Notes

Where *Is* Everybody?

[1] **Pg 1 reading the works of Isaac Asimov** The American author Isaac Asimov (1920–1992) was one of the 20th century's most prolific authors. He wrote on a vast number of topics—from the Bible to Shakespeare—but it was his science books, both fiction and non-fiction, that had the most impact on me. For a memoir, written towards the end of his life, see Asimov (1994).

[2] **Pg 1 appeared in successive issues** The "pro-Fermi" article, by the American geologist and science fiction writer Stephen Lee Gillett (1953–), appeared in the August 1984 issue of *Asimov's*. The rebuttal, by the American scientist and author Robert A. Freitas Jr (1952–), appeared in the September issue. A few years later, Gillett expanded upon his original article and pointed out a different interpretation of the "lemming paradox" introduced by Freitas and discussed here on page 2. If Earth were empty except for lemmings then the creatures *would* be everywhere; but Earth teems with other living things, which out-compete lemmings and limit their spread. The correct conclusion to draw from the non-observation of lemmings is that Earth has an abundance of living species competing for resources (which we knew anyway, because we see life all around us). When we look into space, however, we see *nothing* that indicates the presence of life.

[3] **Pg 5 latest cosmological measurements** The WMAP and *Planck* space missions have tied down the key numbers describing our universe. For details see, for example, NASA (2012) and ESA (2014).

The Physicist Enrico Fermi

[4] **Pg 10 precocious ability in mathematics** For details of Fermi's life I consulted two sources: a biography written by his wife Laura (Fermi 1954); and

S. Webb, *If the Universe Is Teeming with Aliens ... WHERE IS EVERYBODY?*,
Science and Fiction, DOI 10.1007/978-3-319-13236-5

a readable account of Fermi's life in physics, written by Emilio Segré (1905–1989), a friend, student and collaborator of Fermi (Segré 1970). Segré himself won the Nobel Prize for physics in 1959. A symposium held in Chicago in 2001 to commemorate the centenary of Fermi's birth highlighted the sheer breadth of his impact on physics; the proceedings were later published (Cronin 2004).

[5]**Pg 10 quickly outstripped his teachers** Luigi Puccianti (1875–1952), Fermi's teacher, was the director of the physics laboratory at the Scuola Normale Superiore in Pisa. According to Laura's account (Fermi 1954) Puccianti asked the young Fermi to teach him relativity. "You are a lucid thinker", Puccianti said, "and I can always understand what you explain".

[6]**Pg 13 pile went critical** The man in overall charge of the project that aimed to achieve the first self-sustaining nuclear reaction was Arthur Holly Compton (1892–1962), an American physicist who won a Nobel prize for his work in subatomic physics. When it was clear Fermi had attained the goal, Compton telephoned James Bryant Conant (1893–1978), the President of Harvard University. The telephone call was cryptic: "Jim, you'll be interested to know that the Italian navigator has just landed in the new world". See Compton (1956) for details of the project.

Paradox

[7]**Pg 13 word paradox comes from** See Poundstone (1988) for an entertaining and readable book dealing with a variety of paradoxes. As well as those I discuss here, you can read about Russell's barber paradox, Newcomb's psychic paradox and many others—but not the Fermi paradox.

[8]**Pg 14 Rapoport once remarked** The Russian-born biomathematician Anatol Rapoport (1911–2007) is known for his work in a variety of fields, including the analysis of a famous mathematical paradox: the prisoner's dilemma. For a short, readable introduction to this paradox, see Rapoport (1967).

[9]**Pg 15 intentional vagueness** Our word "sorites" comes from the Greek word *soros* meaning "heap", since it was first used in the type of reasoning described in the text. (In other words, one grain of sand doesn't make a heap; if one grain of sand doesn't make a heap, then neither do two grains; and so on *ad infinitum*.) See Williamson (1994) for a comprehensive account of the sorites paradox.

[10]**Pg 15 raven paradox** The raven paradox was developed by the German-born philosopher Carl Gustav Hempel (1905–1997), one of the leaders of the logical positivist movement. The paradox first appeared in Hempel (1945a, b).

[11]**Pg 16 generated a huge literature** The paradox of the unexpected hanging was first noticed by the Swedish mathematician Lennart Ekbom when he heard the following wartime announcement by the Swedish Broadcasting Company: "A civil defense exercise will be held this week. In order to make sure that the civil defense units are properly prepared, no-one will know in advance on what day this exercise will take place." For more details on this paradox, see Gardner (1969). Although Martin Gardner (1914–2010) was best known for his mathematics columns in *Scientific American*, he trained as a philosopher and published scholarly articles on paradox.

[12]**Pg 17 fact of interstellar travel** Although the twin paradox involves Einstein's special theory of relativity, Einstein himself of course understood his own theory well enough not to present this phenomenon as a paradox. However, although Einstein was also one of the founders of quantum theory, he was less sure of his ground in this field. He and his co-workers Boris Podolsky (1896–1966) and Nathan Rosen (1909–1995) constructed a marvelously subtle argument (now called the EPR paradox) intended to prove that quantum physics is incomplete. Again, a full analysis shows there is no paradox—but at the expense of introducing a "spooky" (Einstein's own word) phenomenon called entanglement. The EPR result tells us that everything we have ever touched is invisibly tied to us by the weird rules of quantum theory. Clear accounts of the EPR paradox can be found in Mermin (1990) and Gribbin (1996). The paradox was originally described in Einstein et al. (1935).

[13]**Pg 17 first proposed in 2012** The paper that proposed the firewall paradox was available as a preprint in 2012, and appeared in print the following year. See Almheiri et al. (2013).

[14]**Pg 18 proposed an idea** See for example Webb (2004).

[15]**Pg 19 named after Heinrich Olbers** The dark-sky paradox was named after the German astronomer Heinrich Wilhelm Matthäus Olbers (1758–1840), but several other astronomers, including most notably Johann Kepler (1571–1630) and Edmond Halley (1656–1742), had considered the problem before

Olbers published his analysis in 1826. See Harrison (1987) for a thorough, elegantly written discussion of Olbers' paradox, including the early history of the question of why the sky is dark at night.

The Fermi Paradox

[16]**Pg 21 whose report I draw heavily upon** Eric Jones, an astronomer who spent most of his career at Los Alamos, contacted Emil John Konopinski (1911–1990), Edward Teller (1908–2003) and Herbert Frank York (1921–2009), Fermi's luncheon companions on the day he asked his famous question, and requested them to record their recollections of the incident. He published their accounts in Jones (1985). During the early 1950s, the Americans Konopinski and York were both involved in theoretical work on the development of nuclear weapons, as was the Hungarian-born Teller (who has been described as "the father of the H-bomb"). All three of them would have enjoyed Fermi's input into their discussions on nuclear physics.

[17] **Pg 24 after the radio astronomer** The American astronomer Frank Donald Drake (1930–) was the first person in history to use a radio telescope to search for ETCs. A fascinating account of what led him to a life in astronomy, and of the prospects for finding ETI, can be found in Drake and Sobel (1991).

[18]**Pg 26 formulate the argument as a paradox** See for example Haqq-Misra and Baum (2009) or Prantzos (2013).

[19]**Pg 26 a scientific visionary** The Russian author and philosopher Konstantin Eduardovich Tsiolkovsky (1857–1935) was born into a poor family in the eastern city of Izhevsk. From the age of nine he suffered almost total deafness following a streptococcus infection. Nevertheless, he educated himself and studied chemistry and physics. As early as 1898 he explained the need for liquid-fueled rockets for spaceflight, and in his 1920 SF novel *Beyond the Earth* he described how people would live in orbiting colonies. He promoted his ideas on extraterrestrial life in two essays entitled "There are also planets around other suns" (dated 1934) and "The planets are occupied by living beings" (dated 1933). For a description of Tsiolkovsky's philosophy and his anticipation of the Fermi paradox, see Lytkin et al. (1995).

[20]**Pg 27 clearly stated the dilemma** See Viewing (1975).

[21]**Pg 27 a 1975 paper** See Hart (1975). It was this paper more than any other, I believe, that generated widespread interest in the Fermi paradox.

[22]**Pg 28 the House of Lords** Lord Douglas of Barloch (1889–1980) suggested (Douglas 1977) that the number of evolutionary steps leading from primitive life to intelligence was so large that the probability of it happening elsewhere was infinitesimal.

[23]**Pg 28 Tipler reasoned** The American mathematical physicist Frank Jennings Tipler III (1947–) has published several popular articles on the use of probes to colonize the Galaxy. See, for example, Tipler (1980).

[24]**Pg 28 coolest and best summary** Glen David Brin (1950–) trained as an astronomer, but is much better known as an award-winning SF writer. His article on the "Great Silence" (Brin 1983) remains one of the clearest treatments of the subject. In a popular article (Brin 1985) he gives a brief treatment of 24 possible solutions to the Fermi paradox.

[25]**Pg 28 proceedings were published** See Zuckerman and Hart (1995). The updated second edition of this very readable book is easier to obtain than the first.

[26]**Pg 28 the probability of extraterrestrial life is 1** See Aczel (1998) for a breezy account suggesting that the sheer number of stars in the universe means there *must* be life elsewhere: give something enough of a chance to happen and eventually it will. However, many readers may find the arguments leading to this conclusion unconvincing.

[27]**Pg 28 Smolin wrote that** See Smolin (1997).

[28]**Pg 28 Gould wrote that** See Gould (1985).

[29]**Pg 28 and the economist** Mention of economists reminds me of a proof of the non-existence of time travelers that employs Fermi paradox-like reasoning (Reinganum 1986–7): if time travelers existed, then interest rates would not be positive! In fact, if people could travel back in time, then interest rates would have to be 0%—otherwise savers could use banks as bottomless ATM machines. Savers could simply travel back in time a few thousand years, deposit

a few dollars, then return to the present; compound interest on even a small sum would guarantee riches.

[30]**Pg 29 the acid test of experiment** A good example of the need for experiment was Tipler's argument that, in the distant future, we will all be resurrected in software by a God-like intelligence (Tipler 1994). His argument rested on the universe possessing certain cosmological properties; modern observations seem to exclude these properties and thus at least the initial version of Tipler's theory. We wouldn't know this, however, unless astronomers had looked.

They Are Here and They Call Themselves Hungarians

[31]**Pg 32 The joke originated** McPhee (1973) ascribes the "theory" that Hungarians are descended from Martians to Leo Szilard, who would have been one of the Martians. However, a posthumously published letter (Morrison 2011) provides a slightly different—and more likely—account of the tale.

[32]**Pg 32 a formidable array of intellect** The five "Martians" mentioned in the text did indeed constitute an extraordinary grouping of talent. Edward Teller has already been mentioned in a previous note. Leo Szilard (1898–1964) made contributions to molecular biology as well as nuclear physics—and also invented a novel type of home refrigerator; his co-inventor was Einstein! (See Lanoutte (1994) for a good biography of Szilard.) Eugene Paul Wigner (1902–1995) was one of the leading experts in quantum theory. John von Neumann (1903–1957) was hugely influential and made immense contributions in a number of fields. Theodore von Kármán (1881–1963) was one of the world's foremost aeronautical engineers. All five were born in Budapest. Another physicist born in Budapest around the same time, although he never worked at Los Alamos, was Dennis Gabor (1900–1979); he was awarded the Nobel prize for his invention of holography. The radiochemist George de Hevesy (1885–1966) was awarded the 1943 Nobel prize in chemistry; he too was born in Budapest. Such a grouping of talent is rare, but probably not unique. Other pockets of brilliance have occurred from time to time. For example, the 1979 Nobel prize-winning particle theorists Sheldon Lee Glashow (1932–) and Steven Weinberg (1933–), who worked independently on electroweak unification, were in the same class at the Bronx High School of Science. Also in the class was Gerald Feinberg (1933–1992), who developed the idea of the tachyon. In addition to Glashow and Weinberg, the Bronx High School has produced three other Nobel prize-winning physicists! A rather more sinister

constellation of people occurred in 1913 in Vienna, the capital of the Austro-Hungarian Empire: Adolf Hitler, Joseph Stalin, Joseph Tito, Leon Trotsky and Sigmund Freud all lived within a couple of miles of each other. Coincidences happen.

They Are Here and They Call Themselves Politicians

[33]**Pg 34 According to Icke** See, for example, Icke (1999). Icke's was once a well known face on English TV so when I learned about his beliefs I found myself compelled to read one of his books. The book I chose started out badly, rapidly descended to that curious level where something is so bad it's good, but unfortunately continued its descent so that after a few pages I could take no more.

[34]**Pg 34 members of President Obama's administration** See Citizen Hearing on Disclosure (2013) for details of Hellyer's testimony, along with that of 39 other witnesses.

[35]**Pg 34 local election success** At the time of writing, Parkes represents the Stakesby Ward of Whitby Town Council. For details of the 2012 election results, see Scarborough Borough Council (2012). An internet search for Parkes will provide links to several television appearances in which he discusses his dealings with "Mantid" aliens.

[36]**Pg 35 take them seriously** See Nasar (1994) for a thought-provoking biography of the mathematician John Forbes Nash, Jr (1928–), published at around the same time as Nash was awarded the Nobel prize for economics.

They Are Throwing Stones at Radivoje Lajic

[37]**Pg 35 book on materials science** See Miodownik (2013). I know of only one other popular book on materials science that is better than Miodownik's *Stuff Matters*, and that's the classic *New Science of Strong Materials or Why You Don't Fall Through the Floor* (Gordon 1991).

[38]**Pg 35 about 100,000 meteorites** See Brown et al. (2002) for an estimate of the rate at which small objects strike Earth. Although any particular square meter of Earth is unlikely to be struck by a meteorite during any given year, there's at least one well documented case of an extraterrestrial object striking

a human. The Sylacauga meteorite fell in Alabama on 30 November 1954; a fragment crashed through a roof, bounced off a wooden cabinet radio, and struck Ann Hodges on the hip while she slept on a couch.

[39]**Pg 35 lost their ticket** See Guardian (2001) for the story of the couple who failed to claim their winnings in time.

[40]**Pg 36 student called Martin Andrews** For one of the earliest mentions of Gorman's fake story see Digital Spy (2013). A quick internet search will be sufficient to demonstrate how the story mutated.

They Are Watching Us from UFOs

[41]**Pg 37 strange lights in the sky** Ezekiel 1:4–28 contains a description of a wheel in the sky that some have chosen to interpret as a flying saucer. The interpretation of apocalyptic writings is notoriously difficult, but it's probably fair to say that the prophet Ezekiel wasn't describing a physical event. Depending upon one's outlook on these things, he could have been describing a message from God or he might have eaten some funny mushrooms.

[42]**Pg 37 flying his private plane** Kenneth Arnold (1915–1984) wrote about his sighting in *The Coming of the Saucers* (Arnold 1952).

[43]**Pg 37 As surveys consistently show** Many surveys have examined peoples' attitudes to UFOs over the past few decades. Depending on the precise nature of the question asked, the percentage of Americans professing to a belief in the existence of UFOs—which presumably equates to a belief in the existence of extraterrestrial spacecraft—generally ranges between 30 and 50%. For the results of a recent survey see, for example, Harris Interactive (2013).

[44]**Pg 38 coined by Edward Ruppelt** The relatively early death of Edward J. Ruppelt (1922–1959), due to a heart attack, sadly but inevitably sparked more than a few conspiracy theories. A biography of Ruppelt, and a discussion of the 1950s UFO phenomenon from the point of view of "ufologists", is given in Hall and Connors (2000).

[45]**Pg 39 noted skeptic Robert Sheaffer** Many books have been written in support of the thesis that UFOs are alien spacecraft; skeptical approaches

are much less common. One of the clearest skeptical essays on the UFO phenomenon is in Sheaffer (1995).

[46]**Pg 41 we should use Occam's razor** The law of parsimony—the principle which states that entities are not to be multiplied beyond necessity—must have been invoked by numerous philosophers and scientists before the 14th century. But William of Occam (1284–1347) applied the principle so frequently and so sharply that it became known as Occam's razor.

They Were Here and Left Evidence of Their Presence

[47]**Pg 42 footprints of alien technology** See Davies (2012) for a discussion of "astroforensics" and the difficulties involved in searching for traces of past alien activity. In addition to his technical physics writing, Paul Davies is an outstanding writer of popular science; see for example Davies (2010) for some beautifully clear explanations of the Great Silence.

[48]**Pg 42 traces that might yet survive** We can try to get a handle on the present traces of possible past technological activity by asking what elements of our current civilization might survive into the far future. If every person died tomorrow, what evidence that our species had once walked the Earth would survive for a million years? Or ten million years? Or longer? See Weisman (2007) for a popular-level account of the question; a more scientific account, written by a geologist, can be found in Zalasiewicz (2009).

[49]**Pg 42 the Oklo reactor** See Meshik (2005) for a clear, non-technical discussion of the Oklo reactor.

[50]**Pg 44 famous for a series of books** Erich Anton von Däniken (1935–), a Swiss author, wrote his most famous book, *Chariots of the Gods*, when he was working as a hotel manager. He followed it up with titles such as *The Gold of the Gods* and *The Return of the Gods* (see von Däniken 1969, 1972, 1997). For an excellent and entertaining discussion of why these books are wrong-headed, see Story (1976).

[51]**Pg 45 covered them** See Crawford et al. (2008) for a related problem: the survivability and detectability of terrestrial meteorites on the Moon.

[52]**Pg 45 past extraterrestrial visitations** See Davies and Wagner (2013) for a strategy that could be employed to search for alien artefacts on the Moon.

[53]**Pg 45 a bridge** Six decades on it seems strange to us that anyone would claim to have observed a bridge on the Moon, but the Welsh astronomer Hugh Percy Wilkins (1896–1960) was a fine observer. He produced some excellent maps of the near side of the Moon, and was honored in 1961 by having a 57-km diameter lunar crater named after him.

[54]**Pg 46 where might we find them** For a treatment of how we might search for Earth-observing probes, see Freitas and Valdes (1980) and Freitas (1983a, b).

[55]**Pg 46 view the entire planet from space** The idea that a probe might observe Earth over a period of millennia is not so outlandish. Even with our present level of technology, the KEO project plans to put a passive satellite in orbit 1400 km above Earth's surface and have it stay in orbit for 50,000 years. The project was the brainchild of French artist Jean-Marc Phillipe (1939–2008), who came up with the idea in 1994. Phillipe hoped to send a message to our descendants, just as the cave artists of Lascaux sent a message to us. The information was to be encoded on radiation-resistant DVDs, and there would be symbolic instructions in several formats to show any future finders how to build a suitable reader. The current planned launch date is 2015, although at the time of writing it's far from clear that this will be achieved (the launch was initially planned for 2003, but has been delayed several times). See KEO (2014).

[56]**Pg 46 best known are the Lagrangian points** The Italian–French mathematician Joseph-Louis Lagrange (1736–1813) was undoubtedly one of the greatest mathematicians of the 18th century. Perhaps his most important astronomical investigations concerned calculations of the libration of the Moon and of the orbits of the planets. For a brief biography of Lagrange, see Rouse Ball (1908).

[57]**Pg 48 not provide the stable vantage point** Lissauer and Chambers (2008) ran a series of numerical simulations that showed how the gravitational influence of the planets, when combined with the much larger influence of the Sun, are enough to destabilize the orbits on a timescale of a few million years.

[58]**Pg 48 A more prosaic explanation** An explanation of LDEs was given by Lawton and Newton (1974). Their paper responded to the hypothesis presented at length by Lunan (1974) that LDEs were evidence of ETC probes at L4 or L5. See Faizullin (2010) for a different take on the issue.

[59]**Pg 48 long been thought to be home to life** For an excellent account of observations of Mars, see Sheehan (1996).

[60]**Pg 49 in a series of observations beginning in 1877** The Italian astronomer Giovanni Virginio Schiaparelli (1835–1910), director of the observatory at the Brera Palace in Milan, made important observations of meteors and comets before turning his attention to the planets. He wasn't the first to record channels on Mars; the first true map of Mars, published in 1830 by the German astronomers Wilhelm Beer (1797–1850) and Johann Heinrich von Mädler (1794–1874), contains at least one feature that seems to be a channel. Nevertheless, Schiaparelli so popularized the idea of *canali* that they became the defining theme of Mars. Perhaps the most famous of the stories that tapped into the public's subsequent fascination with the red planet was *War of the Worlds* (Wells 1898) by English author Herbert George Wells (1866–1946).

[61]**Pg 49 Lowell also saw** Percival Lowell (1855–1916) came from a wealthy Boston family and only took up astronomy in earnest at the relatively late age of 40. He achieved a lot in science, despite his late start: he had the determination to initiate the search for a planet beyond Neptune, and the Lowell Observatory in Arizona is named after him. However, he'll always be associated with his ideas concerning Mars. For an interesting article about Lowell, see Zahnle (2001).

[62]**Pg 49 in the early 1960s** The Ukrainian astrophysicist Josif Samuelevich Shklovsky (1916–1985) is best known for his explanation of continuum radiation from the Crab Nebula, but he also made important contributions in cosmic ray astronomy and on the distance scale for planetary nebulae. His popular book *Intelligent Life in the Universe*, which Carl Sagan had translated from the Russian and then expanded upon, is a classic in the field (Shklovsky and Sagan 1966). The American astronomer Bevan P. Sharpless (1904–1950), on whose observations Shklovsky based his suggestion regarding Phobos, worked at the US Naval Observatory; poor health hampered his work throughout his career and he died early. The fifth largest crater on Phobos is named after him.

[63]**Pg 49 Salisbury pointed out** The German-born astronomer Heinrich Louis d'Arrest (1822–1875), who became director of the Copenhagen Observatory, mounted a thorough search for Martian moons in 1862. However, it was the American astronomer Asaph Hall (1829–1907) who discovered the moons in 1877 (see Sheehan 1996 for further details). The reason Hall found them and d'Arrest did not is simple: the Martian satellites are much closer to the planet than d'Arrest thought possible. Hall looked in the right place; d'Arrest did not. Thus, the suggestion by American biologist Frank Boyer Salisbury (1926–) that Phobos and Deimos were artificial satellites launched between 1862–1877 is unnecessary.

[64]**Pg 53 but no human face** The Cydonian "face" was first pointed out in 1977 by American electrical engineer Vincent DiPietro. The view that the face is artificial has been championed most strongly by the American writer Richard C. Hoagland (1945–). See, for example, Hoagland (1987). See Hancock et al. (1998) for another book in similar vein. For a refreshingly sane article about the face, see Gardner (1985).

[65]**Pg 54 Papagiannis argued** The Greek–American astronomer Michael Demetrius Papagiannis (1932–1998) was the first president of the International Astronomical Union's commission on bioastronomy. See Papagiannis (1978) for his suggestion regarding hiding places for colonies in the Asteroid Belt. Kecskes (2002) offers reasons why humanity might end up as "asteroid dwellers". Is this another solution to the paradox: ETCs choose to colonize not space, which is difficult, but their home system's Asteroid Belt?

[66]**Pg 54 mine the asteroids for natural resources** There has been discussion about the possibility of mining the asteroids for various minerals; however, it might turn out that such activity is prohibitively expensive. See Elvis (2014).

[67]**Pg 54 the result of an astroengineering project** See Stephenson (1978).

[68]**Pg 55 Loeb and Turner showed** See Loeb and Turner (2012) for a discussion of how it would be possible to search for artificially illuminated objects in the outer Solar System.

[69]**Pg 55 a professor of electrical engineering** The first paper to calculate the minimum distance for the Sun's gravitational lens was von Eshleman (1979).

[70]**Pg 56 Maccone, who perhaps more than anyone** For more on the possibility of exploiting the Sun as a gravitational lens, see Maccone (1994, 2000, 2009, 2011, 2013) and Maccone and Piantà (1997).

[71]**Pg 56 the Belgian astrophysicist Michaël Gillon** For details of the argument that SETI could do worse than focusing on the solar focus, see Gillon (2014).

[72]**Pg 56 spectacular observatories** In Webb (2012) I give an account of the many observatories that have recently come on line or are in the planning stage.

[73]**Pg 57 can't rule out the possibility** See Haqq-Misra and Kopparapu (2012) for an in-depth discussion of why it's difficult to assert that there are no small (say, 1–10 m) probes in the Solar System. They argue that searching the Solar System at the spatial resolution required to detect a 1–10 m probe is analogous to searching for a needle in a 1000-ton haystack.

[74]**Pg 57 has yet been uncovered** See Freitas (1983, 1985).

[75]**Pg 58 embed some sort of signal** See shCherbak and Makukov (2013) for the claim that a signal is embedded in the terrestrial genetic code.

[76]**Pg 58 a few investigations have been performed** See Yokoo and Oshima (1979).

They Exist and They Are Us—We Are All Aliens!

[77]**Pg 59 dates back to Anaxagoras.** Anaxagoras (c. 500–428 BC), one of the greatest of Greek philosophers and the teacher of Socrates, spoke of the "seeds of life" from which spring all organisms. See O'Leary (2008).

[78]**Pg 59 a book by Arrhenius** The Swedish chemist Svante August Arrhenius (1859–1927) is best known as the man who helped lay the foundations of modern physical chemistry. His book *Worlds in the Making* popularized the notion that life on Earth might have arrived from space. See Arrhenius (1908).

[79]**Pg 60 mass outbreaks of disease** The astronomers Fred Hoyle (1915–2001) and Nalin Chandra Wickramasinghe (1939–) have made exceptional contributions to science, but they have also proposed several hypotheses that go against received wisdom. This is one such hypothesis. Nevertheless Hoyle, Wickramasinghe and collaborators have published widely on the subject. See for example Hoyle and Wickramasinghe (2000) and references therein. The physicist Thomas Gold (1920–2004) was another scientist who liked to propose unorthodox ideas. He jokingly proposed the "garbage" scenario for the origin of terrestrial life: ETCs landed here, dumped their waste, and the contamination from the garbage was the seed for life!

[80]**Pg 60 the ability of some extremophiles** Calculations tend to suggest that life would struggle to survive the radiation environment found in space; see for example Secker, Wesson and Lepock (1996). Nevertheless, Lage (2012) demonstrates the remarkable capacities for survival of extremophiles in conditions that attempt to simulate those found in the space environment.

[81]**Pg 60 inactivated virus-like organisms** See Wesson (2010) for the interesting notion of necropanspermia.

[82]**Pg 60 *directed* panspermia** See Crick and Orgel (1973) and Crick (1981). The English biophysicist Francis Harry Compton Crick (1916–2004) gained fame for his discovery, along with the American biochemist James Dewey Watson (1928–), of the double-helix structure of DNA. The English-born biochemist Leslie Eleazer Orgel (1927–2007) made major contributions to the study of life's origins. The Crick–Orgel idea of directed panspermia originated at the first conference on communication with extraterrestrial intelligence, organized in 1971 by Sagan and Kardashev, and held at the Byurakan Astrophysical Observatory in Armenia. Many of the luminaries in the field of SETI attended this conference.

The Zoo Scenario

[83]**Pg 61 zoo scenario was proposed** The American astronomer John Allen Ball (1935–) has written extensively on the Fermi paradox. For the zoo hypothesis, see Ball (1973).

[84]**Pg 61 be in control of the universe** Hair (2011) argues that if the oldest civilization still present in the Galaxy had a hundred million year "head start"

on the next oldest civilization then they could have established a hegemony that guides the development of younger civilizations; in that case, he suggests, a modified zoo scenario is an appealing answer to the Fermi paradox. See Forgan (2011) for a criticism of the idea that a total hegemony could be established that would allow the zoo scenario to occur.

[85]**Pg 62 editorship of John Campbell** Asimov's famous "humans-only" Galaxy was a reaction against Campbell's insistence that humans should always win out against aliens. Asimov thought that human civilization would be less advanced than any extraterrestrial civilizations we might encounter, and he couldn't bring himself to write stories in which primitive Earth technology triumphed over superior alien technology (see Asimov 1979). On the other hand, he wanted to sell stories to Campbell. He therefore removed the potential source of conflict, and his *Foundation* trilogy described a Galaxy containing only humans. If the Fermi paradox implies that we are alone, then perhaps an empire something like Asimov reluctantly described will come to pass.

[86]**Pg 62 to slowly prepare us** The leaky embargo hypothesis was proposed by James Warner Deardorff (1928–2014), a retired atmospheric physicist; for details of the proposal see Deardorff (1986, 1987). Although Deardorff had a scientific background, his leaky embargo hypothesis is unscientific. For a nice introduction to scientific method, which uses Deardorff's hypothesis as an example to be critiqued, see Carey (1997).

The Interdict Scenario

[87]**Pg 63 expanded form of the zoo scenario** See Fogg (1987) for the original presentation of the interdict hypothesis; Fogg (1988) is a more popular account. Martyn J. Fogg (1960–) originally trained as a dentist. He's now one of the foremost authors on "speculative" engineering techniques, such as terraforming.

[88]**Pg 64 Asimov pointed out** See Asimov (1981) for a dated but still readable introduction to the subject. Asimov was an optimist and argued that half a million planets in our Galaxy are home to technological civilizations.

[89]**Pg 64 a *Codex Galactica* is established** The notion of a *Codex Galactica* is discussed in Newman and Sagan (1981); note, however, that this is yet another idea that appeared in the pages of SF magazines before gaining respectability in the pages of a refereed journal.

The Planetarium Hypothesis

[90]**Pg 66 Baxter has proposed** The British writer Stephen Baxter (1957–) is known for his "hard" science fiction. For details of his planetarium hypothesis, see Baxter (2000a).

[91]**Pg 67 a fake town** Many examples exist of this paranoid trope in SF. The earliest such story of which I'm aware is "The Earth-Owners" by Edmond Hamilton (1904–1977), which describes an Earth invaded by aliens in disguise; the aliens, of course, are busy manipulating us. Hamilton's story appeared in the August 1931 issue of *Weird Tales*. Historians of science fiction could doubtless point to even earlier examples. The Asimov story was "Ideas Die Hard" (*Galaxy*, October 1957). Weiner's "The News from D Street" appeared in the September 1986 issue of *IASFM*. The philosophical considerations underpinning the planetarium hypothesis are well discussed in Deutsch (1998); see also Tipler (1994).

[92]**Pg 69 Bekenstein showed** The Bekenstein bound is named after the Mexican-born US–Israeli physicist Jacob David Bekenstein (1947–), who introduced the concept in terms of the thermodynamics of black holes.

[93]**Pg 70 most readers would wager is the case** The idea that our universe is a simulation is being debated quite seriously by heavyweight philosophers, so perhaps we shouldn't be too quick to discount the idea. See for example Bostrom (2003) and Bostrom and Kulczycki (2011). A physics paper that takes the proposition seriously (Beane et al. 2012) concludes that in principle there'll always be the possibility for the simulated to discover the simulators.

God Exists

[94]**Pg 70 think of them as gods** A haunting short story called the "The Last Question" (see Asimov 1959) tells how a pair of drunken technicians one night ask a supercomputer whether there is a way to reverse the increase of entropy and thereby halt the death of the universe. The computer says there is insufficient data for a meaningful answer. The same question is asked of the computer six times over many different epochs. I won't spoil the story by telling you the computer's final answer!

[95]**Pg 72 evolutionary ideas to cosmology** See Smolin (1997) for a discussion of why we might want to apply Darwinian thinking to the problem of the universe as a whole.

[96]**Pg 74 a specific forecast** The Austrian–British philosopher Karl Raimund Popper (1902–1994) propounded the notion that scientific hypotheses must be falsifiable. The drive to falsify hypotheses is the essence of science. If an hypothesis cannot be tested and perhaps found to be false, then it isn't a valid part of the process of science. See for example Popper (1963). Although his views about scientific progress have been attacked, they remain influential. Smolin's idea is certainly falsifiable, since it makes specific testable predictions; the novelty is that it must be tested by calculation rather than experiment.

[97]**Pg 74 speculation one step further** See Harrison (1995). Byl (1996) criticizes Harrison's speculation as being post hoc, unverifiable and essentially a more elaborate version of the theistic or anthropic principles. For further reading about the notion of a multiverse see Gribbin (2010) for a popular account and Carr (2007) for more technical aspects. See Vaidya (2007) for a mention of the Fermi paradox in the multiverse setting.

They Exist, But We Have Yet to See or Hear from Them

[98]**Pg 77 the aestivation hypothesis** At the time of writing, details are only available as a preprint (Sandberg et al. 2014).

The Stars Are Far Away

[99]**Pg 79 Voyager will take** For information about Voyagers 1 and 2 see Voyager (2013). For useful material on several of the advanced propulsion concepts discussed in this section see NASA (2013).

[100]**Pg 79 the speed of light** According to the theory of special relativity, massless objects such as photons always travel at light speed c, while objects with non-zero mass inevitably travel more slowly. Of course, it's possible to accelerate a slow-moving body to a faster speed by acting upon it with a force. Unfortunately for the prospects for space travel, special relativity tells us that the faster things move the more massive they become. At speeds close to c, the accelerating force tends to make the body more massive rather than make it move faster. The speed of light is a barrier that can't be reached by any object with mass—including space ships. For a good introduction to these concepts, see French (1968).

[101]**Pg 79 nearest star to our Sun** See Webb (1999) for an in-depth discussion of astronomical distances.

[102]**Pg 79 Bernal proposed the idea** John Desmond Bernal (1901–1971), an Irish physicist, published the idea of a generation ship in a visionary book (see Bernal 1929). His book contains the following quote, which is relevant to any discussion of the Fermi paradox. "Once acclimatized to space living, it is unlikely that man will stop until he has roamed over and colonized most of the sidereal universe, or that even this will be the end. Man will not ultimately be content to be parasitic on the stars but will invade them and organize them for his own purposes." For "man" read "ETC". So—where *are* they?

[103]**Pg 79 Heinlein's story *Universe*** The short novel *Universe*, written by the American author Robert Anson Heinlein (1907–1988), appeared in the May 1941 issue of *Astounding Science Fiction*. (It can be found more easily in Bova (1973).) The story is one of many SF classics penned by Heinlein.

[104]**Pg 80 things that we can learn** Crawford (2009) makes the science case for interstellar spaceflight. There's only so much one can learn by telescopic observation. In order to make progress in astronomy, astrobiology and planetary science, there's a strong argument that we must develop interstellar spaceflight.

[105]**Pg 80 possible within a human lifetime** This possibility was dramatized by the American writer Poul William Anderson (1926–2001) in his novel *Tau Zero* (Anderson 2000). The novel tells the story of a ramjet that accelerates to speeds so close to *c* that circumnavigation of the universe becomes possible.

[106]**Pg 82 might be able to detect them** For a possible addition to the SETI search strategy, see Garcia-Escartin and Chamorro-Posada (2013). The authors suggest that we should look for reflected light from objects traveling at relativistic speeds.

[107]**Pg 82 a navigation problem** For an interesting discussion of the problems inherent in navigating to a particular star, see Hemry (2000).

[108]**Pg 82 by Eugen Sänger** In addition to as conceiving the idea of an antimatter rocket, the Austrian scientist Eugen Sänger (1905–1964) pioneered several practical ideas in rocketry. For superb introductions to many different proposals for interstellar travel, see Mallove and Matloff (1989) and Crawford (1995).

[109]**Pg 83 a *fusion ramjet*** Bussard's idea for the ramjet appeared over half a century ago (Bussard 1960). Since then, various authors have made proposals and suggestions for the improvement of the initial ramjet design.

[110]**Pg 83 Forward began to consider** Robert Lull Forward (1932–2002), as with many of the scientists mentioned in this book, was also a successful SF writer. For a technical discussion of the laser sail, and how it might be used in a round-trip interstellar mission, see Forward (1984).

[111]**Pg 83 have designed schemes** See Dyson (1982) for a discussion of how laser sails could be used in colonization methods; see Wright (1992) for a general discussion of space sailing.

[112]**Pg 83 sail would be expensive** For a discussion of the costs and required technologies associated with different types of sail, see Andrews (2004).

[113]**Pg 84 a gigantic, massive mirror** Shkadov (1987) introduced the thruster idea. See Forgan (2013) for how we might detect the use of a Shkadov thruster by an ETC. Benford and Niven (2012) give a fictional account of a star thruster.

[114]**Pg 84 near light speed** Stanislaw Marcin Ulam (1909–1984), a Polish-born mathematician, contributed to several fields. His autobiography (Ulam 1976) is fascinating. (Ulam appears in fig. 4.9 on page 116.) The English-born physicist Freeman John Dyson (1923–) is one of the most imaginative physicists of his generation, and has contributed to many topics mentioned in this book. For the papers on gravitational propulsion, see Ulam (1958a) and Dyson (1963).

[115]**Pg 85 negative mass** For a discussion of negative mass, see Forward (1990).

[116]**Pg 85 no evidence such particles exist** In September 2011, the OPERA experiment shocked physicists by announcing they had observed muon neutrinos traveling faster than c (OPERA Collaboration 2011). A few months later they retracted their claim, stating the original results were affected by equipment failures.

[117]**Pg 87 novel *Contact*** Carl Edward Sagan (1934–1996) based the science in his novel *Contact* (Sagan 1985) on work by the American theoretician Kip

Stephen Thorne (1940–) who has been prominent in investigating the properties of wormholes. (For a popular account of this work, see Thorne (1994).) In 1997, Sagan's novel was made into a movie of the same name, starring Jodie Foster.

[118]**Pg 87 a certain class of wormhole** For details of the Krasnikov tube, see Krasnikov (1998).

[119]**Pg 88 surfs a spacetime wave** Miguel Alcubierre Moya (1964–), a Mexican theoretical physicist, is now Director of the Nuclear Sciences Institute at the National Autonomous University of Mexico. See Alcubierre (1994) for his paper describing the warp drive.

[120]**Pg 88 unrealistic features** For details on the possibility of using wormholes for transport, see Krasnikov (2000). For details on Van Den Broeck's warp drive, see Van Den Broeck (1999). These matters have been covered in detail, and at a non-mathematical level, in John Cramer's "Alternate View" columns in *Analog*.

[121]**Pg 89 The Casimir effect** In 1948, the Dutch physicist Hendrik Brugt Gerhard Casimir (1909–2000) predicted that quantum fluctuations of the EM field would cause a small attractive force to act between two close parallel uncharged conducting plates. The first measurement of the Casimir force between parallel plates took place in 2002 (see Bressi et al. 2002). The experiment confirmed Casimir's predictions. For articles propounding the idea that mankind might one day mine the zero-point energy see, for example, Haisch et al. (1994) and Puthoff (1996).

[122]**Pg 89 safely to Saturn and back** It might be that the future of human exploration of the Solar System over the next few decades lies in a combination of human and robotic elements. For example, having humans land on Enceladus, a moon of Saturn that provokes interest for a variety of reasons, would be risky and costly. Perhaps a better bet would be to have astronauts orbit Enceladus while they used teleoperation to control rovers and robots on the surface. See Schmidt et al. (2012).

They Have Not Had Time to Reach Us

[123]**Pg 90 temporal explanation of the paradox** One of the first responses to Hart's paper was by Cox (1976). Cox argued that a temporal explanation of the paradox is indeed valid.

[124]**Pg 91 Several authors have developed** See for example Jones (1975, 1981). In Jones (1995) the author has written a particularly entertaining discussion of various colonization processes, from past human expansions through to possible human settlement of the Solar System and nearby stars. See also Finney and Jones (1985).

[125]**Pg 91 demands of population growth** See Newman and Sagan (1981).

[126]**Pg 92 detailed model of galactic exploration** See Bjørk (2007) for details of his exploration algorithm.

[127]**Pg 92 expanded on Bjørk's model** See Cotta and Morales (2009).

[128]**Pg 93 models have been analyzed** See Crawford (2000) for a well-written account of galactic colonization models and their relation to the Fermi paradox. See Fogg (1987) for details of one particular model of galactic colonization.

[129]**Pg 93 Prantzos reinforced this conclusion** See Prantzos (2013) for an interesting framework in which to think about the Fermi paradox.

A Percolation Theory Approach

[130]**Pg 93 bases his model** Geoffrey Alan Landis (1955–), an American physicist who works at NASA, is yet another scientist who is perhaps better known as an SF writer. For details of his approach, see Landis (1998).

[131]**Pg 94 key task in a percolation problem** Percolation theory was developed in 1957 by the British mathematician John Michael Hammersley (1920–2004) and his colleagues. See Stauffer (1985) for the best introduction to the ideas of percolation theory; however, although this excellent book is entertaining reading, readers should be aware that it inevitably contains an element of mathematics.

[132]**Pg 97 conclusion is similar** See Kinouch (2001) for details of the "persistence solution" to the Fermi paradox.

[133]**Pg 97 an economist's point of view** See Hanson (1998) for an interesting model of colonization. To fully appreciate the argument requires some mathematics, but the conclusions are clearly expressed in layman's terms. See also Bainbridge (1984).

[134]**Pg 98 simple extensions of the model** See Wiley (2011) for a detailed critique of the percolation model, as well as various other colonization models.

Wait a Moment

[135]**Pg 99 Martin Gardner popularized** The *Game of Life* was devised by the British mathematician John Horton Conway (1937–) as an offshoot of his thinking on von Neumann's attempt to construct a mathematical model of a self-replicating machine. The game became an immediate hit amongst the public when Martin Gardner (1914–2010) discussed it in his "Mathematical Games" column in *Scientific American* (Gardner 1970).

[136]**Pg 100 Fermi was the first to dabble** See Metropolis (1987) for the early history of the Monte Carlo method, including Fermi's early experimentation and Ulam's.

[137]**Pg 101 to the study of the Fermi paradox** See for example Forgan (2009).

[138]**Pg 101 sophisticated cellular automata** See Vukotić and Ćirković (2012).

The Light Cage Limit

[139]**Pg 102 a model of migration** See McInnes (2002) for a discussion of how ETCs could be hindered by the light cage limit. The basic idea was briefly mentioned much earlier by von Hoerner (1975).

[140]**Pg 103 Baxter calls this radius** See Baxter (2000b) for an interesting fictional take on one possible solution to the Fermi paradox.

They Change Their Mind

[141]**Pg 104 planets must be re-engineered** Fogg (1995) is perhaps the most comprehensive resource on terraforming, and how it might be possible to engineer a planet so that it becomes suitable for life.

[142]**Pg 104 some simple equations** See Gros (2005) for details of rate equations that govern the population dynamics of civilizations that are assumed to be able to change character and priorities.

We Are Solar Chauvinists

[143]**Pg 105 simply inapplicable** This resolution to the Fermi paradox was discussed in Rood and Trefil (1981), a book that is now sadly out of print.

[144]**Pg 105 encloses the star** The concept of the Dyson sphere first appeared in Dyson (1960). (A Dyson sphere is a *loose* collection of bodies moving on independent orbits around a star; a rigid sphere would be unstable.) The idea inspired two great SF novels: *Ringworld* (Niven 1970) and *Orbitsville* (Shaw 1975). Scientists have suggested numerous other mega-engineering projects that technologically advanced ETCs might embark upon. For example, Roy et al. (2013) discuss the possibility of "shell worlds". A shell world is formed by enclosing an airless, sterile body by a shell of material to create a cozy home for life.

[145]**Pg 106 a better analogy for colonization** Kecskes (1998, 2002) outlines a possible "trajectory" for the development of technical civilizations: they move from being planet dwellers to asteroid dwellers to interstellar travelers to interstellar space dwellers. In this picture we don't meet extraterrestrials because our habitats are different.

Aliens Are Green

[146]**Pg 108 Haqq-Misra and Baum propose** See Haqq-Misra and Baum (2009) for a discussion of the "sustainability solution" to the Fermi paradox.

They Stay at Home . . .

[147]**Pg 110 happened on 20 July 1969** The American astronauts Neil Alden Armstrong (1930–2012) and Edwin Eugene Aldrin Jr. (1930–) landed at the edge of Mare Tranquillitatis on 20 July 1969; Armstrong walked on the Moon at 22:56 (Eastern Daylight Time). The *last* man to walk on the Moon was Eugene Andrew Cernan (1934–), and unfortunately he seems set to hold this honor for quite some time to come. Cernan recounts his experiences of the Apollo program in Cernan and Davis (1999). Smith (2005) is an evocative account of the Apollo era.

[148]**Pg 111 China expanded her empire** The two emperors mentioned in the text were Hongwu (1328–1398) and Yongle (1359–1424). The incredible voyages of the admiral Zheng He (c. 1371–c. 1435), a court eunuch and diplomat, have only relatively recently come to light. For a readable account of the seven epic voyages made by Zheng He, see Levathes (1997).

[149]**Pg 111 cause us serious problems** "Inconstant Moon", one of the finest stories by the American author Laurance (Larry) van Cott Niven (1938–), describes the events of a single night when the full moon shines brighter than ever before. It's a gem of a tale, and deservedly won the 1972 Hugo award for best short story; it's available in Niven (1973).

[150]**Pg 111 Zuckerman has shown** See Zuckerman (1985).

. . . and Surf the Net

[151]**Pg 113 plausible future for humankind** Set a billion years in the future, *The City and the Stars* (Clarke 1956) imparts a sense of wonder and magnificent scope few novels can match. In the novel Arthur Clarke presents at least two explanations of the Fermi paradox, including the notion that beings might prefer to stay in the "City"—safe from facing the realities of a harsh universe.

Against the Empire

[152]**Pg 114 Ćirković points out** See Ćirković (2008) and references therein.

[153]**Pg 115 already being debated** See for example Rummel (2001) for thoughts about the problems of contamination when we engage in planetary exploration.

[154]**Pg 115 Bostrom's term** For a definition of the term "singleton", see Bostrom (2005). See also Caplan (2008) for a discussion of the problems with singletons.

Bracewell–von Neumann Probes

[155]**Pg 117 As long ago as 1980** For an early discussion of interstellar exploration by probe, see Freitas (1980). As mentioned in chapter 2, the relevance of self-reproducing probe technology to the Fermi paradox was considered by Tipler (1980). One could argue that the starting point for the discussion is even earlier, with Crick's motto for directed panspermia (see page 60): "bacteria go further". Crick and Orgel argued that a small probe filled with a payload of bacteria would be easy to construct, cheap to propel, and would enable an ETC to seed the Galaxy. However, a bacteria-filled probe is of little use to an ETC wanting to explore and learn about the Galaxy. To be successful in that endeavor, a Bracewell–von Neumann probe would be better.

[156]**Pg 118 The first person to suggest** The Australian-born electrical engineer Ronald Newbold Bracewell (1921–2007) was for many years a leading light in SETI. See Bracewell (1960).

[157]**Pg 118 more recent investigations** See for example Forgan et al. (2013) and Nicholson and Forgan (2013) for discussions of how the judicious use of the slingshot effect could reduce the time for galactic exploration by probe; in particular, if self-reproducing probes make use of the slingshot effect then colonization times can be similar to that calculated by Tipler. See Barlow (2013) for yet another analysis of galactic colonization in the context of Bracewell–von Neumann probes. Cartin (2013) discusses a different approach to colonization, which doesn't involve self-reproducing probes.

[158]**Pg 119 probes for interplanetary exploration and exploitation** Mathews (2011) argues that probes are a natural extension of our planetary explorer craft. We'll send out robots, not humans, to explore the Solar System. Perhaps the development of this technology will lead us on a path to the sort of self-reproducing probes discussed in the text.

[159]**Pg 119 not exactly a risk-free technology** For a criticism of galactic exploration via Bracewell-von Neumann probes, and why it might not work, see Chyba and Hand (2005). Wiley (2011), however, concludes that criticisms of the self-reproducing probe approach to galactic colonization possess little merit.

[160]**Pg 120 significantly sharpened the paradox** See Armstrong and Sandberg (2013).

Information Panspermia

[161]**Pg 121 an interesting hypothesis** For details of the argument that the universe might be full of low-complexity bit strings, see Gurzadyan (2005). See Scheffer (1993) for an earlier and thorough defense of the notion that "information transfer" is a much cheaper option for interstellar travel than physical travel. Scheffer resolves the Fermi paradox by arguing that the first civilization to colonize its galaxy will have done all the hard work; for any emerging society it will be overwhelmingly attractive to join the existing civilization rather than try to physically colonize the galaxy. There will be a single, unified civilization. If that first civilization in our Galaxy didn't bother to contact Earth, for whatever reason, then subsequent societies won't have bothered either.

[162]**Pg 121 *Kolmogorov complexity*** The idea that a measure of the complexity of a system can be the length of an algorithm that produces that system is due to Andreii Nikolaevich Kolmogorov (1903–1987), who was one of the outstanding mathematicians of the twentieth century. For an appreciation of just some of Kolmogorov's output, see for example Parthasarathy (1988).

[163]**Pg 122 our extinct cousins, the Neanderthal** In December 2013, scientists published a high-quality genome sequence from a Neanderthal woman who lived 130,000 years ago in what is now Siberia. The DNA came from one of her toe bones. See Prüfer et al. (2013).

Berserkers

[164]**Pg 123 famous berserker stories** The American author Fred Thomas Saberhagen (1930–2007) wrote many stories about berserkers, with the first

collection appearing in *Berserker* (Saberhagen 1967). The concept of a Doomsday weapon was brilliantly satirized by Stanley Kubrick in *Dr. Strangelove*, and the original *Star Trek* television series aired an episode called *The Doomsday Machine*, which dramatized the notion of an indestructible world-killing machine (though Kirk & Co. managed to destroy it, of course). The machine in *Star Trek* was a single, large, slow-moving object. My mental picture of berserkers is somewhat different: I imagine swarms of small, fast-moving machines. A novel entitled *The Unreasoning Mask*, by the American author Philip José Farmer (1918–2009), is another that treats the notion of world-killers (Farmer 1981). But perhaps the idea of malignant killing machines has been treated most thoroughly by the American astrophysicist Gregory Benford (1941–), who is also one of the finest modern SF writers; see, for example, Benford (1977).

They Are Signaling but We Don't Know How to Listen

[165]**Pg 126 no plausible signatures** See Jugaku and Nishimura (1991). They continued their search of the solar neighborhood, but failed to find any candidates; see Jugaku and Nishimura (1997, 2000)

[166]**Pg 126 found nothing unusual** See Mauersberger et al. (1996)

[167]**Pg 126 Carrigan carried out** See Carrigan (2009). For an entertaining essay on whether interstellar archaeology is possible, see Carrigan (2010, 2012).

[168]**Pg 126 Wright and his colleagues** For a discussion of the G-HAT search for Kardashev civilizations see for example Battersby (2013).

[169]**Pg 127 Minsky pointed out** It was at the seminal Byurakan conference on communication with extraterrestrial intelligence that the American computer scientist Marvin Lee Minsky (1927–) pointed out that a truly advanced energy-conscious ETC might radiate at a temperature just above the cosmic background. See Minsky (1973).

[170]**Pg 127 beacons can be transmitted** Whitmire and Wright (1980) was not the first paper to suggest the stars themselves could be used to send signals. Philip Morrison (1915–2005) suggested the "eclipse" method 20 years earlier, and Drake had made similar suggestions before. But their paper is perhaps

the first to give detailed calculations of how to modify stellar spectra to send a signal.

[171]**Pg 127 rule out a natural phenomenon** See page 245 of Sullivan (1964). See also Arnold (2013).

[172]**Pg 128 brainchild of Ray Davis** The American chemist Raymond Davis Jr. (1914–2006) ran his solar neutrino experiment for more than three decades, and was awarded the 2002 Nobel prize for his research. See Bahcall and Davis (2000) for the early history of neutrino astronomy.

[173]**Pg 129 neutrino beams to communicate** For discussions of neutrino-based searches for extraterrestrial intelligence, see for example Learned et al. (1994), Silagadze (2008) and Learned et al. (2009).

[174]**Pg 130 problem of detecting gravitational waves** Einstein's theory of general relativity predicted the existence of gravitational waves—ripples in spacetime. Such waves were demonstrated indirectly by the American physicists Joseph Hooten Taylor Jr. (1941–) and Russell Alan Hulse (1950–) through exquisitely accurate observations of PSR 1913+16. This pulsar is part of a binary system, its partner being another neutron star. As the two stars orbit each other, they lose energy in precisely the manner predicted by general relativity: the binary system is radiating gravitational energy in the form of waves. See Weisberg and Taylor (2005) for more information. The current generation of detectors is typified by LIGO (Laser Interferometer Gravitational-wave Observatory). If LIGO doesn't observe gravitational waves then astronomers will pin their hopes on the next generation of detectors, of which the Einstein Observatory is perhaps most advanced.

They Are Signaling but We Don't Know at Which Frequency to Listen

[175]**Pg 133 first to consider this question** The Italian physicist Giuseppe Cocconi (1914–2008) worked at Cornell University with Morrison before returning to Europe to work at CERN, where he eventually became Director. Their paper (Cocconi and Morrison 1959) is one of the classics in SETI.

[176]**Pg 134 it will send a *narrowband signal*** Although there are good reasons for concentrating on narrowband signals, increasing attention is being paid to

the possibility of wideband signals. The search for wideband signals is much more challenging than the search for narrowband signals; on the other hand, a wideband beacon can carry vastly more information than a narrowband beacon. For more information on wideband SETI see, for example, papers by Benford, Benford and Benford (2010a, b); Harp et al. (2011); Messerschmitt (2012); Morrison (2012).

[177]**Pg 137 study other frequencies** For suggestions of some other likely SETI frequencies see Kardashev (1979), Mauersberger et al. (1996) and Kuiper and Morris (1977).

[178]**Pg 138 a new search strategy** Hair (2013) considers some of the difficulties in applying statistical techniques to any "long stare" strategy that hopes to construct an archive of provocative radio transients.

[179]**Pg 138 from some unknown terrestrial source** See Gray (2011) for an entertaining and in-depth discussion of the "Wow!" signal, and one man's attempt to understand it better.

[180]**Pg 139 increased in sophistication over time** See Tartar (2001) and Bowyer (2011) for more background on SETI projects.

[181]**Pg 139 developed in 1985 by Paul Horowitz** Paul Horowitz (1942–), a Harvard astronomer, has been at the forefront of SETI research for several years. Much of the funding for META came from Steven Spielberg (1947–), the director of the film *E.T. the Extra-Terrestrial*. See Lazio, Tarter and Backus (2002) for a discussion of Project META

[182]**Pg 139 piggybacks on radio telescopes** The idea for SERENDIP originated with the American astronomers C. Stuart Bowyer (1934–) and Jill Tarter (1944–) in 1978. Tarter, who in 2012 announced her retirement from the position as director of research at the SETI Institute, is an icon in the field. She is widely believed to have been the inspiration for Sagan's heroine in *Contact*. See for example Korpela et al. (2011) for further information about SERENDIP and other SETI-related projects.

[183]**Pg 139 has great potential** For background on and papers about the Allen Telescope Array see, for example, Welch et al. (2009), Siemion et al. (2010) and Tarter et al. (2011).

[184]**Pg 139 also play a role** For contrasting viewpoints on how the SKA might be relevant to SETI see, for example, Penny (2004), Loeb and Zaldarriaga (2007), Forgan and Nichol (2011), Rampadarath et al. (2012).

[185]**Pg 139 Optical SETI is not as advanced** The slow uptake of OSETI is perhaps due to the relative novelty of the technology. Credit for the invention of the laser is a matter of some dispute (see, for example, Hecht (2010). The American physicists Arthur Leonard Schawlow (1921–1999) and Charles Hard Townes (1915–2015) were both awarded the Nobel prize for laser-related work (Townes in 1964 and Schawlow in 1981). Townes was far-seeing in regard to the potential of lasers. The suggestion that SETI should consider optical searches is almost as old as the Cocconi–Morrison paper: see Schwartz and Townes (1961).

[186]**Pg 140 starting to develop large-scale projects** For two early examples of optical searches, see Eichler and Beskin (2001) and Reines and Marcy (2002). See Korpela et al. (2011) for further details of Project SEVENDIP.

[187]**Pg 140 Ball once hypothesized** See Ball (1995).

[188]**Pg 140 play the role of "synchronizers"** See Corbet (1999) for a discussion of the role that gamma-ray bursts might play in synchronizing signals; essentially, they would act as universal timing markers.

[189]**Pg 141 Local Group of galaxies** See LePage (2000).

They Are Signaling but We Don't Know Where to Look

[190]**Pg 142 taken this approach** See Turnbull and Tarter (2003a, b) for details of the *Hipparcos* habstars.

[191]**Pg 142 judged to be most amenable** Siemion et al. (2013) discuss a targeted search of 86 *Kepler* objects of interest; they looked for radio emission from ETCs, but found none.

[192]**Pg 142 more readily discovered** See Nussinov (2009) for an interesting suggestion about preferred directions for SETI.

[193]**Pg 142 straight-line alignments** For details of this suggestion, and for one way in which pulsars might be used as beacons, see Edmondson and Stevens (2003) and Edmondson (2010).

[194]**Pg 143 as many stars as possible** See Hohlfeld and Cohen (2000) and Cohen and Hohlfeld (2001).

[195]**Pg 144 a universal frequency** The "universal" frequency standard was first discussed by Drake and Sagan (1973). See also Gott (1995).

The Signal is Already There in the Data

[196]**Pg 145 logged several pulses** From a total of about 60 trillion events, META researchers found only 11 good candidate signals. If these signals were really attempts at communication, however, why could astronomers not observe them again? One suggestion was that interstellar plasmas or gravitational microlenses, passing between the sources and Earth, caused what were steady beacon-like signals to "twinkle"—and temporarily become strong enough for us to detect. A detailed analysis of the data ruled out this possibility, however, and the result seemed to indicate that the Galaxy contains at most one other civilization with a comparable level of technology to ours that is deliberately trying to contact us. See Lazio, Tarter and Backus (2002).

We Haven't Listened Long Enough

[197]**Pg 146 profoundly change the world** Drake wrote this in the Preface to *Is Anyone Out There?* (Drake and Sobel 1991).

[198]**Pg 146 have to be patient** At the turn of the millennium, 39% of almost 75,000 respondents to an online poll stated they believed that the discovery of an ET signal would happen within 10 years (SETI@home 2000). Fourteen years later, we're still waiting.

They Are Signaling but We Aren't Receiving

[199]**Pg 147 an amateur scientist** Although Smith is an "amateur" scientist, he has published in a variety of reputable and peer-reviewed journals across a range of fields. Regarding his contribution to the Fermi paradox debate, see Smith (2009).

Everyone is Listening, No One is Transmitting

[200]**Pg 149 no one is transmitting** This idea, that we might live in a universe where there are lots of searchers but no senders, has been dubbed the "SETI" paradox by Zaitsev (2006).

[201]**Pg 149 detect our inadvertent** If ETCs could detect our television transmissions, then they could deduce a great deal about our planet even without decoding the programs. Astronomers have shown how an ETC could deduce the rotational speed of Earth, estimate its size, the length of our year, the distance of Earth from the Sun, and the Earth's surface temperature! See Sullivan, Brown and Wetherill (1978).

[202]**Pg 149 been some deliberate transmissions** Denning (2010) gives a partial list of deliberate broadcasts to the sky, but this reference is of more interest for its treatment of the debate about whether we *should* transmit to the sky.

[203]**Pg 150 more cost-effective to listen** Billingham and Benford (2011) discuss the costs of traditional SETI compared to active SETI.

[204]**Pg 151 *Hipparcos* mission** For more information on the ESA *Hipparcos* mission, see Webb (1999).

[205]**Pg 151 thinkers are opposed** Not everyone is convinced that active SETI is a good idea. Billingham and Benford (2011) call for a moratorium on active SETI and Haqq-Misra et al. (2013) urge caution. Denning (2010) and Musso (2012) give good overviews of the "to transmit or not to transmit" debate. Vakoch (2011) is more upbeat about active SETI. He argues that if we transmit then the burden of decoding and interpreting the message is placed on them; since they are likely to be older, and presumably more advanced, the task will be easier for them and thus communication will be facilitated. Penny (2012) makes the point that transmitting might be dangerous but then

so might listening (as dramatized in "A for Andromeda" by Hoyle and Eliot (1963)); indeed, it's even possible that in some cases even *not* listening could be dangerous. We just don't know.

[206]**Pg 151 ways of signaling** The idea that we could send a signal to extraterrestrial civilizations is almost 200 years old. In 1820 the German mathematician Johann Karl Friedrich Gauss (1777–1855), one of the greatest of all mathematicians, suggested planting forests of pine trees in such a way that they illustrated the Pythagorean theorem. The idea was expanded upon by Joseph Johann von Littrow (1781–1840), director of the Vienna Observatory, who suggested digging large ditches with geometrical shapes, filling them with kerosene, and setting them ablaze. He believed that light from these plainly artificial fires would be visible throughout the Solar System. In 1869, the French physicist Charles Cros (1842–1888) suggested that reflecting sunlight toward Mars using suitably arranged mirrors would be the best way to signal our presence to Martian astronomers. See Cerceau and Bilodeau (2012) for a comparison of old and new attempts at communication.

[207]**Pg 152 other communications** See Zaitsev (2012) for a list of all cosmic messages sent up to that date.

[208]**Pg 152 content of the signal** See Atri et al. (2011) for a proposed protocol for active SETI.

[209]**Pg 152 ethical difficulties** For a discussion of this suggestion, as well as for general SETI questions, see SetiLeague (2013).

[210]**Pg 152 game-theory analysis** For a game-theory approach to the problem of passive and active SETI, see de Vladar (2013).

They Have No Desire to Communicate

[211]**Pg 153 caution is a general trait** Drake tells the story of how the English astronomer Martin Ryle (1918–1984), an Astronomer Royal who was awarded the Nobel prize for physics, was distraught upon learning of the 1974 Arecibo transmission toward M13. Ryle was worried that advanced ETCs might prey upon us. More recently, Stephen Hawking has warned against humanity trying to initiate contact with alien intelligences; see Hawking (2010). Korhonen

(2013) analyses the risk of ETCs initiating an attack by drawing inferences from the Cold War and mutually assured destruction scenarios. My favorite fictional description of a species whose defining trait is extreme caution — taken to the point of cowardice—is that of “Puppeteers”. They occur in Larry Niven’s “Known Space” stories, including the award-winning *Ringworld* (Niven 1970).

[212]**Pg 154 taking place in the Galactic Club** Kuiper and Morris (1977) argue that “Complete contact with a superior civilization (in which their store of knowledge is made available to us) would abort [our] further development”.

[213]**Pg 154 different for societies** See page 210 of Drake and Sobel (1991).

They Develop a Different Mathematics

[214]**Pg 155 as Wigner put it** See Wigner (1960) for the source of this quotation.

[215]**Pg 155 an anti-Platonic stance** For a critique of the Platonic view of mathematics, see for example Chaitin (1997), Dehaene (1997), Hersh (1997), Davies (2007) and Abbott (2013).

[216]**Pg 156 rudimentary numerical judgments** For a critique of what animals might be doing when we say they are counting, see Budiansky (1998). Budiansky gives a superb introductory account of animal cognitive processes.

[217]**Pg 157 Why should they?** For a powerful argument as to why we *should* be able to converse with aliens using our system of mathematics, and perhaps a language such as LINCOS, see Minsky (1985).

[218]**Pg 157 different systems can’t exist** One author who might have been able to imagine alien mathematics was Jorge Luis Borges (1899–1986), perhaps the greatest Spanish-language writer of the last century. Borges (1998) contains several mathematical-based stories; Bloch (2008) examines the mathematical ideas in one of Borges most famous stories.

[219]**Pg 157 if mathematics itself is universal** Lemarchand (2008) suggests that the golden section ϕ, which arises in the problem $a/b = b/(a+b)$, might

be a cognitive universal and possess the potential to be used for interstellar communication codes, semantics and interstellar artistic works. However, a great deal of nonsense has been written about the golden section. It isn't the universal it's claimed to be in the human sphere, let alone the extraterrestrial one; see for example Devlin (2007).

They Are Calling but We Don't Recognize the Signal

[220]**Pg 158 one can imagine various options** One could imagine trying to communicate with extraterrestrials using icons, for example. As mentioned in Solution 31, Gauss suggested this approach: for example, giant geometrical figures, drawn on the Siberian tundra and constructed from pine forest and crops such as wheat, would signal our intelligence to observers on Mars. Perhaps something more sophisticated could be attempted for interstellar communication. Musso (2011) suggests something more interesting: a cosmic language based on analogy.

[221]**Pg 158 Hogben's *Astraglossa*** In *Astraglossa*, which was developed by the British mathematician Lancelot Hogben (1895–1975), the counting numbers are represented by radio pulses. For example, three pulses would represent the number three. A mathematical concept such as "equals" would be represented by a *radioglyph*—a pattern of longer pulses. The scheme was outlined in Hogben (1963). Philip Morrison expanded upon the radioglyph idea; see Morrison (1962).

[222]**Pg 158 or Freudenthal's** The LINCOS language was developed by the German mathematician Hans Freudenthal (1905–1990). There are a few websites devoted to LINCOS, but if you really want to learn the language I believe there is only one source: the original, but out of print, book (Freudenthal 1960). Freudenthal's book dealt only with mathematics. Although he planned a second part that would consider the problem of communicating non-mathematical concepts, he lost interest in the topic. His colleague Alexander Ollongren (1928–) took up the challenge and has developed LINCOS in a number of ways; see for example Ollongren (2011, 2013).

[223]**Pg 158 the Voynich Manuscript** The best print resource for the mysterious Voynich Manuscript is a small-press book (D'Imperio 1978), which is difficult to find. However, many websites describe the various tantalizing aspects of the Voynich Manuscript puzzle.

[224]**Pg 159 the early 15th century.** See Hodgins (2012).

[225]**Pg 159 a medieval hoax** There have been many suggestions about who might have created a hoax manuscript and why they might have done it. And the hoax theory explains why we haven't found meaning in the Voynich Manuscript: there *is* no meaning to be found. On the other hand, a variety of scientists believe they have found patterns in the Voynich Manuscript that suggest the words aren't random, that there's meaning contained in the sentences. See, for example, Amancio et al. (2013).

[226]**Pg 160 would be frustration** Elliott (2011) discusses a protocol for how, after a signal has been detected but not yet deciphered, scientists might disseminate of timely and accurate information to an expectant world. See also Elliott and Baxter (2012) and Elliott (2012).

[227]**Pg 160 indistinguishable from blackbody radiation** If EM radiation is used to transmit information, the most efficient format for a given message is indistinguishable from blackbody radiation (to a receiver who is unfamiliar with the format). This was first shown by Caves and Drummond (1994). The same result, using different arguments, was derived by Lachman et al. (2004).

Message in a Bottle

[228]**Pg 161 clear but counter-intuitive** Their work (Rose and Wright 2004) appeared as a letter in *Nature* and caused quite a stir in the SETI community. For a theoretical paper it's remarkably easy to follow.

Oops . . . Apocalypse!

[229]**Pg 165 "home of the next supernova"** Fermilab's management became so exasperated with Dixon's protests that they discussed the matter in their newsletter *FermiNews* (FNAL 1998).

[230]**Pg 165 collapse of the quantum vacuum state** Kurt Vonnegut (1963), in his novel *Cat's Cradle*, gives a fictional account of the effects of a phase transition (albeit a phase transition involving not the quantum vacuum state but the imaginary "ice-nine"—a form of H_2O that's more stable than ordinary water at room temperature.)

[231]**Pg 165 suggesting this could be the case** The idea that our universe might not be in the "true" vacuum didn't originate from cranks! Martin John Rees (1942–), an English astrophysicist, was appointed Astronomer Royal in 1995 and between 2005 and 2010 was the President of the Royal Society. Lord Rees is one of Britain's foremost scientists. His Dutch colleague Piet Hut (1952–) works at the Princeton Institute for Advanced Studies. See Hut and Rees (1983) for details of their suggestion.

[232]**Pg 165 higher than anything physicists can achieve** On 15 October 1991 the Fly's Eye detector in Utah detected a cosmic ray with an energy of 320 EeV. (This energy is so large that the rarely-used SI prefix "Exo" was pressed into action; the prefix represents a factor of 10^{18}.) The particle detected by Fly's Eye packed a *staggering* amount of energy: about 50 J. In other words, this single subatomic particle carried more kinetic energy than a tennis ball traveling at 180 mph. Its energy was more than 10 million times greater than the maximum achievable energy of the largest accelerator ever been planned. How this particle acquired so much energy is something of a mystery. No obvious process can produce a particle with this much kinetic energy; yet *whatever* produced it must have been relatively nearby, because if it had traveled cosmological distances its interactions with the microwave background would have slowed it down. See Bird (1995).

[233]**Pg 166 usual arrangement of quarks** The existence of strange quarks has been known for decades (see Webb 2004). Their key properties were first highlighted by George Zweig (1937–) and Murray Gell-Mann (1929–) in 1964. However, their presence was first evident in cosmic-ray experiments performed by Clifford Charles Butler (1922–1999) and George Rochester (1909–2001) in 1947; it's an injustice they weren't awarded a Nobel prize for their work.

[234]**Pg 166 surrounding electron cloud** These calculations were the work of the American physicist Robert Loren Jaffe (1946–) and others. For a non-technical account, see Matthews (1999). For a more in-depth analysis, see Jaffe et al. (2000).

[235]**Pg 167 a piece by two lawyers** See Johnson and Baram (2014).

[236]**Pg 167 patiently answered the worries** See for example Ellis et al. (2008).

[237]**Pg 168 investigate earth's core** See Stevenson (2003).

[238]**Pg 168 a rather dangerous activity** See Ćirković and Cathcart (2004).

[239]**Pg 169 different subject areas** The term "nanotechnology" was popularized by the American physicist K. Eric Drexler. In an influential book (Drexler 1986) he presented his vision of a forthcoming revolution in nanoscale engineering. Drexler introduced the term "nanotechnology" to refer to molecular manufacturing (the construction of objects to complex, atomic specifications using sequences of chemical reactions directed by non-biological molecular machinery) together with its techniques, its products, and their design and analysis. Recently, the term has come to denote any technology that has nanoscale effects—submicron lithography (or etching) for example. To distinguish his original concept from the work currently taking place in laboratories, Drexler now refers to "molecular nanotechnology". The field of nanotechnology itself might be said to have started with a lecture given by Feynman (1959), in which he considered the direct manipulation of individual atoms.

[240]**Pg 169 potential to improve health care** For a collection of SF stories that deal with medicine, as well as a discussion of the science behind the stories, see Aiken (2014). Many of the stories touch in some way on nanotechnology.

[241]**Pg 169 a self-replicating machine** A Royal Society (2004) report discussed the potential of nanotechnology and concluded that regulators need not concern themselves with self-replicating machines, for a while at least. Their development lies too far in the future.

[242]**Pg 170 the gray goo problem** One of the best fictional treatments of the grey goo problem is Greg Bear's wonderful short story "Blood Music", which was published in 1983—three years before Drexler's book. The story is available in a collection (Bear 1989).

[243]**Pg 170 less than three hours** See Freitas (2000) for a detailed mathematical assessment of the environmental risks of nanotechnology.

Ouch . . . Apocalypse!

[244]**Pg 171 on the verge of demonstrating** Drake and Sobel (1991) report how Shklovsky, who as we saw earlier was one of the first to publicize the Fermi paradox, lost heart in the SETI enterprise in the years before his death. Shklovksy was convinced that nuclear war was inescapable, and the same inevitable holocaust would occur with other technological civilizations.

[245]**Pg 171 ruinous for our species** See Turco et al. (1983) for a discussion of the consequences of a nuclear winter.

[246]**Pg 171 knowledge is preserved** Walter Michael Miller Jr. (1923–1996) was an American radioman and tailgunner on 53 bombing raids over Italy and the Balkans in World War II. His award-winning *A Canticle for Liebowitz* (Miller 1960) is one of the classic post-apocalyptic SF novels. He wrote the novel in response to the Allied attack on Monte Cassino—a raid in which he took part and which almost certainly affected him psychologically. (The detailed effects of a nuclear winter were only determined quite recently so, although Miller's post-holocaust world is vividly described, it necessarily lacks scientific accuracy. Nevertheless, the novel is highly recommended.)

[247]**Pg 173 Cooper offers bioterrorism** See Cooper (2013) for a discussion of bioterrorism and its link to the Fermi paradox.

Heat Wave

[248]**Pg 176 Charles Keeling began measuring** The American chemist Charles David Keeling (1928–2005) worked at the Scripps Institution of Oceanography for more than four decades, and throughout that period maintained beautiful observations of atmospheric carbon dioxide. For substantial biographies of Keeling, see Weart (2008) or Bowen (2006).

[249]**Pg 177 average surface temperature** IPCC (2013) contains details of the increases in Earth's surface temperature averaged over land and oceans.

[250]**Pg 178 latest research suggests** Goldblatt and Watson (2012) argue that it's probably impossible for humanity to trigger a runaway greenhouse by burning fossil fuels. They also point out that their work offers no comfort to the climate change deniers: they clearly state that anthropogenic greenhouse

gas emissions are a major threat to human civilization. They also point out that, even if their work is correct and a runaway greenhouse is not possible, nothing in their models exclude an abrupt change to a "hot, moist greenhouse" state: this wouldn't be a runaway process, but it would be a truly dire outcome.

Apocalypse When?

[251]**Pg 179 reasoned in the following way** J. Richard Gott III (1947–) is a professor of astrophysics at Princeton University. His original paper on the Doomsday argument (Gott 1993) purported to show, among other things, that mankind is unlikely to colonize the Galaxy; see Gott (1997) for a simplified account of the argument. The article generated an extremely interesting correspondence (Buch et al. 1994). The philosopher John Leslie independently developed the Doomsday argument (Leslie 1996). Perhaps the first person to appreciate the power of this type of reasoning was the Australian physicist Brandon Carter (1942–); Carter's anthropic arguments are outlined in chapter 5.

[252]**Pg 183 an ingenious manner** See Wells (2009) for a fascinating look at the question of human survival, by way of the recorded lifetimes of stage shows and businesses! Wells was one of the few students that Feynman mentored, and I find something of Feynman's irreverence and fearless questioning in this book.

Cloudy Skies Are Common

[253]**Pg 183 a planet in a system of six stars** At the time of writing, we have yet to find a planetary system as extreme as that in *Nightfall*. In 2012, however, astronomers discovered an example of a planet in a four-star system; see Schwamb et al. (2013). An artist's representation of the planet appears in fig. 4.25.

[254]**Pg 184 a wonderful story** *Nightfall*, written in 1941, is routinely voted as the best SF short story of all time. It can be found in many collections, including Asimov (1969).

As Good as it Gets

[255]**Pg 186 final element of the standard model** For a lucid description of the discovery of the Higgs boson, and why it was so important, see Carroll (2013).

[256]**Pg 187 telescopes of quite astounding capability** See Webb (2012) for a discussion of new and planned observatories.

They Are Distance Learners

[257]**Pg 188 Lampton, a scientist** Lampton is involved in SETI activities at the University of California, Berkeley, and in particular the optical SETI program that I outlined in Solution 26. For further details of his proposed solution to the paradox, see Lampton (2013).

[258]**Pg 189 we wouldn't need to send astronauts** The notion that we could replicate Martian life on Earth by having a genome-sequencing probe on Mars transmit genetic information back here, and then use bioprinters to "build" them, is discussed in Venter (2013)

They Are Somewhere but the Universe is Stranger Than We Imagine

[259]**Pg 190 universe A and universe B** The American physicist Hugh Everett III (1930–1982) developed the many-worlds interpretation of quantum mechanics for his PhD thesis at Princeton. See Everett (1957) for a summary of the thesis. Unfortunately his ideas weren't taken seriously at the time of publication, and he became dispirited and left academia. See Byrne (2010) for well researched account of Everett's rather sad life story.

[260]**Pg 191 *really* interesting places** Alfred Bester (1913–1987) first published his famous novel *The Stars My Destination* under the title *Tiger! Tiger!* (Bester 1956). Arthur Clarke's most ambitious work is perhaps *Childhood's End* (Clarke 1953). Seemingly *outré* speculations aren't limited to science fiction, however. Theoretical physicists also delight in dreaming up wild ideas; see, for example, Tegmark and Wheeler (2001).

[261]**Pg 191 move through the "bulk"** This idea appears in Gato-Rivera (2006); it's a seemingly sincere suggestion, but I find it difficult to take it seriously.

Intelligence Isn't Permanent

[262]**Pg 192 philosophical speculations** See Schroeder (2002).

[263]**Pg 192 an "adaptationist" solution** See Ćirković (2005) and Ćirković, Dragićević and Berić-Bjedov (2005).

We Live in a Postbiological Universe

[264]**Pg 194 noted historian of science** See Dick (2003, 2008) for lucid explanations of the implications for SETI if we live in a postbiological universe. His book *The Biological Universe* (Dick 1996) is also highly recommended.

[265]**Pg 194 Stapledon was a British philosopher** Stapledon's science fiction novels influenced writers such as Brian Aldiss, Arthur C. Clarke, Stanislaw Lem and Vernor Vinge. In addition to the novels *Last and First Men* and *Star Maker* mentioned here (Stapledon 1930, 1937), he wrote other influential novels including *Sirius* and *Odd John*.

[266]**Pg 194 give or take 37 million years** The best estimate of the age of the universe comes from a combination of data from the ESA *Planck* satellite and previous missions such as the NASA WMAP satellite; both *Planck* and WMAP worked by measuring the cosmic microwave background radiation. I find it incredible that astronomers can specify fundamental cosmological parameters with such accuracy. When I was a student, realistic estimates for the age of the universe differed by billions of years! See Webb (2012) for a discussion of these space-based missions.

[267]**Pg 195 using an argument based upon stellar evolution** See Norris (2000). Norris's paper appears in a very interesting volume edited by Allen Tough.

[268]**Pg 196 Martin once wrote** *A Song For Lya* appeared in *Analog* magazine in 1974 and went on to win the Hugo Award for Best Novella. It appears in a story collection of the same name (Martin 1976).

They Are Hanging Out Around Black Holes

[269]**Pg 197 a scale of inward manipulation** See Barrow (1998).

[270]**Pg 197 plenty of room at the bottom** See Feynman (1959). He gave the lecture entitled "There's Plenty of Room at the Bottom" to a meeting of the American Physical Society at Caltech on 29 December 1959. In it, Feynman considered the possibility of directly manipulating individual atoms—it's a lecture that in many ways prefigured the field of nanotechnology.

[271]**Pg 197 Vidal argues** Vidal's PhD thesis is entitled *The Beginning and the End: the Meaning of Life in a Cosmological Perspective* (Vidal 2013).

[272]**Pg 197 nothing can escape** We can't look inside a black hole—not even light can reach us from beyond the event horizon that cloaks a hole—but if we *could* look inside a particular type of black hole might we see an extraterrestrial civilization living there? In 2011, a Russian physicist showed that stable periodic orbits can exist inside a black hole and he hypothesized that KIII civilizations could live safely inside a supermassive black hole. Such a civilization would by definition be invisible to our telescopes. Could *that* be the resolution to the paradox? That ETCs choose to live inside black holes and thus are unable to communicate with us? See Dokuchaev (2011).

[273]**Pg 198 store or extract energy** Inoue and Yokoo (2011) suggest that KIII civilizations might construct what would essentially be a Dyson sphere around a supermassive black hole. However, they make no reference to the Barrow scale: this is essentially a souped-up version of a "traditional" Dyson sphere.

They Hit the Singularity

[274]**Pg 200 Back in 1965** Gordon Earle Moore (1929–) co-founded Intel in 1968 and quickly became one of the world's richest individuals. See Moore (1965) for the first statement of his "law".

[275]**Pg 201 some time before 2030** The American mathematician Vernor Steffen Vinge (1944–) has explored the idea of the Singularity in several SF novels and short stories. A non-fictional account of the idea can be found in Vinge (1993). A discussion of the seemingly inexorable development of computing power can be found in Moravec (1988).

[276]**Pg 201 calls such an event** The term "singularity" was used in the 1950s by von Neumann, who is quoted as saying: "The ever accelerating progress of technology . . . gives the appearance of approaching some essential singularity in the history of the race beyond which human affairs, as we know them, could not continue". See Ulam (1958).

[277]**Pg 201 transcendental event** Vinge wasn't the first to explore the idea that mankind's intellectual development might profoundly change our global society. The French Jesuit priest Pierre Teilhard de Chardin (1881–1955) thought individual minds would somehow merge to form the noösphere—an expanding sphere of human knowledge and wisdom; spiritual and material would eventually merge to form a new state of consciousness he called the Omega point. His argument, although mystical and woolly, reaches a conclusion that seems similar to Vinge's Singularity. There are two main differences between Vinge and Teilhard de Chardin. First, Vinge has extrapolated real-world trends to suggest specific mechanisms that might get us to the Singularity. Second, organic evolution requires millions of years to construct the noösphere; we (and our successors) construct the Singularity in a few decades. For an insight into this sort of thinking, see for example Teilhard de Chardin (2004).

[278]**Pg 202 a non-biological substrate** See Searle (1984) and Penrose (1989) for two stimulating books criticizing the idea that human-level "artificial" intelligence can exist. I happen to disagree with the conclusions of these highly distinguished thinkers, but the two references here make for extremely interesting reading.

[279]**Pg 202 typeset this book** TEX was developed by the American computer scientist Donald Ervin Knuth (1938–). See Knuth (1984). He wrote the TEX (along with a program for designing typefaces) just so that he could typeset his multi-volume *Art of Computer Programming* to his own satisfaction!

The Transcension Hypothesis

[280]**Pg 203 a paper published in 2012** See Smart (2012). In this paper Smart builds on a decade of thinking about transcension and its relationship to the Fermi paradox.

[281]**Pg 204 the World Health Organization** For details on urban population growth, see WHO (2013).

[282]**Pg 206 new ideas of evolutionary developmental biology** For a readable account of evolutionary developmental biology, see Carroll (2006).

The Migration Hypothesis

[283]**Pg 207 futurologist Robert Bradbury** See Ćirković and Bradbury (2006) for details of the migration hypothesis. Robert J. Bradbury (1956–2011) was interested in a variety of unorthodox scientific pursuits, including options for radical life extension. Sadly, he did not live to benefit personally from the life-extending technologies in which he was interested.

Infinitely Many Civilizations Exist but Only One Within Our Particle Horizon: Us

[284]**Pg 209 done so much to promote** Hart is a particularly clear and forceful writer. For a description of his proposal of how an infinite number of life-bearing planets exist, yet we are alone in the observable universe, see Hart (1995). An equally clear treatment of the subject, by a cosmologist, appears in Wesson (1990).

[285]**Pg 210 Guth has presented** See Guth (2007).

[286]**Pg 210 one of the key underpinning concepts** See Webb (2014) for a discussion of inflation, and of how it's possible that observational results made public in 2014 might provide confirmation of inflation.

They Don't Exist

[287]**Pg 213 a stimulating and thought-provoking book** The book *Rare Earth* (Ward and Brownlee 1999) articulated the growing suspicion of a number of astrobiologists that Earth is unusual, perhaps unique, in harboring complex forms of life.

[288]**Pg 214 will seem narrow-minded** For an imaginative, unorthodox and challenging book on the possible forms that life may take, see Feinberg and Shapiro (1980). The authors discuss the notions of plasma life in stars, radiant life in interstellar clouds, silicate life, low-temperature life and many other possibilities. One of the earliest and most delightful SF stories about alien biochemistries was *A Martian Odyssey* by Stanley G. Weinbaum (in *Wonder Stories*, July 1934). You can find the story in several anthologies, including Asimov (1971).

The Universe is Here for Us

[289]**Pg 214 a dozen such steps** See, for example, Mayr (1995).

[290]**Pg 215 some astronomers believe** The Sun's luminosity has increased by about 25% since the formation of the Solar System. Earth's surface temperature has been quite stable over that time, however, mainly thanks to negative feedback loops that reduce the CO_2 greenhouse effect. These loops will be unable to maintain Earth's surface temperature at a level that's suitable for complex life beyond another billion years or so. See for example Bergman et al. (2004).

[291]**Pg 217 presented by Brandon Carter** See Carter (1974).

[292]**Pg 217 recent analysis** See Watson (2008) for an extension of Carter's work. See also McCabe and Lucas (2010).

[293]**Pg 217 observational bias** See Bostrom (2002) for a thorough discussion of anthropic bias.

[294]**Pg 218 will never die out** See Barrow and Tipler (1986)—a remarkable and stimulating book, which covers the various types of anthropic principle in detail.

[295]**Pg 218 expanded upon the notion** See Tipler (1994)

The Canonical Artefact

[296]**Pg 219 searching for a "theory of everything"** For a beautiful treatment of the motivations behind the hunt, see Weinberg (1993).

[297]**Pg 219 addressed by Gerard Foschini** Foschini has won numerous awards for his contributions to communications engineering. See Foschini (1994) for the intriguing notion of the canonical artefact.

Life Can Have Emerged Only Recently

[298]**Pg 223 takes issue with** See Livio (1999).

[299]**Pg 225 occurred billions of years ago** Work by Sobral et al. (2013) suggests that the rate of star formation peaked about 11 billion years ago, which is rather earlier in the history of the universe than previously thought.

Planetary Systems Are Rare

[300]**Pg 226 originating in more exotic locales** The novels mentioned in the text are *Integral Trees* (Niven 1984) and *Dragon's Egg* (Forward 1980).

[301]**Pg 227 competing scenarios for planetary formation** The French naturalist George-Louis Le Clerc, Comte de Buffon (1707–1788), proposed in 1749 that the planets formed when a comet collided with the Sun. The German philosopher Immanuel Kant (1724–1804) proposed the nebular theory of planetary formation in 1754. See Williams and Cremin (1968) for a comparative survey of the various different ideas that had been proposed to explain the origin of the Solar System.

[302]**Pg 227 condensed to form the planets** The first models of planetary formation through stellar collisions were developed by the American scientists Thomas Chrowder Chamberlin (1843–1928) and Forest Ray Moulton (1872–1952). The models were improved by the British mathematicians James Hopwood Jeans (1887–1946) and Harold Jeffreys (1891–1989). See Taylor (1998) for a fascinating tour of the Solar System, including its formation. Taylor reaches the conclusion that life on Earth might be the result of chance; and perhaps this means that life is unlikely to occur elsewhere.

[303]**Pg 229 exoplanetary discovery** For more details on the newest planetary discoveries, visit *The Extrasolar Planets Encyclopædia* (Exoplanet Team 2014). For a haunting, beautifully written account of the scientists who search for exoplanets, see Billings (2013).

Rocky Planets Are Rare

[304]**Pg 230 formation of Earth itself** The accepted age of the Earth, as calculated by geochemists using radioisotopic dating techniques, is 4.54 ± 0.05 billion years. A value close to this was first presented in 1956 by the American geochemist Clair Cameron Patterson (1922–1995); research since then has refined Patterson's value, but not substantially revised it. For more details on how scientists determined the age of the Earth, see for example Dalrymple (2001).

[305]**Pg 230 precise nature of the chondrules** References to what we now know are chondrules were made in the scientific literature as far back as 1802. They were named in 1864, by the German mineralogist Gustav Rose (1798–1873). The English geologist Henry Clifton Sorby (1826–1908), one of the great amateur scientists, used a petrographic microscope—a device he invented—to carry out the first detailed study of chondrules. He suggested that chondrules, which he described as being "like drops of a fiery rain", might be pieces of the Sun that had been ejected in solar prominences. See Sorby (1877).

[306]**Pg 231 a nearby gamma-ray burst** See McBreen and Hanlon (1999). See also Duggan et al. (2003).

[307]**Pg 232 most accurate dating** For further details, see Connelly et al. (2012).

A Water Based Solution

[308]**Pg 233 a mineral called zircon** Uranium (U) decays to lead (Pb) through two different chains (^{238}U decays to ^{206}Pb with a half-life of 4.47 billion years; ^{235}U decays to ^{207}Pb with a half-life of 0.704 billion years). Zircon strongly rejects lead, so any lead that's detected in the mineral must have come from radioactive decay. This gives rise to the possibility of a uranium–lead dating mechanism, and Valley et al. (2014) have shown that the uranium–lead "clock" in zircon is reliable. They confirmed that a scrap of zircon from the Jack Hills region of Western Australia formed 4.4 billion years ago.

[309]**Pg 234 saw the same abundance** See Hartogh *et al.* (2011) for details of the Hartley 2 observations; see Lis et al. (2013) for details of the Honda–Mrkos–Pajdušáková observations.

Continuously Habitable Zones Are Narrow

[310]**Pg 235 a system's habitable zone** One of the first books to discuss the conditions that might be required to make a planet habitable was Dole (1964). Although now extremely dated, it remains a good guide. The book was the outcome of a RAND study and is rather technical. A popular version, also recommended, is Dole and Asimov (1964). Seager (2013), published almost half a century after the Dole study, provides a detailed summary of the factors that might affect an exoplanet's habitability.

[311]**Pg 235 a "tilted" terrestrial world** See Armstrong et al. (2014) for a discussion of how a fluctuating obliquity does not necessarily preclude the existence of life, and in some cases might actually be a boon for life.

[312]**Pg 236 one recent study** See Vladilo et al. (2013), which considers the effect of atmospheric pressure on the habitable zone.

[313]**Pg 236 just the right place** In several calculations of the boundaries of the habitable zone, Earth can be seen pushing the limits. It's easy to take an "Earth-centric" view of the possibilities for life, but increasingly scientists are discovering that liquid water could exist in a wide variety of situations. Heller and Armstrong (2014) point out that some planets might be *more* suitable for life than Earth is.

[314]**Pg 236 results of computer models** See Hart (1978, 1979).

[315]**Pg 237 most Earth-like planet** For details of the discovery of Kepler-186f, see Quintana et al. (2014).

[316]**Pg 237 models developed by James Kasting** The American geologist James Fraser Kasting (1953–) has made several contributions to our understanding of the long-term stability of Earth's climate. The models he and his colleagues use are much more detailed than Hart's original model. See for example Kasting, Reynolds and Whitmire (1992) and Selsis et al. (2007) for further details.

[317]**Pg 237 could be wider than Hart thought** Rushby et al. (2013) consider a simple model of how the habitable zone evolves over time, and show that some exoplanets can spend many billions of years in their star's habitable zone.

[318]**Pg 238 one-in-five Sun-like stars** Petigura, Howard and Marcy (2013) analyzed *Kepler* and Keck data on exoplanets to conclude that 22% of Sun-like stars harbor Earth-size planets orbiting in their habitable zones.

[319]**Pg 238 galactic habitable zone** See Gonzalez, Brownlee and Ward (2001) for an initial definition of the galactic habitable zone, and Lineweaver, Fenner and Gibson (2004) for a detailed discussion of the size and time evolution of the zone. Gowanlock, Patton and McConnell (2011) describe a model of the GHZ in terms of the spatial and temporal dimensions of the Galaxy that may favor the development of complex life.

Earth is the First

[320]**Pg 239 analysis of the exoplanets** See Buchhave et al. (2012).

[321]**Pg 240 the star HIP 102152** A detailed study of this solar twin is given in Monroe (2013).

Earth has an Optimal "Pump of Evolution"

[322]**Pg 240 physicist John Cramer** See Cramer (1986) for a popular account of the idea that Jupiter might affect evolution on Earth.

[323]**Pg 240 gap in the Asteroid Belt** The American geologist George West Wetherill (1925–2006) was well known for his research into the role that Jupiter plays in the Solar System. That resonance effects should cause gaps to exist in the Asteroid Belt was first suggested in 1866 by the American astronomer Daniel Kirkwood (1814–1895). Jack Leach Wisdom (1953–), an American physicist, was one of the first scientists to apply the modern techniques of nonlinear dynamics to the study orbits in the Solar System. Wisdom looked at the Asteroid Belt's 3:1 resonance in detail. For an authoritative and up-to-date account of many of these ideas, as well as a more general discussion of the origin and evolution of the Solar System, see Yeomans (2012).

The Galaxy is a Dangerous Place

[324]**Pg 242 pose an interesting threat** Magnetars are neutron stars with exceptionally strong magnetic fields. The field of SGR1900+14 is estimated to be 5×10^{10} tesla—compare that with the strongest non-destructive magnetic field scientists have made, which is only a little over 100 tesla. The magnetic field of a magnetar is so strong that it could suck the keys from your pocket at a distance of more than 100,000 miles. Of course, if you were standing that close to a magnetar, then the radiation and charged-particle wind that it spews out would kill you instantly. At the time of writing, 21 magnetars have been discovered. See Mereghetti (2008) for more information.

[325]**Pg 245 30 light years of Earth** Gehrels et al. (2003), for example, calculate that a Type II supernova occurring within 8 pc could double the "biologically active" ultraviolet flux at Earth's surface.

[326]**Pg 247 origin was completely unknown** Astronomers first detected gamma-ray bursts in 1969 using data from the VELA satellites, which were in orbit to look for gamma-rays from possible nuclear explosions, but it wasn't until 1997 that astronomers obtained proof that bursts occur at cosmological distances. Even now, the detailed nature of the progenitor events is a matter for debate. See Vedrenne and Atteia (2009).

[327]**Pg 248 responsible for mass extinctions** Melott et al. (2004) suggest that a GRB might have initiated the late Ordovician mass extinction some 440 million years ago. For further details on this suggestion see Thomas (2009).

[328]**Pg 248 proposed by James Annis** See Annis (1999).

[329]**Pg 249 consumed by fire** Arthur Clarke's short story "The Star" describes how humans find the remains of a civilization destroyed by an astronomical explosion. Light from the explosion would have reached Earth about two thousand years ago—a fact that gives the story its haunting quality. I find it poignant that within a few hours of Clarke's death in 2008, the Swift satellite detected GRB 080319B—an explosion so tremendously powerful that, despite occurring 7.5 billion years ago, was potentially visible to the naked eye for half a minute."The Star" appears in many anthologies. See, for example, Asimov (1972).

A Planetary System is a Dangerous Place

[330]**Pg 249 much closer to home** For an in-depth look at planetary threats, see Bostrom and Ćirković (2008).

[331]**Pg 250 Snowball Earth events** The notion that Earth experienced a global glaciation in the Neoproterozoic age is not new: the English geologist Walter Brian Harland (1917–2003) postulated precisely this as long ago as 1964. At the same time, the Russian geologist Mikhail Budyko (1920–2001) showed how a runaway icehouse effect could take place. Only recently, however, has the notion been taken seriously—largely due to the work of groups led by the American geologists Joseph Kirschvink and James Kasting, who have investigated the escape route from "Snowball Earth". For an early introduction, see Harland and Rudwick (1964). A clearly written introduction to Snowball Earth theories appears in Hoffman and Schrag (2000). More technical papers include Hoffman et al. (1998) and Kirschvink (1992).

[332]**Pg 253 reduction in biodiversity** There might well have been many more extinctions earlier in Earth's history, particularly in Snowball Earth events, but only in the past half billion years have creatures with hard skeletons become common; only relatively recently could creatures become fossils. Indeed, we are now living in the geological eon known as the Phanerozoic era, the name

coming from Greek words meaning "visible life". Nature began experimenting with the present animal phyla in the Cambrian explosion, 540 million years ago; the 4 billion years before the Cambrian explosion is known as the Cryptozoic era, from Greek words meaning "hidden life". For most of Earth's history, virtually all organisms lived and died without leaving traces. For more information about the explosion of animal life in the Cambrian, see Gould (1986).

[333]**Pg 253 great mass-extinction events** See Raup (1990).

[334]**Pg 253 large meteorite impact** The idea that a meteorite impact killed the dinosaurs is an old one. The key paper is Alvarez et al. (1980). Years before that paper appeared, however, a remarkably prescient article was published in an SF magazine (see Enever 1966). It described the consequences of a large meteor hitting Earth. An entertaining look at the evidence for a meteorite impact causing the Cretaceous–Tertiary extinction appears in Alvarez (1997); the book is as good as its title!

[335]**Pg 256 species are becoming extinct** See Leakey and Lewin (1995).

Earth's System of Plate Tectonics is Unique

[336]**Pg 256 killed each year because of earthquakes** See McClean (2010).

[337]**Pg 257 gives rise to plate tectonics** The first to marshal evidence for the suggestion that continents move was the German meteorologist Alfred Lothar Wegener (1880–1930). He published his ideas on continental drift in 1915, but they were met with ridicule. One of the seeming flaws in his theory was that no known mechanism could account for the drift of continents. Wegener died in a blizzard on an Arctic expedition, shortly before the British geologist Arthur Holmes (1890–1965) suggested that convection might provide a suitable mechanism to explain continental drift. Holmes was a respected geologist; he was the first, for example, to suggest a reasonable timescale for geological processes—his 1913 estimate of 4 billion years for the age of the Earth was far better than any previous estimate. But it was to be almost another 20 years before the idea of continental drift became established. In 1960, the American geologist Harry Hammond Hess (1906–1969) showed that the seafloor was spreading from vents in mid-ocean rifts. As magma welled up and cooled, it pushed the existing seafloor away from both sides of the rifts. It was this force

that moved the continents. See Oreskes (2003) for an in-depth account of how the theory of plate tectonics came into being. Marshak (2009) is a superb textbook that explains the details behind the concepts discussed in this section.

[338]**Pg 258 plate tectonics controls temperature** The first description of Earth's geological-timescale carbon dioxide thermostat appeared in Walker, Hays and Kasting (1981). This mechanism doesn't take into account the effect that biological organisms might have had on stabilizing global surface temperature. Several prominent scientists take the view that life itself has played the key role in keeping temperature at an equable level.

The Moon is Unique

[339]**Pg 261 the impact hypothesis** Two groups of American scientists independently arrived at the idea of lunar formation by a Mars-sized impactor. One group was led by the American astronomers William Kenneth Hartmann (1939–) and Donald Ray Davis (1939–), who work at the Planetary Science Institute in Arizona. The other group was led by the Canadian-American astronomer Alastair Graham Walter Cameron (1925–2005) of Harvard University. See Hartmann and Davis (1975) and Cameron and Ward (1976).

[340]**Pg 262 identical in Earth and Moon rocks** For details of the oxygen isotope ratios in Moon rock samples, see Wiechert et al. (2001). For details of the titanium isotope ratios in Moon rock samples, see Zhang et al. (2012).

[341]**Pg 262 wrong stage of development** Jacobson (2014) pins down the Moon-forming event to 95 million years (give or take 32 million years) after the Solar System formed. This is rather later than many previous estimates, but a high-energy collision that occurred relatively late in the development of the Solar System is consistent with the observation that Moon and Earth have an identical isotopic composition (see text).

[342]**Pg 263 been any different** For an entertaining treatment of the importance of the Moon, which is aimed at non-scientists, see Comins (1993).

Life's Genesis is Rare

[343]**Pg 267 two different types of prokaryote exist** The classification of living organisms into the domains of archaea, bacteria and eukarya is relatively recent. The proposal originated in the late 1980s and early 1990s with the American biophysicist Carl Richard Woese (1928–2012), who discovered micro-organisms living in extreme environments (extremes of heat, salinity, acidity—places previously thought to be hostile to life). At first it was thought that these organisms were bacteria that had managed to adapt to extreme conditions; certainly, the cell nucleus of these organisms was not enclosed within a nuclear membrane, which made them look like bacteria. However, Woese and co-workers embarked on a study of the ribosomal RNA of these extremophiles. (In cells, ribosomal RNA is the site of protein synthesis—the place where amino acids are assembled into proteins. It is thus found in all living cells, and a study of the nucleotide sequence of rRNA provides an ideal "evolutionary chronometer".) They found that the rRNA of extremophiles differs quite radically from the rRNA of bacteria. These and other fundamental differences made it clear to Woese that life consists of *three* domains. The landmark paper is Woese, Kandler and Wheelis (1990).

[344]**Pg 271 deoxyribonucleic acid** The story of nucleic acids goes back a long way. The first to investigate the chemical structure of the nucleic acid molecule was Albrecht Kossel (1853–1927), a German biochemist. Kossel isolated the nitrogen bases and named them adenine, guanine, cytosine and thymine. He was awarded the 1910 Nobel prize for his work. Forty years later, the role that DNA might play in heredity was one of the burning issues of biology. In 1953, Francis Crick and James Watson made one of the key breakthroughs in all of science when they proposed the double-helix model of the DNA molecule. For details of the story, and the personalities involved, see Watson (2010) and Ridley (2011).

[345]**Pg 272 two extra letters** The work on expanding the genetic "alphabet" is described in Malyshev et al. (2014).

[346]**Pg 277 many excellent sources available** If you have access to a good library, Brooker (2011) is a popular introductory textbook on genetics.

[347]**Pg 278 in interstellar space** Elisa, Glavin and Dworkin (2009), for example, report the existence of the amino acid glycine in material brought back to Earth from comet Wild 2 by the Stardust spacecraft. A number of polycyclic

aromatic hydrocarbons—molecules that might be important as starting material for life—have been detected in the interstellar medium. The basic building blocks that form complex organics are common in space.

[348]**Pg 278 chemistry of early Earth** The story of scientific research into the question of life's origin is long and fascinating. It began in 1924 with the Russian biologist Alexander Ivanovich Oparin (1894–1980), who suggested that small lumps of organic matter might have formed naturally and become the precursor of modern proteins. Along with the British biologist John Burdon Sanderson Haldane (1892–1964), he produced the evocative idea of the primordial soup, from which living material arose. It wasn't until 1953 that the American biologist Stanley Lloyd Miller (1930–2007), a graduate student working in the laboratory of the Nobel prize-winning chemist Harold Clayton Urey (1893–1981), put these ideas to an experimental test. The results of Miller's experiments suggested that at least the basic building blocks of life could form naturally on a primordial Earth. Nevertheless, there are many steps leading from these building blocks to life itself, and the route remains shrouded in fog. This is a fascinating and active area of research. See Deamer (2012) for an account by someone working in the field.

[349]**Pg 279 being created by chance** For an argument as to why the emergence of life might be a rare occurrence, see Hart (1980). I believe the arguments in the paper are wrong, but as usual Hart states his case clearly and forcefully.

[350]**Pg 280 as genetic material and as enzymes** The first ribozymes—enzymes made of RNA—were discovered independently in 1983 by the American biochemist Thomas Robert Cech (1947–) and the Canadian biochemist Sidney Altman (1939–), who shared the 1989 Nobel prize for chemistry for this work. A good overview of the RNA world is given by Bernhardt (2012).

[351]**Pg 280 progress in these fields is rapid** There are numerous proposals regarding the genesis of life. The following references, which give only a flavor of the wide range of thinking on offer, all appeared within the timescale of the writing of this book. Sharov and Gordon (2013) take what I believe is a hugely speculative approach, and argue that life's origin lies 9.7 billion years ago; compare that with Earth's age of 4.5 billion years. Quite a claim! England (2013) takes a much more traditional approach, but nevertheless arrives at an equally stunning claim: he believes he has identified fundamental physical principles

that drive the origin of life. If England is correct, life arises quite naturally. Deacon (2013) talks about "autogenesis"—a physical process of reciprocal catalysis and self-assembly that can not only *create* order, but also *preserve* order and *reproduce* it; those are the sorts of properties we look for when we talk about life. Martins et al. (2013) discuss the possibility that the chemicals necessary for life were created in shocks when icy comets struck rocky bodies, or rocks impacted on icy surfaces. As you might conclude from this brief sample of papers, the fascinating question of the origin of life is a subject of continuing debate. Indeed, Gollihar, Levy and Ellington (2014) point out that the origin of life remains mysterious in part, paradoxically, because scientists are aware of lots of possible mechanisms that could have led to self-replication of nucleic acids and the creation of cells!

[352]**Pg 281 in existence at this time** See Pons et al. (2011) for the suggestion that life began in mud volcanoes in Isua, Greenland about 3.85 billion years ago.

[353]**Pg 281 Earth's crust formed** As mentioned in the discussion of Solution 56, researchers have dated a tiny zircon crystal from Western Australia to 4.4 billion years. The speck is the oldest known part of our planet. See Valley et al. (2014).

[354]**Pg 282 modern discipline of astrobiology** There are now many introductions to and textbooks on the relatively new science of astrobiology. Three that I can recommend are Dartnell (2007), Sullivan and Baross (2007) and Catling (2014).

[355]**Pg 282 large subsurface ocean** See Witze (2014).

Life's Genesis is Rare (Revisited)

[356]**Pg 284 unlikely to be small** See Lineweaver and Davis (2002).

[357]**Pg 285 formula is indispensable** For a discuss of the history behind the Bayes formula, and its importance in the modern world, see McGrayne (2011).

[358]**Pg 285 clergyman Thomas Bayes** Not a huge amount is known about the life of Thomas Bayes. His formula appears in Bayes (1763).

[359]**Pg 286 study shows that** For research on how medical professionals often fail to use Bayesian reasoning see, for example, Casscells, Schoenberger and Graboys (1978); Eddy (1982); Gigerenzer and Hoffrage (1995).

[360]**Pg 286 infamous Monty Hall problem** The Monty Hall problem rose to prominence in 1990, when a columnist in *Parade* magazine (see vos Savant, 1990) argued that it pays to switch. The columnist was Marilyn vos Savant, who is clearly a very bright woman: from 1986 to 1989 she was listed in the *Guinness Book of World Records* as possessor of the "Highest IQ (women)"; she ceased to appear not because some other woman was deemed to possess a higher IQ, but because the editors at *Guinness* saw sense and realized that attaching a number to intelligence in this way is essentially meaningless. Her proposed solution to the Monty Hall problem nevertheless provoked outrage from several mathematics professors; at least one academic argued that by publishing such nonsense she was doing a disservice to the public understanding of mathematics. And yet her analysis was perfectly correct.

[361]**Pg 287 my reaction** In failing to spot the answer to the Monty Hall problem I was in good company. Paul Erdös was one of the most prolific mathematicians of the twentieth century. Mathematicians and scientists like to boast of their "Erdös number". If you co-authored a paper with him you have an Erdös number of 1; if you co-authored a paper with someone who has an Erdös number of 1 then you have an Erdös number of 2; and so on. (See Hoffman (1998) for a biography of Erdös.) My own Erdös number is a rather poor 5. Anyway, even the great Paul Erdös only accepted the correct conclusion after he saw computer simulations.

[362]**Pg 288 just such a Bayesian analysis** For the full technical details of the analysis, see Spiegel and Turner (2012).

Goldilocks Twins are Rare

[363]**Pg 289 flutter of interest** The research in question was presented at the Goldschmidt Conference in Florence; see Benner (2013).

[364]**Pg 290 having a Martian origin** See for example Belbruno et al. (2012).

[365]**Pg 290 strong enough to eject** See Worth, Sigurdsson and House (2013).

The Prokaryote–Eukaryote Transition is Rare

[366]**Pg 294 ignited the Cambrian explosion** See Knoll and Carroll (1999).

[367]**Pg 295 period of tectonic stability** For a billion year period, tectonic activity on Earth was minimal. Cawood and Hawkesworth (2014) describe the timescales on which the mechanism of plate tectonics has operated.

[368]**Pg 296 biochemist Peter Mitchell** Peter Dennis Mitchell (1920–1992) was awarded the 1978 Nobel prize in chemistry for his proposal of the chemiosmotic hypothesis—the notion that ATP synthesis occurs thanks to a potential difference across a membrane. Mitchell's idea was met with huge skepticism when he proposed it (Mitchell 1961); it took many years before the weight of experimental observation proved the correctness of his hypothesis.

[369]**Pg 297 cells of different size** For a beautifully clear discussion of the development of the eukaryotic cell, and of a variety of other topics in evolutionary biology, see Lane (2010).

Toolmaking Species are Rare

[370]**Pg 299 some species make them** There is a wide literature on animal tool use, though there's no single definition of what constitutes tool use—is a dog using a wall as a tool when it scratches its back? Depending upon one's definition, many animals have been observed to use tools. With regard to chimps, for example, see Boesch and Boesch (1984, 1990). With regard to capuchin monkeys, see Visalberghi and Trinca (1989). With regard to elephants, see Chevalier-Skolnikoff and Liska (1993). Three good general books on the subject of tool use (including the development of human tool use) are Calvin (1996), Gibson and Ingold (1993) and Griffin (1992).

[371]**Pg 300 Kanzi, a bonobo** For the story of this remarkable bonobo, Kanzi (1980–), see Savage-Rumbaugh and Lewin (1996).

High Technology is Not Inevitable

[372]**Pg 303 but Denisovans** The story of our Denisovan cousins is still being written. The discovery of *Homo denisova* was announced in Krause (2010). Since then, a mitochondrial genome sequence of an ancient hominim (Meyer,

2013) has led to the suggestion that Denisovans interbred with an as-yet unidentified hominid species. At the time of writing, the chronicle of human evolution is difficult to read, but the incredible advances being made by geneticists will surely bring about some clarity.

[373]**Pg 304 they were no mugs** An introductory article describing how various hominid species must once have co-existed is given in Tattersall (2000). For four excellent books on early-human tool use, see Tattersall (1998), Schick and Toth (1993), Leakey (1994) and Kohn (1999). A modern synthesis of these ideas, and of what might distinguish modern humans from Neanderthals, is Stringer (2012). Svante Pääbo is the "master of Neanderthal DNA"; see Pääbo (2014) for the fascinating story of how modern technology is transforming out understanding of both humans and Neanderthals.

[374]**Pg 304 the Neanderthal's a disservice** See Soressi et al. (2013) for details of bone lissoirs found in Neanderthal sites in present-day Dordogne. Appenzeller (2013) gives two sides of the debate surrounding the putative achievements of Neanderthals.

[375]**Pg 305 began to dazzle** For a discussion of cave art see, for example, Sieveking (1979).

Intelligence at the Human Level is Rare

[376]**Pg 307 intelligence in other creatures** Herzing (2014) offers an attempt to assess and compare various non-human intelligences, as part of the larger goal of preparing for the assessment of intelligence in life on other planets. We might need to take a flexible approach if we ever encounter extraterrestrial species. For example, if we came across a species that could build a structure complete with cultured gardens, internal temperature control and ventilation would we consider the species to be intelligent? Well, termites build such structures and we generally don't attribute an individual termite with a high level of intelligence. Or is intelligence to be found in the termite "hive mind"? This possibility has been discussed in many science fiction stories; perhaps scientists and philosophers will one day have to grapple with the question for real.

[377]**Pg 307 lived about 65 million years ago** See O'Leary et al. (2013) for details of research on the likely appearance of the ancestor of all mammals.

[378]**Pg 310 Lineweaver pointed out** See Lineweaver (2008) for a strong and beautifully reasoned argument suggesting that human-level intelligence is not a convergent feature of evolution.

[379]**Pg 311 scientists showed how crows** This research appeared in Viet and Nieder (2013).

[380]**Pg 311 development of a fly's eye** In 1993, Walter Gehring and Rebecca Quiring found a gene called *eyeless* that seemed to act as a master control gene for the formation of an eye in fruit flies (see Quiring et al. (1994) and Halder et al. (1995) for more information). By suitable manipulation, they could "turn the gene on" in different places and have a fly sprout an ectopic eye on its wing or its leg or its antenna. *Eyeless* was not the gene "for" an eye—the way genes work is much more subtle—but it seemed, among other functions, to orchestrate the action of thousands of other genes that form an eye in the early development of an embryo. It soon became clear that the fly *eyeless* gene was similar to a mouse gene called *small eye*. A mouse with a defective *small eye* gene develops shrunken eyes. Furthermore, the gene is similar to a human gene responsible for the condition Aniridia, sufferers of which can have defects of the iris, lens, cornea and retina. When geneticists made a detailed comparison it was discovered that the "eye genes" in these three quite different species—fruit fly, mouse and man—were essentially identical in two crucial locations. Georg Halder and Patrick Callaerts decided to implant the mouse *small eye* gene into a fruit fly. The gene worked. It caused the fly to develop ectopic eyes—fruit fly eyes, not mouse eyes. The eyes were not wired to the brain, but they looked like normal insect compound eyes and they responded to light. So although eyes take on different designs across the animal kingdom, the biochemical pathways that allow eyes to function seem to have been laid down very early in history.

Language is Unique to Humans

[381]**Pg 312 lions do not** Budiansky (1998) is an accessible account of research into animal cognition. For a different take on the question of animal consciousness and intelligence, see Rogers (1997).

[382]**Pg 313 if they lacked language** See Olson (1988) for a discussion of the relevance of human linguistic abilities to the Fermi paradox.

[383]**Pg 315 fossilized Neanderthal hyoid bone** See D'Anastasio et al. (2013).

[384]**Pg 315 philosopher and linguist Noam Chomsky** The American linguist Avram Noam Chomsky (1928–), one of the world's most respected intellectuals, writes widely on political and social issues as well as on linguistics. His linguistic work is highly abstruse, but for an introduction to the revolution that he sparked in 1959—and to the advances made by others in the intervening decades—look no further than Pinker (1994), which is a superbly readable book.

[385]**Pg 318 natural selection of heritable variations** Half the members of a British family known as KE suffer from severe language difficulties: not only do they struggle with grammar, writing and comprehension, they can't properly coordinate the complex mechanical motor sequences required for fluid speech. Geneticists (Lai et al. 2001) discovered that the source of the problem was a mutation in the gene Forkhead box protein P2—FOXP2, for short. Normally, FOXP2 coordinates the expression of other genes, but in affected members of the KE family it was broken. This was the first time that scientists had implicated a specific gene in a speech and language disorder, and so it's not surprising that journalists began calling it "the language gene". This was taking the interpretation much too far: FOXP2 isn't a language or a grammar gene. But it *is* an interesting gene, and ongoing research will clarify the role it seems to play in language.

Science is Not Inevitable

[386]**Pg 320 50,000 years ago** Genetic studies suggest that Aboriginal people are descended from the first humans to migrate out of Africa. They migrated to Asia about 70,000 years ago and somehow made the journey to Australia about 50,000 years ago. See Rasmussen et al. (2011).

[387]**Pg 321 rise of modern science** There are many good accounts of the historical development of science. See, for example, Asimov (1984).

Consciousness is Not Inevitable

[388]**Pg 322 chilling science fiction novel** Watts (2006) packs his novel *Blindsight* with speculations based on hard science. By making the case for separating intelligence from consciousness he succeeds in describing creatures that appear

to be truly alien. The novel has a thoroughly bleak outlook on life, but is well worth reading—particularly since the author has been kind enough to make the novel available for free online.

[389]**Pg 323 captured the experiment on film** For a good discussion of the blindsight phenomenon, see de Gelder (2010); the article also links to video of the experiment mentioned in the text. The film shows a patient TN successfully navigating a litter-strewn corridor; also shown in the film, walking behind TN, is the British psychologist Lawrence Weiskrantz (1926–) who in the 1970s discovered and named the phenomenon of blindsight.

[390]**Pg 324 far as my reading has taken me** On the basis of Watts' recommendation in *Blindsight*, I'm employing Metziger (2003) as a tour guide to the phenomenon of consciousness and subjectivity. It's tough going (I find most philosophy books tough going) but Metzinger is clearly a brilliant thinker and his arguments are compelling.

Gaia, God or Goldilocks?

[391]**Pg 324 history of clement weather** For details of the argument in this section, and of the various ways in which Earth might be special, see Waltham (2014).

[392]**Pg 326 originated by James Lovelock** Although he is best known for developing the Gaia hypothesis, Lovelock (1919–) has several inventions to his name and a number of contributions to science, even though he's an unaffiliated, independent scientist. For more on Gaia, and humankind's possible future, see for example Lovelock (2009, 2014).

Conclusion

[393]**Pg 331 resolutions of the Fermi paradox** Note that new solutions to the paradox, and new work that is inspired by the paradox, appear frequently in the scientific and science fictional literature. Whates (2014), for example, is an anthology of original science fiction stories inspired by Fermi's question. It was published just weeks before this book went to print.

The Fermi Paradox Resolved . . .

[394]**Pg 332 the Douglas Adams response** The quote appears, of course, in *The Hitchhiker's Guide* (Adams 1979).

[395]**Pg 332 one recent estimate** The estimate of 100 billion for the number of habitable, Earth-like planets is larger than previous estimates, but is not unreasonable. The estimate appears in Abe et al. (2013).

[396]**Pg 333 stands for Graham's number** The story of Graham's number first appeared in Martin Gardner's *Scientific American* column (Gardner 1977), in which it was called "the largest number ever used in a serious mathematical proof". Gardner's column referred to a number used by Graham in an unpublished proof. In 1971, Graham co-published a paper that discussed the problem mentioned in the text (although the problem was couched in terms of coloring the lines connecting vertex pairs of an *n*-dimensional hypercube, rather than in terms of committees and subcommittees); see Graham and Rothschild (1971). The upper bound calculated by Graham and Rothschild was much smaller than Graham's number, but still vast. The lower bound has been improved, and now stands at 13. The upper bound has been improved, too, and now stands at $2 \uparrow\uparrow 2 \uparrow\uparrow 2 \uparrow\uparrow 9$.

[397]**Pg 337 biologist Jacques Monod** See Monod (1971). This translation from the French original is by A. Whitehouse.

References

Abbott D (2013) The reasonable ineffectiveness of mathematics. Proc IEEE 101:2147–2153

Abe F et al (2013) Extending the planetary mass function to earth mass by microlensing at moderately high magnification. Mon Not R Astro Soc 431:2975–2985

Aczel A (1998) Probability 1: why there must be intelligent life in the universe. Harcourt Brace, New York

Adams D (1979) The Hitchhiker's guide to the galaxy. Pan, London

Aiken B (2014) Small doses of the future: a collection of medical science fiction stories. Springer, Berlin

Alcubierre M (1994) The warp drive: hyper-fast travel within general relativity. Class Quantum Gravity 11:L73–L77

Almheiri A, Marolf D, Polchinski J, Sully J (2013) Black holes: complementarity or firewalls? J High Energy Phys 2013(2):1–20

Alvarez L et al (1980) Extra-terrestrial cause for the Cretaceous–Tertiary extinction. Science 208:1094–1108

Alvarez Q (1997) T-Rex and the crater of doom. Princeton University, Princeton

Amancio DR, Altmann EG, Rybski D, Oliveira ON Jr, Costa L da F (2013) Probing the statistical properties of unknown texts: application to the Voynich Manuscript. PLoS ONE 8(7):e67310

Anderson P (2000) Tau zero (SF Collector's Edition). Orion, London.

Andrews DG (2004) Interstellar propulsion opportunities using near-term technologies. Acta Astronaut 55:443–451

Annis J (1999) An astrophysical explanation of the great silence. J Br Interplanet Soc 52:19

Appenzeller T (2013) Neanderthal culture: old masters. Nature 497:302–304

Armstrong JC, Barnes R, Domagal-Goldman S, Breiner J, Quinn TR, Meadows VS (2014) Effects of extreme obliquity variations on the habitability of exoplanets. Astrobiology 14:277–291

Armstrong S, Sandberg A (2013) Eternity in six hours: intergalactic spreading of intelligent life and sharpening the Fermi paradox. Acta Astronaut 89:1–13

Arnold K (1952) The coming of the saucers (Privately published)

Arnold L (2013) Transmitting signals over interstellar distances: three approaches compared in the context of the Drake equation. Int J Astrobiol 12:212–217

Arrhenius SA (1908) Worlds in the making. Harper and Row, New York

S. Webb, *If the Universe Is Teeming with Aliens … WHERE IS EVERYBODY?*, Science and Fiction, DOI 10.1007/978-3-319-13236-5

Asimov I (1959) Nine tomorrows. Doubleday, New York
Asimov I (1969) Nightfall and other stories. Doubleday, New York
Asimov I (ed) (1971) Where do we go from here? Doubleday, New York
Asimov I (ed) (1972) The Hugo winners, volumes 1 and 2. Doubleday, New York
Asimov I (1979) In memory yet dreen. Doubleday, New York
Asimov I (1981) Extraterrestrial civilizations. Pan, London
Asimov I (1984) Asimov's new guide to science. Basic Books, New York
Asimov I (1994) I, Asimov: a memoir. Doubleday, New York
Atri D, DeMarines J, Haqq-Misra J (2011) A protocol for messaging to extraterrestrial intelligence. Space Policy 27:165–9
Bahcall JN, Davis R (2000) The evolution of neutrino astronomy. CERN Cour 40(6):17–21
Bainbridge WS (1984) Computer simulation of cultural drift: limitations on interstellar colonization. J Br Interplanet Soc 37:420–429
Ball JA (1973) The zoo hypothesis. Icarus 19:347–349
Ball JA (1995) Gamma-ray bursts: the ETI hypothesis. www.haystack.mit.edu/hay/staff/jball/grbeti.ps
Barlow MT (2013) Galactic exploration by directed self-replicating probes, and its implications for the Fermi paradox. Int J Astrobiol 12:63–68
Barrow JD (1998) Impossibility: the limits of science and the science of limits. OUP, Oxford
Barrow JD, Tipler FJ (1986) The anthropic cosmological principle. OUP, Oxford
Battersby S (2013) Alien megaprojects: the hunt has begun. New Sci 2911:42–45
Baxter S (2000a) The planetarium hypothesis: a resolution of the Fermi paradox. J Br Interplanet Soc 54:210–216
Baxter S (2000b) Manifold: space. Voyager, London
Bayes T (1763) An essay towards solving a problem in the doctrine of chances. Phil Trans R Soc 53:370–418
Beane SR, Davoudi Z, Savage MJ (2012) Constraints on the universe as a numerical simulation. arXiv:1210.1847v2
Bear G (1989) Tangents. Warner, New York
Belbruno E, Moro-Martín A, Malhotra R, Savransky D (2012) Chaotic exchange of solid material between planetary systems: implications for lithopanspermia. Astrobiology 12:754–74
Ben-Bassat A, Ben-David-Zaslow R, Schocken S, Vardi Y (2005) Sluggish data transport is faster than ADSL. Ann Improbable Res 11:4–8
Benford G (1977) In the ocean of night. Dial, New York
Benford G, Niven L (2012) Bowl of heaven. Tor, New York
Benford J, Benford G, Benford D (2010a) Messaging with cost-optimized interstellar beacons. Astrobiology 10:475–90
Benford J, Benford G, Benford D (2010b) Searching for cost-optimized interstellar beacons. Astrobiology 10:491–8
Benner SA (2013) Planets, minerals and life's origin. Mineral Mag 77:686

Bergman NM, Lenton TM, Watson AJ (2004) COPSE: a new model of biogeochemical cycling over Phanerozoic time. Am J Sci 304:397–437
Bernal JD (1929) The world, the flesh and the devil. Cape, London
Bernhardt HS (2012) The RNA world hypothesis: the worst theory of the early evolution of life (except for all the others). Biol Direct 7:23. doi:10.1186/1745-6150-7-23
Bester A (1956) The stars my destination. Sidgwick and Jackson, London
Bezsudnov I, Snarskii A (2010) Where is everybody?—Wait a moment . . . New approach to the Fermi paradox. arXiv:1007.2774v1
Billingham J, Benford J (2011) Costs and difficulties of large-scale "messaging", and the need for international debate on potential risks. arXiv:1102.1938v2
Billings L (2013) Five billion years of solitude: the search for life among the stars. Current, New York
Bird DJ (1995) Detection of a cosmic ray with a measured energy well beyond the expected spectral cutoff due to cosmic microwave radiation. Astrophys J 441:144–151
Bjørk R (2007) Exploring the galaxy using space probes. Int J Astrobiol 6:89–93
Bloch WG (2008) The unimaginable mathematics of Borges' library of Babel. OUP, Oxford
Boesch C, Boesch H (1984) Mental map in wild chimpanzees: an analysis of hammer transports for nut cracking. Primates 25:160–170
Boesch C, Boesch H (1990) Tool use and tool making in wild chimpanzees. Filia Primatol 54:86–99
Borges JL (1998) Collected fictions. Viking, London
Bostrom N (2002) Anthropic bias: observer self-selection effects in science and philosophy. Routledge, New York
Bostrom N (2003) Are you living in a computer simulation? Phil Q 53(211):243–255
Bostrom N (2006) What is a singleton? Ling Phil Investig 5:48–54
Bostrom N, Ćirković MM (2008) Global catastrophic risks. OUP, Oxford
Bostrom N, Kulczycki M (2011) A patch for the simulation argument. Analysis 71:54–61
Bova B (ed) (1973) The science fiction hall of fame, volume 2A. Doubleday, New York
Bowen M (2006) Thin ice: unlocking the secrets of climate in the world's highest mountains. Holt, New York
Bowyer S (2011) A brief history of the search for extraterrestrial intelligence and an appraisal of the future of this endeavor. Proc. SPIE: Instruments, Methods, and Missions for Astrobiology XIV 8152 Ed. R B Hoover, P C W Davies, G V Levin and A Y Rozanov
Bracewell RN (1960) Communication from superior galactic communities. Nature 186:670–1
Bressi G, Carugno G, Onofrio R, Ruoso G (2002) Measurement of the Casimir force between parallel metallic surfaces. Phys Rev Lett 88:041804
Brin GD (1983) The "great silence": the controversy concerning extraterrestrial intelligent life. Q J R Astro Soc 24:283–309
Brin GD (1985) Just how dangerous is the Galaxy? Analog 105(7):80–95
Brooker RJ (1998) Genetics: analysis and principles, 4th edn. McGraw Hill, New York

Brown P, Spalding RE, ReVelle DO, Tagliaferri E, Worden SP (2002) The flux of small near-earth objects colliding with the earth. Nature 420:294–296
Buch P, Mackay AL, Goodman SN (1994) Future prospects discussed. Nature 358:106–108
Buchhave LA et al (2012) An abundance of small exoplanets around stars with a wide range of metallicities. Nature 486:375–377
Budiansky S (1998) If a lion could talk. Weidenfeld and Nicolson, London
Bussard RW (1960) Galactic matter and interstellar flight. Acta Astronaut 6:179–194
Byl J (1996) On the natural selection of universes. Q J R Astro Soc 37:369–371
Byrne P (2010) The many worlds of hugh Everett III. OUP, Oxford
Calvin WH (1996) How brains think. Basic Books, New York
Cameron AGW, Ward WR (1976) The origin of the moon. Abstr Lunar Planet Sci Conf 7:120–122
Caplan B (2008) The totalitarian threat. In: Bostrom N, Ćirković MM (eds) Global catastrophic risks. OUP, Oxford, pp 504–519
Carey SS (1997) A beginner's guide to scientific method. Wadsworth, Stamford
Carr B (ed) (2007) Universe or multiverse? CUP, Cambridge
Carrigan RA Jr (2009) IRAS-based whole-sky upper limit on Dyson spheres. Astrophys J 698:2075–2086
Carrigan RA Jr (2010) Starry messages: searching for signatures of interstellar archaeology. J Br Interplanet Soc 63:90–103
Carrigan RA Jr (2012) Is interstellar archeology possible? Acta Astronaut 78:121–126
Carroll S (2013) The particle at the end of the universe. Oneworld, London
Carroll SB (2006) Endless forms most beautiful: the new science of Evo Devo. Norton, New York
Carter B (1974) Large number coincidences and the anthropic principle in cosmology. In: Longair MS (ed) Confrontation of cosmological theories with observation. Reidel, Dordrecht
Cartin D (2013) Exploration of the local solar neighbourhood I: fixed number of probes. Int J Astrobiol 12:271–281
Casscells W, Schoenberger A, Graboys TB (1978) Interpretation by physicians of clinical laboratory results. N Engl J Med 299:999–1001
Catling DC (2014) Astrobiology: a very short introduction. OUP, Oxford
Caves CM, Drummond PD (1994) Quantum limits on bosonic communication rates. Rev Mod Phys 66:481–537
Cawood PA, Hawkesworth C (2014) Earth's middle age. Geology 42:503–506
Cerceau FR, Bilodeau B (2012) A comparison between the 19th century early proposals and the 20th–21st centuries realized projects intended to contact other planets. Acta Astronaut 78:72–9
Cernan E, Davis D (1999) The last man on the moon. St Martin's, New York
Chaitin GJ (1997) The limits of mathematics. Springer, Berlin
Chevalier-Skolnikoff S, Liska J (1993) Tool use by wild and captive elephants. Anim Behav 46:209–219

Chyba CF, Hand KP (2005) Astrobiology: the study of the living universe. Ann Rev Astron Astrophys 45:31–74
Ćirković MM (2005) Permanence—an adaptationist solution to Fermi's paradox? J Br Interplanet Soc 58:62–70
Ćirković MM (2008) Against the empire. J Br Interplanet Soc 61:246–254
Ćircović MM, Bradbury RJ (2006) Galactic gradients, postbiological evolution and the apparent failure of SETI. New Astron 11:628–39
Ćirković MM, Cathcart RB (2004) Geo-engineering gone awry: a new partial solution of Fermi's paradox. J Br Interplanet Soc 57:209–215
Ćirković MM, Dragićević I, Berić-Bjedov T (2005) Adaptationism fails to resolve Fermi's paradox. Serb Astron J 170:89–100
Citizen Hearing on Disclosure (2013) The citizen hearing on disclosure homepage http://citizenhearing.org. Accessed 17 Jan 2014
Clarke AC (1953) Childhood's end. Del Rey, New York
Clarke (1956) The City and the Stars. New American Library, New York
Cocconi G, Morrison P (1959) Searching for interstellar communications. Nature 184:844–6
Cohen N, Hohlfeld R (2001) A newer, smarter SETI strategy. Sky Telesc 101(4):50–51
Comins NF (1993) What if the moon didn't exist? Harper Collins, New York
Compton AH (1956) Atomic quest. OUP, Oxford
Connelly JN, Bizzarro M, Krot AN, Nordlund A, Wielandt D, Ivanova MA (2012) The absolute chronology and thermal processing of solids in the solar protoplanetary disk. Science 338:651–655
Cooper J (2013) Bioterrorism and the Fermi paradox. Int J Astrobiol 12:144–148
Corbet R, H D (1999) The use of gamma-ray bursts as direction and time markers in SETI strategies. Pub Astron Soc Pacific 111:881–885
Cotta C, Á M (2009) A computational analysis of galactic exploration with space probes: implications for the Fermi paradox. J Br Interplanet Soc 62:82–88
Cox LJ (1976) An explanation for the absence of extraterrestrials on earth. Q J R Astro Soc 17:201–208
Cramer JG (1986) The pump of evolution. Analog 106(1):124–127
Crawford IA (1995) Interstellar travel: a review. In: Zuckerman B, Hart MH (eds) Extraterrestrials: where are they? CUP, Cambridge
Crawford IA (2000) Where are they? Sci Am 283(7):28–33
Crawford IA (2009) The astronomical, astrobiological and planetary science case for interstellar spaceflight. J Br Interplanet Soc 62:415–421
Crawford IA, Baldwin EC, Taylor EA, Bailey J, Tsembelis K (2008) On the survivability and detectability of terrestrial meteorites on the moon. Astrobiology 8:242–252
Crick F, H C (1981) Life itself. Simon and Schuster, New York
Crick FHC, Orgel LE (1973) Directed panspermia. Icarus 19:341–6
Cronin JW (2004) (Ed) Fermi remembered. UCP, Chicago
Dalrymple GB (2001) The age of the earth in the twentieth century: a problem (mostly) solved. Geol Soc London, Special Publ 190:205–221

D'Anastasio R et al (2013) Micro-biomechanics of the Kebara 2 hyoid and its implications for speech in Neanderthals. PLOS ONE doi:10.1371/journal.pone.0082261
Dartnell L (2007) Life in the universe: a beginner's guide. Oneworld, London
Davies EB (2007) Let platonism die. Euro Math Soc Newsletter (June) 64:24–25
Davies P, C W (2010) The Eerie silence. Allen Lane, London
Davies P, C W (2012) Footprints of alien technology. Acta Astronaut 73:250–7
Davies PCW, Wagner RV (2013) Searching for alien artifacts on the moon. Acta Astronaut 89:261–5
Deacon T (2013) Life before genetics: autogenesis, and the outer solar system. https://www.youtube.com/watch?v=jeMwy3xuEs8. Accessed 8 May 2014
Deamer D (2012) First life: discovering the connections between stars, cells, and how life began. University of California, Oakland
Deardorf JW (1986) Possible extraterrestrial strategy for earth. Q J R Astro Soc 27:94–101
Deardorf JW (1987) Examination of the embargo hypothesis as an explanation for the Great silence. J Br Interplanet Soc 40:373–379
de Gelder B (2010) Uncanny sight in the blind. Sci Am 302:60–65
Dehaene S (1997) The number sense: how the mind creates mathematics. OUP, Oxford
Denning K (2010) Unpacking the great transmission debate. Acta Astronaut 67:1399–1405
Deutsch D (1998) The fabric of reality. Penguin, London
de Vladar HP (2013) The game of active search for extra-terrestrial intelligence: breaking the "Great Silence". Int J Astrobiol 12:53–62
Devlin K (2007) The myth that will not go away. MAA Online (May). www.maa.org/external_archive/devlin/devangle.html. Accessed 21 Feb 2014
Dick SJ (1996) The biological universe: the twentieth century extraterrestrial life debate and the limits of science. CUP, Cambridge
Dick SJ (2003) Cultural evolution, the postbiological universe and SETI. Int J Astrobiol 2:65–74
Dick SJ (2008) The postbiological universe. Acta Astronaut 62:499–504
Digital S (2013) "Jesus Christ image" found in fabric conditioner www.digitalspy.co.uk/fun/news/a474585/jesus-christ-image- found-in-fabric-conditioner.html. Accessed 20 Jan 2014
D'Imperio ME (1978) The Voynich manuscript—an elegant enigma. Aegean Park Press, Laguna Hills
Dokuchaev VI (2011) Is there life inside black holes? Class Quantum Gravity 28:235015
Dole SH (1964) Habitable planets for man. Blaisdell, New York
Dole SH, Asimov I (1964) Planets for man. Random House, New York
Douglas F (1977) The absence of extraterrestrials on earth. Q J R Astro Soc 18: 157–158
Drake FD, Sagan C (1973) Interstellar radio communication and the frequency selection problem. Nature 245:257–8
Drake FD, Sobel D (1991) Is anyone out there? Simon and Schuster, London
Drexler KE (1986) Engines of creation: the coming era of nanotechnology. Doubleday, New York

Duggan P, McBreen B, Carr AJ, Winston E, Vaughan G, Hanlon L, McBreen S, Metcalfe L, Kvick AA, Terry AE (2003) Gamma-ray bursts and X-ray melting of material to form chondrules and planets. Astron Astrophys 409:L9–L12

Dyson FJ (1960) Search for artificial sources of infrared radiation. Science 131:1667

Dyson FJ (1963) Gravitational machines. In: G W Cameron A (ed) Interstellar communication. Benjamin, New York

Dyson FJ (1982) Interstellar propulsion systems. In Zuckerman B, Hart MH (eds) Extraterrestrials: where are they? CUP, Cambridge

Eddy DM (1982) Probabilistic reasoning in clinical medicine: problems and opportunities. In Kahneman D, Slovic P, Tversky A (eds) Judgment under uncertainty: heuristics and biases. CUP, Cambridge, pp 249–267

Edmondson WH (2010) Targets and SETI: shared motivations, life signatures and asymmetric SETI. Acta Astronaut 67:1410–1418

Edmondson WH, Stevens IR (2003) The utilization of pulsars as SETI beacons. Int J Astrobiol 2:231–271

Eichler D, Beskin G (2001) Optical SETI with air Cerenkov telescopes. Astrobiology 1:489–493

Einstein A, Podolsky B, Rosen N (1935) Can a quantum-mechanical description of physical reality be considered complete? Phys Rev 41:777–780

Elliott JR (2011) A post-detection decipherment strategy. Acta Astronaut 68:441–444

Elliott JR (2012) Constructing the matrix. Acta Astronaut 78:26–30

Elliott JR, Baxter S (2012) The DISC quotient. Acta Astronaut 78:20–25

Ellis J, Giudice G, Mangano ML, Tkachev T, Wiedemann U (2008) Review of the safety of LHC collisions. J Phys G Nucl Part Phys 35:115004

Elsila JE, Glavin DP, Dworkin JP (2009) Cometary glycine detected in samples returned by Stardust. Meteor Planet Sci 44:1323–30

Elvis M (2014) How many ore-bearing asteroids? Planet Space Sci 91:20–6

Enever JG (1966) Giant meteor impact. Analog 77(3):62–84

England JL (2013) Statistical physics of self replication. J Chem Phys 139:121923

ESA (2013) ESA home page http://sci.esa.int/planck/

Everett H (1957) "Relative state" formulation of quantum mechanics. Rev Mod Phys 29:454–462

Exoplanet Team (2014) http://exoplanet.eu. Accessed 1 April 2014

Faizullin RT (2010) Geometrical joke(r?)s for SETI. arxiv.org/abs/1007.4054

Farmer PJ (1981) The unreasoning mask. Putnam, New York

Feinberg G, Shapiro R (1980) Life beyond earth. Morrow, New York

Fermi L (1954) Atoms in the family. UCP, Chicago

Feynman RP (1959) There's plenty of room at the bottom. Lecture given to the American Physical Society at Caltech, 29 Dec

Finney BR, Jones EM (eds) (1985) Interstellar migration and the human experience. University of California, Berkeley

Fischer DA et al. (2002) A second planet orbiting 47 Ursae Majoris. Astrophys J 564:1028–1034

FNAL (1998) The universe lives on and rumors of its imminent demise have been greatly exaggerated. www.fnal.gov/pub/ferminews/FermiNews98-06-19.pdf
Fogg MJ (1987) Temporal aspects of the interaction among the first galactic civilizations: the "interdict hypothesis". Icarus 69:370–384
Fogg MJ (1988) Extraterrestrial intelligence and the interdict hypothesis. Analog 108(10):62–72
Fogg MJ (1995) Terraforming: engineering planetary environments. SAE, New York
Forgan DH (2009) A numerical testbed for hypotheses of extraterrestrial life and intelligence. Int J Astrobiol 8:121–131
Forgan DH (2011) Spatio-temporal constraints on the zoo hypothesis, and the breakdown of total hegemony. Int J Astrobiol 10:341–347
Forgan DH (2013) On the possibility of detecting class A stellar engines using exoplanet transit curves. J Br Interplanet Soc 66:144–154
Forgan DH, Nichol RC (2011) A failure of serendipity: the square kilometre array will struggle to eavesdrop on human-like ETI. Int J Astrobiol 10:77–81
Forgan DH, Papadogiannakis S, Kitching T (2013) The effects of probe dynamics on galactic exploration timescales. J Br Interplanet Soc 66:171–178
Forward RL (1980) Dragon's egg. Del Rey, New York
Forward RL (1984) Roundtrip interstellar travel using laser-pushed lightsails. J Spacecraft 21:187–195
Forward RL (1990) The negative matter space drive. Analog 110(9):59–71
Foschini GJ (1994) The canonical artefact and its cosmological interpretations. Proc Math Phys Sci 444:3–16
Freitas RA Jr (1980) A self-reproducing interstellar probe. J Br Interplanet Soc 33:251–264
Freitas RA Jr (1983a) If they are here, where are they? Observational and search considerations. Icarus 55:337–343
Freitas RA Jr (1983b) The search for extraterrestrial artifacts (SETA). J Brit Interplanet Soc 36:501–506
Freitas RA Jr (1985) There is no Fermi paradox. Icarus 62:518–520
Freitas RA Jr (2000) Some limits to global ecophagy by biovorous nanoreplicators, with public policy recommendations. Available from www.foresight.org/nano/Ecophagy.html
Freitas RA Jr, Valdes F (1980) A search for natural or artificial objects located at the earth–moon libration points. Icarus 42:442–447
French AP (1968) Special relativity. Norton, San Francisco
Freudenthal H (1960) Design of a language for cosmic intercourse. North Holland, Amsterdam
Garcia-Escartin JC, Chamorro-Posada P (2013) Scouting the spectrum for interstellar travellers. Acta Astronaut 85:12–18
Gardner M (1969) The unexpected hanging and other mathematical diversions. Simon and Schuster, New York
Gardner M (1970) The fantastic combinations of John Conway's new solitaire game "Life". Sci Am 223:120–123
Gardner M (1977) Mathematical games. Sci Am 237:18–28

Gardner M (1985) The great stone face and other nonmysteries. Skept Inquirer 10(2): 14–18
Gato-Rivera B (2006) The Fermi paradox in the light of the inflationary and brane world cosmologies. Trends in general relativity and quantum cosmology. Nova, New York
Gehrels N, Laird CM, Jackman CH, Canizzo JK, Mattson BJ, Chen W (2003) Ozone depletion from nearby supernovae. Astrophys J 585:1169–1176
Gibson KR, Ingold T (eds) (1993) Tools, language and cognition in human evolution. CUP, Cambridge
Gigerenzer G, Hoffrage U (1995) How to improve Bayesian reasoning without instruction: frequency formats. Psych Rev 102:684–704
Gillon M (2014) A novel SETI strategy targeting the solar focal regions of the most nearby stars. Acta Astronaut 94:629–633
Goldblatt C, Watson AJ (2012) The runaway greenhouse: implications for future climate change, geoengineering and planetary atmospheres. Phil Trans R Soc A 370:4197–4216
Gonzalez G, Brownlee D, Ward PD (2001) Refuges for life in a hostile universe. Sci Am 285(4):60–67
Gordon JE (1991) The new science of strong materials or why you don't fall through the floor (2nd revised ed.). Penguin, London
Gott JR III (1993) Implications of the Copernican principle for our future prospects. Nature 363:315–319
Gott JR III (1995) Cosmological SETI frequency standards. In Zuckerman B, Hart MH (eds) Extraterrestrials: where are they? CUP, Cambridge
Gott JR III (1997) A grim reckoning. New Scientist 15 Nov pp 36–39
Gould SJ (1985) SETI and the wisdom of Casey Stengel. In: The Flamingo's smile. Penguin, London
Gould SJ (1986) Wonderful life. Norton, New York
Gowanlock MG, Patton DR, McConnell SM (2011) A model of habitability within the Milky Way galaxy. Astrobiology 11:855–873
Graham RL, Rothschild BL (1971) Ramsey's theorem for *n*-parameter sets. Trans American Math Soc 159:257–292
Gray RH (2011) The elusive wow: searching for extraterrestrial intelligence. Palmer Square, Chicago
Gribbin J (1996) Schrödinger's kittens. Phoenix Press, London
Gribbin J (2010) In search of the multiverse. Penguin, London
Griffin DR (1992) Animal minds. Chicago University, Chicago
Gros C (2005) Expanding advanced civilizations in the universe. J Br Interplanet Soc 58:108–110
Guardian (2001) It could've been you. www.theguardian.com/society/2001/may/02/lottery.g2. Accessed 20 Jan 2014
Gurzadyan VG (2005) Kolmogorov complexity, string information, panspermia and the Fermi paradox. Observatory 125:352–355
Guth AH (2007) Eternal inflation and its implications. J Phys A Math General 40:6811
Hair TW (2011) Temporal dispersion of the emergence of intelligence: an inter-arrival time analysis. Int J Astrobiol 10:131–135

Hair TW (2013) Provocative radio transients and base rate bias: a Bayesian argument for conservatism. Acta Astronaut 91:194–197

Haisch B, Rueda A, Puthoff HE (1994) Beyond $E = mc^2$. Science 34(6):26–31

Halder G et al (1995) Induction of ectopic eyes by targeted expression of the eyeless gene in *Drosophila*. Science 267:1788–1792

Hall MD, Connors WA (2000) Captain Edward J. Ruppelt: summer of the saucers. Rose, Albuquerque

Hancock G, Bauval R, Grigsby J (1998) The Mars mystery. Michael Joseph, London

Hanson R (1998) Burning the cosmic commons: evolutionary strategies for interstellar colonization. http://hanson.gmu.edu/filluniv.pdf

Haqq-Misra J, Baum S (2009) The sustainability solution to the Fermi paradox. J Br Interplanet Soc 62:47–51

Haqq-Misra J, Kopparapu RK (2012) On the likelihood of non-terrestrial artifacts in the solar system. Acta Astronaut 72:15–20

Haqq-Misra J, Busch M, Som S, Baum S (2013) The benefits and harms of transmitting into space. Space Policy 29:40–48

Harland WB, Rudwick MJS (1964) The great infra-Cambrian glaciation. Sci Am 211(2):28–36

Harp GR, Ackermann RF, Blair SK, Arbunich J, Backus PR, Tarter JC, ATA Team (2011) A new class of SETI beacons that contain information. In: Vakoch DA (ed) Communication with extraterrestrial intelligence (CETI). State University of New York, Albany, pp 45–70

Harris I (2013) Americans' belief in God, miracles and heaven declines. www.harrisinteractive.com. Accessed 23 Jan 2014

Harrison E (1987) Darkness at night. Harvard University, Cambridge

Harrison E (1995) The natural selection of universes containing intelligent life. Q J R Astro Soc 36:193–203

Hart MH (1975) An explanation for the absence of extraterrestrials on earth. Q J R Astro Soc 16:128–135

Hart MH (1978) The evolution of the atmosphere of the earth. Icarus 33:23–39

Hart MH (1979) Habitable zones about main sequence stars. Icarus 37:351–357

Hart MH (1980) *N* is very small. In strategies for the search for life in the universe. Reidel, Boston, pp 19–25

Hart MH (1995) Atmospheric evolution, the Drake equation and DNA: sparse life in an infinite universe. In Zuckerman B, Hart MH (eds) Extraterrestrials: where are they? CUP, Cambridge

Hartmann WK, Davis DR (1975) Satellite-sized planetesimals and lunar origin. Icarus 24:504–14

Hartogh P et al. (2011) Ocean-like water in the Jupiter-family comet 103P/Hartley 2. Nature 478:218–220

Hawking SW (2010) Stephen Hawking warns over making contact with aliens. BBC News (25 April). http://news.bbc.co.uk/1/hi/8642558.stm. Accessed 14 March 2014

Hecht J (2010) Beam: the race to make the laser. OUP, Oxford

Heller R, Armstrong J (2014) Superhabitable worlds. Astrobiology 14:50–66

Hempel CG (1945a) Studies in the logic of confirmation I. Mind 54(213):1–26
Hempel CG (1945b) Studies in the logic of confirmation II. Mind 54(214):97–121
Hemry JG (2000) Interstellar navigation or getting where you want to go and back again (in one piece). Analog 121(11):30–37
Hersh R (1997) What is mathematics really? OUP, Oxford
Herzing DL (2014) Profiling nonhuman intelligence: an exercise in developing unbiased tools for describing other "types" of intelligence on earth. Acta Astronaut 94:676–80
Hoagland RC (1987) The monuments of Mars. North Atlantic, Berkeley
Hodgins G (2012) Forensic investigations of the Voynich MS. Voynich 100 Conference www.voynich.nu/mon2012/index.html. Accessed 4 March 2014
Hoffman P (1998) The man who loved only numbers. Hyperion, New York
Hoffman PF, Schrag DP (2000) Snowball earth. Sci Am 282(1):68–75
Hoffman PF, Kaufman AJ, Halverson GP, Schrag DP (1998) A neoproterozoic snowball earth. Science 281:1342–6
Hogben LT (1963) Science in authority. Norton, New York
Hohlfeld R, Cohen N (2000) Optimum SETI search strategy based on properties of a flux-limited catalogue. SETI beyond Ozma. SETI Press, Mountain View
Höss M (2000) Ancient DNA: neanderthal population genetics. Nature 404:453–4
Hoyle F, Eliot J (1963) A for Andromeda. Corgi, London
Hoyle F, Wickramasinghe NC (2000) Astronomical origins of life. Kluwer, Dordrecht
Hut P, Rees MJ (1983) How stable is our vacuum? Nature 302:508–509
Icke D (1999) The biggest secret. Bridge of Love, Newport
Inoue M, Yokoo H (2011) Type III Dyson sphere of highly advanced civilisations around a super massive black hole. J Br Interplanet Soc 64:58–62
IPCC (2013) Climate change 2013: the physical science basis. WMO, Geneva
Jacobson SA, Morbidelli A, Raymond SN, O'Brien DP, Walsh KJ, Rubie DC (2014) Highly siderophile elements in earth's mantle as a clock for the moon-forming impact. Nature 508:84–7
Jaffe RC et al. (2000) Review of speculative "disaster scenarios" at RHIC. Rev Mod Phys 72:1125–1140
Johnson EE, Baram M (2014) New US Science Commission should look at experiment's risk of destroying the earth. Int. Business Times www.ibtimes.com. Accessed 7 March 2014
Jones EM (1975) Colonization of the Galaxy. Icarus 28:421–2
Jones EM (1981) Discrete calculations of interstellar migration and settlement. Icarus 46:328–36
Jones EM (1985) Where is everybody? An account of Fermi's question. Physics Today (Aug) pp 11–13
Jones EM (1995) Estimates of expansion timescales. In Zuckerman B, Hart MH (eds) Extraterrestrials: where are they? CUP, Cambridge
Jugaku J, Nishimura SE (1991) A search for Dyson spheres around late-type stars in the IRAS catalog. In: Heidemann J, Klein MJ (eds) Bioastronomy: the search for extraterrestrial life (lecture notes in physics) 390. Springer, Berlin

Jugaku J, Nishimura SE (1997) A search for Dyson spheres around late-type stars in the solar neighborhood II. In: B Cosmovici C, Bowyer S, Wertheimer D (eds) Astronomical and biochemical origins and the search for life in the universe. Editrice Compositori, Bologna, pp 707–10

Jugaku J, Nishimura SE (2000) A search for Dyson spheres around late-type stars in the solar neighbourhood. III. In: Lemarchand G, Meech K (eds) Bioastronomy: a new era in the search for life. UCP, Chicago

Kardashev NS (1979) Optimal wavelength region for communication with extraterrestrial intelligence—$\lambda = 1.5$mm. Nature 278:28–30

Kasting JF, Reynolds RT, Whitmire DP (1992) Habitable zones around main sequence stars. Icarus 101:108–128

Kecskes C (1998) The possibility of finding traces of extraterrestrial intelligence on asteroids. J Br Interplanet Soc 51:175–180

Kecskes C (2002) Scenarios which may lead to the rise of an asteroid-based technical civilisation. Acta Astronaut 50:569–577

KEO (2014) Welcome to KEO. www.keo.org

Kinouchi O (2001) Persistence solves Fermi paradox but challenges SETI projects. arXiv:cond-mat/0112137v1

Kirschvink JL (1992) Late proterozoic low-latitude global glaciation: the snowball earth. In Schopf JW, Klein C (eds) The Proterozoic biosphere. CUP, Cambridge

Knoll AH, Carroll S (1999) Early animal evolution: emerging views from comparative biology and geology. Science 284:2129–2137

Knuth DE (1984) The TEX book. Addison Wesley, Reading

Kohn M (1999) As we know it. Granta, London

Korhonen JM (2013) MAD with aliens? Interstellar deterrence and its implications. Acta Astronaut 86:201–210

Korpela EJ et al (2011) Status of the UC-Berkeley SETI efforts. Proc. SPIE: Instruments, Methods, and Missions for Astrobiology XIV 8152 Ed. R B Hoover, P C W Davies, G V Levin and A Y Rozanov

Krasnikov SV (2000) A traversible wormhole. Phys Rev D 62:084028

Krause J, Fu Q, Good JM, Viola B, Shunkov MV, Derevianko AP, Pääbo S (2010) The complete mitochondrial DNA genome of an unknown hominin from southern Siberia. Nature 464:894–897

Kuiper TBH, Morris M (1977) Searching for extraterrestrial civilizations. Science 196:616–621

Lachman M, Newman MEJ, Moore C (2004) The physical limits of communication, or why any sufficiently advanced technology is indistinguishable from noise. Am J Phys 72:1290–1293

Lage C (2012) Probing the limits of extremophilic life in extraterrestrial environment-simulated experiments. Int J Astrobiol 11:251–256

Lai C, S L et al. (2001) A forkhead-domain gene is mutated in a severe speech and language disorder. Nature 413:519–523

Lampton M (2013) Information-driven societies and Fermi's paradox. Int J Astrobiol 12:312–3

Landis GA (1998) The Fermi paradox: an approach based on percolation theory. J Br Interplanet Soc 51:163–166

Lane N (2010) Life ascending. Profile, London

Lanoutte W, Szilard B (1994) Genius in the shadows: a biography of Leo Szilard, the man behind the bomb. UCP, Chicago

Lawton AT, Newton SJ (1974) Long delayed echoes: the search for a solution. Spaceflight 6:181–187

Lazio TJW, Tarter J, Backus PR (2002) Megachannel extraterrestrial assay candidates: no transmissions from intrinsically steady sources. Astron J 124:560–564

Leakey R (1994) The origin of humankind. Weidenfeld and Nicolson, London

Leakey R, Lewin R (1995) The sixth extinction. Doubleday, New York

Learned JG, Pakvasa S, Simmons WA, Tata X (1994) Timing data communications with neutrinos: a new approach to SETI. Q J R Astro Soc 35:321–329

Learned JG, Pakvasa S, Zee A (2009) Galactic neutrino communication. Phys Lett B 671:15–19

Lemarchand GA (2008) Counting on beauty: the role of aesthetic, ethical, and physical universal principles for interstellar communication. arXiv:0807.4518

LePage AJ (2000) Where they could hide. Sci Am 283(7):30–31

Leslie J (1996) The end of the world. Routledge, London

Levathes L (1997) When China ruled the seas: the treasure fleet of the dragon throne. OUP, Oxford, pp 1405–1433

Lineweaver CH (2008) Paleontological tests: human-like intelligence is not a convergent feature of evolution. In: Seckbach J, Walsh M (eds) From fossils to astrobiology. Springer, Berlin, pp 355–68

Lineweaver CH, Davis TM (2002) Does the rapid appearance of life on earth suggest that life is common in the universe? Astrobiology 2:293–304

Lineweaver CH, Fenner Y, Gibson BK (2004) The galactic habitable zone and the age distribution of complex life in the Milky Way. Science 303:59–62

Lis DC et al (2013) A Herschel study of D/H in water in the Jupiter-family comet 45P/Honda–Mrkos–Pajdušáková and prospects for D/H measurements with CCAT. Astrophys J Lett 774:L3–L8

Lissauer JJ, Chambers JE (2008) Solar and planetary destabilization of the earth–moon triangular Lagrangian points. Icarus 195:16–27

Livio M (1999) How rare are extraterrestrial civilizations, and when did they emerge? Astrophys J 511:429–431

Loeb A, Turner EL (2012) Detection technique for artificially illuminated objects in the outer solar system and beyond. Astrobiology 12:290–294

Loeb A, Zaldarriaga M (2007) Eavesdropping on radio broadcasts from galactic civilizations with upcoming observatories for redshifted 21 cm radiation. J Cosmol Astropart Phys. doi:10.1088/1475-7516/2007/01/020

Lovelock JE (2009) The vanishing face of Gaia: a final warning—enjoy it while you can. Allen Lane, London

Lovelock JE (2014) A rough ride to the future. Allen Lane, London

Lunan D (1974) Man and the stars. Souvenir, London

Lytkin V, Finney B, Alepko L (1995) Tsiolkovsky, Russian cosmism and extraterrestrial intelligence. Q J R Astro Soc 36:369–376
Maccone C (1994) Space missions outside the solar system to exploit the gravitational lens of the Sun. J Br Interplanet Soc 47:45–52
Maccone C (2000) The gravitational lens of Alpha Centauri a, b, c and of Barnard's star. Acta Astronaut 47:885–897
Maccone C (2009) Deep space flight and communications—exploiting the Sun as a gravitational lens. Springer, Berlin
Maccone C (2011) Focusing the galactic internet. In: Paul Schuch H (ed) Searching for extraterrestrial intelligence: SETI past, present and future. Springer, Berlin, pp 325–49
Maccone C (2013) Sun focus comes first, interstellar comes second. J Br Interplanet Soc 66:25–37
Maccone C, Piantà M (1997) Magnifying the nearby stellar systems by FOCAL space missions to 550 AU. Part I. J Br Interplanet Soc 50:277–280
Mallove EF, Matloff GL (1989) The starflight handbook. Wiley, New York
Malyshev DA, Dhami K, Lavergne T, Chen T, Dai N, Foster JM, Corrêa IR, Romesberg FE (2014) A semi-synthetic organism with an expanded genetic alphabet. Nature. doi:10.1038/nature13314
Marshak S (2009) Essentials of geology, 3rd edn. Norton, New York
Martin G, R R (1976) A song for Lya. Avon, New York
Martins Z, Price MC, Goldman N, Sephton MA, Burchell MJ (2013) Shock synthesis of amino acids from impacting cometary and icy planet surface analogues. Nat Geosci 6:1045–1049
Mathews JD (2011) From here to ET. J Br Interplanet Soc 64:234–241
Matthews R (1999) A black hole ate my planet. New Scientist 28 Aug pp 24–27
Mauersberger R et al (1996) SETI at the spin-flip line frequency of positronium. Astron Astrophys 306:141–144
Mayr E (1995) A critique of the search for extraterrestrial intelligence. Bioastronomy News 7(3)
McBreen B, Hanlon L (1999) Gamma-ray bursts and the origin of chondrules and planets. Astron Astrophys 351:759–765
McCabe M, Lucas H (2010) On the origin and evolution of life in the galaxy. Int J Astrobiol 9:217–226
McClean D (ed) (2010) World disaster report 2010. International Federation of Red Cross and Red Crescent Societies, Geneva
McGrayne SB (2011) The theory that would not die. YUP, Yale
McInnes CR (2002) The light cage limit to interstellar expansion. J Br Interplanet Soc 55:279–284
McPhee J (1973) The curve of binding energy. Farrar, Straus and Giroux, New York
Melott AL, Lieberman BS, Laird CM, Martin LD, Medvedev MV, Thomas BC, Cannizzo JK, Gehrels N, Jackman CH (2004) Did a gamma-ray burst initiate the late Ordovician mass extinction? Int J Astrobiol 3:55–61

Mereghetti S (2008) The strongest cosmic magnets: soft gamma-ray repeaters and anomalous x-ray pulsars. Astron Astrophys Rev 15:225–287

Mermin ND (1990) Boojums all the way through. CUP, Cambridge

Meshik AP (2005) The workings of an ancient nuclear reactor. Sci Am 293(5):83–91

Messerschmitt DG (2012) Interstellar communication: the case for spread spectrum. Acta Astronaut 81:227–38

Metropolis N (1987) The beginning of the Monte Carlo method. Los Alamos Science (Special issue dedicated to Stanislaw Ulam). pp 125–130

Metzinger T (2003) Being no one: the self-model theory of subjectivity. MIT Press, Cambridge

Meyer M et al. (2013) A mitochondrial genome sequence of a hominin from Sima de los Huesos. Nature 505:403–406

Miller WM Jr (1960) A canticle for Liebowitz. Lippincott, Philadelphia

Minsky M (1973) Talk given at the Communication With Extraterrestrial Intelligence (CETI) conference. In C Sagan (ed) Proceedings of a Conference Held at Byurakan Astrophysical Observatory, Yerevan, USSR, 5–11 Sept 1971 p ix (Cambridge, MA: MIT Press)

Minsky M (1985) Communication with alien intelligence. In Regis E (ed) Extraterrestrials: science and alien intelligence. CUP, Cambridge

Miodownik M (2013) Stuff matters. Viking, London

Mitchell P (1961) Coupling of phosphorylation to electron and hydrogen transfer by a chemi-osmotic type of mechanism. Nature 191:144–148

Monod J (1971) Chance and necessity. Collins, London

Monroe T, W R et al. (2013) High precision abundances of the old solar twin HIP 102152: insights on Li depletion from the oldest Sun. Astrophys J Lett 774:L32(6pp)

Moore GE (1965) Cramming more components onto integrated circuits. Electronics 38(8):114–117

Moravec H (1988) Mind children. Harvard University, Cambridge

Morbidelli A, Chambers J, Lunine JI, Petit JM, Robert F, Valsecchi GB, Cyr KE (2000) Source regions and timescales for the delivery of water on earth. Meteor Planet Sci 35:1309–1320

Morrison IS (2012) Detection of antipodal signalling and its application to sideband SETI. Acta Astronaut 78:90–98

Morrison P (1962) Interstellar communication. Bull Phil Soc Wash 16:68–81

Morrison P (2011) Hungarians as Martians: the truth behind the legend. In: Schuch HP (ed) Searching for extraterrestrial intelligence: SETI past, present and future. Springer, Berlin, pp 515–517

Musso P (2011) A language based on analogy to communicate cultural concepts in SETI. Acta Astronaut 68:489–499

Musso P (2012) The problem of active SETI: an overview. Acta Astronaut 78:43–54

NASA (2012) Wilkinson Microwave Anisotropy Probe home page. http://wmap.gsfc.nasa.gov

NASA (2013) Voyager home page. http://voyager.jpl.nasa.gov

Nasar S (1994) A beautiful mind. Simon and Schuster, New York

Newman WI, Sagan C (1981) Galactic civilizations: population dynamics and interstellar diffusion. Icarus 46:293–327

Nicholson A, Forgan D (2013) Slingshot dynamics for self-replicating probes and the effect on exploration timescales. Int J Astrobiol 12:337–344

Niven L (1970) Ringworld. Ballantine, New York

Niven L (1973) Inconstant moon. Gollancz, London

Niven L (1984) Integral trees. Del Rey, New York

Norris RP (2000) How old is ET? In Tough A (ed) When SETI succeeds: the impact of high-information contact. Foundation for the Future, Bellevue, pp 103–105.

Nussinov S (2009) Some comments on possible preferred directions for the SETI search. arXiv:0903.1628v1

O'Leary M (2008) Anaxagoras and the origin of panspermia theory. iUniverse, Bloomington

O'Leary MA et al (2013) The placental mammal ancestor and the post-K-Pg radiation of placentals. Science 339:662–667

Ollongren A (2011) Recursivity in Lingua Cosmica. Acta Astronaut 68:544–8

Ollongren A (2013) Astrolinguistics. Springer, New York

Olson EC (1988) N and the rise of cognitive intelligence on earth. Q J R Astro Soc 29:503–509

OPERA Collaboration (2011) Measurement of the neutrino velocity with the OPERA detector in the CNGS beam. arXiv:1109.4897v1

Oreskes N (2003) Plate tectonics: an insider's history of the modern theory of the earth. Westview, Boulder

Pääbo S (2014) Neanderthal man: in search of lost genomes. Basic, London

Papagiannis MD (1978) Are we all alone, or could they be in the asteroid belt? Q J R Astro Soc 19:236–251

Parthasarathy KR (1988) Obituary: Andreii Nikolaevich Kolmogorov. J Appl Prob 25:445–450

Penny AJ (2004) SETI with SKA. The scientific promise of the SKA (SKA Workshop, Oxford)

Penny AJ (2012) Transmitting (and listening) may be good (or bad). Acta Astronaut 78:69–71

Penrose R (1989) The emperor's new mind. OUP, Oxford

Petigura EA, Howard AW, Marcy GW (2013) Prevalence of earth-size planets orbiting Sun-like stars. Proc Natl Acad Sci. doi:10.1073/pnas.1319909110

Pinker S (1994) The language instinct. Allen Lane, London

Pons M-L, Quitte G, Fujii T, Rosing MT, Reynard F, Moynier F, Douchet C, Albarede F (2011) Early Archean serpentine mud volcanoes at Isua, Greenland, as a niche for early life. Proc Natl Acad Sci. doi:10.1073/pnas.1108061108

Popper K (1963) Conjectures and refutations: the growth of scientific knowledge. Routledge, London

Poundstone W (1988) Labyrinths of reason. Penguin, London

Prantzos N (2013) A joint analysis of the Drake equation and the Fermi paradox. Int J Astrobiol 12:246–253

Prüfer K et al (2013) The complete genome sequence of a Neanderthal from the Altai mountains. Nature 505:43–49

Puthoff HE (1996) SETI, the velocity of light limitation, and the Alcubierre warp drive: an integrating overview. Phys Essays 9:156

Quintana EV (2014) An earth-sized planet in the habitable zone of a cool star. Science 344:277–280

Quiring R et al (1994) Homology of the eyeless gene of Drosophila to the small eye in mice and aniridia in humans. Science 265:785–789

Rampadarath H, Morgan JS, Tingay SJ, Trott CM (2012) The first very long baseline interferometric SETI experiment. Astron J 144(2):38

Rapoport A (1967) Escape from paradox. Sci Am 217(1):50–56

Rasmussen M et al (2011) An Aboriginal Australian genome reveals separate human dispersals into Asia. Science 334:94–98

Reines AE, Marcy GW (2002) Optical SETI: a spectroscopic search for laser emission from nearby stars. Pub Astron Soc Pacific 114:416–426

Reinganum MR (1986–1987) Is time travel impossible? A financial proof. J Portfolio Manage 13(1):10–12

Ridley M (2011) Francis Crick. Harper Perennial, London

Rogers LJ (1997) Minds of their own. Westview, Boulder

Rood RT, Trefil JS (1981) Are we alone? Charles Scribner's, New York

Rose C, Wright G (2004) Inscribed matter as an energy-efficient means of communication with an extraterrestrial civilization. Nature 431:47–9

Rouse Ball WW (1908) A short account of the history of mathematics. Dover, New York

Roy KI, Kennedy RG III, Fields DE (2013) Shell worlds. Acta Astronaut 82:238-245

Royal S (2004) Nanoscience and nanotechnologies. Royal Society, London

Rummel JD (2001) Planetary exploration in the time of astrobiology: protecting against biological contamination. Pub Natl Acad Sci 98:2128–2131

Rushby AJ, Claire MW, Osborn H, Watson AJ (2013) Habitable zone lifetimes of exoplanets around main sequence stars. Astrobiology 13:833–849

Saberhagen F (1967) Berserker. Ballantine, New York

Sagan CE (1985) Contact. Simon and Schuster, New York

Sandberg A, Armstrong S, Ćirković MM (2014) That is not dead which can eternal lie: what are the physical constraints for the aestivation hypothesis? Preprint

Savage-Rumbaugh S, Lewin R (1996) Kanzi: the ape at the brink of the human mind. Wiley, New York

Scarborough Borough Council (2012) Election results, Stakesby Ward of Whitby Town Council. http://democracy.scarborough.gov.uk/mgElectionAreaResults.aspx?ID=91&RPID=0. Accessed 20 Jan 2014

Scheffer LK (1993) Machine intelligence, the cost of interstellar travel and Fermi's paradox. Q J R Astro Soc 35:157–175

Schick KD, Toth N (1993) Making silent stones speak: human evolution and the dawn of technology. Simon and Schuster, New York

Schmidt GR, Landis GA, Oleson SR (2012) Human exploration using real-time robotic operations (HERRO): a space exploration strategy for the 21st century. Acta Astronaut 80:105–113

Schroeder K (2002) Permanence. Tor, New York

Schwamb ME et al (2013) Planet hunters: a transiting circumbinary planet in a quadruple star system. Astrophys J 768:127 (21pp)

Schwartz RN, Townes CH (1961) Interstellar and interplanetary communication by optical masers. Nature 190:205–208

Seager S (2013) Exoplanet habitability. Science 340:577–581

Searle JR (1984) Minds, brains and programs. Harvard University, Cambridge

Secker J, Wesson PS, Lepock JR (1996) Astrophysical and biological constraints on radiopanspermia. J R Astro Soc Canada 90:184–192

Segré E (1970) Enrico Fermi: physicist. UCP, Chicago

Selsis F, Kasting JF, Levard B, Paillet J, Ribas I, Delfosse X (2007) Habitable planets around the star Gliese 581? Astron Astrophys 476:1373–1387

SETI@home (2000) SETI@home poll results. http://boinc.berkeley.edu/slides/xerox/polls.html. Accessed 14 Feb 2014

SETI@home (2013) SETI@home homepage. www.SetiAtHome.ssl.berkeley.edu. Accessed 14 Feb 2014

SetiLeague (2013) Ask Dr SETI www.setileague.org/askdr/index.html. Accesssed 14 Feb 2014

Sharov AA, Gordon R (2013) Life before earth. arXiv:1304.3381

Shaw B (1975) Orbitsville. Gollancz, London

shCherbak VI, Makukov MA (2013) The “Wow! signal” of the terrestrial genetic code. Icarus 224:228–242

Sheaffer R (1995) An examination of claims that extraterrestrial visitors to earth are being observed. In Zuckerman B, Hart MH (eds) Extraterrestrials: where are they? Cambridge, CUP

Sheehan W (1996) The planet Mars: a history of observation and discovery. University of Arizona, Tucson

Shklovsky IS, Sagan C (1966) Intelligent life in the universe. Holden-Day, San Francisco

Siemion APV, von Korff J, McMahond P, Korpela E, Werthimer D, Anderson D, Bowera G, Cobb J, Foster G, Lebofsky M, van Leeuwen J, Wagner M (2010) New SETI sky surveys for radio pulses. Acta Astronaut 67:1342–1349

Siemion APV, Demorest P, Korpela E, Maddalena RJ, Werthimer D, Cobb J, Howard AW, Langston G, Lebofsky M, Marcy GW, Tarter J (2013) A 1.1 to 1.9 GHz SETI survey of the Kepler field: I. A search for narrow-band emission from select targets. Astrophys J 767:94

Sieveking A (1979) The cave artists. Thames and Hudson, London

Silagadze ZK (2008) SETI and muon collider. Acta Phys Polonica B 39:2943–2948

Smart JM (2012) The transcension hypothesis: sufficiently advanced civilizations invariably leave our universe, and implications for METI and SETI. Acta Astronaut 78:55–68

Smith A (2005) Moondust: in search of the men who fell to earth. Bloomsbury, London

Smith RD (2009) Broadcasting but not receiving: density dependence considerations for SETI signals. Int J Astrobiol 8:101–105

Smolin L (1997) The life of the cosmos. Weidenfeld and Nicolson, London

Sobral D, Smail I, Best PN, Geach JE, Matsuda Y, Stott JP, Cirasuolo M, Kurk J (2013) A large, multi-epoch Hα survey at $z = 2.23$, 1. 47, 0.84 & 0.40: the 11 Gyr evolution of star-forming galaxies from HiZELS. Mon Not R Astro Soc 428:1128–1146

Sorby HC (1877) On the structure and origin of meteorites. Nature 15:495–498

Soressi M et al. (2013) Neandertals made the first specialized bone tools in Europe. Proc Natl Acad Sci 110:14186–14190

Spiegel DS, Turner EL (2012) Bayesian analysis of the astrobiological implications of life's early emergence on earth. Proc Natl Acad Sci 109:395–400

Stapledon O (1930) Last and first men. Methuen, London

Stapledon O (1937) Star maker. Methuen, London

Stauffer D (1985) Introduction to percolation theory. Taylor and Francis, London

Stephenson DG (1978) Extraterrestrial cultures within the solar system? Q J R Astro Soc 19:277–281

Stevenson DJ (2003) Mission to earth's core—a modest proposal. Nature 423:239–240

Story R (1976) The space gods revealed. Barnes and Noble, New York

Stringer C (2012) The origin of our species. Penguin, London

Sullivan WS (1964) We are not alone. Pelican, London

Sullivan WT III, Baross J (eds) (2007) Planets and life: the emerging science of astrobiology. CUP, Cambridge

Sullivan WT III, Brown S, Wetherill C (1978) Eavesdropping: the radio signature of the earth. Science 199:377–388

Tarter J (2001) The search for extraterrestrial intelligence (SETI). Ann Rev Astron Astrophys 39:511–548

Tarter J et al. (2011) The first SETI observations with the Allen telescope array. Acta Astronaut 68:340–346

Tattersall I (1998) Becoming human. OUP, Oxford

Tattersall I (2000) Once we were not alone. Sci Am 282(1):56–62

Taylor SR (1998) Destiny or chance. CUP, Cambridge

Tegmark M, Wheeler JA (2001) 100 years of the quantum. Sci Am 284(2):68–75

Teilhard deCP (2004) The future of man. Image, London

Thomas B (2009) Gamma-ray bursts as a threat to life on earth. Int J Astrobiol 8:183–186

Thorne K (1994) Black holes and time warps. Norton, New York

Tipler FJ (1980) Extraterrestial intelligent beings do not exist. Q J R Astro Soc 21:267–281

Tipler FJ (1994) The physics of immortality. Anchor, New York

Turco RP et al (1983) Nuclear winter: global consequences of multiple nuclear explosions. Science 222:1283–1297

Turnbull MC, Tarter J (2003a) Target selection for SETI. I. A catalog of nearby habitable stellar systems. Astrophys J Supp 145:181–198

Turnbull MC, Tarter J (2003b) Target selection for SETI. II. Tycho-2 dwarfs, old open clusters, and the nearest 100 stars. Astrophys J Supp 149:423–436

Ulam SM (1958a) On the possibility of extracting energy from gravitational systems by navigating space vehicles. Report LA-2219-MS. (Los Alamos, NM: Los Alamos National Laboratory)

Ulam SM (1958b) Tribute to John von Neumann, 1903–57. Bull Am Math Soc 64:1–49

Ulam SM (1976) Adventures of a mathematician. University of California, Berkeley

Vaidya PG (2007) Are we alone in the multiverse? arXiv:0706.0317v1

Vakoch DA (2011) Asymmetry in active SETI: a case for transmissions from earth. Acta Astronaut 68:476–488

Valley JW et al. (2014) Hadean age for a post-magma-ocean zircon confirmed by atom-probe tomography. Nat Geosci 7:219–223

Van Den Broeck C (1999) A "warp drive" with more reasonable total energy requirements. Class Quantum Gravity 16:3973–3979

Vedrenne G, Atteia J-L (2009) Gamma-ray bursts: the brightest explosions in the universe. Springer, Berlin

Venter C (2013) Life at the speed of light: from the double helix to the dawn of digital life. Viking, New York

Vidal C (2013) The beginning and the end: the meaning of life in a cosmological perspective. PhD thesis, Vrije Universiteit Brussel.

Viet L, Nieder A (2013) Abstract rule neurons in the endbrain support intelligent behaviour in corvid songbirds. Nat Commun 4. doi:10.1038/ncomms3878

Viewing D (1975) Directly interacting extra-terrestrial technological communities. J Br Interplanet Soc 28:735–744

Vinge V (1993) VISION-21 Symposium (NASA Lewis Research Center)

Visalberghi E, Trinca L (1989) Tool use in capuchin monkeys: distinguishing between performing and understanding. Primates 30:511–521

Vladilo G, Murante G, Silva L, Provenzale A, Ferri G, Ragazzini G (2013). The habitable zone of earth-like planets with different levels of atmospheric pressure. Astrophys J 76:65 (23 pp)

von Däniken E (1969) Chariots of the gods. Souvenir, London

von Däniken E (1972) The gold of the gods. Bantam, New York

von Däniken E (1997) The return of the gods. Element, London

von Eshleman R (1979) Gravitational lens of the Sun: its potential for observations and communications over interstellar distances. Science 205:1133–1135

von Hoerner S (1975) Population explosion and interstellar expansion. J Br Interplanet Soc 28:691–712

Vonnegut K (1963) Cat's cradle. Holt, Rinehart and Winston, New York

vos Savant M (1990) "Game show problem". marilynvossavant.com. Accessed 30 May 2014

Voyager (2013) HPL home page. www.jpl.nasa.gov/index.cfm

Vukotić B, Ćirković MM (2012) Astrobiological complexity with probabilistic cellular automata. Orig Life Evol Biosph 42:347–371

Walker J, Hays P, Kasting J (1981) A negative feedback mechanism for the long-term stabilization of the earth's surface temperature. J Geophys Res 86:9776–9782

Waltham D (2014) Lucky planet. Icon, London

Ward PD, Brownlee D (1999) Rare earth. Copernicus, New York

Watson AJ (2008) Implications of an anthropic model of evolution for emergence of complex life and intelligence. Astrobiology 8:175–185

Watson JD (2010) The double helix: a personal account of the discovery of the structure of DNA. Phoenix, London

Watts P (2006) Blindsight. Tor, New York

Weart SR (2008) The discovery of global warming: revised and expanded edition. Harvard University, Cambridge

Webb S (1999) Measuring the universe. Springer, Berlin

Webb S (2004) Out of this world. Praxis, Chichester

Webb S (2012) New eyes on the universe. Springer, New York

Webb S (2014) Ripples from the start of time? In: Mason J (ed) Patrick Moore's yearbook of astronomy 2015. Macmillan, London, pp 243–265

Weinberg S (1993) Dreams of a final theory: the search for the fundamental laws of nature. Hutchinson, London

Weisberg JM, Taylor JM (2005) The relativistic binary pulsar B1913+16: thirty years of observations and analysis. In Rasio F A and Stairs I H (eds) Astron Soc Pacific Conf Series 328, p. 25

Weisman A (2007) The world without us. Picador, New York

Welch J et al. (2009) The Allen Telescope Array: the first widefield, panchromatic, snapshot radio camera for radio astronomy and SETI. Proc IEEE Spec Issue Adv Radio Telesc 97:1438–47

Wells HG (1898) War of the worlds. Heinemann, London

Wells W (2009) Apocalypse when? Praxis, Chichester

Wesson PS (1990) Cosmology, extraterrestrial intelligence, and a resolution of the Fermi–Hart paradox. Q J R Astro Soc 31:161–170

Wesson PS (2010) Panspermia, past and present: astrophysical and biophysical conditions for the dissemination of life in space. Space Sci Rev 156:239–252

Whates I (2014) Paradox: stories inspired by the Fermi paradox. NewCon Press, Cambridgeshire

Whitmire DP,Wright DP (1980) Nuclear waste spectrum as evidence of technological extraterrestrial civilizations. Icarus 42:149–156

WHO (2013) Urban population growth. http://www.who.int/gho/urban_health/situation_trends/urban_population_growth_text/en/

Wiechert U, Halliday AN, Lee D-C, Snyder GA, Taylor LA, Rumble D (2001) Oxygen isotopes and the moon-forming giant impact. Science 294:345–358

Wigner E (1960) The unreasonable effectiveness of mathematics in the natural sciences. Commun Pure Appl Math 13(1):1–14

Wiley KB (2011) The Fermi paradox, self-replicating probes, and the interstellar transportation bandwidth. arXiv:1111.6131v1

Williams IP, Cremin AW (1968) A survey of theories relating to the origin of the solar system. Q J R Astro Soc 9:40–62

Williamson T (1994) Vagueness. Routledge, London

Witze A (2014) Icy Enceladus hides a water ocean. Nature. doi:10.1038/nature.2014.14985

Woese CR, Kandler O, Wheelis ML (1990) Towards a natural system of organisms: proposal for the domains Archaea, Bacteria, and Eucarya. Proc Natl Acad Sci U S A 87:4576–4579

Worth RJ, Sigurdsson S, House CH (2013) Seeding life on the moons of the outer planets via lithopanspermia. Astrobiology 13:1155–1165

Yeomans DK (2012) Near-earth objects: finding them before they find us. Princeton University, Princeton

Yokoo H, Oshima T (1979) Is bacteriophage phi X174 DNA a message from an extraterrestrial intelligence? Icarus 38:148–153

Zahnle K (2001) Decline and fall of the Martian empire. Nature 412:209–213

Zaitsev A (2006) The SETI paradox. Bull Spec Astrophys Obs 60

Zaitsev A (2012) Classification of interstellar radio messages. Acta Astronaut 78:16–19

Zalasiewicz J (2009) The earth after us: what legacy will humans leave in the rocks? OUP, Oxford

Zhang J, Dauphas N, Davis AM, Leya I, Fedkin A (2012) The proto-earth as a significant source of lunar material. Nat Geosci 5:251–255

Zuckerman B (1985) Stellar evolution: motivation for mass interstellar migration. Q J R Astro Soc 6:56–59

Zuckerman B, Hart MH (eds) (1995) Extraterrestrials—where are they? CUP, Cambridge

Index

S. Webb, *If the Universe Is Teeming with Aliens . . . WHERE IS EVERYBODY?*, Science and Fiction, DOI 10.1007/978-3-319-13236-5

G

H