The Search for Signals from Other Civilizations

The waiting time for answers may be greater than the longevity of the technical state of mind.

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A search for extraterrestrial signals from an intelligent source should be guided by two estimates, one of the probable nature of such signals and the other of the distance from which they might come. We cannot search for something without at least a rough idea of what to look for, and we cannot detect an object if the range of our means of perception is too short. The present article (*1*) is concerned in large part with the distance. The objective in making such estimates is not to make statements about other civilizations but solely to lead to a working hypothesis which could guide a search.

Because we have no knowledge whatsoever about other civilizations, we have to rely completely on assumptions. The one basic assumption we want to make can be formulated in a general way:

Anything seemingly unique and peculiar to us is actually one out of many and is probably average. (1)

As a demonstration of the power of this method one can show that even the ancient Greeks could have estimated the distance of the sun from the earth, and even the distance between neighboring stars, if they had just applied the foregoing assumption to the earth, assuming it to be an average planet, and to the sun, assuming it to be an average star. They would have assumed that the earth was of average diameter, albedo, and distance from the sun; comparison of the average apparent brightness of the five known planets with that of the sun, together with the Greeks' knowledge of the diameter of the earth, would have given them a distance to the sun which is too large by a factor of 2. They would have assumed that the sun had average absolute brightness; comparison of the average apparent brightness of the ten brightest stars with that of the sun, together with the distance of the sun as derived above, would have yielded a distance between neighboring stars which is too small by 5 percent.

All that is needed in this approach is the right classification and one absolute value to start with (in the foregoing examples, the diameter of the earth). The resulting estimate can be, of course, completely wrong, but the probability that it will be is very small, and the probability that the result will be right is high. This is the best we can demand.

The basic assumption in the present article is that our planetary system and our civilization are about average and that life and intelligence will develop by the same rules of natural selection wherever the proper surroundings and the needed time are given. This includes the assumption that the average civilization will reach our present level of intellectual concern or state of mind (science, technology, search for interstellar communication) after about the same length of time as we did and will face about the same difficulties as we do. However, we should also assume that our present state of mind is just one of many possibilities and that it will be succeeded by other interests and activities.

We should not underestimate the power of two critical factors that can terminate the life of a civilization once the technical state has been reached. Science and technology have been brought forward (not entirely, but to a high degree) by the fight for supremacy and by the desire for an easy life. Both of these driving forces tend to destroy if they are not controlled in time: the first one leads to total destruction and the second one leads to biological or mental degeneration. In summary, we assume that a state of mind not too different from our own will have developed at many places but will have only a limited longevity.

Distance between Civilizations

All of the following quantities are supposed to be average ones within a solar neighborhood of, say, 1000-parsec radius (*2*). We call ν_0 the fraction of all stars which have planets where life can develop, T_0 the time needed to develop a technical civilization (defined, for example, by the presence of highly advanced radio techniques), l the longevity (*3*) of the technical civilization, T the age of the oldest stars, and ν the fraction of all stars which at present have a technical civilization. If we assume, for the present purpose, that the rate of star formation has been constant over the time T, we then have

$$\nu = \begin{cases} \nu_0 (T - T_0)/T & \text{if } l \geq T - T_0 \\ \nu_0 (l/T) & \text{if } l \leq T - T_0 \end{cases} \qquad (2)$$

If we call D_0 the mean distance between neighboring stars, then the mean distance between neighboring technical civilizations, D, is given by

$$D = D_0 \nu^{-1/3} \qquad (3)$$

In order to obtain the average longevity l, we have to go into some detail. We adopt the following five alternatives by which the longevity of a technical civilization (or of its technical state of mind) might be limited: 1) complete destruction of all life; 2) destruction of higher life only; 3) physical or mental degeneration and decay; 4) loss of interest in science and technology; 5) no limitation at all. In cases 2 and 3, another civilization might develop on the same planet out of the unaffected lower forms of life, and we assume that the time needed for such recurrence is small compared with T_0. Now, we call $l_1 \ldots l_5$ the average longevity in the above five

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alternative cases and $p_1 \ldots p_5$ the probability of their occurrence. If $l_1 \ldots l_4 \leq T - T_o$, we have

$$\nu = \nu_o \{ [(p_1 l_1)/T] + \ldots + (p_4 l_4/T) + p_5(T - T_o)/T \} \times [1 + (p_2 + p_3) + (p_2 + p_3)^2 + \ldots] \quad (4)$$

or

$$\nu = \nu_o Q(l/T) \quad (5)$$

with the average longevity l defined by

$$l = \sum_{i=1}^{4} p_i l_i + p_5(T - T_o) \quad (6)$$

and a recurrence factor Q, defined by

$$Q = 1/[1 - (p_2 + p_3)] \quad (7)$$

Another interesting question is the following: At what stage are the first civilizations we meet most likely to be? We call t the time from the beginning of their technical phase (defined by advanced radio techniques) to the present. The probability that the first civilizations we contact will be of group i is given by $P_i = \nu_i/\nu$, and their average "technical age" at the moment of contact is $t_i = l_i/2$. The most likely value for their technical age, then, is

$$t = \Sigma P_i t_i = (\Sigma p_i l_i^2)/2l \quad (8)$$

The probability is

$$p_r = p_2 + p_3 = (Q - 1)/Q \quad (9)$$

that there will have been other civilizations before them on the same planet.

The foregoing analysis seems to be fairly straightforward up to this point, but it tends to become a matter of personal opinion when one begins to adopt numerical values for the average longevities, l_i, and the probabilities of occurrence, p_i, of the various alternative cases. As a justification for doing so at all, I mention two arguments. First, one cannot design an adequate receiving system without some estimate of this kind. Second, the uncertainty of l enters Eq. 3 only with the power 1/3:

$$D \sim l^{-1/3} \quad (10)$$

In Table 1 appear the values which in my opinion are the most likely ones, and for the sake of brevity I omit all the long discussions which led to these values ($p_5 = 0$, for example, means that I do not believe in this one at all). Maybe this very subjective guess seems a little pessimistic, but I want to be on the safe side. From these values we find

$$l = 6500 \text{ years} \quad \text{and} \quad Q = 4 \quad (11)$$

If we adopt $T = 10^{10}$ years, $\nu_o = 0.06$ [somewhat less than the estimate of Su Shu Huang (*4*)], and $D_o = 2.3$ parsec (as the average distance of the ten nearest stars from the sun), we get

$$\nu = 2.6 \times 10^{-7} \quad (12)$$

as the fraction of stars which have technical civilizations at present, and

$$D_o = 360 \text{ parsec} \quad (13)$$

as the average distance to the ten nearest technical civilizations. Furthermore, we find from Eq. 8 that the first civilization we receive signals from will have a most probable "technical age" of

$$t = 1.2 \times 10^4 \text{ yr} \quad (14)$$

and thus will have weathered the first crisis (destruction) a long time ago; and there is a probability of

$$p_r = 75 \text{ percent} \quad (15)$$

that it will be the successor of older, extinct civilizations on the same planet. On the other hand, the chance of meeting a civilization in exactly the same phase that we are in [still confronted with the crisis of destruction (groups $i = 1$ and $i = 2$)] is only 0.4 percent. Finally, we define the average longevity of the most frequent civilizations by $L = 2t$ and obtain

$$L = 2.4 \times 10^4 \text{ yr} \quad (16)$$

First Conclusions

As mentioned earlier, this estimate should be regarded only as a working hypothesis for the purpose of guiding a future search for extraterrestrial signals. If we assume that the values adopted in Table 1 are not too wrong, and if we neglect the "feedback effect" discussed in the next section, we can draw the following conclusions.

1) The value $\nu = 2.6 \times 10^{-7}$ means that only one in 3 million stars will have a technical civilization, and this implies that we cannot search for signals from a certain number of individual, conspicuous stars; we must scan the whole sky continuously.

2) This value also implies that no other civilization will send contacting signals (intended to attract attention and to establish contact) in the direction of our sun as one of the conspicuous stars. But such contacting signals might be sent from beacons in all directions over the whole sky.

3) The value $D = 360$ parsec means that the antenna-receiver system to be used for a search should be able to reach a distance of at least, say, 400 parsec, and this also demands an estimate of the probable nature of the signals and the power emitted.

4) The civilizations we find will very probably be much older than we are, and they will be more advanced. Our chance of learning from them might be considered the most important incentive for our search.

5) Since 360 parsec is about 1000 light years, the waiting time t_w for an answer to a question will be about 2000 years on the average; this implies three consequences: (*a*) the contacting signals would already contain messages (including an introduction to a language); (*b*) there would be no need to hurry in "speaking," and relatively slow pulses might be used; (*c*) there might be some "speaking" and "listening," but "mutual exchange" of ideas would be rather limited because of the long time scale involved.

Possible "Feedback" Effect

The mutual exchange of ideas just mentioned leads to the consideration of a feedback effect of the longevity, via radio communication, on itself. Suppose that the estimated value for the (unaffected) longevity l (Eq. 11) is too large, so that in reality the waiting time for answers, t_w, is greater than the longevity of the technical state of mind. Then nobody will ever get an answer to his call. Some still-hopeful civilizations (after having made too optimistic an estimate for l) might, for a while, send signals which might be picked up occasionally by others. But if the search for signals, on the average, is not successful, then loss of interest will usually come soon. This we call case A. On the other hand, suppose that our estimated value of l is too small and that a real exchange is possible. This will have a tendency to keep interest alive over a very long period and might even lead to civilizations' helping one another to solve problems and weather crises. This we call case B. Thus, in my opinion, there is a high likelihood that there will be either no exchange or a great deal, but a low likelihood of an in-between situation. A small amount of exchange is, so to speak, a nonequilibrium state. Unfortunately, our estimate for the unaffected longevity just happens to fall into this unstable region, so it is hard to tell which one of the two alternatives is the one which will prevail.

The governing quantity in this problem is the ratio of the average longevity of the most frequently occurring civilizations, L, to the average waiting time for answers, t_w. This ratio is

$$K = L/t_w \tag{17}$$

where $L = 2t$, t is given by Eq. 8, and $t_w = 2D/c$ (c is the velocity of light). From the values of our estimate (Eqs. 13, 14, and 16) we obtain

$$K = 10.2 \tag{18}$$

Ten conversations per lifetime of a civilization would mean some exchange, but not much, and the question still remains open whether this is enough to trigger, through feedback, case B. In order to show more clearly in what way the quantity K depends on the assumptions made, we write

$$K = c/2D_0[v_0Q)^{\frac{1}{3}}(\Sigma p_i l_i^2/T^{\frac{1}{3}} l^{\frac{2}{3}})] \tag{19}$$

and for simplicity we will assume that, from the various alternate groups of Table 1, only one group, index k, has a high value of the product $p_i l_i$ as compared with the values for the other groups. We then have $L = l_k$ and

$$K = (c/2D_o)(v_oQp_k)^{\frac{1}{3}}(L^{4/3}T^{\frac{1}{3}}) \tag{20}$$

We see that, unfortunately, the most uncertain quantity, L, enters with a high power, while the remaining somewhat less difficult quantities Q, v_o, and p_k enter only with the power 1/3. Therefore, we throw all uncertainty into L and write

$$K = (L/L_o)^{4/3} \tag{21}$$

with a critical longevity L_o defined by

$$L_0 = (8D_0T/c^3v_0Qp_k)^{1/4} \tag{22}$$

If we use the values $D_o = 2.3$ parsec, $T = 10^{10}$ yr, $c = 3 \times 10^{10}$ cm/sec, $v_o = 0.06$, $Q = 4$, and $p_k = 1/3$, Eq. 22 finally gives

$$L_o = 4500 \text{ yr} \tag{23}$$

Because of the exponent 1/4 in Eq. 22, I think the value for the critical longevity (Eq. 23) should not be too far wrong. Everything depends, then, on the question of whether the unaffected longevity is great compared with 5000 years. If it is, the feedback will be triggered, generating case B, and this will increase the longevity L considerably, up to some limiting value L_m.

At this point, however, we have reached the limit of our method of estimate, because, having had no communication with other civilizations, we have nothing to start with and we cannot know how strong the effect of the feedback will be. It is purely a personal belief if we think that L_m will not be higher than, say, a million years and that it will probably be much less than that.

In order to illustrate the variation of the different quantities with the longevity L, I have made some calculations, with the results given in Table 2. Using the values that we used for Eq. 23, we get

$$\begin{aligned} v &= v_oQp_kK/T = L/(1.25\text{x}10^{11} \text{ yr}); \\ D &= D_o/v^{1/3} = 2.3 \text{ parsec}/v^{1/3}; \\ K &= (L/L_o)^{4/3} = (\text{L}/4500 \text{ yr})^{4/3}; \\ t_w &= 2D/c = 15 \text{ yr}/v^{1/3} \end{aligned} \tag{24}$$

I wish to emphasize that the longevity L is the one extremely uncertain quantity, while all the other quantities in Eqs. 24 may be trusted to a fair degree. Thus, whatever L we choose requires that the answers of Table 2 for this L then be accepted.

Especially, we must accept very long waiting times t_w (of at least 1000 years and probably more) if L is to stay within reasonable limits, and this is a rather disappointing result. It means that the feedback and case B can be triggered only if the more highly advanced civilizations are able to think, to plan, and to act in terms of thousands of years. This is extremely different from our own situation, in which we would be happy if we could solve the problems of the next 5 years. But it is not impossible, either, that natural selection and increasing good sense might work in this way. Furthermore, even if the average value for K is too small to trigger case B, there might be large fluctuations of K in time and space; if the feedback has triggered case B once somewhere, the resulting effect then would tend to go on in time and to expand in space. It is amazing how similar this seems to be to the problem of the origin of life in general (and one might feel a strong temptation to draw some more parallels).

In summary, I think that the feedback effect will play an important role, in one direction or the other. The basic idea is just that of giving up if one is disappointed and of increasing the effort if one is successful. But I am unable to say in which of the two directions the effect is more likely to be felt. We expect to find either a high activity in communication at shorter distances (200 to 300 parsec) between civilizations of extremely long time scales (case B) or very little if any activity at greater distances (600 to 1000 parsec) from civilizations similar to our own (case A). We should be prepared for both possibilities.

Table 1. The most likely values for l_i and p_i (see text).

Alternative	Estimated range for l_i (yr)	Value adopted		$p_i l_i$ (yr)
		l_i (yr)	p_i	
Complete destruction	0–200	100	0.05	5
Destruction of higher life	0–50	30	0.60	18
Degeneration	10^4–10^5	3×10^4	0.15	4500
Loss of interest	10^3–10^5	10^4	0.20	2000
No limitation	$\geqq T - T_o$	$T - T_o$	0.00	0

Table 2. Variation of $1/\nu$, D, t_w, and K with longevity L (see text).

L (yr)	$1/\nu$	D (parsec)	t_w (yr)	K
100	1.3×10^9	2,480	16,200	0.006
300	4.2×10^8	1,720	11,200	.027
1,000	1.3×10^8	1,150	7,500	.13
3,000	4.2×10^7	796	5,190	.58
10,000	1.3×10^7	534	3,480	2.9
30,000	4.2×10^6	370	2,420	12.4
100,000	1.2×10^6	248	1,620	61.7
300,000	4.2×10^5	172	1,120	268
1,000,000	1.2×10^6	115	750	1,330

Second Conclusions

If the feedback plays the role we think it will, then some of our first conclusions must be modified. Because we cannot decide as to the direction of the feedback, both possibilities must be considered.

1) No essential change is needed for Nos. 1, 2, 4, 5*a*, and 5*b* of our first conclusions; we cannot search for single stars, and nobody sends messages to us especially; the civilizations we meet will be much more advanced than we are, and contacting signals will already contain messages which might use relatively slow pulses.

2) Our receiving system should be able to reach a distance of either 200 to 300 parsec in case *B* or of 600 to 1000 parsec in case *A*.

3) In case *A* there would be little or no interstellar communication. In case *B* we should expect a highly developed communication system and much activity.

4) According to the law of natural selection, a variety either has the will and the ability to maintain itself or it soon dies out. Thus, if the feedback effect has triggered case *B* and *still* maintains case *B*, this implies that some effective means exist for "beginners" to establish contact with other civilizations (contacting signals).

Nature of the Signals

In order to have a reasonable hope of success, we should be guided in our search by a definite idea of what to look for. This idea might turn out to be wrong, and we would then have to start with a better one. But it seems hopeless to search the whole sky, all the time, over all frequencies and with extremely narrow bandwidth, just for "something."

I suggest that we assume that the nature of the signals will be defined entirely by two things: (*a*) the purpose they serve; (*b*) the most economical way to achieve it. Both of these we might be able to guess. The argument that other civilizations could be completely different does not help at all in guiding a search, even if it is true, whereas the foregoing assumption will lead to a definite program, even if it is invalid; only by trying can we tell whether it is valid or invalid. To summarize, I think that a search has a fair probability of success if it is guided by the best guess we can make, but almost none if it is made without a definite plan. The following considerations are very incomplete and tentative; my main purpose in proposing them is to stimulate the formulation of better ones that finally could be used.

As to the purpose, we can think of three general possibilities: local communication on the other planet, interstellar communication with certain distinct partners, and a desire to attract the attention of unknown future partners. Thus, the things we should look for we might call local broadcast, long-distance calls, and contacting signals. The local broadcast has the highest likelihood of existing but may be extremely difficult to detect because of its relative weakness. Long-distance calls would not be intended for us but might hit us just by chance; the probability is small, however. Contacting signals would be intended for exactly the kind of search we plan to make, and therefore they should have the highest probability of detection, provided they do exist. Local broadcasts would exist in both cases *A* and *B*, as defined earlier, while long-distance calls and contacting signals would exist in case *B* only.

As to the frequencies used, those for the local broadcast might be not too different from our own, but for communication over interstellar distances, the range of frequencies would be limited by considerations of economy. Drake (*5*) calculated the combined influence of galactic and atmospheric noise and found a broad minimum between 1000 and 10,000 megacycles. In a recent paper (*6*) Drake finds, even for sending and receiving from above planetary atmospheres, a very general rule for defining the most economical frequency. It should lie in the range from 1000 to 30,000 megacycles per second, most probably at about 10,000 megacycles per second ($\lambda = 3$ cm), a frequency which still could be observed from within our atmosphere.

Drake (*6*) has pointed out that the local broadcast would occupy a large number of narrow channels, distributed over a larger frequency range. He has worked out a very effective method of detection, a cross-correlation between two independent frequency scans. This method is not concerned with the single signal, with its frequency or its strength, but answers with increased sensitivity the question of whether or not there are a large number of signals at the same frequencies in both scans. This is the first thing to ask.

As for long-distance calls, we have estimated the probability of the earth's being hit by one. Because the answer is not very encouraging I shall skip the details and just give the result. If each civilization speaks, on a permanent basis (and listens, as well), to a number n of its neighbors, if the messages are sent with beamwidth β, and if we are able to detect these signals at q times the distance to which they are sent ($q > 1$ because detecting is easier than understanding), then the probability of our being hit by chance is about

$$P = (\pi/120)\, q^3 \beta^2 n^2 \quad \ldots\ldots \quad (25)$$

a value which is independent of L and D.

If we regard $P = 1/2$ as sufficiently large to warrant a search and regard $q = 5$ and $\beta = 1$ minute of arc as likely values, this would require that each civilization should speak, on a permanent basis, with $n = 1300$ others, and it seems very unlikely that this is the case. But if we regard $n = 50$ as a reasonable value, we would then need the somewhat extreme values $q = 10$ and $\beta = 10$ minutes of arc, which, again, are unlikely. Because all the unknown quantities enter Eq. 25 at high powers, we think that a chance hit is highly unlikely (though not impossible). Another difficulty is that the bandwidth probably would be extremely narrow and that we have no way of guessing the exact frequency used.

The contacting signals form a fascinating problem. Provided they do exist, they are intended to attract the attention of any new civilization. If we were able to guess the most economical method of doing this, we would know exactly what to look for; this would greatly increase the probability of detection and thus (to close the circle) would make this method the most economical. There is just one problem: how to define precisely the word *economical*? I have to admit that I have not found a definition worth writing down, and I must, at present, leave this problem open.

Suppose we had found the right definition. This would enable us to calculate for each method suggested the price C (or whatever we call measure of the effort on our side, on the other side, or on both) which has to be paid in order to yield a probability of detection P_d over a distance D_d within a time t_d. For P_d we might take ½; for D_d, the average distance D (200 to 300 parsec); and for t_d, half of the number of years after which most new civilizations would consider giving up their search if it had not been successful (some hundred years, perhaps). We calculate the value of C for all methods suggested and conçlude that the one with the lowest value of C will be exactly *the* method used by the others, with one condition. The methods we can think of, as well as our definition of *economy*, depend on our present state of advancement. The other civilizations will be much more advanced than we are but will have had experience with beginners, and they will have set a certain standard of what a beginner should know and how much he should be able to guess in order to be considered a future partner. The condition, then, is that we already meet this standard. But whether we do or do not, we shall find out only if we try.

The value of C should be lowest when all power is sent in a single narrow channel at a certain frequency which can be guessed by the listener. As Cocconi and Morrison pointed out (*7*), the only "milestone" we know of in the interesting range of frequencies which might be used for this purpose is the 21-centimeter line. I suggest a modification. The background of a signal would be much stronger within this line than beside it—so strong as to drown out a small signal—and the boundaries of the line are not well enough defined for us to place the signal exactly beside it. The next suggestion, then, might be to use, for example, exactly *twice* the frequency of the 21-centimeter line. If this should fail we would have to look for more sophisticated methods of producing contacting signals.

Each method will consist of a general *plan* for distributing the transmitted power over space, time, and frequency and of a number of *parameters* governing these distributions. We should be able to guess this plan, and to evaluate those parameters which minimize the value of C. As for the parameters which do not influence C, we will just have to try them out until we hit the right values. Thus, the probability of detection has to be calculated under the assumption that the plan and the minimizing parameters are known on our side and that we vary the remaining noncritical parameters systematically over their possible range. These, then, are the rules of this fascinating game.

We should mention two more rules which possibly could play a role. First, because of the long waiting times, the contacting signals would probably contain messages. There are two possibilities: either the whole contacting signal would vary in the manner of a coded message, or its plan would be devised in such a way that it would direct our attention to the exact frequency where the messages were being sent. Because detection has higher priority than the message and detection is easier if no irregularity (code) is involved, and because there would be no requirement for haste, in "speaking," I think that the second case is the more likely, and that a few channels would be enough for the message. Second, the contacting signal should not interfere with other activities, such as already existing communication: this means, for example, that it should not occupy too much of the whole frequency spectrum. (Contacting signals and long-distance calls would have about the same range of most economical frequencies.) To give an idea of the way in which the contacting signal might direct attention to the message, I shall give one example. We distribute a large number of signals over the economical frequency range in a pattern which is symmetrical with respect to the center of this range. Toward this center we decrease the spacing between the signals (and their bandwidth) in proportion to the distance from the center, until we arrive at an extremely narrow channel at the very center of the pattern (all other details of the arrangement are defined entirely by minimizing C). In this center channel an introduction to the language is repeated every 10 years, say, and at the end of this time the listener is told at which frequency to find the next message, and so on, all of these messages being sent simultaneously but being read in the right order. Finally, the listener is told at what frequency and with what power he should answer.

Third Conclusions

1) Our search should be guided by the assumption that the nature of the signals will be defined entirely by the purpose they serve and by the most economical way to achieve this purpose. We should try to guess both, in order to increase the probability of detection.

2) We have considered three kinds of signals, with different purposes, which we called local broadcast, long-distance calls, and contacting signals. The local broadcast has the highest likelihood of existing but would be extremely difficult to detect. Long-distance calls would exist in case B only, and the probability of their hitting us by chance is very small. Contacting signals would exist in case B only, and these have the highest probability of detection because they would be devised for that very purpose. For this reason and because of conclusion No. 4 of my "second conclusions," I recommend that we begin the search under the assumption of case B and look for contacting signals. If this should fail, we might then increase our effort by searching, under the assumption of case A, for local broadcasts.

3) At present, no definite program can be given for the search for contacting signals. But the general reasoning required to arrive at such a program is given: to guess and estimate as much as we can about the nature of the signals and to assume that the sender knows how much we can guess, because this approach leads to the most economical kind of contacting signals.

4) The search for other civilizations will have either a tremendous result or none at all. Thus I recommend, hoping that the first case obtains, that we begin as soon as possible and try as hard as we can. But to be prepared for the second case, I recommend the design of a receiving system which can be used for ordinary astronomy as well, since, because of the size and sensitivity needed for its prime task, it will be extremely powerful. The observing time should then be allocated in equal parts between the two projects assigned to the instrument.

References and Notes

1. It is a pleasure to thank F. D. Drake for many stimulating and helpful discussions and for reading the manuscript.
2. One parsec = 3.26 light-years = 3.086×10^{18} cm = 1.92×10^{13} mi.
3. The importance of this quantity and its connection with the distance was first pointed out R. N. Bracewell [*Nature* **186**, 670 (1960)].
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