Bayesian inference from all-sky searches for radio technosignatures

Claudio Grimaldi

Laboratory of Statistical Biophysics
Ecole Polytechnique Fédérale de Lausanne (EPFL) – Switzerland

Centro Ricerche Enrico Fermi (CREF)
Rome – Italy
Technosignature: any (remotely detectable) evidence of extraterrestrial technology

- Intentional (unintentional) radio or optical transmissions
- EM emissions from megastructures (ex. Dyson spheres)
- Artificial illumination of planetary night-sides
- Interstellar propulsion
- Atmospheric pollutants
- Asteroid mining
- Anomalous stellar transits (ex. Clarke exobelts, Dyson swarms)
- Relic artifacts
- Inscribed matter
Technosignature: any (remotely detectable) evidence of extraterrestrial technology

Intentional (unintentional) radio or optical transmissions
EM emissions from megastructures (ex. Dyson spheres)
Artificial illumination of planetary night-sides
Interstellar propulsion

Technoemissions: extraterrestrial artificial EM emissions
Part 1: inferring the population of technoemissions from past, current, and future searches

Part 2: no detection since \( \approx 60 \text{ yr} \) of searches: pessimistic view, optimistic view, and something in between
**Part 1:** inferring the population of technoemissions from past, current, and future searches

**Breakthrough Listen (UC Berkeley 2016-2026)**

10-year 100 M dollar search for radio and optical echoemissions from 1 million nearby stars
Plane and center of the Galaxy
100 nearby galaxies

**Cradle of Life**

SETI with the **Square Kilometre Array**
SKA will carry out systematic, volume-limited searches of exoplanet systems for signals from technologically advanced civilisations.
An emitter in $\vec{r}$ generated at time $t$ in the past
a signal of longevity $L$

At present time, an observer in $\vec{r}_o$ searches
for emitters within a radius $R_o$

Two condition for detectability:

1. $t - L \leq |\vec{r} - \vec{r}_o|/c \leq t$

2. $|\vec{r} - \vec{r}_o| \leq R_o$

$I(\vec{r}, t, L) = \begin{cases} 1 & \text{if detectable} \\ 0 & \text{otherwise} \end{cases}$

CG Sci Rep 2017 ; A Balbi Astrobiology 2018 ; CG, GW Marcy, NK Tellis, F Drake PASP 2018
Statistical independence of technoemissions

Emitters are randomly distributed in the Galaxy

Identically and independently distributed starting times $t$

Identically and independently distributed longevities $L$

Mean number of detectable technoemissions within $R_o$

$$\bar{k}(R_o) = \int dt \Gamma(t) \int dL \rho_L(L) \int d\vec{r} \rho_E(\vec{r}) I(\vec{r}, t, L)$$

- Emission rate at time $t$
- PDF of the emission longevity
- PDF of emitter location
**Statistical independence of technoemissions**

Emitters are randomly distributed in the Galaxy

Identically and independently distributed starting times $t$

Identically and independently distributed longevities $L$

---

**Mean number of detectable technoemissions within $R_o$**

$$
\bar{k}(R_o) = \int dt \, \Gamma(t) \int dL \, \rho_L(L) \int d\vec{r} \, \rho_E(\vec{r}) I(\vec{r}, t, L)
$$

Steady state ($\Gamma$ constant) $\rightarrow$ 

$$
\bar{k}(R_o) = \bar{k} \cdot \pi_o
$$

Mean number of emissions in the galaxy

Probability of one emitter within $R_o$
Statistical independence of technoemissions

Emitters are randomly distributed in the Galaxy
Identically and independently distributed starting times $t$
Identically and independently distributed longevities $L$

\[
\bar{k}(R_o) = \bar{k} \cdot \pi_o
\]

Mean number of emissions in the galaxy
Probability of one emitter within $R_o$
Sampled radius $R_o$

$$R_o = \sqrt{\frac{L^*}{4\pi S_{\min}}}$$

$L^*$ = emitter luminosity

S$_{\min}$ = $\sigma S_{sys} \sqrt{\frac{\Delta \nu}{t}}$

$\sigma$ : signal-to-noise ratio (15)
$S_{sys}$ : system equivalent flux density (SEFD)
$t$ : integration time (10 min)
$\Delta \nu$ : bandwidth (0.5 Hz)

<table>
<thead>
<tr>
<th>telescope</th>
<th>$S_{sys}$ (Jy)</th>
<th>$S_{\min}$ ($10^{-26}$ W/m$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATA</td>
<td>664$^a$</td>
<td>287</td>
</tr>
<tr>
<td>Parkes</td>
<td>43</td>
<td>18.6</td>
</tr>
<tr>
<td>VLA</td>
<td>18</td>
<td>7.8</td>
</tr>
<tr>
<td>GBT</td>
<td>10</td>
<td>4.3</td>
</tr>
<tr>
<td>MeerKAT</td>
<td>8.6</td>
<td>3.7</td>
</tr>
<tr>
<td>Arecibo</td>
<td>3</td>
<td>1.3</td>
</tr>
<tr>
<td>FAST</td>
<td>1.2</td>
<td>0.5</td>
</tr>
<tr>
<td>SKA2</td>
<td>0.3$^b$</td>
<td>0.13</td>
</tr>
</tbody>
</table>
Bayesian inference from searches for technoemissions

\[ p(\bar{k}|D) \propto P(D|\bar{k}) p(\bar{k}) \]

- Posterior PDF of $k$ given the datum $D$
- Likelihood function
- Prior PDF of $k$
Bayesian inference from searches for technoemissions

\[ p(\bar{k} | D) \propto P(D | \bar{k}) p(\bar{k}) \]

- **Posterior PDF of** \( k \) **given the datum** \( D \)
- **Likelihood function**
- **Prior PDF of** \( k \)

\[ P(D_0 | \bar{k}) = e^{-\bar{k} \pi_o} \]

\[ P(\text{not } D_0 | \bar{k}) = 1 - e^{-\bar{k} \pi_o} \]

\[ P(D_1 | \bar{k}) = \bar{k} e^{-\bar{k} \pi_o} \]
It is unlikely that there are detectable technoemissions if no signals are discovered within about 40 kly from Earth.

CG & GW Marcy PNAS 2018
If a signal is discovered within 1000 ly from Earth it is almost certain that there are more than 100 Arecibo-like emitters in the Galaxy, yet to be discovered.

CG & GW Marcy PNAS 2018
Part 1: inferring the population of technoemissions from past, current, and future searches

Part 2: no detection since $\approx 60$ yr of searches: pessimistic view, optimistic view, and something in between
Since the first modern SETI experiment 60 years ago (Frank Drake), no confirmed technoemission has been detected.

**Popular interpretations**

1. The parameter search space is vast. Technoemissions are there, we just have to search harder.

2. Extraterrestrial technological life is so rare that practically does not exist.
Since the first modern SETI experiment 60 years ago (Frank Drake), no confirmed technoemission has been detected.

**Popular interpretations**

1. The parameter search space is vast. Technoemissions are there, we just have to search harder.

2. Extraterrestrial technological life is so rare that practically does not exist.

3. Technoemissions might still exist, but none have crossed the Earth for at least 60 years.
Pore-size model

The Earth is the center of a "test sphere" of diameter $\delta$

The time interval between two successive "overlaps" is $\tau = \delta/c$

As long as $\tau < 10^5$ yr, the time interval between successive crossing events is greater than $\tau$ with probability:

$$e^{-\Gamma \tau}$$

This is independent of the longevity
Bayesian inference of the emission rate $\Gamma$ from $\tau_o = 60$ years of nondetection

\[ p(\Gamma|\tau_o) = \frac{e^{-\Gamma\tau_o} p(\Gamma)}{\int d\Gamma e^{-\Gamma\tau_o} p(\Gamma)} \]

Rates much greater than $1/\tau_o \approx 0.02$ yr are strongly disfavored

Prior PDFs with different degrees of optimism

\[ p(\Gamma) \propto \begin{cases} 
\text{constant,} & \text{optimistic} \\
1/\sqrt{\Gamma}, & \text{moderately optimistic} \\
1/\Gamma, & \text{marginally optimistic} \\
\end{cases} \] (Log-uniform prior)
Bayesian inference of the emission rate $\Gamma$ from $\tau_0 = 60$ years of nondetection

**Prior PDFs with different degrees of optimism**

$$p(\Gamma) \propto \begin{cases} 
\text{constant}, & \text{optimistic} \\
1/\sqrt{\Gamma}, & \text{moderately optimistic} \\
1/\Gamma, & \text{marginally optimistic} 
\end{cases}$$

(Log-uniform prior)

Rates much greater than $1/\tau_0 \approx 0.02$ yr are strongly disfavored.

$\Gamma < 1\text{-}5$ emissions per century with credible level of 95%
Bayesian inference of the waiting time $\Delta \tau$ until the next crossing event

Probability of the waiting time being greater than $\Delta \tau$ given that $\tau_0 = 60$ yr

$$P(\Delta \tau | \tau_0) = \int d\Gamma e^{-\Gamma \Delta \tau} p(\Gamma | \tau_0)$$

50% probability that the next crossing event will not occur before the next 60 – 1800 years
Bayesian inference of the longevity

Probability of the average longevity being greater than $\bar{L}$ given that $\tau_o = 60$ yr

$$P(\bar{L}|\tau_o) = \int d\Gamma e^{-\Gamma(\tau_o + \bar{L})} p(\Gamma|\tau_o)$$

Technoemissions need not to be short-lived to allow for 60 years of nondetection
Conclusions

There is almost complete ignorance about the possible population of ET emitters in the Galaxy.

A statistical Bayesian approach is still possible by considering possible outcomes of future extensive SETI all-sky surveys.

It is unlikely that there are Arecibo-like emitters in the Galaxy. If no signals are discovered within about 40 kly from Earth.

If a signal is discovered within 1000 ly from Earth it is almost certain that there are more than 100 Arecibo-like emitters in the Galaxy, yet to be discovered.

No crossing events in the last 60 years is an hypothesis consistent with data.

It follows that there is an upper bound on the technoemission rate of 1 - 5 emissions per century in the entire galaxy (comparable to the rate of supernovae in the Milky Way).

The next crossing event will not occur before 60 years (most optimistic scenario) or before 1800 years (least optimistic scenario) with a 50% probability.

Is commensal SETI a better strategy than direct searches for technosignatures?