Civilizations are probably spreading quickly through the universe, researchers claim

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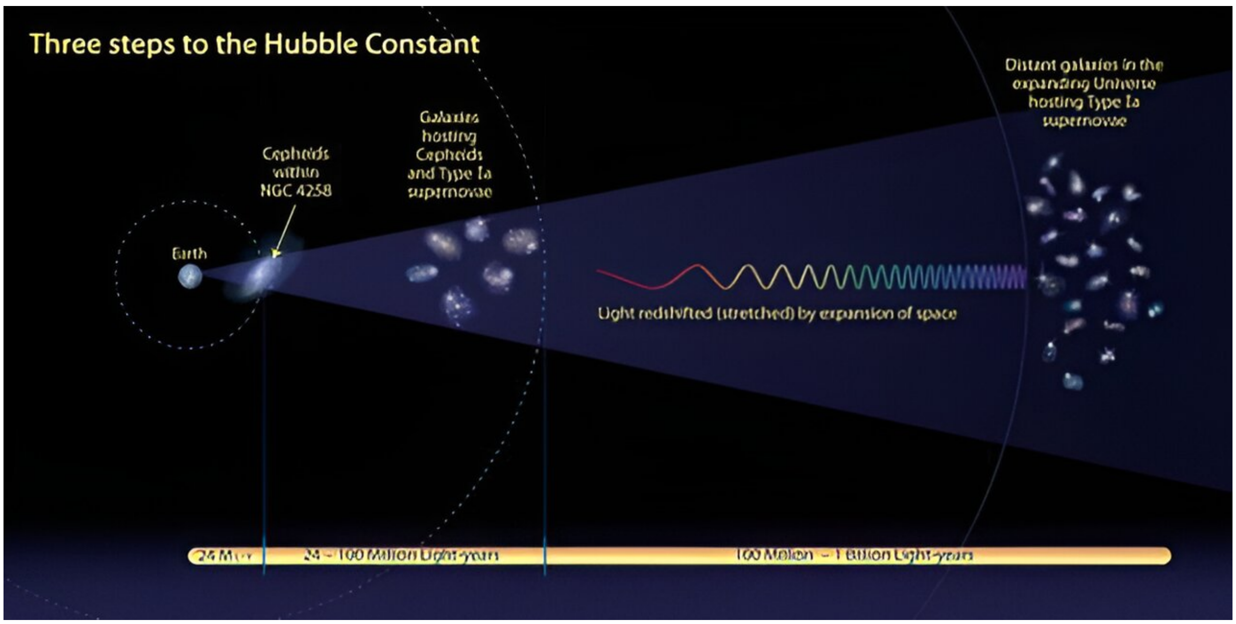

Steps to the Hubble Constant. Credit: NASA, ESA, and A. Feild (STScI)

The Search for Extraterrestrial Intelligence (SETI) has always been plagued by uncertainty. With only one habitable planet (Earth) and one technologically advanced civilization (humanity) as examples, scientists are still confined to theorizing where other intelligent life forms could be (and what they might be up to).

Sixty years later, the answer to Fermi's famous question ("Where is

Everybody?") remains unanswered. On the plus side, this presents us with many opportunities to hypothesize possible locations, activities, and technosignatures that future observations can test.

One possibility is that the growth of civilizations is limited by the laws of physics and the carrying capacity of the planetary environments—aka the percolation theory hypothesis. In a recent study, a team from the University of the Philippines Los Banos looked beyond traditional percolation theory to consider how civilizations might grow in three different types of universes (static, dark energy-dominated, and matter-dominated). Their results indicate that, depending on the framework, intelligent life has a finite amount of time to populate the universe and is likely to do so exponentially.

The study was conducted by Allan L. Alinea and Cedrix Jake C. Jadrin, an Assistant Professor of Physics and a Teaching Associate with the Institute of Mathematical Sciences and Physics at the University of the Philippines Los Banos. The preprint of their paper, "Percolation of 'Civilization' in a Homogeneous Isotropic Universe," was recently posted to the *arXiv* preprint server.

For their study, the team considered how traditional Percolation Theory could be interpreted in terms of a Logistic Growth Function (LGF), where a population's per capita growth rate gets smaller as population size approaches a maximum imposed by the limits of local resources (aka carrying capacity).

Percolation theory

In brief, percolation theory describes how networks behave when nodes or links are removed, wherein they will break down into smaller connected clusters. The first known instance of this theory being applied to the Fermi Paradox was perhaps made by Carl Sagan and William I.

Newman in 1981. In a paper titled "Galactic Civilizations: Population Dynamics and Interstellar Diffusion," they argued that the reason humanity has not encountered extraterrestrial civilizations (ETCs) is because interstellar exploration and settlement are not linear phenomena.

In contrast to the Hart-Tipler conjecture, which argues that advanced ETCs would have colonized our galaxy long ago (hence, they do not exist), Sagan and Newman postulated that interstellar exploration is a matter of diffusion. Geoffrey A. Landis argued these same sentiments in his 1993 paper, "The Fermi Paradox: An Approach Based on Percolation Theory," where he argued that the laws of physics impose limits on interstellar growth. According to Landis, there is no "uniformity of motive" to be expected from extraterrestrial civilizations:

"Since it is possible, given a large enough number of extraterrestrial civilizations, one or more would have certainly undertaken to do so, possibly for motives unknowable to us. Colonization will take an extremely longtime, and will be very expensive. It is quite reasonable to suppose that not all civilizations will be interested in making such a large expenditure for a pay off far in the future. Human society consists of a mixture of cultures which explore and colonize, some times over extremely large distances, and cultures which have no interest in doing so."

Similarly, Prof. Adam Frank and colleagues from NASA's Nexus for Exoplanetary Systems Science (NExSS) wrote a paper in 2019 titled "The Fermi Paradox and the Aurora Effect: Exo-civilization Settlement, Expansion, and Steady States." Inspired by the 2015 novel Aurora by Kim Stanley Robinson, they argued that the interstellar settlement would occur in clusters since not all potentially habitable planets would be hospitable to an alien species. In short, the laws of physics, biology, and evolution impose limits on how far and fast a species can settle our galaxy.

To constrain those limits, the team considered the three main cosmological models of the universe, including static, matter-dominated, and dark energy-dominated. A static universe, as originally described by Einstein and his Cosmological Constant, is infinite in terms of space and time and is neither expanding nor contracting. A matter-dominated universe describes the state of the universe prior to 9.8 billion years after the Big Bang, a time when the energy density of matter exceeded both the energy density of radiation and the vacuum energy density.

A dark energy-dominated universe describes the latest phase of cosmic evolution, which began roughly 9.8 billion years ago and is characterized by an accelerated rate of expansion. The team also considered all three scenarios in terms of a Logistic Growth Function to determine the number of planets settled with time. From this, the team obtained the two parameters of their study: T, the time needed to settle a spherical section of an ideal universe that is both homogeneous and isotropic, and H, the Hubble parameter that describes the rate of cosmic expansion—aka the Hubble Law or Hubble-Lemaitre Law.

For a static universe, they found that settlement follows the LGF, similar to how population growth, the spread of infectious diseases, and chemical reactions do. As they noted in their study, these dynamical systems follow a general pattern beginning with a relatively slow start due to limited sources (in this case, habitable planets). But, as they continue to expand and acquire new sources, this multiplies the number available, and the propagation speeds up. This continues until the number of sources begins to dwindle and/or the elements of the system are exhausted.

To their surprise, the team noted similar behaviors when looking at a matter-dominated and dark-energy universe. As Dr. Alinea told Universe Today via email.

"Remarkably, when the space itself is expanding as in the dark-energy and matter-dominated universes, the process of settlement, for the most part, still follows the Logistic Growth Function. We did not expect this result because a system with expanding space appeared to us as vastly different from a static system. Most of the studies we know on percolation are based on a static lattice (e.g., spread of forest fire, propagation of disease, information diffusion) where the logistic growth behavior is usually observed. Our study 'extends' this behavior to cases where the lattice is expanding like our very own universe."

Nevertheless, they did find there was a delay in an expanding universe in terms of the rate of settlement compared to a static one. For a dark energy-dominated universe, they found that the total settlement time (T) was marked with divergence for a large enough expansion rate (H). In accordance with Hubble's Law, when H is large enough, some planets would expand beyond the horizon and become "unreachable." In essence, distant planets can be receding faster than the speed of light, making it improbable that an expanding civilization would ever reach them.

They also found that in cases where the Hubble Sphere (H) was smaller, the relation between T and H was linear—in other words, T was roughly equal to H (T ~ H). For a matter-dominated universe, their findings indicated that where H was similarly small, the same relation applied, but where H became larger, the relation changed significantly to T~ H2. In comparison to that of a dark energy-dominated universe, T did not increase exponentially or reach infinity unless H was infinite. Said Alinear:

"This is interesting because a matter-dominated universe is also characterized by a horizon. It means that for planets far enough from a reference planet in this universe, they are receding at a velocity faster than light, making it appear that they are unreachable. However, for a matter-dominated universe, in accordance with Friedmann Equation, the comoving Hubble Sphere is shrinking instead of expanding. Put simply and informally, those planets far away from a reference planet in this universe (that are initially 'moving' faster than the speed of light) are 'slowing down,' making them reachable, at least in principle."

So where are they?

From their results, the team determined that advanced civilizations will generally follow a growth trend that is slow to start but will take off over time, eventually slowing and stopping as the number of "reachable" planets is exhausted. As Dr. Alineal described, "This model is marked by a three-phase pattern: slow settlement rate –> fast settlement rate –> slow settlement rate." The question remains: what does this mean for Fermi's time-honored question? How does this three-phase pattern help us refine the search for advanced civilizations expanding across the galaxy?

To that, the team concludes that our galaxy may currently be in Phase I, characterized by a slow settlement rate. This could be because only a few intelligent, advanced civilizations are engaged in interstellar settlement right now. "This slow phase can be exacerbated by large distances between 'living' planets. But once some number of traveling civilizations is reached, we may enter Phase II, characterized by a fast settlement rate. Given enough time upon entering this phase, we may finally say hello to aliens out there."

Moreover, their results address the possibility of humanity becoming an interstellar species someday, perhaps as a means of ensuring the continued survival and development of our species. This represents a challenge in an ever-expanding, ever-accelerating universe dominated by dark energy. But as Dr. Alineal summarized, there are options:

"Given enough technology to travel near the speed of light, it is still challenging to reach any planet in the universe, particularly the far away planets. Having said this, there is a spherical section of this universe, centered in our location, whose planets are reachable, at least in principle, for possible settlement. Beyond this are planets that 'move' away from us at a speed higher than that of light and may not be reachable. Unfortunately, this sphere is shrinking, so a section of the universe that we can inhabit, although large on the human scale, becomes smaller and smaller with time."

"If there is a mechanism to drive the universe to a state such that its expansion rate is the same or similar to that of a matter-dominated universe, then we would be lucky enough to have a universe that can, in principle, be colonized up to any distance from us; that is, the colonization and human influence in the universe is not bounded by any sphere unlike that of the dark-energy dominated universe."

In summary, the answer to Fermi's question may be that advanced civilizations are in an early, slow phase of expansion that has (so far) prevented us from making contact. But as there spherical volume of Hubble Space (H) that we could occupy expands, we are more likely to get close enough to someone else's that we will finally know that we're not alone in the universe. Similarly, while dark energy may limit how far we can reach (within our galaxy, not much farther), a sufficient volume of space would enable our continued development and could prevent a single cataclysmic fate from claiming all of our species.

And who knows? Perhaps cosmic expansion will not carry on as it has for the past 4 billion years, and the universe will slow down and achieve a sort of homeostasis—the kind Einstein preferred to believe in. In that case, our Hubble Spheres may continue to expand indefinitely, and there will be no shortage of intermingling between cosmic civilizations. It does make for some exciting prospects, doesn't it?

More information: Allan L. Alinea et al, Percolation of 'Civilisation' in a Homogeneous Isotropic Universe, *arXiv* (2023). DOI: 10.48550/arxiv.2309.06575

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