A1199
Are We Alone?
The Search for Life in the Universe
Summer 2019

Instructor: Shami Chatterjee


Presentations and Final Paper – please work on them.

Now: Biomarkers, technomarkers, SETI
Biosignatures: gases that are produced by life, accumulate in the atmosphere, are not readily mimicked by abiotic processes, and can be detected by space telescopes.

(Kaltenegger, 2018)

- Oxygen alone? False positives.
- Oxygen, Ozone, and CH$_4$.
- CH$_4$ and N$_2$O.
- Extreme disequilibrium.
- Vegetation red edge.
- Bio-fluorescence?
Technomarkers

• Intelligence and technology: distinguishing the artificial from the natural.
• How do we look for exosystem technology?
• What is the likelihood of a detection?

• … Do we recognize it when we see it?
The Kardashev Scale

• Type I: Harness all the energy that falls on a planet from its parent star, $\sim 10^{16} - 10^{17}$ W.

• Type II: Harness all the energy radiated by a star, $\sim 10^{26}$ W. Dyson sphere, or analog.

• Type III: Harness the energy output of an entire galaxy, $\sim 10^{36}$ W.
The Kardashev Scale

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Generalize: \( K = 0.1 \times (\log_{10}(P) - 6) \)  
(Sagan, 2000)

→ On that scale, humans on Earth are at \( K \sim 0.7 \).
The strange case of Tabby’s Star

- KIC 8462852: F-star in Cygnus, ~450 pc away.
- Unusual lightcurve identified by citizen science project.

Planet Hunters IX. KIC 8462852 – where's the flux? T. S. Boyajian et al. (2016)

- Large, aperiodic dips, up to 22%.
Principles and Paradox

Copernican principle
- We find ourselves on an ordinary planet around an ordinary star in an ordinary galaxy.
- AKA the assumption of mediocrity (we’re mediocre & there must be lots more like us).

Anthropic principle
- The universe necessarily has properties that allow complex beings like ourselves and life generally to have evolved.
- Is the universe ordinary?

Fermi Paradox
- Given CP + AP, if N is large, where is everybody?
\[ N = R \times N_e \times f_{pl} \times f_i \times f_c \times L \]

**DRAKE EQUATION**

The first National Academy of Sciences Conference on the Search for Extraterrestrial Intelligence was held on October 30 to November 3, 1961. In his opening remarks, Frank Drake presented the equation for the number of radio communications signals that may be expected to reach Earth from extraterrestrial civilizations beyond our own.

- \( N \) = number of radio communications signals expected to reach Earth from extraterrestrial civilizations beyond our own.
- \( R \) = rate of star formation in the Galaxy.
- \( N_e \) = rate of solar type star formation in the Galaxy.
- \( f_{pl} \) = fraction of such stars having planetary systems.
- \( f_i \) = fraction of such planets that are inhabited by intelligent life.
- \( f_c \) = fraction of such civilizations that develop a radio capability.
- \( L \) = duration of civilization's existence capable of radio communication.

The factors on the right are essentially unknown, so \( N \) remains a mystery. Nevertheless, the Drake equation served and still serves as an excellent way to categorize our ignorance and thereby stimulate further research.
Drake Equation

\[ N = R^* \cdot f_s \cdot N_p \cdot f_{HZ} \cdot f_l \cdot f_{it} \cdot L \cdot [f_{other}] \]

Example:

\( R^* = 10/\text{yr.} \)
\( f_s = 0.5 \)
\( N_p = 5 \)
\( f_{HZ} = 1/5 \)
\( f_l = 1 \)
\( f_{it} = 0.2 \)

\( L = 10,000 \text{ yr} \ldots \quad N = 10,000 \text{ intelligent civilizations.} \)
\( L = 1,000,000 \text{ yr} \ldots \quad N = 1,000,000 \text{ intelligent civilizations.} \)
The Most Optimistic Case

\[ N \approx L \]

\[ L = \text{average longevity of a civilization in years.} \]
Optimism about \( L \) implies large \( N \).

What can we say about the average \( L \) based on how we view \( L \) for ourselves?

*Rare Earth*: \( N \approx 1 \) or a few.
Drake Equation

\[ N = R^* \cdot f_s \cdot N_p \cdot f_{HZ} \cdot f_i \cdot f_{it} \cdot L \cdot [f_{other}] \]

Example:

\[ R^* = 10/yr. \]
\[ f_s = 0.5 \]
\[ N_p = 5 \]
\[ f_{HZ} = 1/5 \]
\[ f_i = 0.01 \]
\[ f_{it} = 0.01 \]
\[ L = 10,000 \text{ yr} \ldots N = 5 \text{ intelligent civilizations.} \]
\[ L = 2,000 \text{ yr} \ldots N = 1 \text{ intelligent civilization (us).} \]
Why search? Assessing the Odds

• The astrophysical case:
  \( p \) (habitable planets \mid Galaxy)

• The biological case:
  \( p \) (life \mid habitable planets)

• Complexity:
  \( p \) (technology \mid life)
  \( p \) (extroversion \mid technology)
One view of the Drake Equation

*I reject as completely worthless all attempts to calculate from theoretical principles the frequency of occurrence of intelligent life forms in the universe. Our ignorance of chemical processes by which life arose on earth makes such calculations meaningless.*

- Freeman Dyson

Alternative view: the Drake Equation is useful for cataloging our ignorance about key factors.
How Many Planets are in the Galaxy?

- There are approximately 100 billion F,G,K stars.
- About 2/3 of these are in binaries with other stellar companions (not ideal for planets – but see Kepler results).
- Most of the ~30 billion isolated stars likely have planetary systems (and so do some binary systems).

- If 1% of these have planets that are habitable and on which life has formed there could be \( N_p = 300 \) million planets with the potential of harboring life in our Galaxy.

- With these numbers, the nearest life-bearing planet could be ~10 pc away. (cf. Kepler numbers discussed earlier.)
The Fermi Paradox

Enrico Fermi: Italian physicist (1901-1954)
- Worked on the first nuclear reactor.
- Quantum theory.
- Nuclear and particle physics.
- Statistical mechanics.
- Nobel Prize 1938 for transuranic elements.

If intelligent life is common, where is everyone?
The Fermi Paradox according to Sherlock Holmes

“Is there any point to which you wish to draw my attention?”
“To the curious incident of the dog in the night-time.”
“The dog did nothing in the night time.”
“That was the curious incident,” remarked Sherlock Holmes.

-- Silver Blaze, A. Conan Doyle
Types of answers:
1. They do not exist.
2. They exist but have not yet communicated with us.
3. They are here.
What about UFOs?
What about UFOs?

- Smartphones are common today – photo + video recording at fingertips.
- “Dashcams” capture continuous footage: e.g. Chelyabinsk meteor, 2013.
- Robotic survey telescopes continuously monitor night sky.

... Did UFOs become shy just as our ability to record them became commonplace?

Given rates implied by UFO sighting claims in the past, we should have high quality photo / audio / video recordings routinely today.

⇒ Not plausible.
An Analogy

Recall Olbers’ paradox:

An infinite universe that is infinitely old should be infinitely bright.

So why is the night sky dark?

The night sky is dark because the universe is finite both spatially and temporally.

Though the number of stars is huge, the universe is essentially sparse.
Fermi Paradox

• The FP may have a similar solution:
  • “N” may be large (lots of civilizations) but
    the Galaxy is too large for the likelihood of
    one civilization encountering another.
  • … yet.

• The smaller N is, the more sparse the Galaxy.
Galactic Civilizations: Population Dynamics and Interstellar Diffusion

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AND

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Laboratory for Planetary Studies, Cornell University, Ithaca, New York 14853

The interstellar diffusion of galactic civilizations is reexamined by potential theory; both numerical and analytical solutions are derived for the nonlinear partial differential and difference equations which specify a range of relevant models, drawn from blast wave physics, soil science, and, especially, population biology. An essential feature of these models is that, for all civilizations, population growth must be limited by the carrying capacity of the planetary environments. Dispersal is fundamentally a diffusion process; a directed density-dependent diffusivity describes interstellar emigration. We concentrate on two models, the first describing zero population growth (ZPG) and the second which also includes local growth and saturation of a planetary population, and for which we find an asymptotic travelling wave solution. For both models the colonization wavefront expands slowly and uniformly, but only the frontier worlds are sources of further expansion. For nonlinear diffusion with growth and saturation, the colonization wavefront from the nearest independently arisen galactic civilization can have reached the Earth only if its lifetime exceeds $2.6 \times 10^8$ years. If discretization can be neglected, the critical lifetime is $2.0 \times 10^7$ years. For ZPG the corresponding number is $1.3 \times 10^{10}$ years. These numerical results depend on our choices for the specific emigration rate, the distribution of colonizable worlds, and, in the second model, the population growth rate; but the dependence on these parameters is entrancingly weak. We conclude that the Earth is uncolonized not because interstellar spacefaring societies are rare, but because there are too many worlds to be colonized in the plausible lifetime of the colonization phase of nearby galactic civilizations. This phase is, we contend, eventually outgrown. We also conclude that, except possibly early in the history of the Galaxy, there are no very old galactic civilizations with a consistent policy of conquest of inhabited worlds; there is no Galactic Empire. There may, however, be abundant groups of $\sim 10^5$ to $10^8$ worlds linked by a common colonial heritage. The radar and television announcement of an emerging technical society on Earth may induce a rapid response by nearby civilizations, thus newly motivated to reach our system directly rather than by diffusion.

Alexander wept when he heard from Anaxarchus that there was an infinite number of worlds; and his friends asking him if any accident had befallen him, he returned this answer: “Do you not think it a matter worthy of lamentation that when there is such a vast multitude of them, we have not yet conquered one?” —Plutarch, On the Tranquility of the Mind.

We now review the population dynamics processes relevant to our discussion, explore various features of the associated mathematical models, and discuss the implications of the model results. The most significant of these is that the expansion velocity of the colonization front is several orders of magnitude smaller than had been previously anticipated. Thus, the answer to the question “Where are they?” may well be that only now are they about to arrive.
SETI Issues

- Large $N \Rightarrow$ optimism about evolutionary trends leading to technological life, its longevity, and perhaps about Galactic colonization.
- Counterpoints:
  - What took hominids so long to evolve on Earth?
  - ‘Rare Earth’ arguments (Ward & Brownlee).
- Our preconceptions about $N$ have a strong influence on:
  - How luminous ET transmissions must be for detection.
  - Beaming of ET transmissions (toward us?!).
- $N$ determines how far we must look in the Galaxy.
- How far we look determines the role of propagation effects from ISM plasma (radio) or grains (IR/optical).
Research Paper

Implications of an Anthropic Model of Evolution for Emergence of Complex Life and Intelligence

ANDREW J. WATSON

ABSTRACT

Structurally complex life and intelligence evolved late on Earth; models for the evolution of global temperature suggest that, due to the increasing solar luminosity, the future life span of the (eukaryote) biosphere will be “only” about another billion years, a short time compared to the ~4 Ga since life began. A simple stochastic model (Carter, 1983) suggests that this timing might be governed by the necessity to pass a small number, \( n \), of very difficult evolutionary steps, with \( n < 10 \) and a best guess of \( n = 4 \), in order for intelligent observers like ourselves to evolve. Here I extend the model analysis to derive probability distributions for each step. Past steps should tend to be evenly spaced through Earth’s history, and this is consistent with identification of the steps with some of the major transitions in the evolution of life on Earth. A complementary approach, identifying the critical steps with major reorganizations in Earth’s biogeochemical cycles, suggests that the Archean-Proterozoic and Proterozoic-Phanerozoic transitions might be identified with critical steps. The success of the model lends support to a “Rare Earth” hypothesis (Ward and Brownlee, 2000): structurally complex life is separated from prokaryotes by several very unlikely steps and, hence, will be much less common than prokaryotes. Intelligence is one further unlikely step, so it is much less common still. Key Words: Major transitions—Lifespan—Biosphere—Rare Earth—Critical steps—Earth history—Archean—Proterozoic. Astrobiology 8, 175-185.
Gott begins with the assumption that you and I, having no reason to think we’ve been born in a special time, are probably living during the middle 95% of the ultimate duration of our species.

In other words, we’re probably living neither during the first 2.5% nor during the last 2.5% of all the time that human beings will have existed.

Homo sapiens has been around for 200,000 years, so if our location in human history is not special, the human future is probably going to last longer than 5,100 years but less than 7.8 million years.
Implications of the Copernican principle for our future prospects

J. Richard Gott III

Making only the assumption that you are a random intelligent observer, limits for the total longevity of our species of 0.2 million to 8 million years can be derived at the 95% confidence level. Further consideration indicates that we are unlikely to colonize the Galaxy, and that we are likely to have a higher population than the median for intelligent species.

Counter-argument: This does not account for ANY prior information. “Put succinctly, he rejects as irrelevant the process of rational, scientific inquiry, replacing it with a single, universal rule. That has to be wrong.” (Caves)

If you are 20 years old, and in the middle 95% of your life, your lifespan is likely to be another [0.5 year --- 800 years]?

... not a very useful statement.

However, if you really know nothing else, maybe an interesting number?
SEARCHING FOR OTHER CIVILIZATIONS

Technomarkers and SETI
Astrophysical Remote Sensing

Electromagnetic spectrum:
- How do we sample different bands?
- Where do objects in the universe appear?

Other tracers for remote sensing:
- Cosmic rays (electrons, ions, other particles).
- Neutrinos (solar, supernovae).
- Gravitational waves (ripples in space time).

No tracers yet for Dark Matter or Dark Energy.

How complete is our inventory of the universe?
- Kinds of objects.
- Martin Harwit *Cosmic Discovery* (1981): ~ 50%.
# Key Discoveries that Illustrate Discovery Space in Radio Astronomy

<table>
<thead>
<tr>
<th>Discovery</th>
<th>Date</th>
<th>Enabled by</th>
<th>Telescope</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cosmic radio emission</td>
<td>1933</td>
<td>ν</td>
<td>Bruce Array (Jansky)</td>
</tr>
<tr>
<td>Non-thermal radio emission</td>
<td>1940</td>
<td>ν</td>
<td>Reber antenna</td>
</tr>
<tr>
<td>Solar radio bursts</td>
<td>1942</td>
<td>ν, Δt</td>
<td>Radar antennas</td>
</tr>
<tr>
<td>Extragalactic radio sources</td>
<td>1949</td>
<td>Δθ</td>
<td>Australia cliff interferometer</td>
</tr>
<tr>
<td>21 cm line of hydrogen</td>
<td>1951</td>
<td>theory, Δν</td>
<td>Harvard horn antenna</td>
</tr>
<tr>
<td>Mercury and Venus spin rates</td>
<td>1962, 1965</td>
<td>Radar</td>
<td>Arecibo</td>
</tr>
<tr>
<td>Quasars</td>
<td>1962</td>
<td>Δθ</td>
<td>Parkes occultation</td>
</tr>
<tr>
<td>Cosmic Microwave Background</td>
<td>1963</td>
<td>ΔS, calibration</td>
<td>Bell Labs horn</td>
</tr>
<tr>
<td>Confirmation of General Rel.</td>
<td>1964, 1970s</td>
<td>theory, radar, Δt, Δθ</td>
<td>Arecibo, Goldstone, VLA,VLBI</td>
</tr>
<tr>
<td>Cosmic masers</td>
<td>1965</td>
<td>Δν</td>
<td>UC Berkeley, Haystack</td>
</tr>
<tr>
<td>Pulsars</td>
<td>1967</td>
<td>Ω, Δt</td>
<td></td>
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</tbody>
</table>
Exploration

As we know,
There are known knowns.
There are things we know we know.
We also know
There are known unknowns.
That is to say
We know there are some things
We do not know.
But there are also unknown unknowns,
The ones we don't know
We don't know.

-- Former Secretary of Defense Donald Rumsfeld
(DoD Press Briefing, 12 Feb 2002; addressing the lack of evidence linking the government of Iraq to the supply of WMD to terrorist groups.)
Looking for Electromagnetic Signals

- How do we distinguish natural from artificial?
- Do we have and know the full inventory of natural radiation processes and their manifestations?
- Or are there unknown unknowns?
- What features or ‘signature’ in measurements with a radio telescope (say) would catch your attention?
- How would you ‘ground truth’ the measurement to demonstrate that it is real?
## SETI Conundrums

<table>
<thead>
<tr>
<th>Deliberate transmissions</th>
<th>Leakage transmissions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radio</td>
<td>Optical / IR</td>
</tr>
<tr>
<td>Narrowband</td>
<td>Pulsed</td>
</tr>
<tr>
<td>Large N</td>
<td>Small N</td>
</tr>
<tr>
<td>High Luminosity</td>
<td>Low Luminosity</td>
</tr>
</tbody>
</table>
What do we look for?
Reciprocity: what do we radiate?

Radio:
Typical: detectable to ~ few pc.
Strongest: planetary radar ~1 kpc.

Optical/IR:
Typical: nil.
Pulsed IR lasers: ~ few x 10 pc.

$\gamma$-rays:
1 Megaton: ~ 1 AU with e.g. the *Fermi* telescope.
Gamma-ray Large Areas Space Telescope = Fermi Gamma-ray Observatory
What do we look for?
Reciprocity: what do we radiate?

Transmission from Arecibo (1974),
beamed once towards M13 (8 kpc)
at 2.4 GHz.

1679 bits = 23 × 73 grid.

Can you decode it?
What do we look for?
Reciprocity: what do we radiate?

The “Wow!” signal,

Jerry Ehman, Big Ear radio telescope, Ohio State 1977.
Never repeated.
Is this what Arecibo transmission might look like to someone else?
Remote Sensing and SETI

**Targeted Surveys:**

• How might we make appropriate observations to target the detection of life elsewhere?
  
  • The building blocks of life (molecules, chemistry).
  • Extrasolar planets.
  • Habitable planets.
  • Indirect evidence for microbial life (remote sensing of atmospheres).
  • Signals from other civilizations.
Remote Sensing and SETI

“Blind” Surveys:

• Given that we probe the sky to great detail in studies of natural objects, how might we stumble across evidence for life elsewhere?

• Distinction of “natural” from “artificial”.

• The first life or presence of life may be detected completely serendipitously.

• How to assess this?

• Observational “phase space”:
  – Direction, wavelength, flux, time duration or modulation, bandwidth, polarization …
False Alarms in Detecting Life Elsewhere

• Canals on Mars.
• Claimed bacterial remains in Martian meteorite.
  • Meteorite collected on Antarctic glacier.
  • Gaseous content consistent with Mars’ atmosphere.
  • Microscopic features now thought to be natural geochemical signatures, not from bacteria.
• Radio sources that have “artificial” properties.
  • CTA102
    – Early days of quasars = active galactic nuclei.
    – Sinusoidal variations interpreted as a beacon.
• Pulsars (radio pulses).
Figure 8.2. The U.S. Army listens for Martian radio signals, according to the plan of David P. Todd, as pictured in Radio Age for October 1924.
CTA 102

• A powerful celestial source of radio waves, catalogued in the early 1960s by the California Institute of Technology, and proposed, in 1963, by N. S. Kardashev in the scientifically conservative Astronomical Journal of the USSR as evidence of a Type II or Type III Kardashev civilization.

• A worldwide sensation followed a TASS agency announcement that Gennady Sholomitskii of the Sternberg State Astronomical Institute, following up Kardashev's idea, had found CTA-102 to be the beacon of a "super-civilization".

• Shortly after, observations from Palomar Observatory identified CTA-102 with a quasar.
We are indebted to Mr. N. J. Keen and Dr. W. C. Tyler for the technical and engineering effort that led to the high phase stability of the interferometer.

C. M. Wade
B. G. Clark
D. E. Hegge

May 3, 1965
NATIONAL RADIO ASTRONOMY OBSERVATORY*
GREN BANC, WVEST VIRGINIA

REFERENCES
Matthews, T. A. 1964, private communication.
Vernon, P. 1965a, private communication

* Operated by Associated Universities, Inc., under contract with the National Science Foundation.

TIME DEPENDENCE OF THE RADIO EMISSION
FROM CTA 21 AND CTA 102

Sholomitskii (1965) has recently presented evidence for changes in the radio emission from the source CTA 102. Sholomitskii finds that his observed intensities at a wavelength of 22.5 cm may be fitted to a sinusoidal law with a period of about 100 days and an amplitude of ±23 per cent. His result is based on a comparison of the flux densities of CTA 21 and CTA 102 with that of 3C 48, apparently on nine days within the period August, 1964, to February, 1965.

Since their discovery in 1959 (Harris and Roberts 1960), the radio sources CTA 21 and CTA 102 have been studied fairly extensively at this observatory. In particular, we carried out two series of brightness-distribution measurements (Moffet 1962; Malby 1962) during 1960 and early 1961 at a wavelength of 31.3 cm, very close to that used by Sholomitskii. An additional group of observations at this wavelength were made in September, 1961, by Kellermann (1964). In this letter we will restrict our discussion to these 31.3-cm observations. We will show that in 1960 no intensity variation was present having the amplitude and period reported by Sholomitskii.

The 31.3-cm observations of CTA 21 and CTA 102 are summarized in Table 1. The 1959 series at 31.3 cm were made with a Duierce radiometer on one 90-foot antenna. All subsequent observations were made with two 90-foot antennas connected as an interferometer. The interferometer has been described in detail by Read (1961, 1968). Recent high-resolution interferometric studies (Anderson, Donaldson, Palmer, and Rowson 1965) have shown that both CTA 21 and CTA 102 have angular diameters of less than 0.5'. This means that these sources are not at all resolved by any interferometer spacing used in the California Institute of Technology (Caltech) observations; thus each of our observations gives a measure of the total flux from these sources.

In order to look for possible variations in the intensity of a particular radio source, it is necessary to correct for variations in receiver gain and other instrumental factors. The calibration procedures for the Caltech observations have been discussed in the papers cited above. In general, a number of small-diameter sources are used as standards for each day's observations.

The fluxes in Table 1 are on Kellermann's intensity scale, which is about 3.5 per cent lower than that used by Harris and Roberts and by Moffet and Malby. Figure 1 shows the fluxes plotted versus time. For comparison we have included in Figure 1 Sholomitskii's measurements in 1961 and 1965, which are copied from the figure accompanying his note. These have been converted to fluxes by assuming an intensity of $21.0 \times 10^{-28}$ W m$^{-2}$ (c/s)$^{-1}$ for 3C 48. The dashed curve is the sinusoidal intensity variation suggested by Sholomitskii for CTA 102.

Most of the points for our observations represent averages over several days, as is indicated in Table 1. Except for the single-dish observations of 1960, the greatest span of time represented by a single point is thirteen days. If the individual observations were plotted, the scatter would be about the same as the scatter among the points representing the averages at different interferometer spacings.
“... Clarke introduced Kubrick to his telescope and taught him to use a slide rule. They studied the scientific literature on extraterrestrial life. “Much excitement when Stanley phones to say that the Russians claim to have detected radio signals from space,” Clarke wrote in his journal for April 12, 1965: “Rang Walter Sullivan at the New York Times and got the real story—merely fluctuations in Quasar CTA 102.” Kubrick grew so concerned that an alien encounter might be imminent that he sought an insurance policy from Lloyd’s of London in case his story got scooped during production.”
Year over year receiving you
Signals tell us that you’re there
We can hear them loud and clear

We just want to let you know
That we’re ready to go
Out into the universe
We don’t care who’s been there first

On a radio telescope
Science tells us that there’s hope
Life on other planets might exist

(repeated)
In 1967, Jocelyn Bell discovered radio pulses from the sky.

Hewish et al.: interplanetary scintillation at 3.7 m.
In 1967, Jocelyn Bell discovered radio pulses from the sky.

Hewish et al. (1968): Some form of condensed star? (Originally coded LGM-1, 2, 3!)

Gold (1968): “A slight but steady slowing down” predicted for a rotating neutron star.

A radio pulsar was discovered in the Crab nebula (1968) and its period was seen to be increasing (1969).
Initial Ideas About Radio Pulsations

- LGMs 1, 2, 3, and 4.
- White dwarf oscillations.
- Orbital motion of white dwarfs.
- Neutron star spins.
  - Electromagnetic radiation at the spin frequency.
- Similar richness of interpretations for Gamma-ray bursts up to 1990s.
Remote Sensing

Era of large-scale surveys:

– Big science.
– Large yield of astrophysical sources (up to $10^9$).
  • Stars, galaxies, neutron stars, supernova remnants, gamma-ray bursts, active galactic nuclei.
– Discovery of the unknown: what remains to be discovered?
– Large data sets (> Petabyte = $10^3$ TB = $10^6$ GB).
– Data mining.
– Volunteer computing (SETI@home = prototype, Einstein@home).
– Virtual Observatories.
  • Distributed data sets, available over internet, I2, dedicated networks, National Lambda Rail (NLR).
  • Sophisticated tools needed.
  • National, international collaborations.
Rationale for Radio SETI

- No Galactic absorption.
- No background from host stars.
- Maximum S/N in microwave band (1-10 GHz).
- Magic frequency arguments, e.g.,
  - 1.42 GHz $\text{H}^+$ (HI line).
  - 1.67 GHz OH.
  - $\pi \times 1.42$ GHz, etc.
- Narrowband signals $\ll$ thermal Doppler widths of natural, astrophysical sources.
- But: propagation effects (dispersion, scintillation, pulse broadening from ISM) are important.
Rationale for Optical/IR SETI

- Pulsed lasers distinguishable from host star with reasonable power (nanosecond pulses).

- Optical/IR not susceptible to ISM plasma propagation effects.

- But interstellar absorption and scattering from grains important for optical and near IR. (Scattering ⇒ smearing of pulse.)
Laser Power

- Petawatt ($10^{15}$ watts) pulse lasers exist for laser fusion, are sufficient to produce detectable pulses from systems on planets around G-type host stars.
- For nanosecond pulses, a 1-m telescope + photomultiplier is sufficient to detect sources out to ~30 pc.
- Programs at Berkeley, Harvard, amateur.
Anticipated Radio ET Signals
(by ‘strong SETI’ proponents)

• Narrowband (~ 1 Hz).
• Weakly modulated (~ 1 bit/s).
• Drifts in frequency (orbital + planetary motion).\[\frac{df}{dt} \sim 10 \text{ to } 100 \text{ Hz/hour.}\]
  (Some argue that deliberate transmissions to us would be Doppler corrected?)

• Pattern recognition algorithms: search for narrowband, drifting features in the frequency-time plane.\[(\text{De-chirping algorithms}).\]

• Search space: \((B/\Delta\nu)(T/\Delta t)N_{\text{sky}} > 10^{13}\) trials.
  \(\Rightarrow\) Need very high threshold (e.g. 30\(\sigma\)) to achieve small false-alarm rate.
The question of whether intelligent life exists elsewhere is one of the fundamental unknowns about our Universe. Over the past decade extra-solar planets have been discovered, providing new urgency for addressing this question in these or other planetary systems. Independently of this perspective, new radio observatories for cosmology are currently being constructed with the goal of detecting 21 cm emission from cosmic hydrogen in the redshift range $6 \lesssim z \lesssim 15$. The radio frequency band covered by these experiments overlaps with the range of frequencies used for telecommunication on Earth, a regime that was never explored with high sensitivity before. For example, the MWA [...] and other low-frequency observatories (culminating with the Square Kilometer Array) will be able to detect radio broadcast leakage from an Earth-like civilization out to a distance of $\sim 10^{1-2.7}$ pc, within a spherical volume containing $10^{(3-8)} \times (\Omega_b/4\pi)^\alpha$ stars, where $\alpha = 1$ (or 1.5) for a radar beam of solid angle $\Omega_b$ that remains steady (or sweeps) across the sky. Such a radio signal will show up as a series of narrow spectral lines that do not coincide with known atomic or molecular lines. The high spectral resolution attainable with the upcoming observatories will allow us to monitor the periodic Doppler shift of the broadcast lines over the planet's orbital period around the parent star. ... (etc.)
Radio Transmissions from Earth
(from Goldsmith and Owen)

Figure 20.5  The locations of Earth's radio and radar transmitters are heavily concentrated in the United States, Canada, Europe, Japan, and the east coast of Australia.

Figure 20.6  As the Earth rotates, an observer not located directly above one of the Earth's poles will detect a changing amount of radio emission, caused by the fact that radio broadcasts send out radio waves primarily in directions parallel to the broadcaster's horizon. As the most powerful transmitters rise over the horizon or set below it, a distant observer will detect especially large amounts of power from them.
Optimizing radio SETI against background noise
Notable Radio SETI Programs

- Ozma 1960 (Frank Drake): targeted (two nearby stars).
- Serendip I-IV (piggyback surveys at GB and Arecibo).
- Blind surveys (1970s – present):
  - NASA targeted survey + sky survey
  - Targeted: ~1000 nearest G-type stars, single, age > 3 Gyr.

Sky survey: full sky, 1-10 GHz

- Phoenix = privately funded version of NASA targeted survey (SETI Institute; used Arecibo).
- Allen Telescope Array (SETI Institute).
Project OZMA

1960 National Radio Astronomy Observatory.
Green Bank, WV.
1420 MHz.
200 hr.
Two stars (d~4 pc):
\(\varepsilon\) Eridani, \(\tau\) Ceti.

Figure 8.3. The 85-foot Howard E. Tatel radio telescope used by Frank Drake at the National Radio Astronomy Observatory in Green Bank, West Virginia, for Project Ozma in April 1960. Part of the Ozma team reassembled for the 25th anniversary of the project, including Drake, standing second from the right.
Notable Radio SETI Programs II

- META II (Argentina).
- BETA: blind survey (Harvard). - 1.4, 1.6 GHz (H, OH), \( \sim 10^9 \) channels.
- Serendip IV blind survey, (Berkeley), present. - 1.4 GHz, Arecibo, \( \sim 3 \times 10^8 \) channels.
- SETI@Home blind survey, ongoing. 1-2 GHz, baseband sampled data (Arecibo), software data reduction.
- Future: Square Kilometer Array and its prototype arrays (Australia, South Africa).
The “Wow!” signal,
Jerry Ehman, Big Ear radio telescope, Ohio State 1977.
FIVE YEARS OF PROJECT META: AN ALL-SKY NARROW-BAND RADIO SEARCH FOR EXTRATERRESTRIAL SIGNALS

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ABSTRACT

We have conducted a 5 year search of the northern sky ($-30^\circ \leq \delta \leq 60^\circ$) for narrow-band radio signals near the 1420 MHz line of neutral hydrogen, and its second harmonic, using an $8.4 \times 10^6$ channel Fourier spectrometer of 0.05 Hz resolution and 400 kHz instantaneous bandwidth. The observing frequency was corrected both for motions with respect to three astronomical inertial frames, and for the effect of Earth's rotation, which provides a characteristic changing Doppler signature for narrow-band signals of extraterrestrial origin. Among the $6 \times 10^{13}$ spectral channels searched, we have found 37 candidate events exceeding the average detection threshold of $1.7 \times 10^{-23}$ W m$^{-2}$, none of which has been detected upon reobservation. The strongest of these appear to be dominated by rare processor errors. However, the strongest signals that survive culling for terrestrial interference lie in or near the Galactic plane. We describe the search and candidate events, and set limits on the prevalence of supercivilizations transmitting Doppler-precompensated beacons at H I or its second harmonic. We conclude with recommendations for future searches, based upon these findings, and a description of our next-generation search system.

Subject headings: extraterrestrial intelligence — radio lines: general
Non-repeating Signals

• The META candidate signals, like the Wow! signal, have been followed up by re-observing the corresponding sky positions.

⇒ No redetections after 100s of re-observations.

• This is a difficult regime in terms of the scientific method, a keystone of which is repeatability. How to proceed?
Non-repeating Signals

• We can conceive of transmissions we make that are detectable but would not repeat (e.g., planetary/asteroid radar from Arecibo). Not unreasonable to make detections that do not repeat.

• Note the similar case of GRBs: these are stars (hypernovae or merging NS) that destroy themselves; they do not repeat. But GRBs were established as a “real” astrophysical phenomenon because there were many of them (~1/day); however, it took 30 years to establish that they were cosmological and associated with stellar explosions.

• The equivalent for ETI signals (or, at least, candidate ETI signals) is to detect a large-enough number of them that we can establish them as a class of extraterrestrial signal. Perhaps with enough sustained observation we will be able to establish this number.
Radio Scintillation ("twinkling")

- Compact radio sources show intensity variations (scintillations) caused by diffraction in the ISM.
  - Same effect as for optical twinkling of starlight caused by turbulence in the atmosphere (neutral).
  - Radio scintillations are associated with turbulence in the ionized part of the ISM (plasma).
- Just as "stars twinkle, planets do not", compact radio sources like pulsars and any ET sources will scintillate, whereas active galactic nuclei, while compact, are still too large to show diffractive scintillations.
Dynamic spectrum of pulsar scintillation
Dynamic spectrum of pulsar scintillation

Narrowband signals will show deep modulation with exponential statistics.
SCINTILLATION-INDUCED INTERMITTENCY IN SETI

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ABSTRACT

We use scattering theory, simulations, and empirical constraints on interstellar scintillations to discuss the intermittency of radio signals from extraterrestrial intelligence (ETI). The number of ETI sources in the Galaxy has a direct influence on the expected dynamic range of fluxes in a survey, through inverse square-law effects and, equally importantly, by the number of independent statistical trials made on modulations caused by interstellar scintillations. We demonstrate that scintillations are very likely to allow initial detections of narrowband signals, while making redetections extremely improbable, a result that follows from the skewed, exponential distribution of the modulation. This conclusion holds for relatively distant sources but does not apply to radio SETI toward nearby stars (≤100 pc).

Recent SETI has found nonrepeating, narrowband events that are largely unexplained. We consider three models in order to assess these events and to analyze large surveys in general: (model I) radiometer noise fluctuations; (model II) a population of constant Galactic sources that undergo deep fading and amplification due to interstellar scintillation, consistent with ETI transmissions; and (model III) real, transient signals (or hardware errors) of either terrestrial or extraterrestrial origin.

We derive likelihood and Bayesian tests of the models for individual events and globally on entire surveys. Applying them to The Planetary Society/Harvard META data, we find that models II and III are both highly preferred to model I, but that models II and III are about equally likely. In the context of model II, the likelihood analysis indicates that candidate events above threshold (≈32 σ) are combinations of large amplitude noise fluctuations and scintillation gains, making it highly probable that events seen once will only very rarely be seen again. Ruling out model II in favor of model III is difficult—to do so, many more reobservations (e.g., thousands) are needed than were conducted in META (hundreds) or the reobservation threshold must be much lower than was used in META. We cannot, therefore, rule out the possibility that META events are real, intrinsically steady ETI signals.

Our formalism can be used to analyze any SETI program. We estimate the number of reobservations required to rule out model II in favor of model III, taking into account that reobservations made promptly sample the same scintillation gain as in the original detection, while delayed reobservations sample a decorrelated scintillation modulation. The required number is a strong function of the thresholds used in the original survey and in reobservations.

We assess optimal methods for applying statistical tests in future SETI programs that use multiple site and multiple beam observations as well as single site observations. We recommend that results be recorded on many more events than have been made to date. In particular, we suggest that surveys use thresholds that are far below the false-alarm threshold that is usually set to yield a small number of noise-induced “detections” in a massive survey. Instead, large numbers of events should be recorded in order to (1) demonstrate that background noise conforms to the distribution expected for it; and (2) investigate departures from the expected noise distribution as due to interference or to celestial signals. In this way, celestial signals can be investigated at levels much smaller than the false-alarm threshold. The threshold level for archiving candidate intensities and their corresponding sky positions is best defined in terms of the recording and computational technology that is available at a cost commensurate with other survey costs.

Subject headings: extraterrestrial intelligence — ISM: general — methods: observational — methods: statistical — scattering
Only a very small portion of the phase space has been sampled so far!
SETI@Home

- Data from the Arecibo Observatory.
  - Shipped to UC Berkeley then around the world to clients.
  - Software runs as a screen saver and searches for narrowband signals; results sent back to UCB.
  - ~5 Million users over the last 10 years.
“Breakthrough Listen”

Stephen Hawking Joins Russian Entrepreneur’s Search for Alien Life

NY Times
20 July 2015
“Breakthrough Listen”

“Extending his idea of philanthropy beyond the Earth and even the human species, Yuri Milner, the Russian Internet entrepreneur and founder of science giveaways like the annual $3 million Fundamental Physics Prizes, announced in London on Monday that he would spend at least $100 million in the next decade to search for signals from alien civilizations.” – NYT 20 July 2015

- Survey the 1,000,000 closest stars to Earth in hopes of finding conditions suitable to life, searching the entire galactic plane of the Milky Way and beyond to the 100 closest neighboring galaxies.
- Buy observing time at Green Bank, Parkes; also optical surveys.
- Decade-long project. 5x bandwidth, 10x sky coverage, 100x survey speed.
- Use distributed computing infrastructure (SETI@Home) for processing.
- Expert involvement: Martin Rees, Peter Worden, Geoff Marcy, Andrew Siemion, Ann Druyan, Frank Drake, Dan Wertheimer, and others.