Enlivening Introductory Physics With SETI

Art Hobson

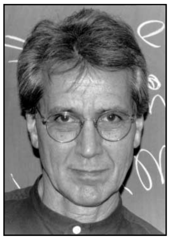
As has been stated before in these pages,[1] it is perplexing that the typical introductory physics course, the only physics course that most students will ever take, fails to present the current scientific view of the physical universe. It is an added paradox that, at a time of declining popularity and physics enrollments, we throw away our most exciting resource, namely modern physics.

We can take a tip from astronomy, a field that is popular both in the classroom and in the bookstores. Introductory astronomy courses are generally contemporary and conceptual (nonalgebraic).[2] One fascinating and physics-packed modern topic usually included in astronomy courses but unfortunately ignored by physics instructors is SETI: the search for extraterrestrial intelligence.

This article outlines teaching materials for one to three SETI lectures, for insertion within a general introductory physics course.[3] This material should be presented only after energy, electrodynamics, and special relativity. For further teaching suggestions and more complete background information, see the author's liberal-arts physics textbook,[4] two collections of readings,[5,6] and practically any recent introductory general astronomy textbook.[7]

SETI and Scientific Methodology

Because of all the pseudoscientific nonsense surrounding extraterrestrial visitations, begin by separating science from pseudoscience, the dogmatic belief in an appealing idea that purports to be scientific but that is not supported by scientific evidence. Present an article from a popular tabloid newspaper that is strong on astonishing claims but weak on evidence and scientific principles. During class discussion, it should become clear that little or no real evidence is offered for such claims as alien visitations, miraculous predictions, communications with the dead, and the like.



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When discussing speculative topics such as SETI, it is important to ask frequently, "How do we know?" and "What is the evidence?" In accordance with the American Association for the Advancement of Science, which has urged that the methods of science form the core of science literacy courses,[8] SETI offers many opportunities to discuss theories, hypotheses, observation, and other facets of scientific methodology.

Most of the class time should be occupied with an analysis of the type carried out by such SETI pioneers as Frank Drake and Carl Sagan, one that follows naturally from the Copernican principle. This analysis (or "resolution into parts," a widely used method of science) divides the question:

1. What is the expected number of Earth-like planets (e.g. in our own galaxy)?
2. For Earth-like (capable of supporting life) planets, what is the likelihood of life arising?
3. If life arises, what is the likelihood that it will develop intelligence?
4. If intelligent life arises, what is the likelihood that it will develop technology (e.g. radio transmitters)?

We need to add Question 4 if we want our SETI quest to have observable content, because intelligent life will probably be undetectable by us in the near future unless it can communicate across space.

The Number of Earth-like Planets

Question 1 leads to lots of contemporary astronomy and physics. There are perhaps 4×10^{11} stars in our galaxy. About 50% are in multiple-star systems. About 90% of the remainder have too much or too little mass for life to originate on surrounding planets. Very high mass stars "burn" (fuse) so brightly that they exhaust their nuclear fuel in only a few hundred million years — probably too soon for life to originate. Very low mass stars radiate so weakly that any planet receiving enough radiation to support life must reside so near the star that it, like our Moon, is "tide-locked," i.e. the same side of the planet always faces the star. This causes any planetary atmosphere to be blown around to the dark side where it freezes out, making life impossible. This leaves some 2×10^{10} stars that are more-or-less "Sun-like."

But do these stars have planets? This question provides an opportunity to bring the present great age of planetary discovery into the classroom.[9] As of November 2000, there were 46 confirmed planets orbiting main-sequence stars, three confirmed protoplanetary disks, 36 ground-based searches for extrasolar planets, and 17 space-based searches. The discoveries themselves, as well as the physics-based methods of observation, are fascinating. Planets are generally detected indirectly, from the wobbling of their central star as observed by tracking the star's position or by the Doppler shift of the star's light. There are at least two reasons to expect that many more extrasolar planets around Sun-like stars will be discovered before long. First, roughly half of all young Sun-like stars show some evidence of protoplanetary disks. Second, most single Sun-like stars rotate slowly rather than rapidly. Angular momentum considerations during the formation of a star from a collapsing gas cloud suggest that these stars have shed much of their angular momentum to a surrounding rotating disk of gas. Nearly five billion years ago, just such a disk coalesced into our own solar system.

The Likelihood of Life Arising

Question 2 has inspired rich biochemical literature and a consensus that life originated by chemical processes on Earth although some of the chemical constituents could have drifted here from space. The 1953 Miller-Urey experiment, in which amino acids and nucleic acids form spontaneously when gases simulating the early Earth atmosphere are put into contact with liquid water and subjected to electric-spark discharges (simulating lightning), is worth describing. Experiments using a variety of simulated atmospheres and energy sources have also generated the building blocks of life. One consistent requirement is the presence of liquid water. As one cosmo-chemist says, "The search for life has been the search for liquid water."[10] Thus, the plausible "habitable zone" for life around a Sun-like star has expanded recently. Given the presence of water, it seems that life could exist in a possible subsurface ocean on Jupiter's moon Europa, on Pluto's moon Charon, or even on rogue planets in interstellar space.[11]

There is chemical evidence for simple bacteria-like life as early as 3.8 Gya (gigayears ago), about 0.8 billion years after Earth formed. Heavy cratering of

Earth around 3.9 Gya made it impossible for present life to have emerged until after that time.[12] So life arose almost as soon as conditions were ripe for it. Evidence for these assertions is based on examination and radioactive dating of Moon rocks brought back by *Apollo* astronauts, of sedimentary rocks containing remains of early life, and of nonsedimentary rocks containing chemical evidence of early life.[13]

Given some 20 billion Sun-like stars, many of them probably surrounded by planetary systems, and given the ease with which life's precursors form and the rapidity with which terrestrial life originated, it is a plausible hypothesis that life exists in many places in the galaxy. Nobel prize-winning biochemist Christian de Duve has gone so far as to conclude that, "Life is almost bound to arise ... wherever physical conditions are similar to those that prevailed on our planet some four billion years ago."[14] This is a highly significant hypothesis, suggesting that the cosmos is teeming with life!

Some instructors might want to include a discussion of the famous Martian meteorite that fueled speculation in 1996 about whether that planet once supported primitive life forms. The story of the crystallization of this rock on Mars about 4.5 billion years ago, the meteorite impact that fractured it, the carbon-rich fluids that were deposited within the fractures, its ejection from Mars 16 million years ago by another impact, its interplanetary trek, its impact on Antarctica 13,000 years ago, its recent discovery by scientists, and the subsequent investigation that revealed the possible presence of microscopic fossil bacteria, is fascinating.[15] However, more recent work casts considerable suspicion on the claim that this rock contains microscopic fossils of primitive life forms. Thus, instructors who do choose to present this story should cast it as an example of scientific work still in progress and highly uncertain at present.[16]

The Likelihood of Intelligence

Questions 3 and 4 can stimulate exciting discussion and worthwhile speculation, but any conclusions must be considered highly speculative. At least 2.2. Gya, life transformed from simple single-celled bacterial "prokaryotes," organisms without cell nuclei in which single-stranded DNA is dispersed throughout the body of the cell, into single-celled "eukaryotes" (cells with nuclei housing single- or double-stranded DNA). It was then another 1.5 Gy until, during 800-600 Mya (megayears ago), precursors of the "Cambrian explosion" appeared. The Cambrian explosion is the relatively abrupt appearance of complex multicellular animal life (having eukaryotic cells, of course) that marks the beginnings of a rich fossil record stemming from shortly after 600 Mya. Biologists do not understand the details of this transition, but it might have been driven by external environmental events such as "snowball Earth" glaciations (massive sheets of ice that may have covered nearly the entire planet).[17]

One plausible hypothesis arising from all of this is that it is much easier for single-celled prokaryotic life to originate on an Earth-like planet than it is for that life to develop into eukaryotic or multicellular forms. Indeed, in their book *Rare Earth*,[18] paleontologist Peter Ward and astronomer Donald Brownlee argue that simple life is common in the universe while complex life is rare because it depends on many special factors. These factors include, for example,

- a star in the right kind of galaxy, far enough from the galactic center to avoid cataclysms yet close enough to have heavy elements, including radioactive ones;
- sufficient planetary mass to retain an atmosphere and water, and to have enough thermal energy for plate tectonics;
- a Jupiter-like neighbor, to promote comet and asteroid impacts as sources of carbon and water, then to sweep them out of the way to avoid further impacts.

The Likelihood of Technology

Null results from radio searches for signals from ET civilizations are beginning to provide some evidence that technology is rare or nonexistent elsewhere in our galaxy. Although it is far too early to form conclusions, initial radio searches covering only a limited range of possible stars, radio frequencies, and power levels are beginning to place interesting limits on the prevalence of radio-transmitting civilizations. The most thoroughly examined channel corresponds to the hydrogen emission frequency, 1.42 GHz, on the premise that extraterrestrials desiring to attract our attention would choose a frequency close to this. To date, searches around this frequency appear to rule out the existence of a civilization within 50 light-years (LY) deliberately transmitting at or above a power level that could be transmitted from our own Arecibo radio telescope in Puerto Rico (used as a narrowly beamed radar system).[19] Furthermore, 10% of the star systems out to 4,000 LY have been searched for transmissions at this power level. Assuming a somewhat higher transmission power level, but still a very plausible power for a civilization even slightly more advanced than ours, searches to date have covered all stars out to 500 LY and 10% of the stars out to 40,000 LY — about 40% of the distance across our galaxy. If there are such technological civilizations, they are either not transmitting, or they are transmitting at a different frequency or mode (such as gravitational waves), or they are not very common. Although this is a rather weak conclusion, it is not trivial.[20]

SETI capabilities will soar in coming years, as the planned Allen Telescope Array goes online around 2005 and the planned Square Kilometer Array (SKA) goes online around 2015. The Allen Array will be the first telescope to look around the clock for life on other planets. It will scan more than a decade of frequencies, 0.5-11 GHz, for narrow bandwidth pulses and continuous waves. Although its initial deployment will mark a significant improvement over current capabilities, its flexible design will allow its scanning power to continue to increase into the future.[21]

The SKA will be designed by radio astronomers from 11 countries as the "largest, most sensitive telescope ever." It will be about 100 times more sensitive than the most powerful existing radio telescope, the Very Large Array in New Mexico, and 100 times larger than the Allen Array. Its long list of things to look for includes cool hydrogen throughout the universe, the earliest stages of galaxy formation, galaxy evolution, evidence of gravitational waves, and extraterrestrial signals. It will detect signals across two frequency decades, 0.15-10 GHz.[22]

Your students can engage in the radio search. The SETI Institute is asking individuals to utilize their computers during idling times, to analyze data sets from the Arecibo radio telescope. Students download free software that works in much the same way a screen saver does. Information is available at URL http://seti.ssl.berkeley.edu/.[23]

Fermi's Question: Where Is Everybody?

Despite the uncertainties of SETI, some scientists have always been willing to speculate further. One of these was Enrico Fermi. Fermi was conversing with physicists Edward Teller, Herbert York, and others over lunch one day at Los Alamos in 1950. The talk turned to possible modes of interstellar travel. All agreed that Earth had not been visited by alien spacecraft. Then Fermi asked, "Don't you ever wonder where everybody is?" He followed this up with a series of calculations, similar to the four-step analysis outlined above. He believed that life was not only abundant, but that it should evolve to become intelligent and technological on many extrasolar planets, from which Fermi concluded that we ought to have been visited long ago and many times over. But he and his friends agreed that we haven't been visited. Fermi could find only three plausible reasons for this absence of visitations: Either (1) interstellar travel is impossible, (2) interstellar travel is always judged not to be worth the effort, or (3) technological civilizations don't last long enough for interstellar travel to happen.[24]

There is a lot of wonderful physics, and all the fascination of *Star Trek*, in Fermi's first suggested explanation for the absence of visitations. Edward Teller, Freeman Dyson, Robert Forward, and others have outlined several modes of interstellar travel that seem feasible for a civilization that has possessed technology for at least many centuries.[25] Controlled nuclear fission could accelerate a rocket for several years until it attained a speed high enough to reach the nearest other star (Alpha Centauri, 4 LY away) in about 10,000 years. Robots, or many generations of humans, or humans in refrigerated suspended animation, might make the trip. Dyson suggests that nuclear fusion bombs could supply much more energy: A fuel supply of 300,000 bombs (!), detonated at a rate of 20 bombs per minute, could maintain a comfortable (for humans) acceleration of 1g in a starship supporting several hundred crew members, reaching 1/30 of lightspeed and arriving at Alpha Centauri in 130 years.

Trips well within a human lifetime are possible using more futuristic technology. With enough time and energy it should be possible to produce and store as much as a few kilograms of antimatter. If combined with a few metric tons of liquid hydrogen, this could fuel a starship that could reach 10–50% of lightspeed and reach Alpha Centauri in 8–40 years. Another concept is the "stellar ramjet," which would use a 100-km wide scoop to gather intragalactic hydrogen gas to fuel a fusion reactor. The starship could accelerate at 1 g for as long as desired, reaching Alpha Centauri in seven years, or the center of our galaxy in 21 years travel time (but more than 30,000 years as measured by Earth clocks!). Starships could also be pushed with laser light beamed from our solar system, perhaps from a laser array in orbit around the planet Mercury and powered from the Sun. A single combined beam could travel 40 LY before spreading significantly, enabling the starship to reach any of the 20 nearest stars within about 17 years ship time and 20 years Earth time.

A civilization able to master any of these technologies could colonize a few nearby stars during a period of several centuries. From each of these stars it could then colonize a few more stars, and so forth. The number of colonized stars would increase exponentially until, within a few million years — a split second in galactic history — most of the habitable places throughout the galaxy were colonized.[26]

Fermi's second suggestion, that interstellar travel is always judged not to be worth the effort, seems plausible only if we assume that the number of technological civilizations in our galaxy is very small. For if there were, as Fermi appears to have believed, many such civilizations, then it is implausible that *every one* of them would regard space travel and colonization to be not worth the effort. If even a single civilization opted for colonization, then the galaxy should be entirely colonized soon thereafter.

Do Civilizations Survive their Own Technology?

Fermi's third suggestion, that technological civilizations don't last long enough for interstellar travel to happen, is sometimes called the "short lifetime hypothesis." Do civilizations survive their own technology? Our only example is us. We bipedal hominids have been here for some five million years, and became technological (in the sense of transmitting radio signals) a mere century ago.

Will we survive as a technological society? The evidence is not encouraging: Organized killing between members of our own species continues all over the world. Already six billion strong and outrunning Earth's resources, we appear headed toward yet another doubling of our numbers. Global warming is by now known to be a substantial and present threat, yet we continue burning fossil fuels as though there were no tomorrow. A few quotations from the lead article in the 1997 issue of *Science* devoted to "Human-Dominated Ecosystems" establish the seriousness with which scientists view our present predicament (see Box).[27]

Whether or not one agrees with Fermi concerning the likelihood of technological civilizations and reasons for the absence of visitations, the great physicist's "short lifetime hypothesis" is a sobering perspective on the sustainability of our own civilization, and a powerful catalyst of classroom discussion on the state of the planet. All in all, SETI is a stimulating scientific feast that we should be eager to share with our students.

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"Estimates of the fraction of land transformed or degraded by humanity … fall in the range of 39 to 50%…. Land transformation represents the primary driving force in the loss of biological diversity worldwide."

"The modern increase in CO_2 represents the clearest and best documented signal of human alteration of the Earth system…. The CO_2 concentration was more or less stable near 280 ppm for thousands of years until about 1800, and has increased exponentially since then. There is no doubt that this increase has been driven by human activity…. The fact that increased CO_2 affects species differentially means that it is likely to drive substantial changes in the species composition and dynamics of all terrestrial ecosystems."

"Humanity now uses more than half of the runoff water that is fresh and reasonably accessible, with about 70% of this use in agriculture…. In the U.S. only 2% of the rivers run unimpeded…. Major rivers, including the Colorado, the Nile, and the Ganges, are used so extensively that little water reaches the sea."

"Overall, human activity adds at least as much fixed nitrogen to terrestrial ecosystems as do all natural sources combined…. Beyond any doubt, humanity is a major biogeochemical force on Earth."

"Recent calculations suggest that rates of species extinction are now on the order of 100 to 1000 times those before humanity's dominance of Earth…. At present 11% of the remaining birds, 18% of the mammals, 5% of fish, and 8% of plant species on Earth are threatened with extinction."

"All these seemingly disparate phenomena trace to a single cause — the growing scale of the human enterprise. The rates, scales, kinds, and combinations of changes occurring now are fundamentally different from those at any other time in history; we are changing Earth more rapidly than we are understanding it."

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