strike a living world, either ending life or driving evolution, e.g., asteroid collisions, volcanoes, etc. (E)

D. Intelligence

Of all the myriad species that have arisen and disappeared on Earth, only one developed the capacity for radio communications and space travel. This suggests to some that the probability of such species occurring is very small. Is mankind an evolutionary accident? (See also Ref. 5.)

39. **"The Absence of Extraterrestrials on Earth,"** Lord Douglas of Barloch, Q. J. R. Astron. Soc. **18**, 157–158 (1977). A very succinct statement of the pessimist position adopted by many theorists in biological evolution. (E)
40. **"The Probability of Extraterrestrial Intelligent Life,"** E. Mayr, in *Extraterrestrials: Science and Alien Intelligence*, edited by E. Regis, Jr. (Cambridge U. P., Cambridge, 1985), pp. 23–30. A summary of the arguments supporting the view of pessimistic biologists. (E)
41. **"The Pump of Evolution,"** J. Kramer, Analog **106**, (1), 124–127 (1986). Evolution of intelligence may have been driven by ecological calamities, which forced life forms to adapt and change. An example of the concept of "punctuated equilibrium." (E)
42. **"Evolution and Tinkering,"** F. Jacob, Science **196**, 1161–1166 (1982). Convergence: Can evolution solve the same problem in the same way in different times and places? See also Ref. 7. (I)
43. **"The Evolution of Ecological Systems,"** R. M. May, Sci. Am. **239** (3), 161–175 (1978). More on convergence: From the dawn of the age of mammals until 2 million years ago, North and South America had no direct link. Morphologically similar species—including the wolf, rhinoceros, and sabretooth cat—evolved independently. The South American equivalents were marsupials, providing a remarkable case of convergent evolution. (E)
44. **"Exponential Evolution: Implications for Intelligent Extraterrestrial Life,"** D. A. Russell, Adv. Space Res. **3**, 95–103 (1983). The brain mass of terrestrial species, in relation to body mass, has increased exponentially with time, and is currently very similar for many species. Other species could reach mankind's current level of intelligence in about 10 million years. If primates had not evolved intelligence, another family could have. (A)
45. **"The Evolution of Primate Behavior,"** A. Jolly, in Am. Sci. **73**, 230–239 (1985). "If there is an essence of being a primate, it is the progressive evolution of intelligence as a way of life." (E)
46. **"Animal Thinking,"** D. R. Griffin, in Am. Sci. **72**, 456–464 (1984). "When animals live in complex social groupings ... they need to have internal models of the behavior of their companions, to feel with them, and thus to think consciously about what the other one must be thinking or feeling." (E)

E. The rise (and fall?) of technical civilization

Even if intelligent life develops, what is the probability that it will become skilled at matter and energy manipulation and develop technology at least comparable to ours? And, if it does, how long might such a civilization survive? Both factors are of great importance in estimating the number of detectable civilizations now existing.

47. **"Godliness & Work,"** L. Casson, Science **81**, 36–42 (1981). "The Greeks invented steam engines but never used them. The Romans knew about water wheels but disdained them." Similarly, the great Chinese and Indian civilizations did not exploit their technological discoveries. Is our explosive growth of science and technology unusual? (E)
48. **"Astronomical Aspects of Interstellar Communication,"** S. von Hoerner, Astronaut. Acta **18**, 421–429 (1973). Even without interstellar travel, the effects of advanced technology should be visible as astronomical phenomena. If the probability of evolving technology is not small, very detectable civilizations might still be rare because (a) they soon abandon technology, (b) they destroy themselves, (c) they stagnate, or (d) they manifest themselves in ways we do not yet recognize. (E)
49. **"Ecological Consequences of Nuclear War,"** S. McNaughton, R. Ruess, and M. Coughenour, Nature **321**, 483–487 (1986). A recent review of the controversial hypothesis that mankind could destroy itself with a nuclear war, by cutting off the sunlight with soot and dust. An example of ways advanced civilizations might fall. (I)

See also Ref. 5, which proposes that an intelligent species may never make the step to high technology. One reason may be that most Earthlike worlds are water covered. See also Refs. 38 and 41.

IV. WHERE ARE THEY?

Proponents of radio searches based much of their argument on a crucial assumption that any advanced civilization would remain at the star where it evolved. However, in the middle 70s the view that interstellar travel and colonization is feasible gained a number of vocal adherents. This suggests that the Drake equation should be expanded to include factors for the rate of expansion of an interstellar civilization and the probability that we would be able to detect it.

For the physics teacher, these references offer many possibilities for interesting discussions and problems about special relativity, dynamics, diffusion, and other topics related to interstellar travel.

A. Interstellar travel: feasibility

Many papers describe possible propulsion systems for interstellar flight. It is sufficient for our purposes to sample a few.

50. **"The General Limits of Space Travel,"** S. von Hoerner, Science **137**, 18–23 (1962). The energy requirements for interstellar travel are found to be so extreme that space travel will probably always and everywhere be limited to planetary systems. Reprinted in Ref. 1. (A)
51. **"Feasibility of Interstellar Travel,"** D. F. Spencer and L. D. Jaffe, Astronaut. Acta **9**, 49–58 (1963). Interstellar travel at a few tenths of the speed of light with staged fission or fusion rockets is theoretically feasible, though expensive. (A)
52. **"Interstellar Transport,"** F. J. Dyson, Phys. Today **21** (10), 41–45 (1968). Project Orion developed a viable, but as yet untried, method of propelling rockets by nuclear explosions. (A)
53. **"The Colonization of Space,"** G. K. O'Neill, Phys. Today **27** (9), 32–40 (1974). We are already capable of building pleasant, self-sufficient dwelling places in space. (I)
54. **"Antiproton Annihilation Propulsion,"** R. Forward, J. Propulsion Power **1**, 360–374 (1985). A discussion of methods for generating, trapping, storing, and using antimatter as a rocket fuel. (A)
55. **"Solar Sail Starships: The Clipper Ships of the Galaxy,"** G. L. Matloff and E. Mallove, J. Br. Interplanet. Soc. **34**, 371–380 (1981). Large human habitats may be propelled by large photon sails 0.01–0.1 μm thick, and travel to the nearest stars in about 1000 years. The analysis is further pursued in J. Br. Interplanet. Soc. **36**, 201–209 (1983), and a BASIC program is provided. (A)

*56. **"Feasibility of Interstellar Travel: A Review,"** R. L. Forward, J. Br. Interplanet. Soc. **39**, 379–384 (1986). A recent review. (I)

57. **"Fastships and Nomads: Two Roads to the Stars,"** E. Jones and B. Finney, in *Interstellar Migration and the Human Experience*, edited by B. R. Finney and E. M. Jones (University of California Press, Berkeley, 1985), pp. 88–104. Offers a way to travel among the stars very slowly, with relatively low technology. (E)

B. Interstellar travel: Implications

A civilization capable of transmitting radio beacons powerful enough to be detectable by us may also have the means to send colonizing vessels to nearby stars. Estimates of the time required for a wave of colonization to spread throughout the galaxy range as low as a few tens of million