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Eavesdropping: The Radio Signature of the Earth

Television leakage from the earth allows detection of our civilization at interstellar distances.

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Summary. In addition to searches for purposeful signals, those attempting interstellar communication should also consider the possibility of eavesdropping on radio emissions inadvertently "leaking" from other technical civilizations. To understand better the information which might be derivable from radio leakage, the case of planet earth is considered. The most detectable and useful escaping signals arise in a few BMEWS-type radar systems and in normal television broadcasting. A model including over 2000 television transmitters is used to demonstrate the wealth of astronomical and cultural information available from a distant observer's careful monitoring of frequency and intensity variations in individual video carriers (program material is *not* taken to be detectable).

The concept of scientifically attempting to contact an extraterrestrial civilization has come of age. Since the seminal article of Cocconi and Morrison appeared in 1959 (*1*), investigators from a variety of disciplines have debated the various aspects of doing so: Where do we search? How close is our nearest neighbor? What fraction of all stars harbor intelligent life? What is the longevity of a civilization that is able and willing to communicate? What is the best technical means of communication? What will any received message say?

In this article we will concentrate, in a sense, on the last question. One can make either of two basic assumptions about the first contact: (i) that it will arise through a purposeful attempt, perhaps through the use of an interstellar radio beacon, or (ii) that a civilization will be detected through no special efforts of its own. The latter hypothesis, often called eavesdropping, is concerned with the extent to which a civilization can be unknowingly detected through the by-products of its daily activities. While much thought has gone into the idea of purposeful contact, eavesdropping has been somewhat neglected; we will argue that it deserves more attention.

The overall likelihood of contact through eavesdropping depends on the nature and intensity of the civilization's "leakage" as well as on how long that leakage continues. Very general arguments (*2-5*) show that radio waves provide the most economical and reliable means of contact at interstellar distances. This is true not only for intentional contact, but probably for eavesdropping as well. In any case, there can be no argument with the fact, first discussed by Shklovskii in 1963 (*3*), that the presence of humans can already be detected at interstellar distances as a result of the complex communications and transportation network spread over our globe. Of course, we do not know how applicable our present situation is to the more general case of all galactic civilizations over all time. It may be that our present "leaky" state will soon be terminated by advancing technology, but on the other hand it may continue for a very long time, perhaps even longer than any period in which we might have the perseverance to send out purposeful messages. If we are at all typical, then we should perhaps be also looking for unintentional signals from others at least as diligently as for intentional ones.

Our goal in this article is to examine in some detail the radio signature of the earth; that is, the most powerful and detectable portion of its radio spectrum as a function of direction, time, and distance. We hope that this exercise will shed light on the extent to which our own technology is modifying the electromagnetic environment of interstellar regions, as well as guide us in possible attempts to eavesdrop on others. There have been many back-of-the-envelope calculations and generalized statements (*2-7*) but no systematic quantitative study has previously been undertaken. This appears largely to have been due to unwarranted pessimism over the magnitude of the task and the availability of required information; in the following section, however, we demonstrate that the problem is indeed tractable. We show how video carrier signals (but not program material) of television broadcasting stations, as well as a few extremely powerful military radar systems, are the most detectable and useful signals to the extraterrestrial eavesdropper. We then describe our basic model and its results for the radio signature of the earth and its range of detection. The penultimate section contains a discussion of what the outside observer could deduce from the received signals about the nature of our planet and our civilization. Finally, on the assumption that our own case is not

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atypical among galactic civilizations, we close with comments on how these findings may relate to our attempts at interstellar contact with other civilizations.

Which Radio Service Is Most Detectable to an Outsider?

We first examine the radio services on the earth to determine which are the most likely to be detectable by an observer at interplanetary or interstellar distances, using a suitable radio receiver. We assume that the angular resolution of the receiving antenna is insufficient to resolve the diameter of the earth. We also assume that the sensitivity and location of the antenna are such that it will be able to detect only the terrestrial sources with the greatest intensity and reasonably broad directional characteristics; in other words, we are dealing with the "tip" of the radio signature "iceberg." The ability of an observer to detect a signal is then proportional to the received spectral flux density of the radiation; that is, the power per unit area per unit frequency interval (*8*). The areal dependence is the same (inverse distance squared) for all transmissions originating on the earth, so that we need only find the radio services that supply the most "escaping" watts per hertz per steradian. Furthermore, we are concerned with the time-averaged watts per hertz per steradian over periods varying from microseconds to hours. Special attention is paid to services that (i) produce repeatable signals (from day to day), since they will in general contain the information most useful to the observer, and (ii) illuminate a large fraction of the sky, which increases the likelihood of any detection at all.

The fact that the detectability of any signal at interstellar distances is proportional to the time-averaged watts per hertz per steradian gives immediate clues to which radio services will be most important. "Time-averaged" implies that we are most interested in transmitters that radiate continuously, or nearly so; this will allow maximum observation (or integration) time per day to the observer, as well as ensure that signals will be repeatable from day to day. "Power per unit solid angle" means that we are interested not only in the radio transmitter power, but also in how concentrated the power is in a particular region of the sky by the agency of the transmitting antenna; that is, the gain of the antenna.

Finally, "power per unit frequency" is

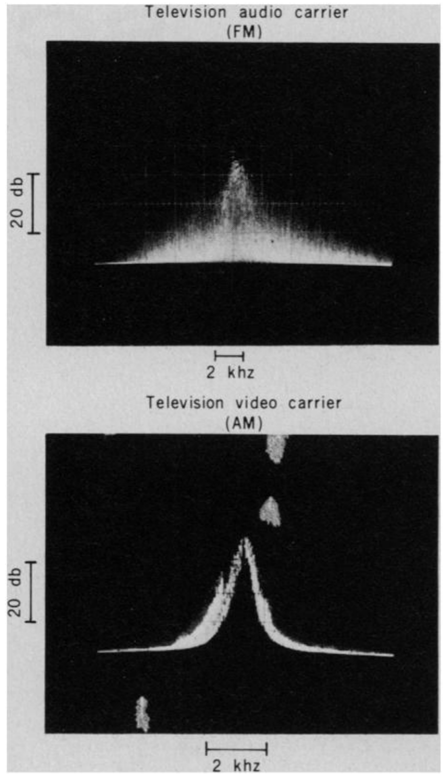


Fig. 1. Power spectra of typical AM and FM signals, averaged over a few seconds. Note the much greater effective bandwidth of the FM signal.

especially of concern since different signal modulation schemes may utilize the same transmitter power, but spread that power out over vastly different bandwidths. Amplitude modulation (AM) and frequency modulation (FM) are the primary methods used to modulate the monochromatic carrier frequency. In brief, both methods create side bands near the carrier frequency spreading over several kilohertz to several megahertz (*9*). In conventional AM a significant fraction (50 to 100 percent) of the total transmitter power remains at the carrier frequency, within typically $\lesssim 1$ hertz (*10*). In FM, while the carrier itself is still very narrow, $\gtrsim 90$ percent of the total power is spread out among hundreds or thousands of side bands. The carrier frequency still displays a greater time-averaged signal than any of the individual side bands, but the time-averaged fraction of the total transmitter power residing in an FM carrier is much less than that in an AM carrier. Typical AM and FM signals are shown in Fig. 1.

Keeping these principles in mind, we now consider the vast frequency range of radio services, extending from worldwide submarine communication systems operating at ~10 khz to communications satellites at several gigahertz. First, we can say immediately that virtually all communication signals from point to point on the earth's surface at frequencies lower than ~20 Mhz will at all times be reflected or absorbed by the ionosphere and therefore need not be considered further (*11*). Although the critical reflection frequency ν_c of the F2 layer of the ionosphere varies in most places from 6 to 12 Mhz at the zenith, these point-to-point communications are typically sent out near the local horizon, striking the ionosphere at an angle α of ~15°. The effective critical frequency, $\nu_c' = \nu_c/\sin \alpha$, then varies from ~20 to ~40 Mhz. Since ν_c' represents the lower frequency limit for any significant escaping radiation, it is apparent that all standard (AM) broadcasting (0.5 to 1.5 Mhz) and ~ 90 percent of all shortwave broadcasting (4 to 26 Mhz) never escapes except under highly unusual ionospheric conditions. Signals in the range 20 to 40 Mhz, however, will sometimes escape, and we must therefore gauge the importance of these signals, as well as those at all higher frequencies, by estimating their total power per hertz per steradian.

Table 1 summarizes our estimates of total power for some typical radio services (*12*). We have also considered the contributions from many other services such as aircraft communications, telephone microwave relays, telegraphy, and communications satellites, but these are not significant when compared to the strongest source in Table 1. If one considers the total time-averaged spectral power, as well as the time-averaged spectral power per steradian per transmitter (since in general only a small fraction of all transmitters can be detected from outside the earth at any given time), it is clear that the last three entries dominate the leakage.

In Table 1 "BMEWS-type radars" refers to the Ballistic Missile Early Warning System radar network which the United States operates at northern latitudes, as well as the presumably comparable Soviet version. Each of these extremely powerful, highly directive radar installations continuously sweeps a large fraction of its local horizon. Their contribution to the radio signature of the earth is quite significant in that (i) a large fraction of all stars are illuminated at some time by one or more of these radars, and (ii) the intensity of the received radiation at a distant point is more than that for any other source on the earth with reasonably broad directional characteristics. To an outsider, the great disadvantage of detecting only BMEWS radiation is that the extremely small number of installations on the earth severely limits the amount of information he can derive. Furthermore, the large bandwidths and continuously shifting frequencies (for security reasons) of these radars would make them highly unsuitable for long-term monitoring in an effort to detect patterns in Doppler shifts. Since these radars are nevertheless somewhat more detectable (by a factor of ~10 to 100) than even the strongest television stations, we consider that they may well act as "acquisition signals" to the outside observer, announcing our presence, but yielding only a minimum amount of further information.

The question remains of which radio service is not only quite detectable, but also rich in information content. The FM radio broadcasting stations of the world have a total effective radiated power (ERP) of ~300 megawatts (*13, 14*). Although ≲10 percent of the time-averaged power resides in the carrier frequency, it still represents the greatest power per hertz in the band (*15*), and Table 1 indicates that the contribution of FM stations, both individually and in total, is indeed large.

Table 1. Estimates of total power for some typical radio services contributing to radio leakage from the earth at frequencies >20 Mhz. Values in columns 3, 4, and 5 are approximate. The values in the last column are time-averaged sums of the effective radiated powers of the individual carriers for all units. Abbreviation: ERP, effective radiated power (*14*).

Service*	Frequency (Mhz)	Transmitters (No.)	Fraction of time transmitters radiate†	Per transmitter: Maximum ERP in carrier (watts)	Per transmitter: Effective carrier bandwidth (hertz)‡	Total time-averaged ERP in all carriers (watt/hertz)
Citizens band	27	10^7	10^{-2}	5	2	2×10^5
Professional land-mobile	20–500	10^5	10^{-1}	20	1	2×10^5
Weather, marine, and air radars	10^3–10^4	10^5	10^{-2}	10^4–10^6	10^6	10–10^3
BMEWS-type radars	~ 400	10	10^{-1}	2×10^{11}	10^3	2×10^8
FM broadcasting	88–108	9000	1	4×10^3	10^{-1}	4×10^8
TV broadcasting (video carrier only)	40–850	2000§	1	5×10^5	10^{-1}	1×10^{10}

*Estimates for the first three listed services are for the United States only; the others are for the entire world. Short-wave broadcasting is not included since only a small fraction of the power is ever radiated at frequencies above 20 Mhz (*40*); moreover, these frequencies are used only when ionospheric conditions are such as to reflect the radio waves back to the earth. †Considering both radiating schedules and pulse duty cycles (for radars). "Beam sweeping" duty cycles for most radars of 10^{-1} to 10^{-2} cause them to be even less detectable than the last column indicates. ‡For radar, bandwidth ~(pulse length)$^{-1}$; for pulses <100 μsec (bandwidths >10 khz), the interstellar plasma also causes significant dispersion, rendering the signal less detectable. §There actually are ~15,000 television transmitters in the world, but the most intense 2000 (those considered in our model) contain ~97 percent of all the power.

Nevertheless, the contribution from television broadcasting is still larger than that from FM broadcasting (*16*). Although a television channel is altogether ~5 Mhz broad, typically 50 to 90 percent of the available video power is found in the ~0.1-hertz width of the carrier (*17*), the rest being spread out over the channel at much lower levels of spectral power density. Thus, much of the 1000-Mw total ERP of the world's television transmitters (*13, 18*) is concentrated in extremely narrow frequency ranges, yielding a total of ~10 Gw/hertz at all broadcast frequencies.

We have not discussed in detail how factors such as antenna gain and day-to-day repeatability influence the relative importance of the various radio services, but a detailed consideration of these factors indicates that television broadcasting still dominates (*19*). Because of this, our basic model emphasizes television broadcast transmitters, as they are individually and in the aggregate more detectable and useful (in terms of information content) than any other radio service on the earth.

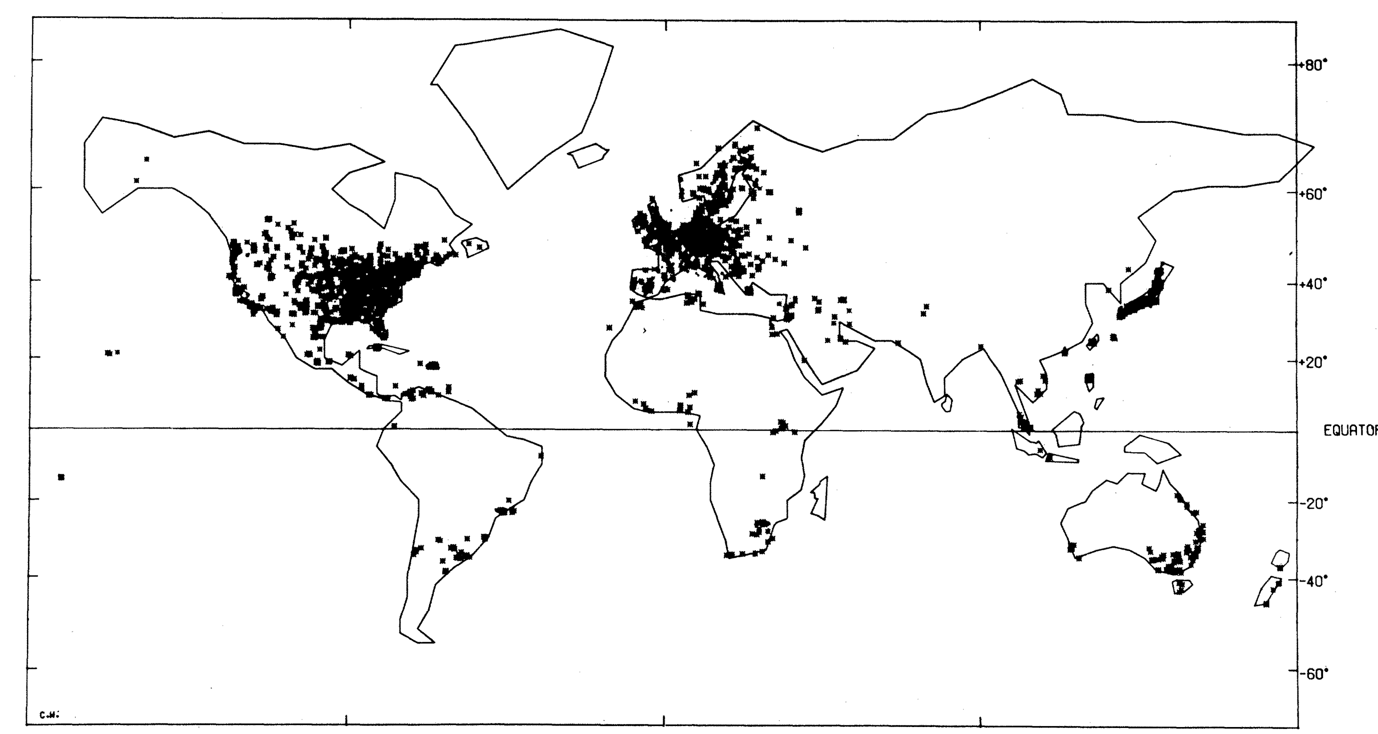


Fig. 2. Map of all (2191) television transmitters with effective radiated power ≥ 50 kw included in our model. Note the marked concentrations in North America, Western Europe, Japan, and Australia. Full information for stations in the Soviet Union and China was not available, but estimates indicate that there is negligible television power in these countries.

Model for Leakage of Television Radiation

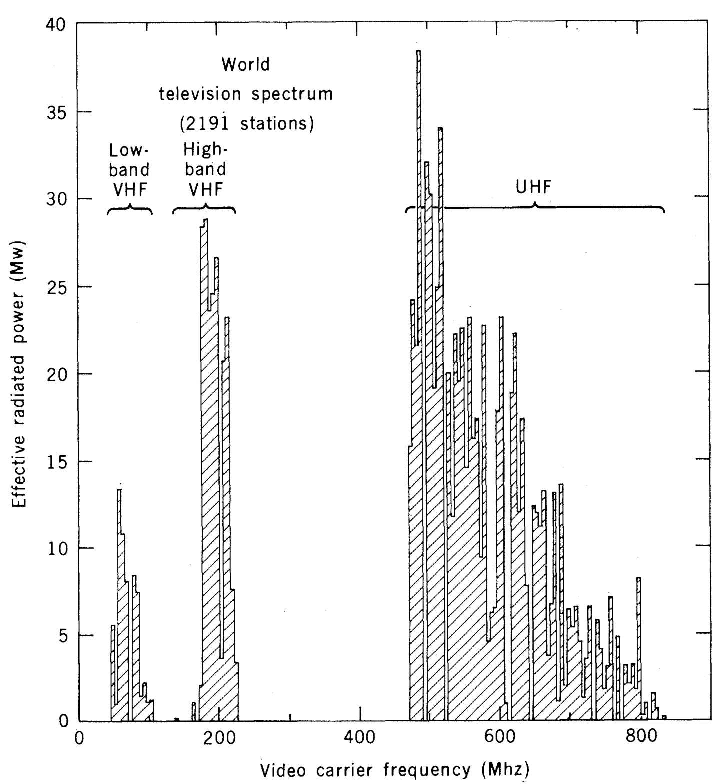
Having narrowed the field to television broadcasting, we now calculate the actual power structure in frequency, time, and direction of this portion of the earth's radio signature as seen by a distant observer. There are ~15,000 television transmitters in the world (as of 1975) (*13, 18*). To reduce the amount of calculation, however, we have investigated their distribution in ERP.

Through random sampling it was estimated that 97 percent of the total power is represented by the ~15 percent most powerful transmitters (hereafter called stations) with ERP ≥ 50 kw. Since this seemed a very good approximation for our purposes, the model finally includes 2191 television stations, of which 999 (or 46 percent) are situated in North America, 636 (29 percent) in Western Europe, 138 (6 percent) in Eastern Europe, 108 (5 percent) in Japan, 81 (4 percent) in Australia, and 229 (10 percent) in the rest of the world (*20*). Figure 2 shows the locations of the included stations. International frequency allocations are such that television broadcasting occurs almost exclusively in three frequency ranges (Fig. 3). In our sample 497 stations are in the low-band very high frequency (VHF) range (40 to 110 Mhz) with a total ERP of 60 Mw, 820 are high-band VHF (140 to 225 Mhz; 194 Mw), and 874 are ultrahigh frequency (UHF) (470 to 835 Mhz; 750 Mw). Our sources contained only limited information on the stations of China and the Soviet Union, but estimates indicate that this introduces little error into our model since the amount of television broadcasting power in those countries is negligible compared to that in the rest of the world. For each station we recorded an identification number (coded by country), longitude and latitude (to the nearest degree in ~90 percent of all cases, within 2° in others), video ERP, and video carrier frequency (*13, 18, 21*).

The next step was assignment of an antenna radiation pattern to each transmitter. We studied numerous patterns of television antennas in Holland, Great Britain, and the United States, some measured and others theoretical, and concluded that a sufficiently accurate procedure was to adopt a standard pattern, the same for all countries, for each of the three primary frequency ranges. All patterns are taken as omnidirectional in azimuth and of Gaussian shape in the elevation angle e above the horizon. Low-band VHF stations have patterns of full width to half-maximum in power (e_0) of 7.0°, high-band VHF, 4.0°, and UHF, 2.0°. For both VHF bands the free-space pattern peaks exactly at the local horizon, $e = 0°$, while UHF antennas usually employ "beam tilt"; our model for UHF stations therefore places the pattern maximum at $e = -0.7°$. While it is clear that there are often considerable variations from our model for individual antennas, we feel that they are not of sufficient importance to change any of our conclusions (*22*).

In addition to the free-space antenna pattern, one must consider ground reflections as well as absorption and refraction by the earth's atmosphere. Ionospheric effects, of importance only for low-band VHF, have not been explicitly included in the model, but their effects will be discussed qualitatively. Tropospheric refraction (amounting to ~0.6° at $e = 0°$) has been included, while the effects of tropospheric absorption (even in heavy rain) and diffraction are negligible in the frequency ranges of interest. A standard antenna height of 300 meters above the average surrounding terrain has been used for all broadcast antennas; this height, coupled with the spherical earth and refraction, means that a particular station actually illuminates elevations extending as low as −1.0°. Finally, our model includes a nominal power reflection coefficient of 0.5, suitable for horizontally polarized waves off typical ground, for each station; the net effect of this reflection is to increase the maximum observed power of the stations by as much as 40 percent over the free-space value. The adopted effective antenna patterns are shown in Fig. 4.

The spectrum of each channel is simply modeled as the video carrier signal 0.1 hertz wide (*17*); this carrier is placed at the nominal frequency within its channel as assigned by each country's standard. Extensive investigation has verified that the remainder of the 4- to 6-Mhz



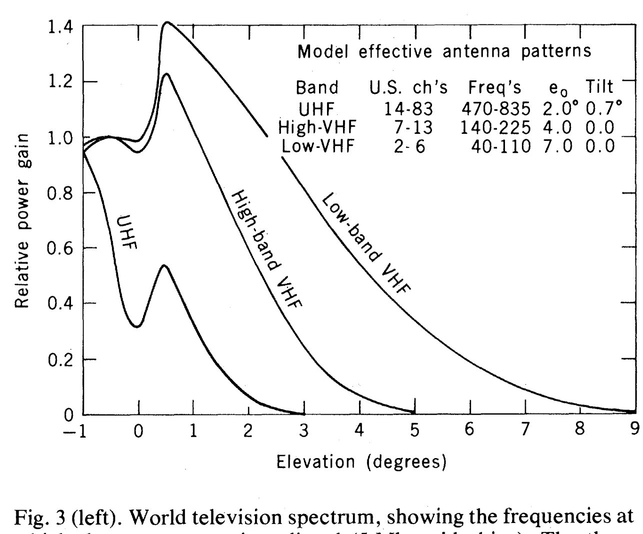


Fig. 3 (left). World television spectrum, showing the frequencies at which the most power is radiated (5-Mhz-wide bins). The three primary bands (channels 2 to 6, 7 to 13, and 14 to 83 in the United States) are also indicated. A distant extraterrestrial observer with a frequency resolution of 5 Mhz would at most times measure a spectrum roughly of this shape. Fig. 4 (right). Effective antenna power patterns adopted in the model for each of the three television frequency bands. The radiation is strongly concentrated to the local horizon of each transmitter and is taken to be omnidirectional in azimuth.

width of a typical television channel consists of a complex frequency structure, but that nowhere is the spectral power density more than 10^{-3} of the video carrier power density. The audio carrier signal is typically rated at an ERP 10 to 20 percent that of the video carrier, but its spectral power density is much lower since it is almost always an FM signal (Fig. 1) (*23*). The time-averaged video power is taken as $\eta_m = 0.4$ of the peak video power, close to the value for a gray transmitted picture (*24*).

The appropriate Doppler shift arising from the rotation of the earth, $V_p = 0.5$ kilometers per second (at the equator), as seen from a fixed celestial position, is calculated separately for each station. This shift typically amounts to a few hundred hertz and is significant because it means that the video carriers of stations with nominally the same assigned frequency do not occur in general at precisely the same frequency. Finally, the fact that television broadcasts are not continuous, but have considerable periods of shutdown, is included. In the model we use the following daily broadcast schedules (local solar time): United States, Canada, Australia, and Japan, 0600 to 0100; Europe (50 percent of stations, randomly chosen), 1000 to 2300; Europe (the other 50 percent), 1700 to 2300; and the rest of the world, 1600 to 2300. These schedules, of course, are not exactly true, but they will serve to illustrate any resulting effects.

Given the time of year and the celestial coordinates and distance of the outside observer, the model allows calculation of the radio power spectrum as a function of time. At any particular Greenwich sidereal time (*25*), each station is tested to see whether the celestial location is at a local elevation e falling within its beam. If the location is being illuminated by the station and if the local solar time indicates that the station is broadcasting, then the contribution of the station to the overall power spectrum at that time is calculated, taking into account the proper Doppler shift. The contribution of the video carrier of a single station to the observed flux density S (watts per square meter per hertz) is given by

$$S = \frac{(\eta_B \eta_m \, \mathrm{ERP}) \, G_d \, \hat{G}(e)}{4\pi \, d^2 \, \delta\nu} \qquad (1)$$

where $\hat{G}(e)$ is the station's "effective antenna pattern" normalized to the peak value in free space (Fig. 4), G_d is the gain of a half-wave dipole (*14*), η_B is the main beam efficiency (*22*), d is the distance to the observer, and $\delta\nu$ is the bandwidth of the video carrier. If we now take $\delta\nu = 0.1$ hertz, $\eta_B = 0.8$, and $\eta_m = 0.4$, and measure d in light years ($= 9.46 \times 10^{15}$ m), ERP in watts, and S in janskys ($\equiv 10^{-26}$ watt m^{-2} hertz^{-1}), then for a single station

$$S = 4.6 \times 10^{-7} \, \frac{\mathrm{ERP} \, \hat{G}(e)}{d^2} \qquad (2)$$

Spectrum and Time Modulations Observed by the Outsider

Figure 5 shows the basic result of this study, namely the total flux density throughout the sidereal day available from all included television stations as seen by an observer located near the celestial equator. The chosen coordinates correspond to those for Barnard's star, third closest to the sun; another observer at the same declination δ, but at a right ascension α different by Δt hours, would see the same pattern, but shifted in phase by Δt (*25*). For a more realistic receiver not covering the entire VHF-UHF frequency range, only a fraction of all stations would ever be detected, but in general the pattern of time modulation shown in Fig. 5 would still hold.

The most striking result, as might be deduced from Fig. 2, is the occurrence of four intense peaks. These peaks occur when the star either rises or sets as seen from Western Europe or from North America; at these times, as a consequence of their antenna patterns (Fig. 4), the dense concentrations of stations in these regions illuminate all objects near their respective horizons. From the star's vantage point, the peaks occur when either Western Europe or North America comes into view or disappears around the limb of the earth (the edge of the earth's disk) as seen from the star. The cover picture shows a sequence of diagrams illustrating the radio limb-brightened earth as it would be seen at various times if the observer had sufficient angular resolution. Since an observer at interstellar distances will not possess such resolution, we show this only for illustrative purposes; the observer can actually record only what is shown in Fig. 5.

The time between the associated star-rise and star-set peaks for a particular station for a star near the celestial equator is always ~12 hours, irrespective of station latitude. The duration of a peak

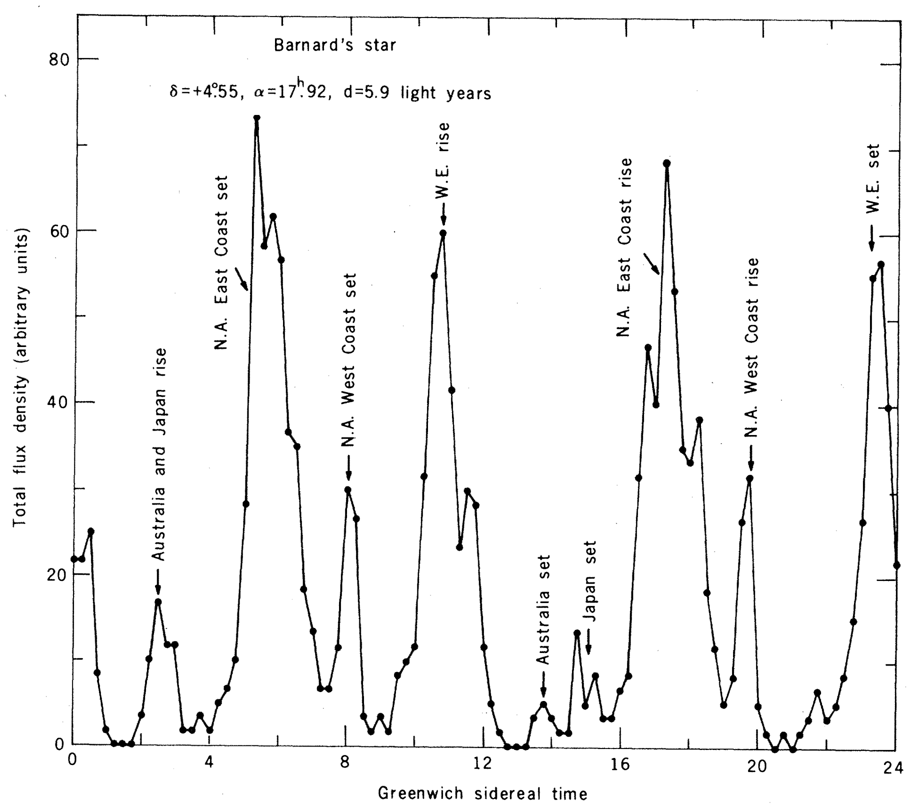


Fig. 5. Relative flux density (summed over all frequencies) of television radiation that would be measured over a sidereal day by an observer located in the direction of Barnard's star, close to the celestial equator. The origin of the various peaks is indicated; "rise" and "set" refer respectively to the appearance at the western limb and disappearance at the eastern limb of a particular region on the rotating earth (see cover). Abbreviations: N.A., North America; W.E., Western Europe. Here, in the cover picture, and in Fig. 6 all stations are taken to be broadcasting 24 hours per day (see Fig. 7). Although units of flux density are arbitrary (dependent on the width and shape of the observer's passband), intensity comparisons between Figs. 5, 6, and 7 are valid.

arising from a single station is determined by the vertical beam width of the antenna and is at least 4 minutes per degree of beam width (the rotation rate of the earth), depending on the angle at which the star crosses the local horizon. For the star CD−36°15693 (18th closest to the sun) at $\delta = -36°$, shown in Fig. 6a, we see that the associated peaks have become much closer to each other in time since such a southerly star never rises far above the horizon as seen from the northern latitudes of North America or especially of Western Europe. The peaks are also broader than for $\delta = +5°$ because of the longer time the star spends in each station's beam. Figure 6b shows the situation for a star at $\delta = +57°$, such as Kruger 60 (23rd closest to the sun). This star lies quite near the celestial north pole and thus never sets or rises as seen from Western Europe or North America. But it does dip near the horizon in the *northern* sky once a day (called lower culmination) as seen from the southerly portions (30°N to 40°N) of North America, Western Europe, and Japan. The result is that each region produces only a single peak in the diurnal pattern at the occurrence of lower culmination. Observers at declinations above +60° or below −60° would not be able to detect the North American or Western European peaks at all, but could receive radiation from the few stations near the equator. Keeping these influences of observer declination in mind, for the sake of brevity we will illustrate all further effects only for an observer at $\delta = +5°$.

The fact that stations tend to cease broadcasting during certain hours based on a local *solar* schedule implies that an annual modulation will be observed in the *sidereal* daily intensity curve recorded by a distant observer (*25*). A specification for time of year on the earth determines whether each station will be broadcasting when it appears on the limb of the earth as viewed by the observer. From the terrestrial point of view, this is equivalent to asking whether the time of year is appropriate for the star to be near the local horizon during broadcast hours.

Using the broadcast schedules given above, we show in Fig. 7 the resulting annual modulation of the four prominent daily peaks (Fig. 5) as observed from Barnard's star at $\delta = +5°$. It can be seen that the drastic reductions in intensity are longer-lasting each year for Western Europe than for North America because of the shorter number of daily broadcast hours in Western Europe. It should be remembered that the observer with sufficient frequency resolution would be able to discern that the peaks "lost" during certain seasons were not due to changes in intensity of each station, but rather in the total number of stations transmitting.

The greatest amount of information (and degree of detectability) is obtained when the observer is able to track individual stations in intensity and frequency. This will immediately show that any

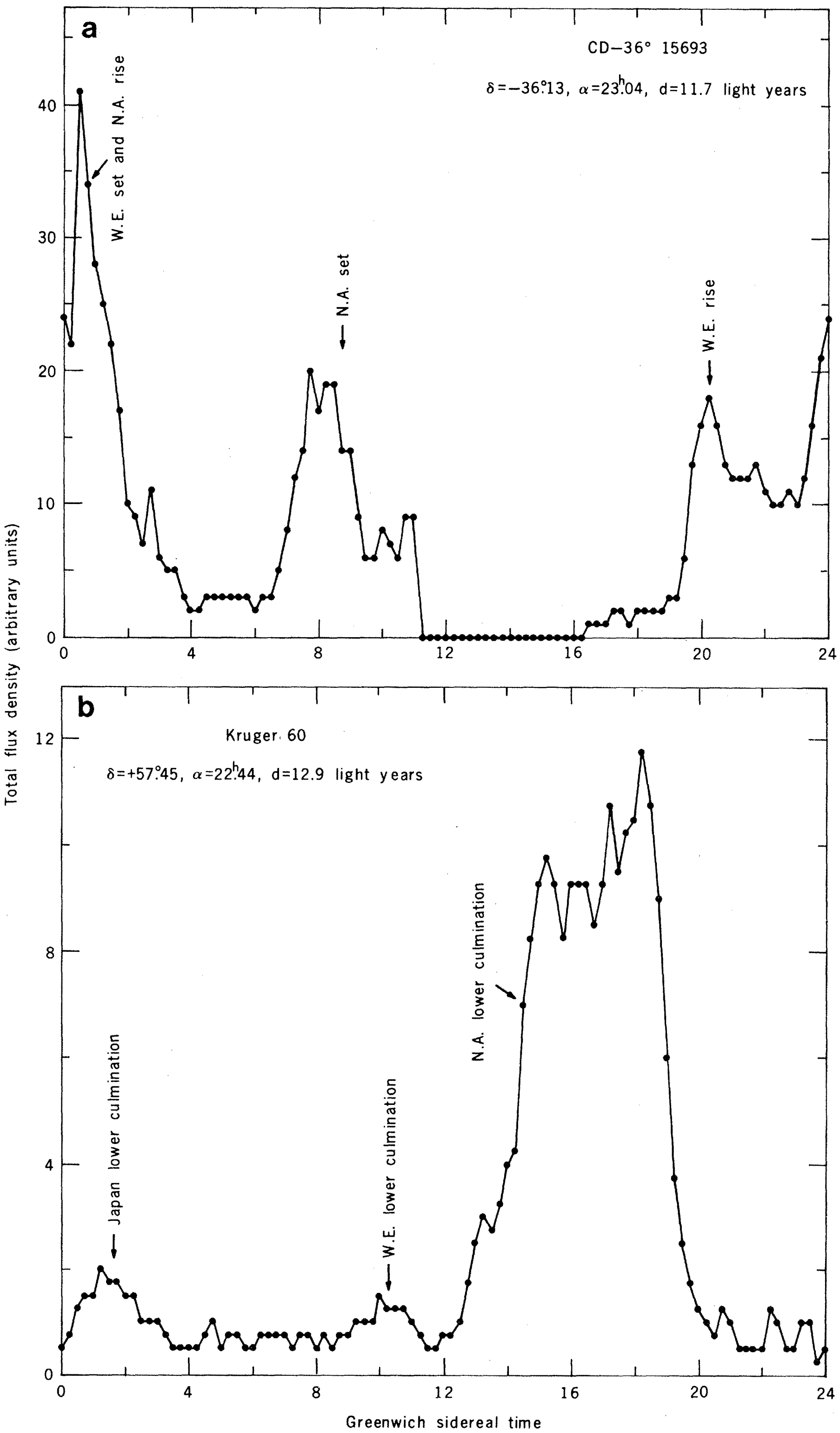


Fig. 6. (a) Sidereal-daily variation of flux density of television radiation as measured by an observer in the direction of the southern star CD −36°15693. The peaks are broader and the associated "rise" and "set" peaks are closer together in time than for the equatorial star of Fig. 5. See the caption of Fig. 5 for further explanation. (b) Same as (a) for the northern star Kruger 60. The peaks now correspond to lower culmination, when the star scrapes the northern horizon for each region. In terms of the cover picture, the various regions illuminate the star when rotation has brought them to the side of the earth opposite the star.

particular station exhibits a substantially different frequency (ν) during its two daily appearances; for δ of observer $\simeq 0°$, $[\nu(\text{rise}) - \nu(\text{set})] \simeq 2V_p\ \nu \cos \phi/c$ (where c is the velocity of light) is ~1000 hertz for a typical UHF station at latitude ϕ in North America or Western Europe. Figure 8 shows the actual Doppler pattern that would be seen in one of the most crowded regions of the spectrum, namely channel 3^+ (*26*) at 61.260 Mhz, from Kruger 60 when it is undergoing lower culmination for much of the United States (see Fig. 6b). As the observer's location moves through the beams of the separate stations (along their northern horizons), the intensity and frequency of each station change. Tracks of frequency versus time for a large collection of stations are valuable, since such data quickly reveal strong correlations between the nature of the daily frequency shifts and the daily intensity modulation (see below).

Range of Detectability

To calculate the range of detectability for an outside observer, we employ the standard radiometer equation for the root-mean-square (rms) noise in antenna temperature, $\Delta T_{\text{rms}} = 2T_{\text{sys}}\ (\delta\nu\ \tau)^{-1/2}$, where T_{sys} is the receiver system noise temperature (or figure of merit), $\delta\nu$ is the bandwidth of the receiver, and τ is the integration time (*8*). Further recalling that $\Delta S_{\text{rms}} = 2\ k\ \Delta T_{\text{rms}}/A_e$, where A_e is the effective area of the receiving antenna and k is Boltzmann's constant, the detectable flux density is

$$S_{\min} = \frac{4kT_{\text{sys}}R}{(\delta\nu\tau)^{1/2}A_e} \qquad (3)$$

where R is the minimum detectable signal-to-noise ratio. Combining Eqs. 3 and 1 and taking standard values discussed above, the maximum distance d for detection is given by

$$d = \left(\frac{0.010\ \text{ERP}\ (\delta\nu\tau)^{1/2} A_e}{k\ T_{\text{sys}}\ R\ \delta\nu} \right)^{1/2} \qquad (4)$$

We now need to find appropriate values for the various parameters in this equation.

What is the optimum bandwidth for detection of the earth's radio signature? Assuming that the observer can track an individual station in frequency, at first sight it would seem to be $\delta\nu$ ~0.1 hertz, the width of the station's video carrier. Such frequency resolution, however, requires an integration time τ of at least 10 seconds; the question then arises whether typical Doppler drifts due to the earth's rotation V_p and orbital revolution V_s will be faster than $\delta\nu/\tau \sim 10^{-2}$ hertz/second, thus reducing the coherence and detectability of the signal. The maximum fractional frequency drifts are $\dot{\nu}/\nu \sim (V_p\Omega_p + V_s\Omega_s)/c \sim 1 \times 10^{-10}$ sec^{-1}, where the Ω's are angular rotations. Such a drift over 10 seconds is comparable to or less than the intrinsic short-term frequency stability of the transmitter crystals (*17*). Thus the Doppler shifts still allow an analyzer bandwidth of ~0.1 hertz.

The question now becomes whether stations might be so bunched in frequency that one could profit from a somewhat broadened bandwidth. The applicable criterion is that the signal-to-noise ratio for a broader bandwidth $\Delta\nu$ is improved over that for a bandwidth $\delta\nu$ by a factor $n(\delta\nu/\Delta\nu)^{1/2}$, where $\delta\nu$ is the width of each signal (~ 0.1 hertz) and n is the number of signals (of equal strength) included in that band (*27*). In searching through the most favorable frequency regions and times for high degrees of bunching, the best case available in our model is comparable to that shown in Fig. 8. It should be kept in mind, however, that the real dispersion in frequency of several "channel 3's," all visible at one time for a particular observer, is actually determined by three factors: (i) purposeful offsets assigned by the regulatory agency to avoid interference; in the United States about two-thirds of all television stations are offset by ±10 khz from their nominal frequency and similar schemes are used in Europe (these offsets have already been taken into account in Fig. 8); (ii) unintentional frequency drifts from the assigned frequencies; these typically amount to $\lesssim \pm 200$ hertz offset from nominal (taking place on a time scale of weeks); and (iii) the Doppler spread due to the earth's rotation, typically ~ ± 20 hertz. For the case shown in Fig. 8 [with random offsets of ± 200 hertz from factor (ii) applied], we have $\Delta\nu \simeq 400$ hertz, $\delta\nu = 0.1$ hertz, and $n = 13$; from the criterion given above it is clear that a bandwidth $\Delta\nu$, or in fact any bandwidth broader than 0.1 hertz, is not optimum. This result also implies that the problem of detecting radio leakage from the earth as a whole is essentially identical to the problem of detecting the single strongest station (*28*).

Having established that $\delta\nu \sim 0.1$ hertz is optimum, for the overall detectability we still need to find the available integration time for a single station. This typically will vary from ~10 minutes for (narrow-beamed) UHF stations to ~30 minutes for low-band VHF stations. This assumes that the observer is compensating for Doppler drifts and is sampling in relatively short intervals, trying various possible frequency offsets between successive samples before stacking. Finally, we must adopt a total system noise temperature with contribu-

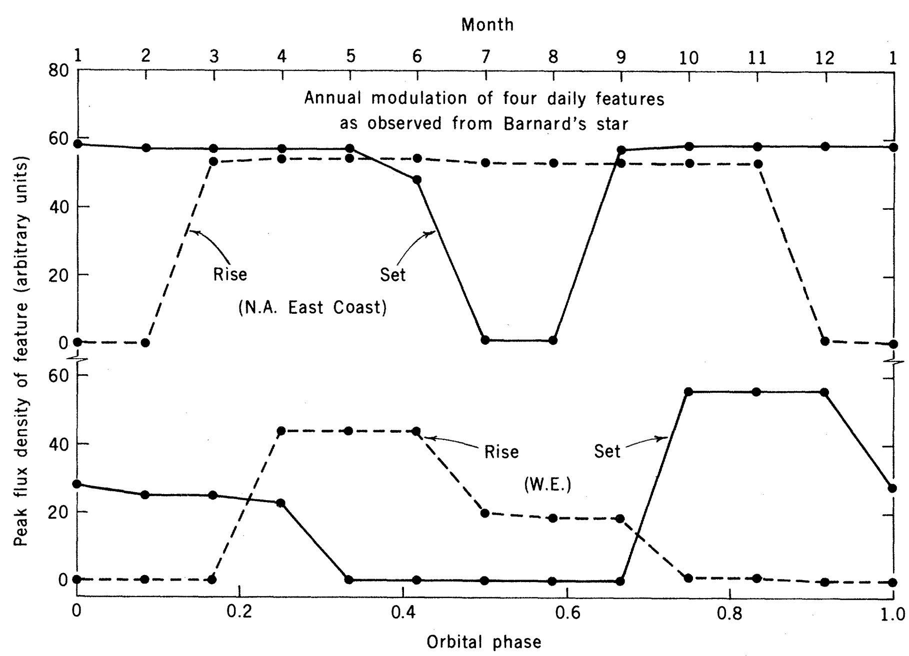


Fig. 7. Annual modulation plotted in terms of the orbital phase of the earth, or equivalently, month of the year, of the four most prominent daily peaks or features as observed from Barnard's star (Fig. 5). The degree and duration of the modulation are directly related to the daily broadcast schedules of the stations comprising each feature. The changing peak intensities are actually the result of differing numbers of stations received at any particular time; 20 of the arbitrary units of flux density correspond roughly to ~120 stations illuminating the star at that time.

tions from both receiver electronics and unavoidable natural sources. The receiver itself might have a noise figure as low as 0.2 decibel (contributing 20K to T_{sys}) and the cosmic background contributes only 2.7K, but the galactic background (arising from synchrotron radiation by cosmic-ray electrons in our galaxy) is the most damaging of all. For low-band VHF, a typical location well away from the galactic plane contributes ~5000K to the effective T_{sys}; for high-band VHF and UHF the numbers are respectively ~200 and ~10K. It is clear then that UHF signals, for which a total $T_{sys} \simeq 30$K is possible, will be most detectable (*29*).

If we now take $A_e = 3 \times 10^4$ m^2 (comparable to that of the Arecibo antenna) and $R = 1$, Eq. 4 indicates that an observer can detect a strong UHF station (ERP = 5×10^6 watts, $\delta\nu = 0.1$ hertz, $\tau = 600$ seconds) at a distance of 1.7×10^{16} m = 1.8 light years (*30*). While this is the detection distance for a strong television video carrier, recall that a BMEWS-type defensive radar (Table 1), although of limited information content, could be detected at distances up to about ten times greater.

There seems little way to increase this short range for television (only about halfway to our nearest neighbor, Alpha Centauri) except through a much larger receiving antenna. For instance, something similar to the proposed Cyclops array (*4*) of 1000 100-m dishes would allow detection of video carriers out to a distance of ~25 light years (which includes ~300 stars) and of BMEWS-type radars out to ~250 light years. Further help might be thought to come from a longer integration time, say of ~3 hours, applicable if the observer picked up successive UHF channels of a particular assigned frequency as his location swept across North America. But since the frequency of a channel varies significantly from station to station, the gain from the increased integration time would be more than offset by the need to adopt a bandwidth much broader than $\delta\nu$.

Finally, we should consider how the radio signature of the earth has changed over the past 30 years since television broadcasting began in earnest. Figure 9 illustrates the growth in time-averaged transmitted power (summed over all television frequencies) in this bubble of radiation expanding at a rate of 1 light year per year. The solid line is a reasonably accurate model for U.S. stations alone (starting dates were not available for other stations). Also shown is an estimate for the whole earth based on the assumption that television broadcasting outside the United States was negligible in total transmitter power before 1957 and grew to its present power ratio with U.S. broadcasting in the ensuing decade. On a cosmically infinitesimal time scale, the earth has indeed become a very bright planet, in fact easily outshining the sun in certain narrow frequency ranges (*30*).

Recognition of the Signal as Artificial

Assuming that an outside observer has detected the characteristics of the earth's radio signature outlined in the previous section, the question immediately arises whether he would recognize them as being "artificial." It is difficult, to say the least, to place oneself in the "shoes" of an outsider from an entirely different civilization and culture. The extremely narrow-band, periodically recurring, linearly polarized signals would show precise patterns in frequency placement and in frequency shifts. Might not one of their clever theorists be able to produce a substance that naturally emits the appropriate spectrum? It is impossible to say, and we will proceed on the assumption that the radio signature is recognized as artificial. But we should add that an observer employing only a broad bandwidth (say $\gtrsim 5$ Mhz, as in Fig. 3) would not have many clues, because of his inability to detect Doppler shifts and precise timings of individual stations, to the source of the four daily peaks, the annual modulation due to station schedules, and so on. He might well be inclined to model the emission in terms of hot spots on a rotating body, the intensity of which would be modulated by action from the sun, by an unseen occulting body, or by wanderings in position.

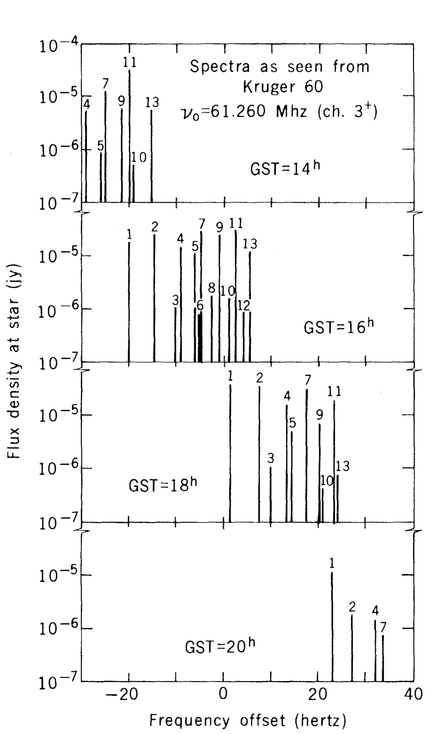


Fig. 8. One of the most crowded regions of the radio signature of the earth: spectra of 0.1-hertz-wide video carriers for channel 3$^+$ (61.260 Mhz) as observed from the star Kruger 60 at a distance of 12.9 light years. The four Greenwich sidereal times cover the period during which the star scrapes the northern horizon at lower culmination as seen from the United States (see Fig. 6b). The illustrated frequency offsets arise solely from the Doppler shift due to the rotation of the earth; in reality the degree of crowding is much less since the frequencies of video carriers often wander by as much as ± 200 hertz from their assigned frequencies. The individual stations, all of which have ERP ≤ 100 kw, are labeled as follows: (1) Phoenix, Arizona; (2) Portales, New Mexico; (3) Lexington, Nebraska; (4) Bryan, Texas; (5) Springfield, Missouri; (6) Mason City, Iowa; (7) Jackson, Michigan; (8) Champaign, Illinois; (9) Chattanooga, Tennessee; (10) Huntington, West Virginia; (11) Savannah, Georgia; (12) Clearfield, Pennsylvania; and (13) Norfolk, Virginia.

Of course the radio signature would certainly be recognized as artificial if an observer 25 light years away could detect television pictures of Korean War news, or if one 5 light years away could detect the Munich Olympic Games. At first one might think that the best chance for this would occur when large numbers of stations were broadcasting identical program material on the same nominal frequency, as for a U.S. national network program or a European championship football match. This is not true, however. First, one is always limited to the stations visible at a particular time. Second, time delays between stations only 100 km apart on the earth's surface are already ~3 msec, causing irreconcilable confusion among different stations (a single line of a television picture is produced about every 0.06 msec). Third, as discussed above, even stations at nominally the same frequency are in fact spread over a range of a few hundred hertz or more.

For a single station, then, we can ask how much more than bare detection of the video carrier signal is required to obtain program material. The answer is that a factor of ~2×10^4 times greater sensitivity over a bandwidth of ~5 Mhz would yield a decent picture (*31*). This means in practice that an antenna with an effective diameter ~100 times more, or at a distance ~100 times closer, would be required for program detection as opposed to carrier detection. Depending on one's opinion of the information content of television broadcasting, this calculation can be taken either as discouraging or reassuring.

Possible Scientific Deductions by the Outsider

This brings us to the astronomical and other data that could be garnered from the radio signature of the earth, assuming detection of only the video carriers (no program material). The entire radio signature participates in a common annual Doppler periodicity arising from the orbital motion of the earth about the sun at $V_s = 30$ km/sec. The peak-to-peak magnitude of these shifts is $\Delta\nu/\nu \sim 2 \times 10^{-4} \cos \beta$, where β is the ecliptic latitude (*32*) of the observer, amounting to well over 1 khz in almost all cases, even for low-band VHF. It would seem inevitable that this longer periodicity would be interpreted as an orbital motion about the associated G2 dwarf star, which we call the sun (*33*).

The situation with regard to the orbital Doppler shifts of any particular station is exactly that of what astronomers refer to as a single-lined spectroscopic binary system. After carefully observing the radial velocity curve for 1 year, the observer could derive (i) the earth's orbital period, (ii) the eccentricity of the earth's orbit, (iii) the longitude of periastron (perihelion), (iv) the time of periastron, (v) the projected semimajor axis of the orbit ($a \cos \beta$, where a is the semimajor axis), and (vi) the mass function of the star-planet system, $M_\bigstar^3 \cos^3\beta/(M_\bigstar + M_p)^2$, where $M_\bigstar$ and M_p are the masses of the star and the planet, respectively (the deduction that a planet is involved is justified below). On the reasonable assumption that $M_p \ll M_\bigstar$ (if for no other reason, because of the lack of detectable Doppler shifts in the solar spectral lines), the mass function becomes $M_\bigstar^3 \cos^3\beta$. Since the observer's astrophysical theory would undoubtedly be sufficiently advanced that he would have a reliable independent estimate of $M_\bigstar$, he could then find $|\beta|$ and thus the true value of the semimajor axis of the earth's orbit. This would be vital in terms of adducing possible physical conditions on the earth, in particular the temperature, and thereby gaining clues to the form of life responsible for this artificial emission.

It would be noticed that the annual period of the Doppler shift was the same as the periodicity of the modulation in the number of stations detected in various daily peaks (caused by stations' individual daily broadcast schedules; see Fig. 7). By concentrating on individual stations, the observer would also find that the time in hours between a station's two daily appearances was equal to the time in half-months between its two annual shutdowns. This relation between the sidereal daily period and the annual modulation period would undoubtedly lead to the conclusion that the length of what we call the solar day is vital to the on-off cycles of the transmitters.

That the intensity behavior of individual stations is due to an occultation of some kind is indicated by the abrupt daily appearance (at star-rise) and abrupt disappearance (at star-set) of each station. The fact that the Doppler shift of a station reaches its daily extrema very shortly after its appearance and again before its disappearance would also indicate that one is observing tangentially beamed radiation from the limb of a rotating body. Other possible scenarios, perhaps involving a pulsating body, would seem too complex.

If, despite the highly unfavorable galactic noise at low-band VHF, the observer could detect VHF as well as UHF stations, ionospheric effects, which are significant only at frequencies below 100 Mhz, would be noticeable. In particular, he would observe that the sidereal-daily periodicity of individual low-band VHF stations exhibited much more "phase jitter"—that is, day-to-day variations of $\lesssim 30$ minutes—than that of UHF stations, although their long-term means were the same. This effect is due to ionospheric refraction (sometimes as much as 5° to 10°), which is highly variable and dependent on frequency, solar activity, latitude, gradients in ionospheric structure over the earth's surface, and so on. It is reasonable to suppose that the great difference in behavior between low-band VHF and higher frequencies would be ascribed to a variable plasmasphere surrounding the planet (*34*).

The most likely possibility for detection of a tropospheric effect appears to be in variations in the beam tilts, which are caused by high winds bending the tallest towers on which broadcast antennas are mounted. A wind of 22 m/sec (50 miles per hour), typically occurring 25 times each year, causes an $\sim 0.3°$ tilt on a tower 300 m above average terrain (*35*). This would cause phase jitter of about $\pm$ 1 minute (in the time of peak signal) to occur on some days for a particular station, and would be most easily detectable in the UHF range because of the narrower beam widths. The identification of this effect with eolian forces would appear to be difficult to establish, although annual modulations in the amount of jitter due to seasonal effects on a station's weather would also be discernible.

The observer would be able to measure the inclination of the earth's axis to the plane of his sky (that is, the absolute value of his declination $|\delta|$ as seen by us) by a careful study of (i) the distribution of times Δt between station appearance and disappearance for each detected station, and (ii) the daily maximum Doppler shift of each station, $V_s = V_p \cos \delta \cos \phi$ (*36*). For instance, observers at $\delta = 0°$ would find $\Delta t = 12$ hours for all stations, whereas observers at an arbitrary $|\delta|$ would see stations near a latitude $\phi = 90° - |\delta|$ appear only once each day (as in Fig. 8). A model fit to these observations then would yield V_p, which, coupled with the sidereal-daily period, gives the radius R_p of the rotating sphere. Such an object of radius $\sim$ 6000 km could be a white dwarf star, a burned-out "black dwarf" star, or a planet. Having established that the signals are artificial, it is likely that the observer would surmise that an emitting civilization would be highly unlikely to have developed in an environment con-

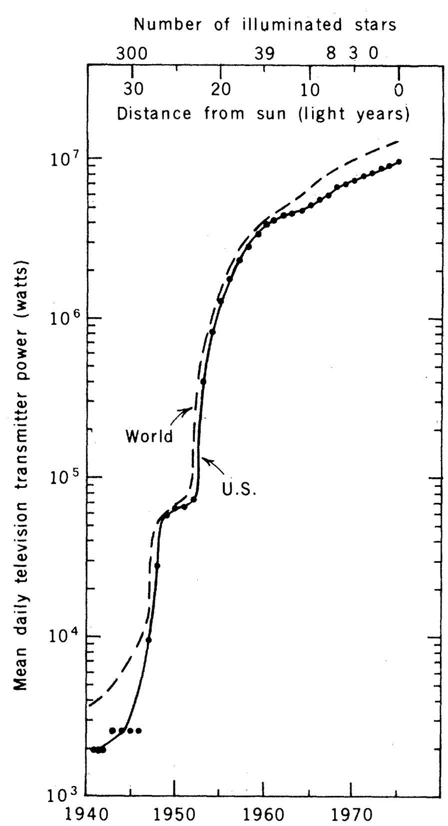


Fig. 9. Estimated growth in time-averaged transmitted power since television broadcasting began. The solid curve for the United States is reasonably accurate since starting dates for all stations were available, but it was still necessary to employ a model for the growth of transmitter power and daily broadcast hours for each station. The dashed curve for the entire world is correct for 1975 and only estimated for earlier dates. The increasing number of stars bathed by the expanding power bubble is indicated at the top of the diagram.

taining ambient forces of $\gtrsim 10^5 g$ (as is true for a white or black dwarf); the object must therefore be a planet.

Besides determining the values of V_p, $|\delta|$, and R_p, these procedures would, of course, yield a map of all station locations on the surface of the earth (Fig. 2). This mapping procedure is extremely accurate; timing accuracies of a few seconds and frequency resolution of $\lesssim 1$ hertz allow placement of a particular station to within a few kilometers of its correct location (*37*).

Finally, the daily trace of an individual station is a reflection of the radiation pattern of the transmitting antenna; with sufficient sensitivity, some side lobes might even be measurable. The angular width of the primary lobe is, together with the earth's rotation rate, the frequency of operation, and the assumption of a diffraction-limited aperture, an excellent indicator of the linear size of the radiator. Antenna sizes of $\sim$ 15 to 20 m would typically be found, yielding clues to the size scales of terrestrial structures.

Speculations on Cultural Deductions by the Outsider

A further question of interest concerns any deductions which the outside observer could make concerning our present culture and civilization. The very fact that we allow all of this power to escape might be taken as a sign of our prodigal nature, or even of our lack of an ethic concerning environmental pollution in our galaxy. If the observer concludes that he is studying inadvertently leaking radiation, then he can try to unravel much the same puzzle as an archeologist endeavoring to understand an ancient city with a knowledge of only its street plan. The derived map of station locations (Fig. 2) would show two marked concentrations and several lesser ones, vast regions with virtually no stations, and a marked dominance of stations in one hemisphere. It would show strongly demarcated geographical boundaries, apparently lines where, for political, economic, or other reasons, the density of stations greatly changes. It would show a distribution of UHF stations different from that of VHF stations, and systematically different sorts of frequency spectra, antenna beams, time schedules, and power levels in the various locales.

The deductions that might be made from this wealth of information can only be conjectured, but certainly the extraterrestrial "humanists" and scientists would all have their favorite theories concerning (i) the purposes of these transmitters, as well as their physical structure; (ii) the nature of this planet's relationship to the sun, as well as its geography, geology, and atmosphere; and (iii) the nature of this civilization's biology, sociology, commerce, politics, economics, philosophy, technology, and science. We feel that far more could be deduced about our culture than one would at first think. For instance, political spheres of influence could be measured quite accurately by noting the frequencies and other technical conventions of stations. Furthermore, the varying broadcast schedules of stations (set by policies of national networks in most cases) would sharply delineate political boundaries, as distinct from spheres of influence. Further possible deductions are left to the imagination of the reader.

Should We Try to Eavesdrop?

The advantages of the eavesdropping strategy vis-à-vis searches for signals deliberately intended to establish contact have been briefly discussed in the introduction. Since we have no way of knowing the relative durations of various phases of a civilization's "radio emission development," both methods seem to have merit. Considering information content, a purposeful message is probably vastly superior; its great disadvantage, however, is in the need to use a code. In contrast, we have shown how, using only standard astronomical techniques and without special code-breaking, a great amount of information can also be acquired from unintentional leakage. It should be noted that some schemes of interstellar contact have called for changing transmission frequencies in such a manner as to compensate exactly for all motions of the earth; while this would improve the chances for contact by obviating the need to track frequencies, it would also prevent the deduction of almost all of the facts discussed above. The final important consideration, maximum distance of detection, is very unfavorable to the eavesdropping strategy if our own radio signature is typical in intensity. While the most intense part of the repeatable portion of the earth's present radio signature could be detected by us only at distances of tens of light years, intentional narrow-band beacons can easily be detected much farther away (*2–5*). On the other hand, other civilizations may well be leaking at prodigious rates compared to ours; if so, the present exercise illustrates more generally the kind of deductions we could make if we were successful in eavesdropping on a large number of narrow-band signals.

In order to greatly increase its useful range, perhaps eavesdropping should be cast in a different light. In our model we have not considered powerful, highly directional, usually nonrepeatable sources of radio emission such as that encountered in a planetary radar experiment with the Arecibo antenna (*38*). Any distant observer who happened to be in this beam while the transmitter was operating (although there are very large odds against this occurring) would detect a signal vastly more intense than those we have been discussing. But he would see it only once or for a few days at most, and the information content, other than the announcement of our presence (or of some strange natural radio flare phenomenon) would be minimal. Nevertheless, his attention would have been drawn to a certain sector of the sky. Assuming adequate sensitivity, he could then begin searching for associated evidence, eventually striking the rich, repeatable radio signature lode, in this case at a level $\sim$ 60 db below the original signal. In this manner such sources as radar astronomical beams, the few ultrapowerful military radars, special continuous-wave (CW) or AM satellite communications uplinks (most such communications are presently FM), and reflections off the earth by satellite downlinks (such as the recently proposed microwave downlink to transfer solar energy gathered by satellite) might act as acquisition beams. These beams yield some information in themselves, but are most useful in calling attention to what lies below.

As to the approach radio astronomers should take in the coming years, it seems that the strategy outlined in the Project Cyclops report (*4*) remains basically sound. Only the nearest stars are suitable candidates for detection of leakage if that leakage is similar to ours. We should definitely search for extremely narrow bandwidths ($\lesssim$ 0.1 to 1.0 hertz) and a variety of Doppler tracking rates in order to optimize our sensitivity—this needs to be stressed since all searches to date have used much coarser resolution. This result is also in accord with Drake's recent arguments (*39*) for sub-hertz bandwidths, which are based on tradeoffs the sender must make between bandwidth and sky coverage. Finally, while consideration of galactic noise favors frequencies $\gtrsim$ 1000 Mhz, it should be kept in mind that such a criterion is not so strong for the purposes of eavesdropping. It might well be that another civilization, with an entirely different technology, exhibits leakage whose intensity increases with decreasing frequency markedly faster than does galactic noise. Narrow-band searches at low frequencies are therefore also warranted.

Conclusions

The signals that are most detectable by and useful to the extraterrestrial eavesdropper are the video carrier signals of television broadcasting stations and a few powerful BMEWS-type military radar signals (Table 1). A model including 2191 television stations around the world has been constructed in order to study the intensity and frequency modulations as measured by an outside observer at interstellar distances. The daily and annual modulations in intensity (Figs. 5 and 7) are a result of the extremely nonuniform distribution of stations (Fig. 2) and daily broadcast schedules. Periodic Doppler shifts in the narrow-band video carrier signals are a result of the earth's rotational and orbital motions (Fig. 8). Despite the presence of so many different signals in the earth's radio signature, the problem of detecting it as a whole is equivalent to that of detecting the strongest single station alone. The most intense, repeatable, and nondirective sources on the earth, namely UHF television stations of 5 Mw effective radiated power and BMEWS-type radars, would be detectable at distances of ~ 25 and ~ 250 light years, respectively, by an observer with our present technology. We argue that the observer able to detect only television carrier signals would still recognize them as artificial—despite the fact that ~ 10^4 times more sensitivity would be required to obtain program material.

After several years of careful monitoring of the intensity and frequency variations of several hundred stations, the observer could deduce (i) the complete orbit of the earth; (ii) the existence of station broadcast schedules influenced by the sun; (iii) the presence of an ionosphere and perhaps even a troposphere; (iv) the size, rotation rate, and axis of rotation of the earth; (v) a complete map of the stations; (vi) the mass and distance to the moon (*37*); (vii) the size of the radiating antennas; and (viii) various cultural inferences concerning our civilization.

While we believe that our attempts to contact extraterrestrial intelligences should also be aimed toward detection of purposeful signals, we hope the present study will lead to a greater awareness of the possibilities of eavesdropping and of the many facets of the radio signature of our civilization.

References and Notes

1. G. Cocconi and P. Morrison, *Nature (London)* **184**, 844 (1959). The first scientific attempt at extraterrestrial communication appears to have taken place shortly after radio communications expanded to a global scale. During a close passage of Mars in 1924, D. Todd obtained cooperation from the U.S. Army and Navy in securing radio silence in order to aid an attempt at picking up martian transmissions (*New York Times*, 21 to 25 August 1924).
2. A. G. W. Cameron, Ed., *Interstellar Communication* (Benjamin, New York, 1963).
3. I. S. Shklovskii, in *Intelligent Life in the Universe*, I. S. Shklovskii and C. Sagan, Eds. (Delta, New York, 1966), pp. 255–257.
4. B. M. Oliver and J. Billingham, "Project Cyclops: A design study of a system for detecting extraterrestrial intelligent life," *NASA Contract. Rep. 114445* (1973).
5. R. N. Bracewell, *The Galactic Club* (Freeman, San Francisco, 1974).
6. Oliver and Billingham (*4*), p. 59; C. Sagan and F. Drake, *Sci. Am.* **232**, 80 (May 1975). The map of FM radio and VHF television radiation shown by Sagan and Drake was a large part of the original inspiration for this article, but the map is incorrect in many essentials.
7. Bracewell (*5*) extensively discussed the concept of a messenger probe which is sent to stellar planetary systems and (through eavesdropping) searches for signs of intelligence before making itself known; our study might help in the design of such a probe.
8. Basic principles of radiometry, antennas, and so on are discussed in J. D. Kraus, *Radio Astronomy* (McGraw-Hill, New York, 1966).
9. Further details may be found in P. F. Panter, *Modulation, Noise, and Spectral Analysis* (McGraw-Hill, New York, 1965).
10. This is not true for other types of AM, such as single-side band, which employ a suppressed carrier, but radio services using single-sideband AM contribute insufficient power to be important in this problem.
11. Radiation at extremely low frequencies (< 20 khz), caused by harmonics of the standard a-c frequencies of high-voltage transmission lines, has been detected by satellite [K. Bullough, A. R. L. Tatnall, M. Denby, *Nature (London)* **260**, 401 (1976)], but is of relatively low intensity and in any case would be severely attenuated in passing through interstellar regions.
12. In much of this discussion we use only statistics and estimates for the United States, since they were more accessible; however, extrapolations to the whole world involve factors of no more than 2 to 5 (for instance, see Fig. 9).
13. *Broadcasting Stations of the World* (Government Printing Office, Washington, D.C., ed. 26, 1974).
14. Effective radiated power is defined as transmitter power times the gain of the antenna, and is therefore proportional to the power radiated per unit solid angle. The broadcasting industry defines the gain of an antenna with respect to that of a half-wave dipole (G_d = 1.64).
15. R. A. Tell and J. C. Nelson, *IEEE Trans. Broadcast.* **BC-22**, 116 (1976).
16. When the FM carrier is not modulated at all, as during "dead time" for a monophonic broadcast (stereophonic broadcasts always have some modulation), all radiated power will be concentrated in the carrier width. Thus there will be certain rare times when the carriers for FM stations become as detectable as television video carriers. Since the worldwide distribution and other relevant characteristics of FM stations are very similar to those of television stations, little additional information concerning the earth and its civilization would be gained by a study of these erratic signals in the FM band. We have therefore not included FM stations in our model.
17. This carrier width is essentially determined by the short-term (~ 1 to 10^3 seconds) frequency stability of the crystal oscillator in each transmitter. Actual measurements of the fractional frequency stability of video carriers, as received in the field from a variety of stations, indicate that it ranges from 1 part in 10^{10} to 1 part in 10^8. In this article we adopt a standard carrier bandwidth of 0.1 hertz.
18. *Television Factbook* (No. 45) (TV Digest, Washington, D.C., 1976).
19. Actual measurements with high-frequency resolution of the ambient spectral activity over the range 0 to 100 Mhz in the U.S. urban environment also reveal that the spectral power density in commercial and government broadcasting services dwarfs that in all other radio services [R. A. Tell, J. C. Nelson, N. N. Hankin, *Radiat. Data Rep.* **15**, 549 (1974)]. We are not aware of similar field measurements in the range 100 to 1000 Mhz.
20. The ratio of all transmitters (including relay, booster, and translator transmitters) in North America to all those in the rest of the world is much smaller, namely ~ 4,000/11,000, but North American primary transmitters are, on the average, more powerful. The countries in our model having at least 20 transmitters with ERP ≥ 50 kw are the United States (896), West Germany (211), Japan (108), the United Kingdom (103), France (82), Australia (81), Sweden (77), Canada (75), Czechoslovakia (50), Italy (33), Mexico (28), Austria (23), Spain (23), and Brazil (20).
21. *The Times Atlas of the World* (Houghton-Mifflin, Boston, 1967).
22. For instance, values of e_0 for a given frequency range vary by a factor of 2 from those quoted, VHF beams are sometimes tilted, and many antennas (especially UHF) are not omnidirectional. Regarding the last point, we can only hope that the data base includes sufficient stations that the assumption of omnidirectionality for each antenna will in general be a reasonable approximation, in the sense that for a particular locale the directionality of neighboring antennas will often be approximately random. On the other hand, the assumption of a Gaussian antenna pattern in elevation is quite good; despite some cases of "null fill" and strong side lobes (> 10 percent), real antennas almost always exhibit a pattern within 10 percent of a Gaussian. We also adopt a main-beam efficiency, η_B, of 0.8; that is, 80 percent of the radiated power is taken to pass through the primary lobe of the pattern.
23. The lone significant exceptions appear to be VHF television in Great Britain and France, which do use AM audio. Our model does not include these audio carriers since they are a small fraction of the total power and in any case would yield very little more information than is obtainable from the video carriers alone.
24. The value η_m = 0.4 holds for two otherwise rather different standards, those of the United States and Great Britain. Other modulation schemes should also be close to this value.
25. Sidereal time refers to the number of hours passed since a fixed location on the sky (taken to be in the constellation Pisces) has passed the meridian at a particular location on the earth. The sidereal day of 24 sidereal hours represents the true rotation period of the earth and is equal to 23 hours 56 minutes of solar time. The standard geocentric celestial coordinate system employs right ascension α, the sidereal time when a particular location on the sky passes the meridian, and declination δ, the angle of a sky location above the earth's extended equatorial plane, the celestial equator.
26. Channel 3^+ refers to the upper of the three closely spaced frequencies which are assigned to channel 3 in the United States.
27. As one increases the analyzer bandwidth, the signal power is $\propto n\delta\nu$ and the uncertainty in its estimate is $\propto (\Delta\nu)^{1/2}$. The signal-to-noise ratio is then $\propto n\delta\nu/(\Delta\nu)^{1/2}$, compared to $\delta\nu/(\delta\nu)^{1/2} = (\delta\nu)^{1/2}$ for the case of a single station.
28. This calculation is related to F. Drake's proposal to detect the ensemble of many narrow-band signals, each of which is undetectable by itself (*4*, pp. 140–141). This involves taking the cross-correlation function of two independent samples of the spectrum, then searching for a peak at zero shift which would be indicative of a recurring signal at the same frequency. Compared to conventional techniques, this method gives an improvement in signal-to-noise ratio of a factor $n^{1/2}(\delta\nu/\Delta\nu)^{1/4}$, where n is the number of signal channels and $\Delta\nu/\delta\nu$ represents the total number of search channels. Since this criterion is very similar to that discussed for the situation in Fig. 8, it can be seen that the method is not advantageous. Using different sets of values of the three parameters, each consistent with the radio spectrum actually observable at some time, we can find no case in our model where the ensemble of signals can be detected more easily than an individual station.

29. This conclusion is not changed by a consideration of propagation effects in the interstellar medium over distances of ≲ 100 light years. These include free-free absorption, frequency dispersion, Faraday rotation, scintillations, and other multipath effects.
30. The minimum level of flux density for this distance (from Eq. 3), $S_{min} = 7.1 \times 10^{-27}$ watt m^{-2} $hertz^{-1}$ = 0.71 jansky, at first sight seems far below modern standards in radio astronomy, but it must be remembered that the signal is wholly contained within the very narrow bandwidth of 0.1 hertz. Using such a bandwidth also obviates any concern that normal radio emission from the sun might be detrimental, since its flux density in the UHF range would be ~ 1000 times weaker. The calculated range is somewhat smaller than that derived in the Project Cyclops study (*4*, p. 59), but our value is more realistic.
31. The figure ~ 2×10^4 is derived from (i) the required 5-Mhz bandwidth, which yields receiver noise $(5 \times 10^6/0.1)^{1/2}$ worse than that for the carrier alone; (ii) the total signal with the broad bandwidth improving by only a factor of ~ 2; and (iii) "decent picture" implying a dynamic range of ~ 5 in black-to-white AM voltage level. Furthermore, in addition to the need to test myriad possibilities for the various electronic conventions (although the line synchronization rate of ~ 16 khz and the picture rate of ~ 30 hertz would be immediately apparent from a spectral analysis of the signal), the observer of our culture must also compensate for frequency dispersion across the bandwidth arising as the signals traverse the interstellar plasma. For UHF frequencies of ~ 500 Mhz, this amounts to ~ 3 μsec per 5 Mhz for each light year of distance (assuming an electron density of 0.03 cm^{-3}). Once the correct dispersion factor was found, this could be used as a rough indicator of the distance to the earth.
32. Ecliptic latitude refers to the angle which a given direction makes with respect to the plane of the earth's orbit about the sun.
33. If the observer should think that for some unknown reason all of the stations were modulating their transmitter frequencies with an annual periodicity, thereby mimicking a Doppler motion, he would even have a possible way to check this. Accurate measurements would reveal that the sidereal-daily period of 23 hours 56 minutes in fact also showed an annual Doppler modulation of ± 1 part in 10^4 (± 10 seconds) over a year. This could reasonably arise only if the planet as a whole were in motion. Measuring daily periods to the required precision should be possible, despite the fact that 10 seconds of time corresponds to an angle of only ~ 2 arc minutes (requiring various parameters, such as antenna patterns and refraction, to be constant to that degree over a year), since the mean period can in principle be deduced from timings of hundreds of stations each day.
34. Changes in the amount and nature of this phase jitter over many annual cycles might even lead an observer to the conclusion that there was an 11-year periodicity (which we call the solar activity cycle) in his data. If he also studied the solar radio continuum over those 11 years, the same periodicity would be found, once again implying a strong solar influence on the earth. Furthermore, the D-layer of the ionosphere strongly absorbs low-band VHF, peaking at local noon (~ 50 percent absorption at $e = 0°$) and at solar maximum. Monitoring of the peak daily intensity of a particular low-band VHF station would then also show an 11-year cycle as well as an annual modulation due to this solar-daily modulation. Thus in the season when he sees many fewer stations (when star-rise occurs in the early morning), the low-band VHF stations that continue broadcasting will in fact be much more intense than average.
35. *National Association of Broadcasters Engineering Handbook* (McGraw-Hill, New York, ed. 6, 1975), chap. 14.
36. Correct assignment of the Doppler-shifted spectral features arising from a particular station at its two daily appearances would be difficult in crowded regions of the spectrum. The observer would find it least confusing to work at first with (i) stations isolated in frequency, time, or both; (ii) stations appearing only once each day; and (iii) stations whose carrier signals can be recognized by other means, such as a distinctive antenna pattern or transmitter instabilities leading to a distinctive short-term behavior of the carrier frequency.
37. The procedure is not unlike the radar astronomer's technique of mapping a planet's surface through the behavior of the returned signal in time delay and Doppler shift, except that the features in the present case are mapped in the $(\Delta t, V_s)$ plane. If the observer were near $\delta \simeq 0°$, however, he could not construct a unique station map since only the absolute value of the latitude of each station is determinable. Furthermore, monitoring the sidereal-daily period over decades might reveal that there were changes in the time lapse Δt between appearances and disappearances of particular stations, the amount of change depending on their latitude. Assuming that this effect was not due to variable station positions on the rotating body, the necessary conclusion would be that the observer's declination is changing. This information, coupled with the observed nonalignment of the earth's orbital and rotational angular momenta $(|\beta| \neq |\delta|)$, would naturally lead to an explanation of the motion in terms of a precessional wobble of the planetary axis. Although the presence of the moon cannot be unambiguously deduced from this precession, both the lunar mass and the earth-moon distance can be found from a study of a monthly periodicity in the Doppler shifts of each station. This arises since the earth-moon system can also be considered as a single-lined spectroscopic binary system where the eavesdropper observes the more massive member. The Doppler shift of the earth is only ~ ± 0.01 cos $|\beta|$ km/sec or ~ 4×10^{-8} c, but continuous monitoring of several hundred stations should nevertheless bring this out. The radial velocity curve then yields both the mass of the moon and the earth-moon separation, when it is assumed that (i) the lunar orbit is in the same plane (already determined) as the earth's orbit about the sun, and (ii) the mass of the earth is estimated from its size and an assumed density.
38. For such a case one has 420 kw directed into a beam ~ 2 arc minutes in size (antenna gain of ~ 4×10^7) and a CW phase-encoded radar over a bandwidth as small as a few hertz. The range of detection is ~ 1000 times greater than that for a UHF television station.
39. F. D. Drake, *Technol. Rev.* **78** (No. 7), 22 (1976).
40. *World Radio/Television Handbook* (Billboard, New York, ed. 29, 1975).

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Predicting Future Atmospheric Carbon Dioxide Levels

The predictions provide a basis for evaluating the possible impact of the continuing use of fossil fuel.

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Since the beginning of industrialization man has been significantly changing the atmospheric carbon dioxide concentration. Until 1974 the fossil fuel CO_2 input into the atmosphere amounted to roughly 21 percent of the preindustrial atmospheric CO_2 content, and as a result the atmospheric CO_2 level increased by about 13 percent. If we continue to exhaust oil and coal reserves at a faster and faster rate, in a few decades the increase of the atmospheric CO_2 concentration will be of the same order of magnitude as the preindustrial CO_2 concentration itself. There is serious concern about the possible environmental consequences of such an increase. The average surface temperature of the earth is about 35°K higher than its radiation temperature of 253°K as seen from interplanetary space (*1*). This is partly due to the so-called greenhouse effect, caused by atmospheric water vapor and CO_2. With a higher CO_2 concentration the greenhouse effect will be enhanced. Using a three-dimensional general circulation model, Manabe and Wetherald (*2*) found that the mean surface temperature would be 2° to 3°K higher for a doubled CO_2 level, with a strong amplification (8° to 10°K warming) in the polar areas. Although some important phenomena, such as changes in cloudiness, could not yet be considered, the climatic models developed so far clearly indicate that man-made CO_2 could trigger climatic changes with seri-

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