A FRAMEWORK TO ADDRESS THE SPATIOTEMPORAL ASPECTS OF SETI. A. Balbi[1], [1]Dipartimento di Fisica, Università degli studi di Roma "Tor Vergata", Via della Ricerca Scientifica, 00133 Roma, Italy, balbi@roma2.infn.it

Overall Goal(s) and Objective(s): We propose a simple and general framework for investigating the abundance of intelligent communicating species in the Universe, allowing for a straightforward treatment of aspects related to their spatiotemporal distribution. This is complementary to the standard approach based on the Drake equation and may be well-suited to incorporate future research dealing with the evolutionary aspects of SETI.

Main Body of Text:

Introduction. In recent years, it has been increasingly clear that discussions on the abundance of intelligent radio communicating species in the Universe have to take into account the spatiotemporal aspects of the problem, and in particular the role played by evolutionary processes, both astrophysical and biological [3]. Several authors have argued that the probability for the appearance of life and the development of complex organisms is likely to vary with time over cosmic history (e.g. [1, 8, 9]). Similarly, spatial inhomogeneities in the distribution of life are plausible (for example, due to the existence of a 'galactic habitable zone' [4]) and should be taken into proper consideration.

Such spatiotemporal features, however, are difficult to treat within the usual framework based on the Drake equation. The reason for that is apparent when one realizes that the Drake equation can be seen as an application of a general result of queueing theory, i.e. Little's law [7]: $N = \lambda L$. This formula relates the long-term average number of items in a stable system, N, with their long-term average arrival rate, λ, and the average time they spend in the system, L. If the system is a volume of space (usually, centered around our location) and the items are the communicating civilizations in it, then this is exactly the Drake equation, with N being the average number of communicating civilizations, λ their average rate of appearance, and L the average length of their communicative period. Since Little's law holds under the assumption of stationarity of the underlying statistical process [5], it prevents one to incorporate evolutionary effects. In particular, the average appearance rate in the Drake equation is usually estimated by guessing its present value as $\lambda = R_\star f_p n_e f_l f_i f_c$: however, not only the average rate of star formation, $R_\star$, certainly has changed over cosmic history, but also the various statistical factors involved (the fraction of stars with planetary systems, the number of planets suitable for life, the fraction where life do appear, and so on) might have had different values at different epochs. One possibility to address the issue might be guessing the time dependence of λ (perhaps relating it explicitly to some model of the time dependence of the various statistical factors involved) and trying to incorporate the result into a time-varying version of Little's law [6].

While this is certainly a direction worth pursuing, we argue that there is a more straightforward approach to the problem. We started exploring such approach in a separate paper [2]: here we highlight the main rationale and some possible future direction of investigation.

Basic Concept. We suggest that a flexible and general framework to investigate how spatiotemporal effects enter in the estimate of the number of communicating civilizations of which we may find empirical proof can be built upon just two simple ingredients: (1) a causal constraint on the detectability of communications; (2) a statistical model of the spatial and temporal distribution of communicating civilizations.

The causal constraint is obvious, being just the requirement that a civilization did not cease communicating (voluntarily or not) at a time in the past larger than D/c, where D is the distance of the civilization from us (otherwise, its last communications reached us in the past and we missed it forever). Therefore, if $t_c \geq 0$ is the time in the past (measured from the present epoch $t = 0$) when a given civilization started radio communications and τ is the duration of its communicative period, we can receive its signals (now or in the future) only if $t_c - \tau \leq D/c$. (If we further require that we have already been reached by the signals, we have to impose the additional condition $t_c \geq D/c$.) This causal constraint, then, acts as a filter on the spatiotemporal properties of the civilizations with which we might come in contact, an effect that can be explored by producing Monte Carlo simulations of the three random variables involved (D, t_c, τ), each drawn from its own probability distribution (P_D, P_{t_c}, P_τ). The choice of a functional form for such distributions is where any theoretical model (physicochemical, biological, sociological, etc.) will enter the stage. In the end, of all the N_{tot} communicating civilizations that might have appeared during cosmic history, only a 'detectable fraction' f_D will pass through the causal filter and will be, in principle, observable by SETI surveys.

As an illustration, using a simple toy model where the distance of communicating civilizations is uniformly distributed within a spherical volume of radius

$R_E = 10^3$ light years around our location, and their communicative longevity is drawn from an exponential distribution with given average, we found [2] that the fraction f_D varies over several order of magnitudes depending on the statistical distribution of the time of appearance of communicating civilizations, t_c. (The result of the Drake equation is recovered when the time of appearance is uniformly distributed.) In other words, given the same total number of civilizations ever appeared, the way they are spread over cosmic history (for example whether they appeared uniformly, or preferentially around a certain epoch) may result in a big difference in the number of civilizations that are in causal contact with us today—and, thus, on the chances of success for SETI.

Because of the travel time of electromagnetic signals, evolutionary processes also enter in the analysis via the extent of the volume under investigation: more distant locations will probe more ancient epochs of cosmic history, which may correspond to varying abundances of civilizations. This is generaly not accounted for in the Drake equation, which essentially produces a snapshot of the present situation (and implicitly assumes that it reflects the average situation at all cosmic epochs). The effect will be generally negligible for searches conducted within our galaxy, but might have important consequences if SETI is extended to extragalactic scales. In fact, exploring distances $D \sim 10^9$ Gy might result in higher chances of picking up communications from ancient short-lived civilizations, whose signals have been traveling for a large fraction of cosmic history. Conversely, since the light crossing time of the Milky Way ($\sim 10^5$ y) is much smaller than its age ($\sim 10^{10}$ y), if we only search in our galactic neighbour the causal constraint would select civilizations with $t_c \sim \tau$, i.e. either very long-lived or almost exactly coeval to us.

The spatial variable is also relevant in itself, since, as we mentioned, not all possible galactic locations have the same likelihood of producing habitable planets conducive to the appearance of complex organisms. This implies that the spatial density distribution of communicating civilizations should be included in the simulations and its influence on the result should be explored.

Conclusion and Future Directions. We highlighted a general framework that can be used to explore how the spatiotemporal distribution of communicating civilizations in the universe affects the likelihood that their signals can be detected by SETI surveys. Our proposal can complement the usual approach based on the Drake equation by easily incorporating the systemic and evolutionary aspects that will certainly constitute a relevant part of a future multidisciplinary SETI roadmap. The Drake equation, however, will remain an invaluable reference to identify the key factors involved in the problem and their relative weight. An important aspect of the proposed strategy is that it provides a focal point for studies addressing different facets of the subject, by indicating a clear, minimal set of deliverables: namely, theoretical models for the probability distribution of the appearance time of communicating civilizations, their communicative longevity, and their spatial density. This is certainly a daunting task, requiring both empirical and conceptual inputs from astrophysics, biology, sociology, etc. For this reason, we believe it can only be addressed through an ambitious collective effort as the one fostered by the creation of a SETI Virtual Institute.

Additional Information:

(A) The theme is relevant for *Question 1* of the *Alien Mindscape* article (*How abundant and diverse is intelligent life in the universe?*)

(B) Big Data Analysis could help advance this concept by providing information that can be distilled into models of the temporal and spatial distribution of complex life in our galaxy and in the universe (possible relevant datasets would include rich catalogues of stellar properties, exoplanetary surveys, maps of the elemental and molecular abundance, detailed simulations of galactic evolution, etc.)

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