a maximum stable size for a cold body? It depends on the mass, but the answer is yes. … Well, it depends on the mass. It's only slight… for a pure hydrogen planet, it's only slightly larger than Jupiter. Yes.

[audience member continues]

SAGAN: The question has to do with the shape of the universe. Oh… well, that's… I think I'll pass that one by. It's because it involves geometries in more dimensions than three. It's kind of hard for me to draw pictures on the blackboard.

[audience member speaks in background]

SAGAN: You mean… Well. So you're making the distinction between the age of the material on the Earth and the age of the Earth itself, right? Let's see what the possibilities are. Is it possible that the Earth has a younger age than the material it's made of? Sure it is. Is it possible that the material is younger than the Earth? No, that's not possible. Well. The kinds of radioactive dating that I've been talking about are the ages of the Earth, they're not the ages of the atoms. The atoms are, of course, older; in fact, there's evidence on when the atoms were made, and they were made slightly earlier. But… I mean, if you read any textbook on radioactive dating of rocks, you'll see that it is the rock itself and not the atoms which are being dated. It has to do with the parent and daughter atoms and the ratios of the two, and there they are in close contact: that's the rock. Yeah. It's OK. Yeah.

[audience member speaks in background]

SAGAN: Yes. Yes. The basic idea is that you start out the universe with hydrogen and maybe some helium, and that every other atom gets made in the deep insides of stars from red giants to supernovae, and that in explosions, this stuff is recirculated back into the interstellar medium and the next generation of star formation comes out of this stuff. Now, the fact that the Earth is not made of hydrogen and helium, but a lot of other stuff, means that all the things that we are are a second- or possibly third-generation solar system. That is, the stuff has been several times cycled through the insides of stars. So, I mean, we have calcium in our bones only because of an alpha addition process that occurred at a temperature of 200 million degrees in the inside of some red giant some 8 billion years ago or something. We are what we are because of, among other things, thermonuclear reactions inside of stars. By the way, that's another tie-in of a fairly fundamental way between us and the rest of the universe. Yes?

[audience member speaks in background]

SAGAN: Why are there no planets farther away than Pluto? There may be planets farther away from Pluto; they're just hard to find. Yeah. They're hard—they're little, they may be very far away. They should be someplace, by the way, where the planets stop; maybe that's Pluto. I think I will entertain maybe one or two more questions and that's all. Yes.

[audience member speaks in background]

SAGAN: Why does a star go nova or supernova? Apparently, all stars go into red giants. And then the question is, do they get to white dwarfs more or less peacefully or more or less violently? And there are a variety of hypotheses on this. It's known that a very massive star, larger than about 1.3 solar masses, cannot stably settle down into a white dwarf. It has to lose matter and it does this by a series of explosions, but the exact processes are not generally agreed upon. Yes?

[audience member speaks in background]

SAGAN: Right. … Right. … Yeah. This is a kind of arcane subject for those people who haven't the latest *Scientific American.* The… I'll show you tomorrow what the giant red spot is. It's orange. [laughter] It was red for a few years back about 1890. I don't know, that's impressed itself on everybody's memory or something. Anyway, here's this enormous oval-type object in the atmosphere of Jupiter into which you could fit about maybe ten Earths or something, and it's been there since Robert Hook saw it in the seventeenth century, and the question is, what the heck is it? Well, the old idea was that it was a kind of raft, or something floating in the atmosphere of Jupiter. But nobody knows… has ever been able to figure out what the raft could be made of, that it's that light that it just floats in the air, and also there are contradictions in the stability of the thing. If it's floating, it should do some things which it doesn't do. So the alternative hypothesis has been proposed that it's a Taylor column. A Taylor column is a relatively stagnant column of gases which might under certain circumstances exist in the Jovian atmosphere, and you can do certain experiments in the laboratory which to some extent simulate the situation on Jupiter, and sure enough you produce a Taylor column. Well, in that case, in order to have a Taylor column, you need either a slight elevation or a slight depression on the surface, and then the atmosphere coming by this elevation or depression is constrained into going into this huge Taylor column. Well, the elevation or depression needn't be larger than about a kilometer, so it's a very small bump on the size of Jupiter, and there's no particular problem about the existence of that. There are, however, problems with Taylor columns, and not everybody is convinced that that's the answer.

Well, to conclude the question period, I've just been thinking about the questions. It's remarkable how many questions you have asked for which there are more than one answer. That is, I think, the sign of a science in a stage which is approaching maturity. There are many hypotheses; they are each testable; there are specific experiments which can be performed to decide which of these alternatives is right, and, as I'll talk about in the next lecture, we are on the verge of developing the tools to find out which is right and which is wrong. Good night.

[applause]

DITTMER: Thank you very much, Dr. Sagan. We look forward to your lecture tomorrow night at eight o'clock in this auditorium. Goodnight.

[program ends]