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BROOKHAVEN LECTURE SERIES

Radioastronomy and Communication Through Space

Edward Purcell

Number 1

November 16, 1960

BROOKHAVEN NATIONAL LABORATORY

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DISCLAIMER

FOREWORD

The Brookhaven Lectures, held by and for the Brookhaven staff, are meant to provide an intellectual meeting ground for all scientists of the Laboratory. In this role they serve a double purpose: they are to acquaint the listeners with new developments and ideas not only in their own field, but also in other important fields of science, and to give them a heightened awareness of the aims and potentialities of Brookhaven National Laboratory.

Before describing some recent research or the novel design and possible uses of a machine or apparatus, the lecturers attempt to familiarize the audience with the background of the topic to be treated and to define unfamiliar terms as far as possible.

Of course we are fully conscious of the numerous hurdles and pitfalls which necessarily beset such a venture. In particular, the difference in outlook and method between physical and biological sciences presents formidable difficulties. However, if we wish to be aware of progress in other fields of science, we have to consider each obstacle as a challenge which can be met.

The lectures are found to yield some incidental rewards which heighten their spell: In order to organize his talk the lecturer has to look at his work with a new, wider perspective, which provides a satisfying contrast to the often very specialized point of view from which he usually approaches his theoretical or experimental research. Conversely, during the discussion period after his talk, he may derive valuable stimulation from searching questions or technical advice received from listeners with different scientific backgrounds. The audience, on the other hand, has on opportunity to see a colleague who may have long been a friend or acquaintance in a new and interesting light.

The lectures are being organized by a committee which consists of representatives of all departments of the Laboratory. A list of the lectures that have been given and of those which are now scheduled appears on the back of this report.

Gertrude Scharff-Goldhaber

The drawing on the cover is taken from a 5th Century B.C. relief on the Acropolis in Athens, the "Dreaming Athena," by an unknown sculptor.

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Radioastronomy and Communication Through Space

Edward Purcell

University Professor, Harvard University
and
Research Collaborator, Brookhaven National Laboratory

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INTRODUCTION

We are very fortunate in having Dr. Edward Purcell as the first speaker in the Brookhaven Lecture Series.

The originality, experimental skill, and great professional competence shown in his research have not prevented him from developing wide general interests in both the sciences and the humanities. Moreover, in spite of his time-consuming research work and his many other duties, he has made teaching a fine art. As you all know, Edward Purcell is University Professor at Harvard University and is at present spending a year as Research Collaborator at our Laboratory.

Dr. Purcell received his scientific training at Purdue and Harvard Universities, and spent the war years at the MIT Radiation Laboratory helping to develop radar. He then returned to Harvard and published in quick succession a number of brilliant papers on the resonance absorption by nuclear magnetic moments in solid, liquid, and gaseous matter. For this work he was awarded the Nobel Prize in Physics in 1952, together with Felix Bloch.

In 1951, he carried his research from the laboratory into outer space. He showed that the same phenomenon that causes the nuclear magnetic resonance absorption he had previously established, is responsible for the emission from the galaxy of a narrow line in the ultra-high frequency region. The wealth of information which followed from this discovery is the topic of his lecture.

GERTRUDE SCHARFF-GOLDHABER

Radioastronomy and Communication Through Space

It is a great privilege for me to open the series of Brookhaven Lectures. The principles on which these are conceived I heartily endorse, but I am just about to violate them by giving a talk which is really not, for the most part, a description of my own work. Indeed some of it will not be a description of any one's work, but instead some speculations about the future. In a way, you might regard this talk as a logical sequel to Dr. DuBridge's Pegram Lectures* of a year ago. It has three parts whose relation to one another will not be obvious until the end. The first part, at least, has to do with solid scientific matter, radioastronomy. Without revealing now the nature or motive of the last two parts, I would like to describe one branch of radioastronomy and what has come out of it in the last several years. I have not been active in this field myself in recent years, but I have been watching it develop.

RADIOASTRONOMY

Until 15 or 20 years ago, all of man's information about the external world beyond the earth came to him in a small band of wavelengths of visible light. Everything the astronomers saw, all the images on their photographic plates, were collected by absorbing light within a range of wavelengths varying by no more than a factor of two from the shortest to the longest waves. It was the discovery, about two decades ago, that there were also radio waves coming through which started off radioastronomy.

These two great apertures, or windows, as they are often called, may be seen in Figure 1, which shows the absorption spectrum of the atmosphere of the earth on a scale of wavelengths, running from very short wavelengths in the ultraviolet region, through the visible, up into the range of radio wavelengths. Over nearly all of that range with two exceptions either the atmosphere, or the ionosphere just beyond it, absorbs 100% of incoming radiation. It is only in these two regions of the spectrum that our atmosphere will let anything come through. The radio "window" extends from a few centimeters to several meters wavelength. Electromagnetic waves in this band from any celestial source can reach our antennas on the earth. The branches of radioastronomy are many because radiation comes to us from all sorts of objects. A great deal of radio energy comes from the sun; radio waves come from stars and various odd astronomical objects. I shall discuss only one branch of radioastronomy, the study of the structure of the galaxy, that is, our Milky Way, by means of radio waves. My purpose in talking about it is to show how much information one can derive, from enormous distances, with little energy.

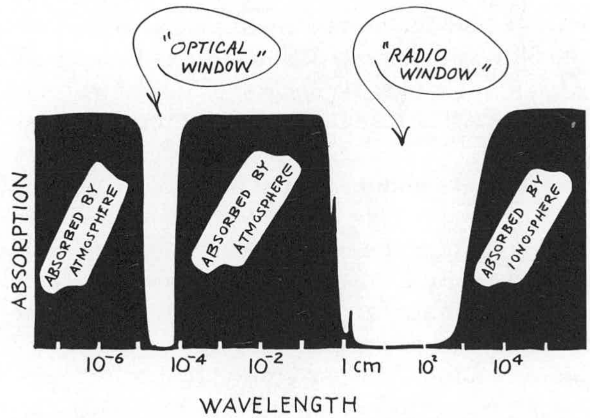


Figure 1. Absorption spectrum of the earth's atmosphere versus wavelength.

To begin with, let us place ourselves in the universe in the usual way by taking a look at a galaxy (Figure 2). No talk like this is complete without a picture of a spiral nebula. This is one of the most beautiful and, furthermore, is one which is probably rather like the galaxy in which we live. Of course it is not the one in which we live, or we could not have taken this picture. This is a large flat cluster of about 100 billion stars seen more or less on a slant. Observe its irregular shape with rather ill-defined arms spiraling off; it is a spiral

*L.A. DuBridge, *Introduction to Space*, Columbia University Press, New York, 1960.

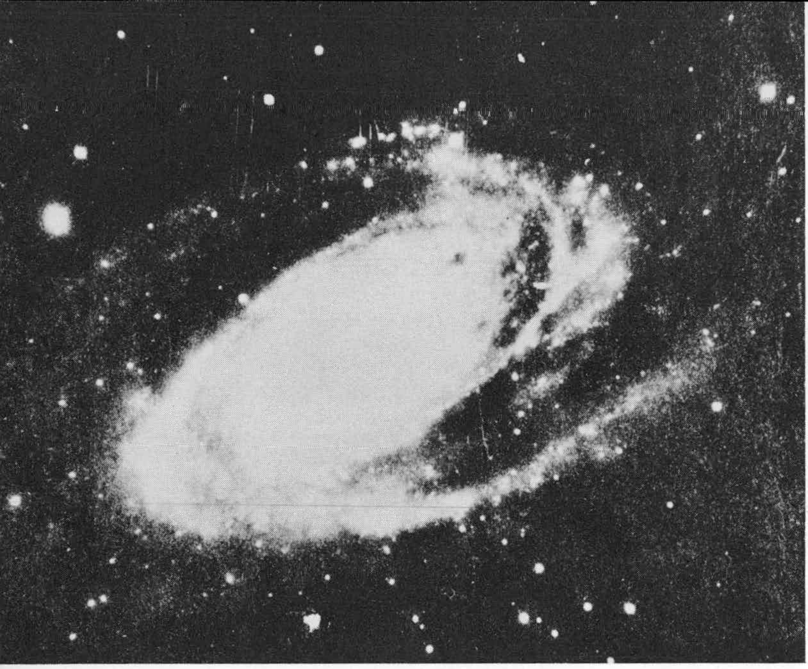


Figure 2. Spiral nebula.

nebula. There are hundreds and thousands of galaxies of this type. We happen to inhabit one of them. The one we inhabit is perhaps an ordinary one, but of course it is of special interest to us, and we would like to know what it looks like. It is very hard to find out because we cannot see it from the outside. Let me describe our galaxy by showing what it might look like in cross section, if we could examine a slice taken right down through the disk (Figure 3).

There are about 10^{11} stars in an object of this sort; the sun is one of these and happens to be out rather near the edge, about 25,000 light years from the center. The thickness of this disk is only some 700 light years on this scale. In addition to the stars, the galaxy has in it dust (small grains of matter) and hydrogen atoms. It has hydrogen atoms to the tune of about one per cubic centimeter through most of the spaces where there are no stars. In saying this I am getting ahead of my story, but it will make the story easier to follow. The stars make up most of the mass, but the hydrogen atoms are a non-negligible part; they make up perhaps ⅓ or ¼ of the mass of this whole assembly. The dust in itself doesn't amount to much – except as a nuisance; the dust makes this large collection of stars almost opaque to visible light. A telescope situated at the position of the sun or the earth can see only a little way into the galaxy, in most directions, because before long the path of vision is interrupted by a cloud of dust. One cannot see anything like the *whole* structure looking out with a telescope, or with the eye. Indeed if one could, the Milky Way, which is what we do see of the galaxy, from our vantage point, would present a very different spectacle. It would be a very narrow, very bright band, absolutely straight, going across the sky like a great circle. We are buried within this pancake, out near the edge, able to see with a telescope only part of the pancake in our vicinity. For this reason, until a tool became available to explore the greater depths of the system, one had rather little idea of the details of its structure. The dust grains, being very small, do not hinder the passage of radio waves at all. A one-meter-wavelength radio wave oozes around a tiny dust grain without the slightest trouble and goes on as if nothing were there. Thus the pancake is, by and large, completely transparent to radio waves, and, if there is a source of them, one can see that source no matter how far away it may be in the disk of stars and gas.

There is a radio wave that is emitted by the gas itself, and I will briefly describe this source before telling what it leads to (Figure 4). The hydrogen atom, which consists of an electron and a proton, happens to have in its structure a natural frequency which is in the radio range. The frequency is 1420 megacycles per second, corresponding to a wavelength of 21 centimeters. This frequency arises from the magnetic interaction between the electron and the proton. The cloud in Figure 4 represents the electron, and the arrow represents the axis about which the electron spins. The proton spins around an axis too. Because of the spin each particle acts like a bar magnet. The two little magnets try to set themselves parallel, but because they are spinning they don't achieve it. Instead, they precess around like gyroscopes. When the

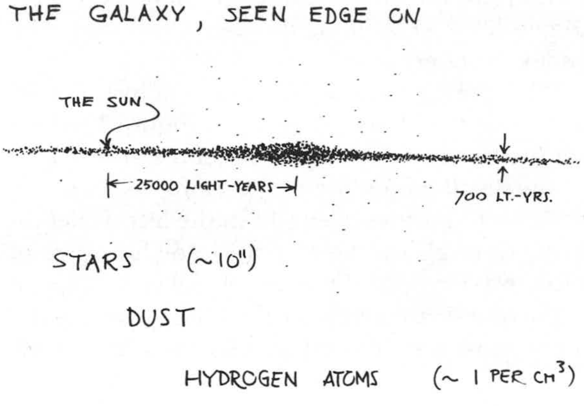


Figure 3.

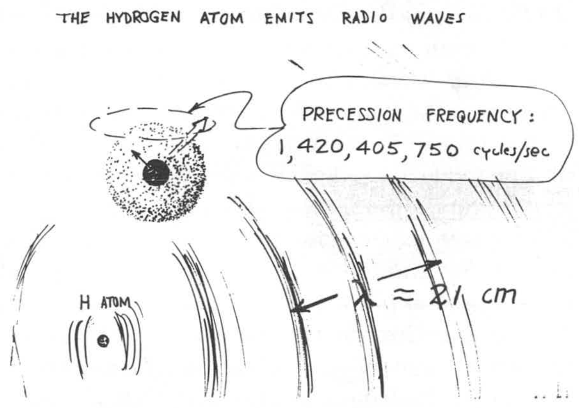


Figure 4.

hydrogen atom is all by itself out in free space, with no perturbations or anything, and is in its lowest possible energy state, the electron spin axis quietly precesses around with a frequency of 1,420,405,750 cycles per second.

I confess that the fact that this number is so long has no bearing whatever on the present subject, but I did want to write it out to show what kind of measurements are made nowadays in the branch of physics which measures these atoms in the laboratory. It is the branch carried on in Dr. Cohen's atomic beam laboratory here at Brookhaven. This number is an actual experimental measurement, not a theoretical number like π, and not a social security number, which it rather resembles. There is, at present, some argument among the fraternity about the last one or two digits. But there is also a recent development in atomic beams which makes it quite certain that within a year or two even more digits will be known. This is probably one of the most accurately known numbers in all of physics. As we shall see, that doesn't really do us very much good in the astronomical problem, but it does some good. From Figure 1, which shows the radio window in the spectrum, it may be seen that, fortunately, the wavelength of 21 centimeters falls right in the middle of the gap where there is practically no absorption in either the atmosphere or the ionosphere. Furthermore, the atom which emits this frequency is by all odds the most abundant atom in the universe. Hydrogen in the ground state makes up probably 99% of the gas in the galaxy. The only difficulty is that the emission from any one atom is exceedingly feeble, so that we just about need that much hydrogen in order to get a result.

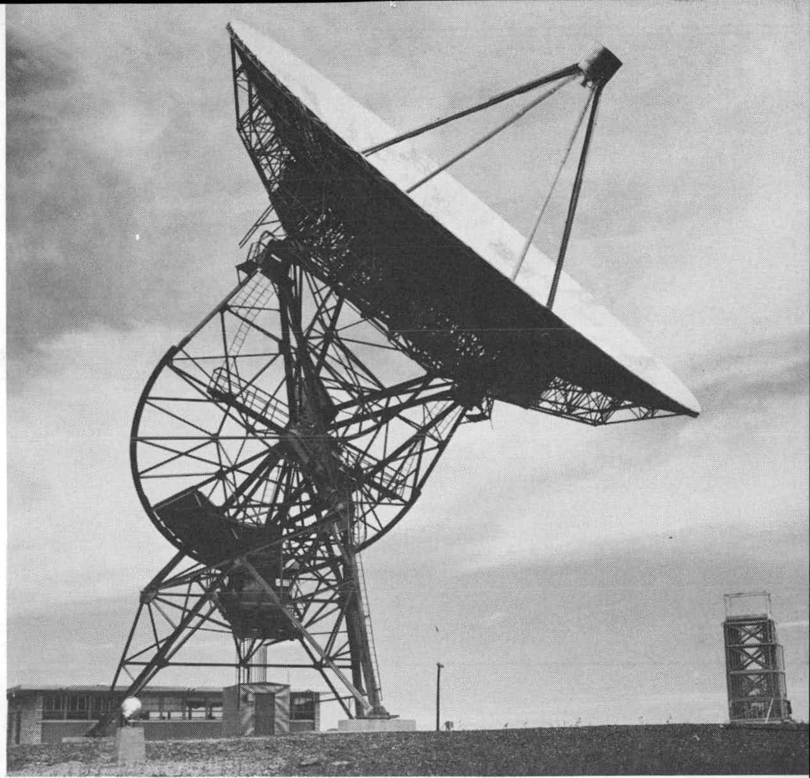
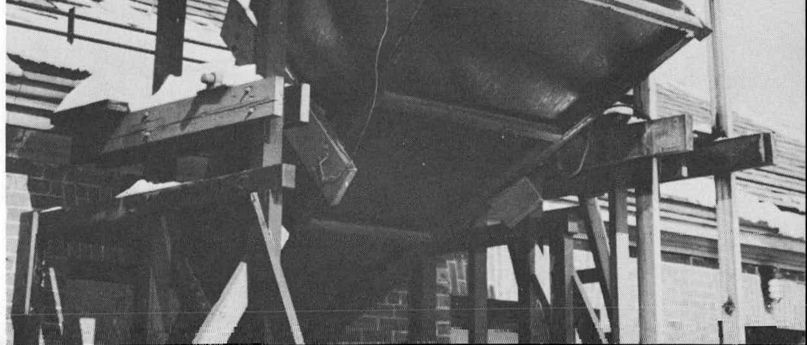


Figure 5. Radio telescope.

Nowadays, there is wide activity in this field. Many observatories are studying the emission that comes in from the hyrogen atoms in the galaxy. This is done with a standard kind of radio telescope. Figure 5 shows a radio telescope at the National Radio Astronomy Observatory in Green Bank, West Virginia, which is a small sister institution to Brookhaven, being run by AUI. This is the 85-foot radio telescope which is used for both hydrogen studies and other observations and is doing very beautiful work in the hands of the group there. In the old days we did this type of work more on a shoestring basis, and, for old times' sake, I have a photograph (Figure 6) show-

Figure 6. First radio telescope antenna at Harvard.



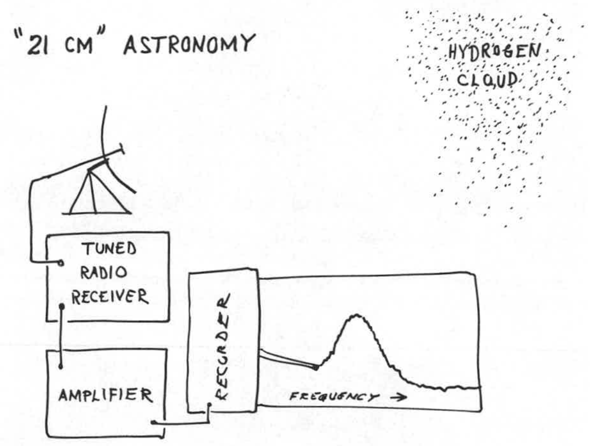


Figure 7.

ing the first antenna at Harvard for the 21-centimeter radiation, with Harold Ewen, who did the work. This antenna, a simple horn, was fashioned by our carpenter and installed on the roof at a total cost of about $400.00. The electronics was all scrounged and no price was ever computed for it. The principle of this kind of astronomy is really very simple; Figure 7 shows it stripped of all irrelevant details. One has a radio receiver and a large antenna. The antenna is large simply so that one can collect more energy or look at a particular spot in the sky. It feeds into a rather conventional receiver, where the radio energy is amplified and, finally, recorded on something to show its intensity. Of course, it isn't music; it's just noise. One records the average energy coming in on a given wavelength band. The recorder cranks out some paper and the pen traces a graph showing that at a particular frequency there was reception of energy. That is really all there is to it, except for the electronics, which calls for some elegance of design if one is to make the most of the very feeble signal. We needn't go into that at all.

If we look at the radiation that does come in from a hydrogen cloud or a concentration of hydrogen that was in the Milky Way, this is what we might see (Figure 8). Indeed this is what we do see in one particular direction. If one were looking at hydrogen in the laboratory, a frequency scan would give a single narrow line, the dotted peak in the figure, at the precise frequency I wrote down earlier. Instead of that, looking out into the galaxy, one sees quite a broad affair which often has a structure such as the three-humped curve I have drawn. The reason is very simple. It is the old business of the Doppler effect. The hydrogen which is emitting this "light" is not at rest with respect to us. It may, as a whole, be moving and streaming. We know that astronomical objects are commonly in motion. If the hydrogen cloud is coming towards us, the line will come in at a somewhat higher frequency, and if it is going away, at a lower frequency, than if it were stationary with respect to our antenna. In this case we know, and I will try to explain in a minute how we know, that the three humps are emissions from hydrogen located at three different places; at these different places the hydrogen is moving with different speeds. And that is about all one can say; something can be inferred about the temperature and density of the hydrogen, but we needn't go into that.

Despite its limitations, the astronomers, notably the Dutch astronomers Oort and Van der Hulst at Leiden, found how to exploit this kind of information. Van der Hulst, incidentally, was the first one to recognize the possibility of detecting the galactic hydrogen emission. Oort and Van der Hulst discovered a way to extract, from records like Figure 8, by a kind of indirect argument, the actual *location* of the hydrogen along the line of sight. Remember, this is not like radar. We are not sending out a wave and getting it back; there is no "echo time" to tell us how far away the stuff is. We are just sitting here receiving, and the only thing we can tell directly is how fast the source is moving toward or away from us. To deduce the location of the source we need to know something else about the galaxy.

Imagine this disk is the galaxy (Figure 9). This is just a cloud of stars, and we know that it is not stationary; it is rotating. Astronomers knew that from

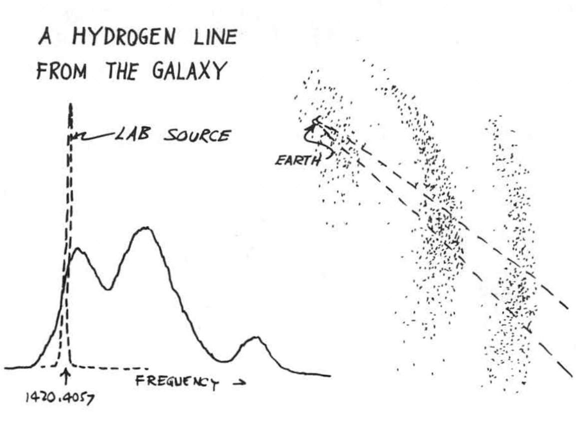


Figure 8.

their observations of the motion of stars. But it is not rotating like a phonograph record, all as one piece, because the stars are not rigidly connected to one another. Rather, it is rotating much more the way the planets revolve around the sun: the outer planets are moving relatively slowly, the inner planets, closer to the central mass, are moving with higher velocity. In fact, one can think of the galaxy as a sort of planetary system. It has no single, dominant body at its center, but it does have a general concentration of mass in the central portion of the disk. The rotational velocity must vary with distance from the center in a way that we can easily predict once we know how the mass is distributed. We begin by adopting a radial mass distribution – a galactic model – that is reasonable in the light of other astronomical evidence. For this distribution we work out the required speed of revolution for material at any given distance from the galactic center – the modified "Kepler's law" for the system.

If one looks out now in a certain direction and sees a source with a certain velocity, one can pin it to a certain position on the line of sight. Of course this involves the assumption about the radial distribution of mass. But one can work backward, and continue until the whole picture is consistent with itself. This is what has been done by the radioastronomers in both Holland and Australia, who have gradually built up a map of the hydrogen gas in the galaxy.

Figure 9 is a model* of the galaxy which shows the locations of the concentrations of hydrogen gas. The chart (Figure 10) is one that was made and published by Westerhout in Leiden, who has been one of the leaders in this exploration. Westerhout, for reasons that we needn't go into here, left out the central part. There is a tremendous amount of hydrogen in the middle but not much is known about it. In making the model we fudged it back in, adding the patches in the center. Of course these bear no relation, in detail, to what is really there. The arms, however, are real. The left half of this picture is the product of the radioastronomers in Sydney, Australia. They have a view of that half of the galaxy from the southern hemisphere. The right half is the product of the group in Leiden under Oort, Van der Hulst, and Westerhout. There is no doubt whatever that this is a spiral nebula. In fact, we can even locate our-

*Made with the help of John Garfield and his staff in the Technical Photography and Graphic Arts Division.

Figure 9. Model of the galaxy showing locations of concentrations of hydrogen gas.

Figure 10. Westerhout's map of the galaxy.

selves in one of the arms. It is also evident that this is still a self-centered view of the galaxy; there is no reason for the near half to look so different from the far half except that we happen to have a better view of the former.

There are other things to be learned which I will point out now on the model. This is a scale model. It is probably the biggest scale that anybody has used around here: one inch = 3000 light years. It is to scale also in thickness. The ¼-inch thickness of the Plexiglas truly represents the relative thickness of the pancake of stars. And the flatness is also true. In fact, it hardly does justice to the galaxy. On this scale, the median surface of the hydrogen distribution is flat, over most of the galactic disk, to 1/32 inch, a fact which came as a surprise to astronomers. No one knows how a distribution of matter which is so irregular in plan view can contrive to be so precisely flat. The fact must have some deep significance for galactic dynamics. Actually, there are interesting systematic departures from flatness near the edge. We went to some trouble to bend the edges of our model to represent the "snap brim" effect, as it has been called. The median surface, as observed by hydrogen emission, appears to turn up a little at one place, and down at the opposite part of the rim.

It is a pity that one cannot say for sure which way the spiral arms go. It is surprising to learn from astronomers that this question was not settled long ago. The naive assumption that because spiral nebulae look like pinwheels they must be moving like pinwheels is hard to defend without a convincing theory of galactic evolution. As for direct observation of another spiral nebula, Doppler shift of spectral lines reveals which side is approaching us, but there is no easy way to tell which edge is *nearer* to us, so the tantalizing ambiguity remains. I believe majority opinion favors the pinwheel sense. Further refinement of the hydrogen map of our own galaxy – where we *know* the absolute sense of rotation – may eventually settle the question beyond doubt.

This is what has been learned from this one branch of radioastronomy, and the point that I would like to make before I turn to the second part of my talk is that this has been learned by receiving a rather astonishingly small amount of energy, energy which has traveled a very long way to us. The total amount of power that comes to the earth in hydrogen radiation from everywhere in the universe, that is, the power falling on the entire earth, is about *one watt.* The radioastronomers at Leiden, Harvard, Sidney, Greenbank, and elsewhere have been picking up a tiny fraction of that with their antennas. A more astonishing figure is one that I had to compute three times before I was sure of my arithmetic: the total *energy* received by *all* 21-centimeter observatories over the past nine years, is less than one erg! From less than one erg of energy we have built this picture of our galaxy. Most of you know what an erg is – you can't knock the ash off your cigarette with an erg. That point I want you to remember. It is germane to the thesis which I shall try to establish in the last two parts of this talk, which depart from sober science and go in other directions.

SPACE TRAVEL

In the second part I shall talk briefly about space travel, and I want to say very distinctly that I am not going to argue the case, pro or con, for travel around the solar system – visiting the moon and Mars and so on. We shall look at wider horizons, as all the astronautical types do, and talk about travel *beyond* the solar system. A lot has been written about this. You are probably as tired of hearing about it as I am, but I hope that if we look at it in one particular way, it may present a fresh aspect. Of course, everything is very far away. The stars are very far away. The nearest star, Alpha Centauri, is 4 light years distant. People have worried about this but they blandly say, "That's all right because we will travel at nearly the speed of light.

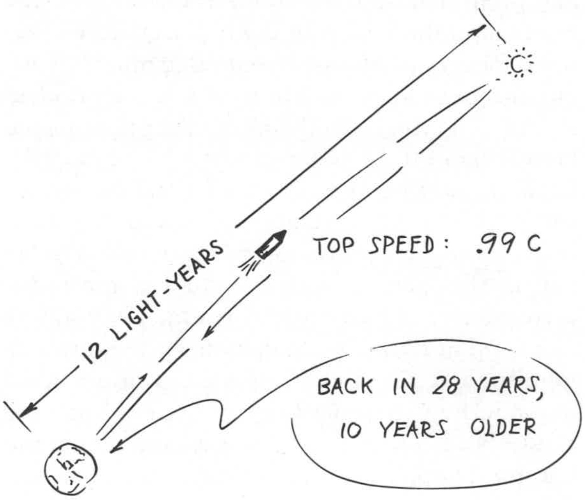


Figure 11. Trip to a place 12 light years away.

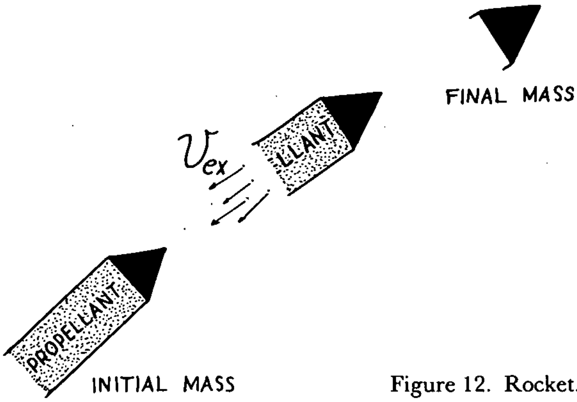


Figure 12. Rocket.

Even without relativity we will get there fast and with relativity we will get there and be young anyway." That is perfectly correct, in my view, so far as it goes. Special relativity is reliable. The trouble is not, as we say, with the *kinematics* but with the *energetics*. I would like to develop that briefly, with a particular example. Figure 11 defines my example. Let us consider taking a trip to a place 12 light years away, and back. Because we don't want to take many generations to do it, let us arbitrarily say we will go and come back in 28 years earth time. We will reach a top speed of 99% speed of light in the middle, and slow down and come back. The relativistic transformations show that we will come back in 28 years, only 10 years older. This I really believe. It would take 24 years for light to go out and come back; it takes the traveler 28 years as seen by the man on earth but the traveler is only 10 years older when he gets back. I don't want to stop and argue the "twin paradox" here because if one *does not* accept its implications then the conclusion that I am going to draw becomes even *stronger*. Personally, I believe in special relativity. If it were not reliable, some expensive machines around here would be in very deep trouble.

Now let us look at the problem of designing a rocket to perform this mission. Let us begin with a reminder of what a rocket is (Figure 12). It is a device that has some propellant which it burns and throws out the back. The mechanical reaction accelerates the rocket. When the propellant is all gone, the rocket has reached its final speed and only the payload remains. That is the *best* one can do – carrying along extra hardware only makes it worse. Staging of rockets, i.e., the use of four or five successively smaller stages, is merely a way of trying to *approach* this ideal. The performance of a rocket depends almost entirely on the velocity with which the propellant is exhausted, V_{ex}, as I have called it, *ex* for exhaust. The rocket people talk about specific impulse, but the impulse they talk about really has the dimensions of a velocity. Let us look at the role this velocity plays in rocket propulsion (Figure 12). Here is the rocket with its V_{ex} and we want to get it up to some final speed V_{max}. Then the elementary laws of mechanics – in this case relativistic mechanics, but still the elementary laws of mechanics – inexorably impose a certain relation between the initial mass and final mass of the rocket in the *ideal* case. This relation, shown in Figure 13, is relativistically exact. It follows very simply from conservation of momentum and energy, the mass-energy relation, and *nothing else*. In other words, the only thing that could possibly be wrong with this equation is that I made a mistake in deriving it. That is always possible, but I don't think I did. It checks all right at the limits.

You can plainly see the disadvantage of low exhaust velocity. If we demand a final speed V_{max} very near the velocity of light, this denominator is going to get awfully small, and the exponent will get large. This is not peculiar to the relativistic domain but occurs in ordinary rocketry too, wherever the final speed required greatly exceeds the exhaust velocity – as it unfortunately does in the case of earth satellites launched with chemically fueled rockets.

For our vehicle we shall clearly want a propellant with a *very* high exhaust velocity. Putting all practical questions aside, I propose, in my first design, to use the *ideal nuclear fusion* propellant (Figure 14). I am going to burn hydrogen to helium with 100% efficiency; by means unspecified I shall throw the helium out the back with kinetic energy, as seen from the rocket, equivalent to the entire mass change. You can't beat that, with fusion.

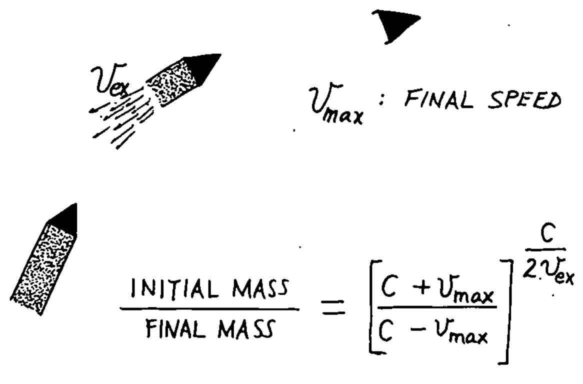


Figure 13. Relation between the initial mass and the final mass of a rocket in the ideal case.

One can easily work out the exhaust velocity: it is about ⅛ the velocity of light. The equation of Figure 13 tells us that to attain a speed 0.99c we need an initial mass which is a little over a *billion* times the final mass. To put up a ton we have to start off with a million tons; there is no way to beat this if we can't find a better reaction.

There simply *are* no better fusion reactions in nature, except one. This is no place for timidity, so let us take the ultimate step and switch to the perfect matter-anti-matter propellant (Figure 15). Matter and anti-matter annihilate; the resulting energy leaves our rocket with an exhaust velocity of c or thereabouts. This makes the situation very much better. To go up to 99% the velocity of light only a ratio of 14 is needed between the initial mass and the final mass. But remember, that isn't enough; we have only reached V_{max} and our mission is only one quarter accomplished, so to speak. We have to slow down to a stop, turn around, get up to speed again, come home, and stop. That does not make the ratio 4×14, that makes it 14^4 which is 40,000. So to take a 10-ton payload over the trip described in Figure 11 I see no way whatever to escape from the fact that at take-off we must have a 400,000-ton rocket, half matter and half anti-matter.

Incidentally, there is one difficulty which I should have mentioned earlier, but at this stage it is comparatively trivial. If you are moving with 99% the velocity of light through our galaxy, which contains one hydrogen atom per cubic centimeter even in the "empty spaces," each of these hydrogen atoms looks *to you* like a six-billion-volt proton, and they are coming at you with a current which is roughly equivalent to 300 Cosmotrons

WITH PERFECT NUCLEAR FUSION PROPELLANT

$$4H \rightarrow He \qquad v_{ex} \approx \frac{1}{8}c$$

IF v_{max} IS TO BE .99 C,

$$\frac{\text{INITIAL MASS}}{\text{FINAL MASS}} = 1.6 \times 10^9$$

Figure 14.

WITH PERFECT ANTI-MATTER PROPELLANT

$$v_{ex} \approx c$$

FOR $v_{max} = .99\,c$, $\frac{\text{INITIAL MASS}}{\text{FINAL MASS}} = 14$

BUT TO STOP, RETURN HOME, AND STOP,

$$\frac{\text{INITIAL MASS}}{\text{FINAL MASS}} = (14)^4 = 40{,}000$$

Figure 15.

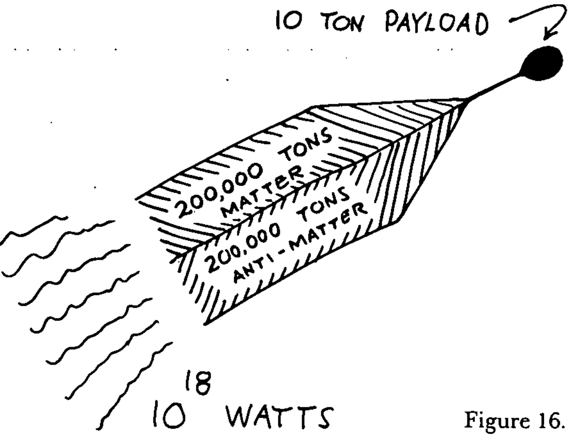


Figure 16.

per square meter. So you have a minor shielding problem to get over before you start working on the shielding problem connected with the rocket engine. That problem is quite formidable as you will see from Figure 16 which shows our final design. We have 200,000 tons of matter, 200,000 tons of anti-matter, and a 10-ton payload, preferably pretty far out. The accelerations required are of the order of 1 g over the whole trip, and not merely in leaving the earth. It just happens that g times one year is about equal to the speed of light, so if we want to reach the speed of light in times of the order of years, we are going to be involved in accelerations of the order of 1 g. (This is the *one* respect in which relativistic astronautics is simple. No space-medical research is needed to assure us that we can stand 1 g. We have been doing it all our lives.) In order to achieve the required acceleration our rocket, near the beginning of its journey, will have to radiate about 10^{18} watts. That is only a little more than the total power the earth receives from the sun. But this isn't sunshine, it's gamma-rays. So the problem is not to shield the *payload*, the problem is to shield the *earth*.

Well, this is preposterous, you are saying. That is exactly my point. It *is* preposterous. And remember, our conclusions are forced on us by the elementary laws of mechanics. All those people who have been seriously talking about *Lebensraum* in space, and so on, simply haven't stopped to make this calculation and until they do, what they say is nonsense – no matter how highly placed they may be or how big a budget they may control.

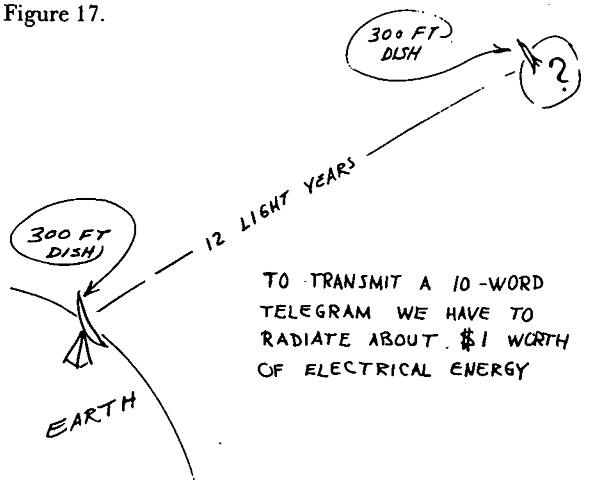
COMMUNICATION THROUGH SPACE

Now I would like to turn to a quite different subject, one which is also speculative, but which involves an entirely different scale of magnitudes, the problem of communication through space. We have already seen how little energy was involved in the amount of information which revealed the structure of our galaxy. An example, in terms of practical communication of messages, is given in Figure 17. If I can transmit a message by point-to-point operation with a reasonably large antenna at each end, a 10-word telegram can be transmitted over the 12-light-year path discussed above with a dollar's worth of electrical energy. This is possible because we can detect, amplify, and identify in a radio circuit an amount of energy exceedingly small, and because the energy travels to us suffering no loss whatever except the "inverse square" diminution of intensity as it spreads.

Of course, the trouble is that there isn't anybody at the other end to communicate to. Or is there? What I would like to talk about now is not a new subject and I may not say anything new about it, but I have thought about it a good bit. It is the question of communicating with other people out there, if there are any.

Let us look at the galaxy again. There are some 10^{11} stars in the galaxy. *Double* stars are by no means uncommon, in fact there appear to be almost as many double stars as single stars. Astronomers take this as a hint that invisible companions in the form of planets may not be very uncommon either. Moreover, a large number of stars have lost their angular momentum and are not spinning. One good way for a star to lose its angular spin is by making planets; that is what probably hap-

Figure 17.



pened in our own solar system. So the chance that there are hundreds of millions of planetary systems among these hundred billion stars seems pretty good. One can elaborate on this, but I am not going to try here to estimate the probability that a planet occurs at a suitable distance from a star, that it has an atmosphere in which life is possible, that life developed, and so on. Very soon in such a speculation the word probability loses operational meaning. On the other hand, one can scarcely escape the impression that it would be rather remarkable if only one planet in a billion, say, to speak only of our own galaxy, had become the home of intelligent life.

Since we can communicate so easily over such vast distances, it ought to be easy to establish communication with a society (let us use that word) in a remote spot. It would be even easier for them to initiate communication, if they were ahead of us. Shall we try to listen for such communications, or shall we broadcast a message and hope someone hears it? If you think about it a little, I think you will agree that we want to listen *before* we transmit. The time scale of the galaxy is very long. Wireless telegraphy is only 50 years old, and really sensitive receivers are much more recent. If we look for people who are able to receive our signals but have not surpassed us technologically, i.e., people who are not more than 20 years behind us but still not ahead, we are exploring a very thin slice of history. On the other hand, if we listen, we are looking for people who are *anywhere* ahead providing they happen to have the urge to send out signals. Also, being technologically advanced, they can transmit much better than we can. (For rather fundamental reasons, transmitting is harder than receiving in this game.)

So it would be silly to transmit before listening for a long time. This is an amusing game to play. I won't dwell on it long because you will have more fun trying it yourself, but let me suggest its nature. In the first place, it is essentially cryptography in reverse. Let me assume – this may not be true, but let me assume it – that there is somebody out there who is technologically ahead of us. He can transmit 10 megawatts as easily as we can transmit a kilowatt, and he wants us to receive his signal. He surely knows more about us than we know about him, and moreover, he is a relatively close neighbor of ours in the galaxy. We share the same environment; he knows all about the hydrogen line – he learned it centuries ago. He knows that that line is the only prominent line in that window of the spectrum.

If you want to transmit to a fellow and you can't agree on a frequency, it's nearly hopeless. To search the entire radio spectrum for a feeble signal entails a vast, and calculable, waste of time. It is like trying to meet someone in New York when you have been unable to communicate and agree on a meeting place. Still, you know you want to meet him and he wants to meet you. Where do you end up? There are only two or three places: Grand Central Station, etc. Here, there is only one Grand Central Station, namely the 1420-megacycle line which is, by a factor of 1000 at least and probably more, the most prominent radio frequency in the whole galaxy. There is no question about where you transmit if you want the other fellow to hear, you pick out the frequency that he knows. Conversely, he will pick the frequency he knows we know, and that is the frequency to listen on. If you play this game carefully you will find the conclusion inescapable. We know what to do; we know where to listen. We don't know quite what his code will be but we know how to set up a computer program to search for various codes. Let us make some reasonable assumptions, for example, about power. Let us give the transmitter the capability of radiating a megawatt within a 1-cycle/second band. This is something we could do next year if we had to; it is just a modest stretch of the present state of the art. Indeed, my information may be obsolete, there may be contracts out now calling for such performance. Suppose we receive with a 300-foot disk and he transmits with one as large. How we process the signals will affect the ultimate range, but, making very simple and conservative assumptions about that part of the problem, I find that we should be able to recognize his signal even if it comes from several hundred light years away. With the new MASER receivers which have just begun to be used in radioastronomy, 500 light years ought to be easy. A sphere only 100 light years in radius contains about 400 stars of roughly the same brightness (± 1 stellar magnitude) as the sun. And remember, the volume accessible by communication goes up as the cube of the range. I have argued that it is ridiculously difficult to travel even a few light years, and ridiculously easy to communicate over a few hundred. I think these numbers actually underestimate the disparity. But even so, the ratio of the volumes is one million (Figure 18).

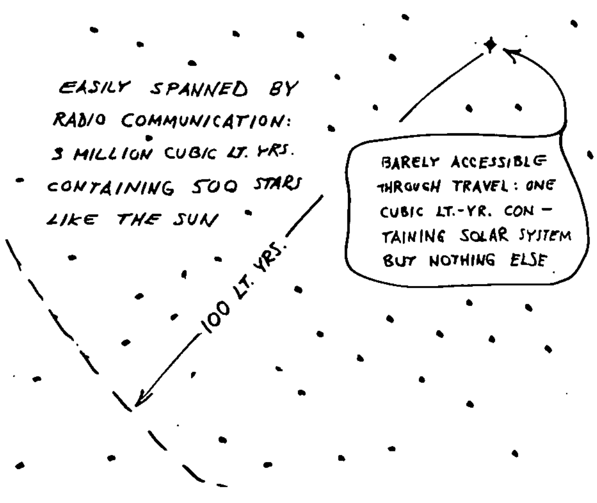


Figure 18.

There are other interesting questions. When we get a signal, how do we know it is real and not just some accident of cosmic static? This I like to call the problem of the axe head. An archeologist finds a lump of stone that looks vaguely like an axe head, down in about the right layer. How does he know it is an axe head and not an oddly shaped lump of stone? Actually, they are usually *very* sure. An arrowhead can look rather like an elliptical pebble, and still there is no doubt that it is an arrowhead. Our axe head problem can be solved in many ways. The neatest suggestion I know of originated with Cocconi and Morrison,* who have published a discussion of this whole subject. Morrison would have the sender transmit a few prime numbers. That's all you need: 1, 3, 5, 7, 11, 13, 15, 17 – by then you *know*. There are no magnetic

*G. Cocconi and P. Morrison, *Nature* **184**, 844 (1959).

storms or anything on Venus making prime numbers.

What can we talk about with our remote friends? We have a lot in common. We have mathematics in common, and physics, and astronomy. We have the galaxy in which we are near neighbors. The Milky Way looks about the same to them; 400 light years is only ⅛ inch on our model here. We have chemistry in common, inorganic chemistry, that is. Whether their organic chemistry has developed along the lines of ours is another question. So we can open our discourse from common ground before we move into the more exciting exploration of what is not common experience. Of course, the exchange, the conversation, has the peculiar feature of built-in delay. You get your answer back decades later. But you are sure to get it. It gives your children something to live for and look forward to. It is a conversation which is, in the deepest sense, utterly benign. No one can threaten anyone else with objects. We have seen what it takes to send *objects* around, but one can send information for practically nothing. Here one has the ultimate in philosophical discourse – all you can do is exchange ideas, but you do that to your heart's content.

I am not sure we are in a position to go about this yet. I am not advocating spending a lot of money setting up listening posts, although, as a matter of fact, a listening program on a very modest scale is going on at Green Bank under Frank Drake, who has some very imaginative and, I think, sound ideas on how it should be done. They haven't heard anything yet.

But in my view, this is too adult an activity for our society to engage in, on a large scale, at the present time. We haven't grown up to it. It is a project which has to be funded by the *century*, not by the fiscal year. Furthermore, it is a project which is very likely to fail *completely*. If you spend a lot of money and go around every ten years and say, "We haven't heard anything yet," you can imagine how you make out before a congressional committee. But I think it is not too soon to have the fun of thinking about it, and I think it is a much less childish subject to think about than astronautical space travel. In my view, most of the projects of the space cadets are not really imaginative. And the notion that you have to *go* there seems to me childish. Suppose you took a child into an art museum and he wanted to *feel* the pictures – you would say, "That isn't what we do, we stand back and look at the pictures and try to understand them. We can learn more about them that way." All this stuff about traveling around the universe in space suits – except for *local* exploration which I have not discussed – belongs back where it came from, on the cereal box.

LIST OF BROOKHAVEN LECTURES

1. Radioastronomy and Communication Through Space, BNL 658
   Edward M. Purcell, Physics Department — November 16, 1960

2. Current Ideas on the Endocrine Regulation of Cellular Processes
   Irving Schwartz, Medical Department — December 14, 1960

3. Inside the Protein Molecule, BNL 649
   Werner Hirs, Biology Department — January 11, 1961

4. Nuclear Chemistry Research With the Cosmotron
   Gerhart Friedlander, Chemistry Department — February 15, 1961

5. Neutron Physics Of and With the High Flux Beam Research Reactor, BNL 664
   Herbert Kouts, Nuclear Engineering Department — March 15, 1961

6. High Energy Accelerators
   Ernest Courant, Accelerator Department — April 12, 1961

7. Dislocations in Crystal Lattices
   George H. Vineyard, Physics Department — May 17, 1961

8. The History of Cosmic Rays in Meteorites
   Oliver A. Schaeffer, Chemistry Department — June 14, 1961