Intragalactically Speaking

The vastness and vagaries of space will force interstellar correspondents into extreme measures

by George W. Swenson, Jr.

Among our galaxy's 100 billion or more stars there may be thousands of advanced civilizations, some scientists suspect—a possibility supported by recent evidence indicating that planetary systems are more common in the Milky Way than was previously thought. For four decades, researchers have sporadically scanned the heavens for any radio signals that an advanced civilization may have emitted into the vastness of the galaxy. This search for extraterrestrial intelligence (SETI) is a passive pursuit, based on the use of dish antennas and sensitive radio receivers to pull in signals that, if they are out there, are probably quite weak by the time they get to us.

Essentially all major SETI programs here on Earth have been based on attempts to receive signals that would have been transmitted decades or, in all probability, centuries or millennia ago. For this reason, little has been published on the complementary problem of SETI, which could be phrased as follows: What would it take to build a radio-transmitting system that would have even the slightest chance of being detected by a receiver tens or hundreds of light-years away?

The exercise is not a mere abstraction—as SETI specialists have long realized, it would be impossible to mount a credible search and receiving effort without having some ideas about the transmission system and strategy that would most likely be used on the other end. Perhaps most important, a step-by-step accounting of the difficulties of beaming a signal over such enormous distances reveals one of SETI's most fundamental concerns: why basic physics indicates that it will be extremely difficult for any civilization to announce its presence to another such civilization in an indeterminate solar system among the galaxy's huge profusion of stars.

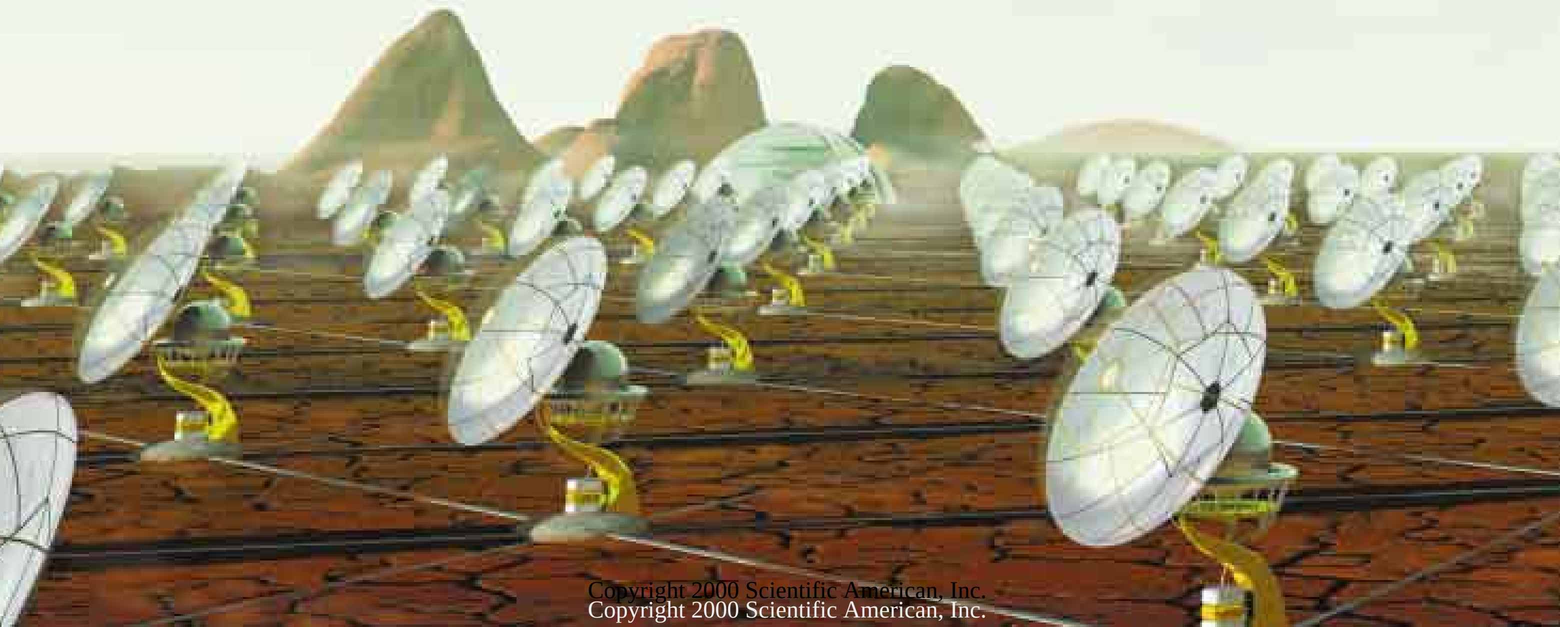
This analysis—along with theories that advanced civilizations may be far rarer than some scientists believe [see "Where Are They?" by Ian Crawford, on page 38]—could shed light on the central paradox of SETI: if thousands of advanced civilizations exist throughout our own Milky Way galaxy, why haven't we heard from any of them?

Being Heard above the Din

The first major task in designing a transmitter capable of sending a signal off into the galaxy is choosing the part of the electromagnetic spectrum that will carry the signal. To keep the scope of this article manageable, I'll choose radio waves. They travel through interstellar space quite well in comparison with some other forms of electromagnetic radiation, such as light, which suffer from, among other factors, scattering and absorption by interstellar dust.

Within the radio spectrum, SETI specialists have settled on a range of frequencies between 1 and 3 gigahertz as being the most likely for interstellar communication. Our engineering techniques are quite advanced in this part of the spectrum. Also, with the exception of emissions from neutral hydrogen in the vicinity of 1.42 gigahertz, absorption and obscuration of waves by interstellar molecules and dust clouds is relatively minimal at these frequencies, as is background radiation from the Milky Way.

Radio emissions move through space in the form of period-



PAT RAWLINGS

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ically varying electric and magnetic fields. The fields travel together at the speed of light, 300,000 kilometers per second. The distance at which a radio wave can be detected depends on five major factors (assuming that the transmitting and receiving antennas have been well designed): the electromagnetic noise environment of the receiver, the sensitivity of the receiver, the power of the transmitted signal, and the size of the transmitting and receiving antennas.

Let's begin with the noise: it is literally everywhere. Electromagnetic radiation can be coherent—that is, regularly structured, like the emissions of a radio transmitter. Alternatively, it can be incoherent, consisting of random impulses such as the hiss you hear from a radio receiver with no station tuned in. That incoherent radiation is known as noise.

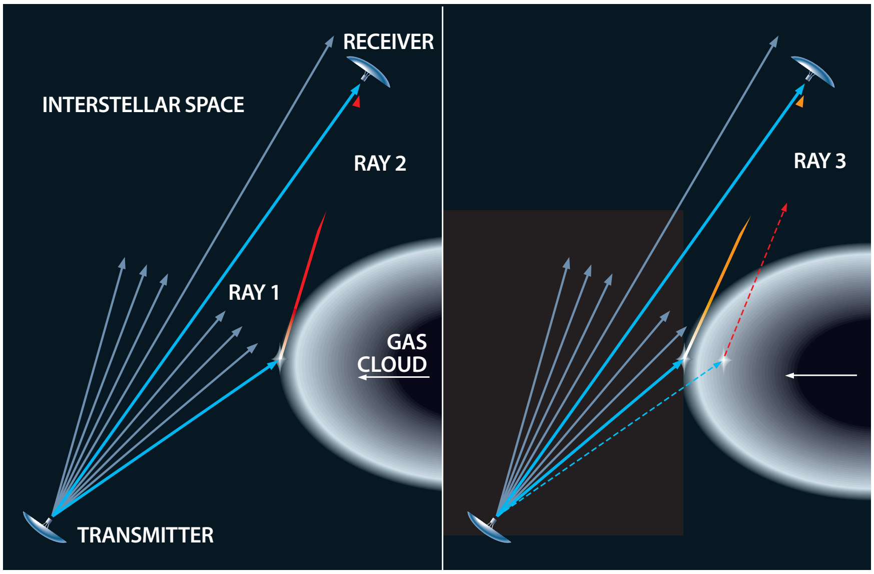
Every material body at a temperature above absolute zero emits electromagnetic radiation—noise—throughout the spectrum, its frequency of maximum intensity being determined by its absolute temperature. For convenience, physicists sometimes characterize this noise by the temperature of an imaginary "black body" representing the sources of noise in, for example, a communications system.

This system noise fundamentally limits our ability to communicate. To receive a signal, its power at the receiving antenna must be at least close to that of the noise at the antenna. An analogous situation involves two people attempting to converse at a boisterous party: they have to raise their voices to a level at which they can compete with the noise around them.

The noise in a radio receiver's amplifier chain comes from two sources: externally, from the antenna, and internally, generated within the amplifiers themselves. Amplifier technology has advanced to the point where it is possible to build a receiver that has internally generated noise of only a few kelvins.

The noise from the external environment is generally beyond the control of the operator, so it dominates the performance of a high-quality receiving system, such as the ones used in astronomy. External noise sources include the ground (for antennas built on a planet), the planetary atmosphere, the galactic background, astronomical sources of radio emissions inside and outside the galaxy, and the cosmic background radiation, the remnant of the big bang that initiated our universe. On Earth, for a receiver at or slightly beyond the current state of the art, all these sources, including the internal noise generated in the receiver, add up to about 15 kelvins in a system shielded to minimize the radiation from the ground.

EXTRATERRESTRIAL RADIO OPERATOR (*above*) might control an array of parabolic "dish" antennas with a large effective area.



MULTIPATH EFFECTS result when an interstellar gas cloud refracts, or bends, a ray (*red* and *orange*) so that it coincides at the receiver with another ray (*blue*) from the same transmitter. As the cloud moves, the difference in path lengths between the direct and refracted rays changes. Thus, the received rays cycle back and forth between constructive reinforcement and cancellation, causing the received signal—the sum of the rays—to scintillate.

SLIM FILMS

How much power must we deliver to the distant receiving antenna to overcome this noise temperature? To calculate that value, we first note that the noise power in the receiver depends on the frequency range, also known as bandwidth, of the receiver. Because noise is distributed across the spectrum, the narrower the receiver bandwidth, the less noise power that is admitted to the receiver. Thus, in order to detect the weakest possible signal, the bandwidth should be restricted to the smallest value that will accommodate the anticipated signal.

On the other hand, the more bandwidth, the higher the rate at which we can send data. For example, normal speech requires about 2.5 kilohertz, and a standard television signal occupies about 4.5 megahertz.

Let's settle on an information rate of five bits per second. Depending on the relative amounts of signal and noise, that will require a bandwidth of about 2.5 hertz. This bandwidth will let us send the message "hello" in five seconds, assuming that five bits are needed to represent each character.

Now that we have a specific bandwidth and noise temperature, we can address our earlier question: How much signal power is needed at the receiving antenna to overcome the noise power? The formula to compute the noise power (P_n) is $P_n = kTB$, where k is Boltzmann's constant, 1.3806×10^{-23} joule per kelvin; T is the noise temperature, 15 kelvins; and B is the bandwidth of the detecting system, 2.5 hertz. Performing the calculation, the system noise power is 5.2×10^{-22} watt, and the receiver would need a signal power from the distant transmitter equal to this value, or nearly so, in order to detect it in the presence of that noise. We will assume for now that the receiving antenna has an effective area of one square meter. Thus, the required intensity of the signal at the receiving antenna is 5.2×10^{-22} watt per square meter.

The power needed from our distant transmitter to deliver this intensity to the receiving antenna depends on how far away we are. It also depends on whether we are transmitting the signal in all directions, more or less, at once ("omnidirectionally") or beaming it in a narrow cone. For the distance, let us arbitrarily pick 100 light-years, which equals 9.46×10^{17} meters. For the transmission mode, let's assume we are radiating the signal omnidirectionally, because we do not know where our putative correspondent is.

Applying the inverse-square relation, we can calculate the power required from a transmitter radiating omnidirectionally at that distance. It is $(5.2 \times 10^{-22}) \times 4\pi \times (9.46 \times 10^{17})^2 = 5.8 \times 10^{15}$ watts. That is, of course, an implausibly large power requirement; for comparison, it is more than 7,000 times the total electricity-generating capacity of the U.S.

Moreover, in galactic terms, 100 light-years is a minuscule distance. Within this distance of Earth there are on the order of 1,000 stars—or less than a millionth of 1 percent of the stars in the galaxy. To have a reasonable chance of happening on an advanced civilization, we would have to reach the stars within a far greater volume.

Is Beaming Better?

As an alternative to omnidirectional transmission and reception, beamed signals may prove more encouraging. In particular, let's consider the trade-off between receiving-antenna size and the signal power required from the transmitter. A receiving antenna whose effective area is very large in comparison with the square of the wavelength it is receiving has a narrow receiving "beam." When such an antenna is aimed at a transmitter, it has a large "gain" in the amount of power extracted from the radio wave. In this case, less power is needed to transmit to the receiver. The disadvantage—that the receiving beam must be aimed in a specific direction—is significant in our case, because we are assuming that any would-be correspondents do not know where we are.

Nevertheless, let's look at the numbers. We had assumed in our previous example that the receiving antenna had an effective area of only one square meter. The unit might be a horn-type antenna or a parabolic "dish" with a diameter of about 1.5 meters. Such an antenna, operating at a wavelength of 20 centimeters, would have a reception "beam" of about 11 degrees, within which a signal would be efficiently received when it was pointing at the transmitter.

Even larger receiving antennas would reduce the transmitter power requirements still further but, again, at a price—a narrower beam. Relative to a hypothetical omnidirectional antenna, the gain represented by a beamed signal is proportional to the antenna's effective area in square wavelengths. Take as an example an array of contiguous antennas one kilometer on a side. At a wavelength of 20 centimeters, this array would have a gain one million times greater than the one-square-meter antenna. It is a pity, though, that it would also have a beamwidth of only 11 thousandths of a degree. The transmitter power required would be reduced a million times, but the narrow beam would require fantastically precise pointing and tracking.

If we employ a similar one-kilometer-square antenna array to transmit our signal, we obtain a similar gain improvement—and beamwidth reduction—as in the receiving case. Suppose there were one-kilometer-square antenna arrays on each end of our communications channel. In this case, the required transmitter power would be only 5,700 watts. It is rather unlikely, however, that the very narrow beams of each of these antennas would ever fortuitously line up with one another.

It is a classic trade-off: with minimal antenna areas the required transmitting power greatly exceeds the generating capacity of the world. With mammoth antennas, on the other hand, the power requirements are modest, but the transmitting and receiving beams are so narrow it would be almost impossible for the would-be correspondents to find one another in the unfathomably large volumes of galactic space.

There are, of course, many compromises among the extreme examples given above. Unfortunately, none promises relief from the basic fact of interstellar communication: the great distances involved require extreme measures.

Still, it is not quite time to give up hope. The communications system parameters we have chosen, though reasonable, are still somewhat arbitrary. We could, for instance, make other assumptions about the distant correspondent's technology, allowing us to adopt a lower signal-to-noise ratio or a narrower bandwidth, which would reduce the power requirements.

More important, a very large receiving antenna, in the form of an aggregated array of individual antennas and receivers, can be programmed to produce many simultaneous receiving beams in different directions, thus expediting the search for an unknown transmitter. Similarly, we could employ many receiving frequency channels simultaneously—a technique used in current SETI programs. These multiplexing advantages cannot be applied to transmission, however, without reductions in the power available to each beam or each frequency channel, because the total power is fixed.

Penetrating the Medium

So far we have discussed only the most elementary design considerations involving the two ends—transmitter and receiver—of an interstellar communications system. The great space in between also presents difficulties, such as so-called multipath effects. To understand these effects, it is necessary to know something about the way in which radio waves propagate. In a vacuum, they will travel in a straight line unless they encounter a material obstacle that absorbs, reflects or refracts them. It so happens that interstellar space contains material, such as gases and particles at low concentrations, as well as quasi-static magnetic fields. Over the enormous distances involved, these can divert radio waves from straight paths, change polarization and produce sporadic fluctuations in received signal strength. Such phenomena militate against the use of very narrow transmitting or receiving beams—thus exacerbating the transmitting-power requirement.

Refraction occurs when the waves enter a gas, say, in which their velocity differs from that in free space. Refraction changes the direction of the waves and can cause two waves originating at the same source to add together to produce a more complex wave. For example, as the wave enters the gas, part of it may be slowed more than another, depending on the distribution of the gas. The variation in velocity could cause a phase shift between components of the resulting wave. Depending on the magnitude of the phase shift and the difference in path length between the wave's components, phase-shifted portions could reinforce each other, or cancel each other, or anything in between.

Now suppose that the patch of gas in the path of the second wave is moving relative to the wave path, so that the phase shift varies with time [*see illustration on opposite page*]. In this case, the aggregate of the two wave components will vary with time, reinforcing itself or canceling itself out at intervals. Similar effects can be produced by many different situations involving reflecting objects, Doppler shifts and multiple wave paths. Such examples of multipath propagation can convert a steady signal as emitted from a transmitter into a strongly modulated signal as detected by a far-off receiver.

As this analysis suggests, the use of radio waves as a medium for making interstellar contact is discouraging. The galaxy's enormous distances inevitably require fantastic measures—stunningly high transmitter power or huge antennas and impractically narrow beams. Certainly the kind of systems that would be needed to mount a realistic project to beam a signal to a large sampling of stars are probably beyond the resources of a society like that of Earth. Furthermore, even if contact could somehow be made, the time delay before a response to a message could be received might very well stretch into many centuries. Even if the formidable physical constraints could be overcome, this is clearly a project for many generations in succession. In all likelihood, it will require an enduring organization based on immutable dogma—like one of the world's major religions.

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Further Information for Special Report

EXTRATERRESTRIALS, WHERE ARE THEY? Edited by Ben Zuckerman and Michael H. Hart. Cambridge University Press, 1995.

VITAL DUST: LIFE AS A COSMIC IMPERATIVE. Christian de Duve. Basic Books, 1995.

SCINTILLATION-INDUCED INTERMITTENCY IN SETI. James M. Cordes, T. Joseph W. Lazio and Carl Sagan in *Astrophysical Journal,* Vol. 487, pages 782–808; October 1, 1997.

ALIENS: CAN WE MAKE CONTACT WITH EXTRATERRESTRIAL INTELLIGENCE? Andrew J. H. Clark and David H. Clark. Fromm International, 1999.

RARE EARTH: WHY COMPLEX LIFE IS UNCOMMON IN THE UNIVERSE. Peter Douglas Ward and Donald Brownlee. Copernicus Books, 2000.

A comprehensive list of SETI programs is available at www.skypub.com/news/special/seti_toc.html

A list of planets discovered outside our solar system is available at cfa-www.harvard.edu/planets

To get involved in the SETI@home program, visit setiathome.ssl.berkeley.edu. Be sure to join the Scientific American team at setiathome.ssl.berkeley.edu/stats/team/team_36552.html