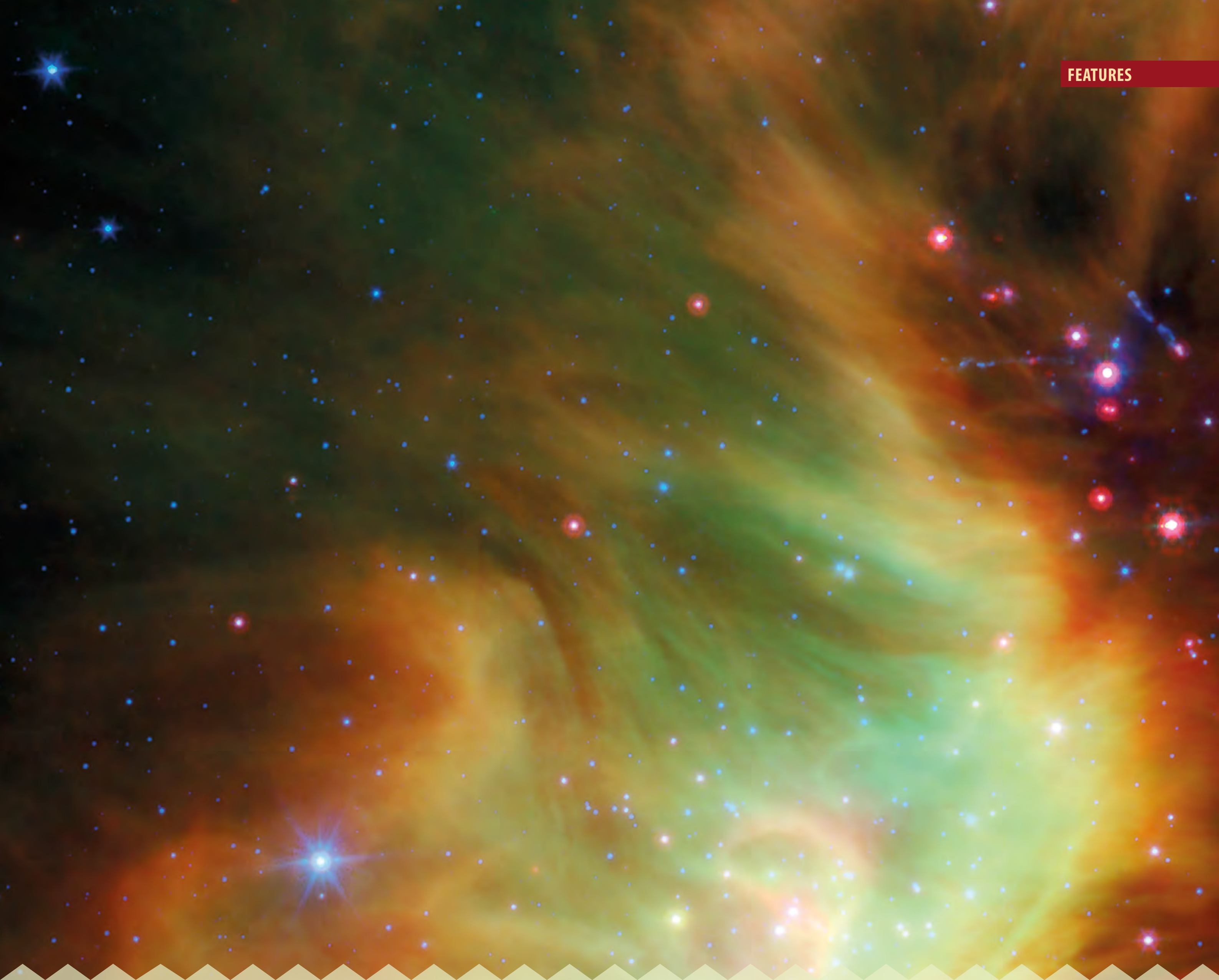

EXTRA-TERRESTRIAL LIFE

IN THE MILKY WAY GALAXY?

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Are we alone? Along with questions about black holes, this is one of the questions most commonly asked of astrophysicists. While the simple answer is that we don't know, logical and rational exploration of the question can be illuminating and a very good way to introduce non-scientists to the "scientific worldview." This short essay is based on a class for students not majoring in science, which I have taught for nearly forty years at the University of Texas at Austin.

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◂ P.33: Stars are forming near the eastern rim of the molecular cloud in the direction of the Perseus constellation, as seen in this infrared image from NASA's Spitzer Space Telescope. The young stars are approximately three million years old and are shown as reddish-pink dots to the right of the image.

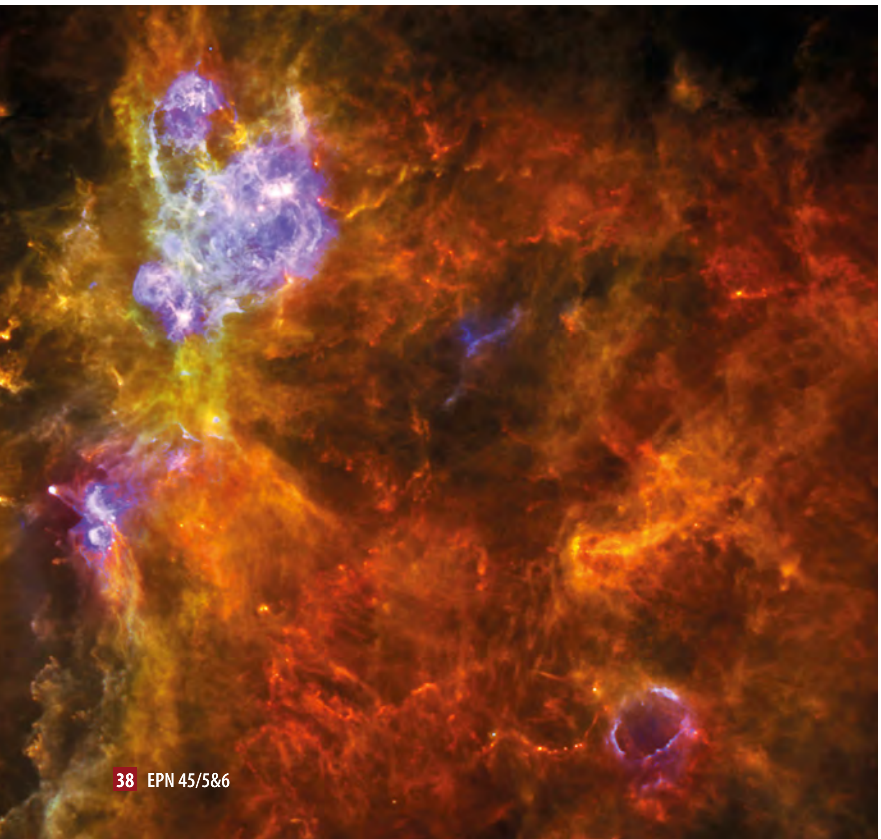
The basis for the class is the Drake Equation, proposed by Frank Drake over 50 years ago. While one can formulate more elaborate versions, the simple form he proposed is sufficient for our purposes (see Box).

A few preliminary considerations are needed before we proceed through the factors. First, we restrict consideration to our own Milky Way galaxy simply because the light travel time for a communication from even the nearest other galaxy is millions of years. Second, we focus on communication because it is much cheaper and faster than travel; the energy required to send a single electron at v = 0.1 c is about 10^9 times the energy cost for a single photon at a frequency of 1 GHz.

The first factor, R_*, is reasonably well known. Models of the Galaxy that include dark matter and gas yield a total mass of stars of about 8×10^{10} solar masses. With an average mass of stars of 0.5 solar masses, this implies about 1.6×10^{11} stars. The age of the Galaxy is about 10^{10} years, so the average star formation rate is 16 stars per year. Star formation has slowed down in the Galaxy (as in most similar types of galaxies), and the current rate is about 4 stars per year (Fig. 1). One might consider a number between 4 and 20 stars per year.

Over 1000 planets

The next factor, f_p, was in principle completely unknown when I started teaching the class, but beginning in the mid-90s, we have discovered a large number of planets around other stars. As of June 2014, the count is 1795 planets in 1114 planetary systems. Because the methods used to find planets are strongly biased towards systems with special characteristics, large corrections for incompleteness are needed, and these suggest that at least half of all stars have planetary systems. A high value for f_p is also supported by observations of young stars, showing that rotating, circumstellar disks of gas and dust are nearly ubiquitous around the youngest stars and that half of stars retain signatures of these disks for 2 to 3 million years. Some considerably older systems show dust emission signatures, thought to be due to collisions between planetesimals that regenerate some small particles as debris. All in all, the evidence that planet formation is a common feature of star formation supports the extrapolation from the known number of planets to a value of $f_p > 0.5$.



▾ FIG. 1: Far-infrared emission from a molecular cloud, as observed with the Herschel observatory. The colours represent emission in three wavelength bands centered on 70, 160, and 250 micrometres. This region hosts a large number of forming stars. Figure is from Rivera-Ingraham *et al.*, *Astrophys. J.* **766**, 85 (2013). Copyright AAS.

Earth-like planets

There is currently intense focus on the next factor, n_e. The subscript "e" for Earth-like reflects the Earth bias usually included in this factor. Very generally, life needs a solvent, and all known life uses liquid water, and the liquid state is extremely rare in the Universe as a whole. The usual considerations assume surface water on a planet with temperature set by stellar heating balanced by thermal radiation from the planet. That leads to a range of distances from a star, called the habitable zone. Stars less massive than the Sun (the great majority of stars) are less luminous, so the habitable zone is closer to the star, and its location is more constant over long periods. Most current planet searching techniques work better for close orbits around small stars, so searches for habitable planets will probably favour lower mass stars in the near future. At present about a dozen possibly habitable planets are known, but the selection effects are strongly against small planets, so huge extrapolations are used to estimate that n_e is substantial, with most estimates from 0.5 to 1.

Considerations of habitability are very complex [1]; two complications are worth mentioning. First, about half of stellar systems are binaries or higher multiples. If the stellar separation is near what would otherwise be the habitable zone, planets are likely to be ejected and may not even form in the first place. About half of binaries may have such a problem, decreasing n_e. On the other hand, greenhouse effects can greatly affect the temperature of a planet, and different planet atmospheres can allow habitable planets closer (relatively dry atmosphere) or much farther (hydrogen-rich atmosphere) from the star than calculated with simple assumptions[2]. Finally, habitable zones may be extended by considerations of sub-surface water kept liquid by internal heat (*e.g.*, Europa and some other moons of giant planets) and other solvents (*e.g.*, Titan with methane lakes).

Life

Now we move into much less certain territory in thinking about f_l. While it is generally accepted by scientists that life began on Earth through a gradual increase in complexity from simple molecules to the ability to metabolize and replicate, there is no completely satisfactory

theory for how this happened. Even if a convincing model for the origin of life on Earth eventually emerges, it will be difficult to extrapolate to other planets to compute f_l. However, if clear evidence can be found for extraterrestrial life anywhere, we could at least be sure that f_l is not vanishingly small. Consequently, it is tempting to search for signs of life outside the Earth. The most obvious target is Mars. Although searches for microbial life by the Viking landers in the 1970s turned up no convincing evidence, we now know that any life (or molecular fossils of early, but now extinct life) would need to be buried under about a metre of soil to avoid degradation by highly reactive molecules on the surface. A series of increasingly sophisticated probes have found strong evidence for sub-surface water. A probe using newer techniques to search for past of current life in samples excavated from deeper soil levels could be sent within a decade [3]. To ensure that any life on Mars arose independently, terrestrial contamination must be convincingly disproved. Missions to penetrate the ice and search for life in the sub-surface oceans of Europa have been considered, but they are more challenging.

To extend the search for life beyond our solar system, we could search for biomarkers in the atmospheres of planets around other stars. The oxygen in the Earth's atmosphere arose from photosynthetic activities by past life, and the current co-existence of oxygen and methane is considered a sign of current life. Studies of atmospheres of planets that transit (pass in front of) their stars have begun, but atmospheric studies of smaller, Earth-like planets are extremely challenging and will require a new generation of telescopes and instruments. At this point, possible values for f_l range from very small (*e.g.*, 10^{-9}) to unity.

Intelligence

Moving on to f_i leads us into evolutionary biology, where once again, we have only our terrestrial experience to guide us. The facts are fairly clear. Life arose between 3 and 4 billion years ago and remained strictly prokaryotic, unicellular life ('microbial' for short) for most of Earth's history (Fig. 2). Multicellular, differentiated life appears between 500 and 600 million years ago and diversified in the Cambrian explosion beginning around 543 million years ago. Most of today's phyla, including ours (Chordata) trace to that period.

An interesting feature is that the timescale to evolve human level intelligence through biological evolution (5×10^9 years) is comparable to the timescale for stellar evolution. If our evolution to intelligence has been twice as fast as on other planets, no other planets with life would have developed complex life. The likely cause of the long period was the need for microbial photosynthesis to produce an oxygen-rich atmosphere. A still more fundamental question is whether intelligent life with the characteristics needed for the next stage (technology) is a likely outcome on another planet. A diverse and changing environment is often invoked to select for intelligence, and it may have played a role in the evolution of Homo sapiens from a diverse array of hominids over the last few million years.

As with f_l, evidence for intelligent life on another planet would provide some constraints on f_i. Unfortunately, prospects for doing this are slim. Complex, non-technological life does not seem to produce any obvious atmospheric biomarkers.

▲ FIG. 2: Currently living stromatolites in Australia. These are microbial mats of cyanobacteria, anaerobic organisms whose waste product of oxygen made more complex life possible. The oldest certain evidence of life is a fossilized stromatolite about 3.5 billion years old.

Communication capability

Now we come to f_c, which assumes we have human level intelligence and is the fraction of planets with that level of intelligence that become "communicable." Since tool use is essential, purely aquatic planets that might have dolphin or whale intelligence probably need to be rejected at this point. While no such water worlds exist in our solar system, there is evidence for some around other stars. As long as we focus on stone-age or metal-age technology, we have several independent "experiments" on Earth. While cultural diffusion confuses the issue for the Africa-Eurasia land-mass, the Americas and Australia/New Guinea provide reasonably isolated cultures. The basis for all technological cultures is the development of agriculture, which allowed settled lifestyles, surpluses, and specialization of roles. It also triggered written language (for business records and taxes), metal extraction from ores, and observational astronomy for calendrical purposes. All these appear to have developed independently at least several times, providing some evidence that f_c is not very small. Of course, no evidence exists for independent origins of higher technology because of the rapid diffusion of such technology around the world.

To engage in interstellar communication, a society must understand the nature of the Universe. For almost all of "Western" intellectual history, the Universe was conceived as geocentric and stars were assumed to be different from the Sun. While this was less true in some other cultures, none developed a correct world-view until the chain of events known as the Copernican Revolution proceeded to a reasonably correct understanding of the Milky Way in the early 20th century. The connections between evolving worldview and technology are intriguing. The telescope played a major role in worldview evolution, while the Galilean and Newtonian revolution in physics was stimulated in part by trying to understand the cosmos. One can argue that technology and worldview (capability and interest in the Drake equation) are coupled, but one can perhaps imagine advanced civilizations on cloudy planets with incorrect worldviews.

The timescale for technology to develop is negligible compared to that for biological evolution. Advanced technological civilizations may produce planet-wide signatures. Ours has introduced novel chemicals, such as CFCs, into the atmosphere, for example. On one of the passages near Earth of the Galileo spacecraft as it was being boosted for its journey to Jupiter in 1990, its instruments were pointed at the Earth. Even with a resolution of 1 km, the cameras found no clear indications of technological civilization; in contrast the radio emission from the Earth provided unambiguous evidence of advanced technology[4]. While no existing radio telescopes on Earth could detect current levels of this "leakage radiation" from extrasolar planets, it would not be prohibitively expensive to build such a telescope. However, the transition to fiber and digital transmission may mean that "radio-loud" planets are short-lived.

Lifetime of Civilizations

Once a communicable civilization arises on a planet, how long does it last? On this question, even our one example that we have used for the previous three factors fails us; we are still here! Technically speaking, a civilization needs only to lose interest in communicating to limit L,

▾ FIG. 3: Communication with extraterrestrial advanced civilisations is usually assumed to use radio wavelengths. Radio telescopes can be quite large as their requirements on surface accuracy are much lower than for telescopes operating at visible wavelengths. This telescope at the Dwingeloo Radio Observatory is 25 metres in diameter. After retirement from active astronomy use, it has become a Dutch industrial heritage monument. It has been refurbished by volunteers and there is some discussion about using it to search for signals from extraterrestrial civilisations.

but it is more interesting to consider what might end the civilization altogether. We can divide the threats to our civilization to human-caused and natural threats. The human-driven threats all arise from the nature of technological civilizations, broadly conceived. Agriculture allows population growth, which leads to resource depletion and pollution. The main resource depletion issue is energy, actually low-entropy sources of energy. While the timescale for fossil fuel depletion is uncertain and contentious, it is probably measured in centuries, after which time, solar energy in various forms provides the only truly long-term source, with nuclear as an important bridging technology. Burning fossil fuels of course increases the greenhouse effect, which may provide some brake on fossil fuel use, but not enough to extend the reserves very much longer. The most apocalyptic possibility is all-out nuclear war, with arsenals like those of the US and USSR during the height of the cold war. Such an exchange could lead to "nuclear winter," causing crop failures and famine. Any survivors might well be disinclined toward, or incapable of, redeveloping such technology. It seems likely that either civilization will collapse or that a new, long-term worldview will emerge within centuries to millennia.

The most immediate natural threat is impact by asteroids or comets, as the recent Siberian incident has reminded us. There are dedicated efforts to find and catalog Near Earth Objects; with sufficient notice, we could modify the orbits of dangerous asteroids. Large objects, like the asteroid that may have finished the extinction of dinosaurs, have timescales of about 10^8 years. The only truly certain natural threat is the evolution of our Sun. While the main sequence of a star is relatively stable, the star increases slowly in luminosity. In about 1 billion years, the rising luminosity will cause the loss of our oceans. In about 5 billion years, when the Sun becomes a red giant, the Earth is likely to spiral into the Sun. The only escape will be to send some people to a habitable planet around another star. Possible values for L range from decades to 5 $\times 10^9$ years. A few long-lived civilizations will completely dominate the average lifetime. This logic indicates that the civilizations we might communicate with are very likely to be much older and presumably more advanced. (The latter presumption depends on an assumption of continued progress, which is debatable.) The fact that our searches have listened for, rather than broadcasted, messages is based on the conclusion that we are the less advanced civilization. If we mark our emergence by our first attempt to listen for a signal, that was about 60 years ago, so we would be one of the youngest civilizations in the Galaxy.

Armed with all the estimates, anyone can calculate his or her own estimate for *N*.

If none of f_l, f_i, or f_c is very small, the answer will depend primarily on the choice of *L*. Of course, the ultimate test of any estimate of *N* would be to detect signals from an extraterrestrial civilization (Fig. 3). The Milky Way "society" will be dominated by the civilizations that develop the "long-view" before they destroy themselves. ■

THE DRAKE EQUATION

The number of civilizations in our Galaxy with which we could communicate is given by

$$N = R_* f_p n_e f_l f_i f_c L, \text{ where}$$

- R_* is the rate of star formation,
- f_p is the fraction of stars with planetary systems,
- n_e is the number of habitable (Earth-like) planets per planetary system,
- f_l is the fraction of habitable planets where life begins,
- f_i is the fraction of planets with life that evolves to a level of intelligence comparable to that of humans,
- f_c is the fraction of those that develop a technological civilization with the capability and interest in interstellar communication, and
- L is the lifetime of such civilizations.

The first three factors are astrophysical, while f_l lies at the transition from chemistry to biology, f_i is biological, and the last two factors involve history and predictions about technological developments and social interactions. The value of the Drake equation is in organizing our thinking rather than in providing an answer.

About the author

Neal Evans obtained his doctorate in physics at the University of California, Berkeley working with Nobel laureate Charles Townes. Evans joined The University of Texas at Austin faculty in 1975, where he teaches several astronomy courses, including a class about extraterrestrial life. Evans has led large programs on both the Spitzer and Herschel space telescopes, studying the formation of stars and planet-forming disks. He is currently the Edward M. Randall, Jr., MD Centennial Professor at the University of Texas at Austin and the Oort Professor for 2014 at Leiden University.

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SUGGESTION FOR FURTHER READING:

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