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The Extended Kardashev Scale

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Abstract

A scale is described for classifying civilizations according to the amount of power they produce, using the whole numbers 0 through 4 to denote 10^6, 10^{16}, 10^{26}, 10^{36}, and 10^{46} W corresponding to the approximate power available at physical scales biological, planetary, stellar, Galactic, and observable universe, extending a Roman numeral scheme introduced by Kardashev and updating it with suggestions from Sagan and Lemarchand including using Arabic numbers to permit decimal subdivisions. Terrestrial civilization circa 2015 would be classified as Type 0.72 on this extended and updated scale. Similar scales can be used to classify information stored, population, and mass of constructions.

Unified Astronomy Thesaurus concepts: Astrobiology (74); Search for extraterrestrial intelligence (2127)

1. Introduction

Kardashev (1964, 1967) published the scale shown in Table 1 for classifying technologically developed civilizations according to their energy consumption. Type I described terrestrial energy consumption in 1964, Type II "a civilization capable of harnessing the energy radiated by its own star," and Type III "a civilization in possession of energy on the scale of its own galaxy" (Kardashev 1964, p. 219) One use of the classification scheme was to show that the isotropic transmission of large amounts of information across the Galaxy would not be possible with all of the energy available to a civilization such as ours in 1964, but would be possible for much more advanced civilizations with access to energy at astronomical scales.

Kardashev noted that power production at a stellar or Galactic scale might seem inordinately high, but he calculated that those levels would be reached after 3200 and 5800 years respectively assuming a 1% annual increase in power production.

Several changes to the original scale have been suggested.

Sagan (1973a) suggested a decimal Type 1.0 for 10^{16} W and Type 1.1 for 10^{17} W, using Arabic numbers rather than Roman numerals to permit decimal subdivisions, which implies Type 2.0 as 10^{26} and Type 3.0 as 10^{36}, although he did not explicitly define those decimal categories and presented no equation; he classified Earth in 1973 with 10^{13} W as Type 0.7. Sagan gave no reason for defining Type 1.0 as 10^{16} W, but it seems clear that he intended to form the series 10^{16}, 10^{26}, 10^{36}, and it is possible that he had insolation in mind for Type 1.0 although 10^{16} W is 17 times smaller than terrestrial insolation of 1.7×10^{17} W (Prša et al. 2016). Sagan characterized the scale as the power a "civilization is able to muster for communications purposes" in his book (Sagan 1973a, p. 233) and in a journal article (Sagan 1973b, p. 351) but neither the original Kardashev scale nor the present version estimates the power that might be used for any specific purpose.

Lemarchand (1994, p. 4) discussed the Kardashev scale and described Type I as "near contemporary terrestrial civilization with an energy capability equivalent to the solar insolation on Earth"—the first mention of insolation found in a literature search—although insolation exceeds the energy capability of contemporary terrestrial civilization by orders of magnitude. Lemarchand did not mention Sagan's decimal Type 1.0 corresponding to 10^{16} W, but he did mention Sagan's suggestion for using Arabic numbers and he gave two examples—Type 1.7 for 10^{23} W and Type 2.3 for 10^{29} W—which implies Type 1.0 corresponds to 10^{16} W and Types 2 and 3 correspond to 10^{26} and 10^{36} W, respectively, as in Sagan's scheme. Lemarchand did not characterize the scale as limited to communication.

This paper presents an extended and updated version of Kardashev's scale, shown in Table 2, extended to include 10^6 W at the lower end and 10^{46} W on the higher end, and updated with some of Sagan's and Lemarchand's suggestions. The scale can be used to characterize the power production of our civilization at various times or that of hypothetical extraterrestrial civilizations, and to assess the type of civilization required for various kinds of interstellar signaling such as isotropic versus targeted, and for predicting technosignatures that might result from very large-scale energy production such as infrared radiation (Dyson 1960).

2. Discussion

2.1. Power Scale

Civilizations can be classified according to the power they produce using the equation

$$K_{\mathrm{P}} = \log_{10}(P/10^6)/10, \qquad (1)$$

where K_{P} is the type of civilization and P is power in watts ($\neq$ 0). The equation yields whole numbers 0, 1, 2... for $P = 10^6$, 10^{16}, 10^{26}... and decimal fractions for intermediate values, resulting in a continuous scale unlike Kardashev's Roman numeral categories. The power P corresponding to a value K_{P} is simply

$$P = 10^{10K_{\mathrm{P}}}10^6. \qquad (2)$$

Equations similar to Equation (1) have been attributed to Sagan, although no equation appears in his book *Cosmic Connection* (Sagan 1973a), which is often cited as the source. The earliest equation found in a literature search was a Wikipedia article on the Kardashev Scale dated 27 November 2004, more than 30 years after Sagan's book, which was cited as the source. Some equations that have appeared are

Table 1
Civilization Type by Power, Original Scale

Type	Civilization Description	Energy (erg s^{-1})	Power (W)
I	Earth 1964	$\sim 4 \times 10^{19}$	$\sim 4 \times 10^{12}$
II	Stellar	$\sim 4 \times 10^{33}$	$\sim 4 \times 10^{26}$
III	Galactic	$\sim 4 \times 10^{44}$	$\sim 4 \times 10^{37}$

summarized below, most equivalent to Equation (1) and all citing Sagan (1973a).

Wikipedia gives the equation

$$K = (\log_{10}(\mathrm{P}) - 6)/10, \quad (3a)$$

where "*P* is the power it uses, in watts."[1]

Piotelat and Cerceau wrote

$$K = \log_{10}(W)/10, \quad (3b)$$

where W is "energy consumption in megawatts" (Piotelat & Cerceau 2013, p. 209).

Wright et al. (2014, p. 2) wrote

$$K = \log_{10}(P/10\,\mathrm{MW})/10, \quad (3c)$$

where P is "the civilization's total energy supply P, measured in units of 10 MW"; the equation yields the expected values using units of 1 megawatt rather than 10.

Ćirković (2015) wrote

$$n = 1 + 1/10 \log_{10}(E/10^{16}\,\mathrm{W}), \quad (3d)$$

where n is the Kardashev type and E is power in watts.

Table 3 presents some examples for historical terrestrial power consumption and future projections illustrating the usefulness of the scale and its decimal subdivision. Power consumption in the years 1800, 1900, and 2000 yield $K_\mathrm{P} = 0.58$, 0.61, and 0.71, respectively, showing long-term changes in the first decimal place. Power consumption in the recent year 2015 yields $K_\mathrm{P} = 0.72$, showing short-term change from 2000 to 2015 in the second decimal place.

2.2. Type 0.0: Biological Scale

Equation (1) yields $K_\mathrm{P} = 0.0$ for 10^6 W, a type and power level not considered by Kardashev, Sagan, or Lemarchand, but a natural extension of the 10^{10} intervals of the planetary, stellar, and Galactic types suggested by Sagan and Lemarchand. One megawatt is very small compared with the other types that have astronomical scales; it is comparable to, among other things, the metabolic power of the largest terrestrial animals and groups of animals. The blue whale *Balaenoptera musculus* has a basal metabolic rate of up to 1.9×10^4 W and active metabolic rate up to 4.6×10^5 W (Lockyer 1981)—nearly half a megawatt. The human basal metabolic rate is approximately 10^2 W and up to 10^3 W in bursts (Smil 2017), so thousands of humans might command a megawatt with muscle power alone, but interstellar signaling would *not* be expected from metabolic power alone. Fossil fuels are an energy source of biological origin accumulated over geological time, and in the terrestrial case accounted for approximately 85% of the 1.7×10^{13} W world primary energy consumption in 2015 (BP 2018), which seems like a reason to characterize the lower part of the scale as biological. Earth circa 2015 would be Type 0.72.

[1] https://en.wikipedia.org/wiki/Kardashev_scale

2.3. Type 1.0: Planetary Scale

The value 10^{16} W is taken as a planetary-scale power level, following Sagan's suggestion for a Type 1.0 at 10^{16} W; Kardashev had no comparable power level and his category I was based on terrestrial power production in 1964, which is no longer useful. The value 10^{16} W is roughly comparable to terrestrial insolation of 1.7×10^{17} W based on the solar constant 1361 W m^{-2} (Prša et al. 2016) and the area of the planet illuminated. Insolation seems like a natural way to think about power at a planetary scale because it can be defined using astronomical information, although planets vary in insolation, and energy is available from many other sources including fossil fuels, hydro, and nuclear. Insolation might be a very rough upper limit to the total power that can be consumed on a planet without causing thermal environmental problems (Rebane 1993). Terrestrial power production in the recent year 2015 was 1.7×10^{13} W from Table 3 which is only 10^{-4} of terrestrial insolation and 1/588 of the categorical 10^{16} W.

A Type 1.0 civilization would be capable of an isotropic broadcast over 10^3 ly requiring $\sim 10^{15}$ W, assuming a search system using a 100 m antenna comparable to the one currently used at the Green Bank Telescope (GBT)—if it dedicated 10% of its energy resources to that purpose, which suggests that isotropic broadcasts require civilizations near that type and likely higher. Highly directional transmissions over 10^3 ly, on the other hand, are possible for a civilization at our current level—for example requiring 10^7 W with 300 m antennas on both ends, or 10 times the power of the Arecibo planetary radar (Campbell et al. 2002).

Table 3 includes terrestrial power projections for future years, P_t, calculated for time, t, assuming a constant growth rate, r, using

$$P_t = P_0(1 + r)^t \quad (4)$$

where P_0 is the value at the starting time. Using Kardashev's 1% growth rate and starting from 2015, terrestrial power production would reach the planetary level 1.0 in the year 2654. Actual energy growth rates are not constant, so such projections are not predictions; the actual growth rate for the years 2006–2016 was 1.7% (BP 2018), and rates such as 2.6% have been used in some earlier projections (e.g., Zubrin 1999).

2.4. Type 2.0: Stellar Scale

The value 10^{26} W is taken as a stellar-scale power level, following Sagan's suggestion. That value differs from Kardashev's 4×10^{26} W value and from the 3.828×10^{26} W luminosity of our Sun (Prša et al. 2016) by a factor of four, but it is broadly representative of the F, G, and K class stars often considered as potentially habitable. The luminosity of M stars is several orders of magnitude smaller, but Sun-like is the class known to have life and therefore possibly technosignatures. A civilization commanding power equivalent to the luminosity of our Sun would be Type 2.06 rather than Type II on the original scale.

Schemes have been suggested for capturing stellar luminosity other than on the surface of a planet, such as solar power satellites, space settlements (O'Neill 1979), and Dyson spheres or swarms (Dyson 1960). Capturing the full luminosity of a star is difficult to envision, but even higher rates of energy production have been imagined, for example by extracting and fusing hydrogen from a star or gas-giant planets

Table 2
Civilization Type by Power, Extended and Updated Scale

Type	Civilization Description	Power (W)	Example	Example Power (W)
0.0	Biological	10^6	Maximum for terrestrial organisms	4.6×10^5
1.0	Planetary	10^{16}	Insolation of a planet like Earth	1.7×10^{17}
2.0	Stellar	10^{26}	Luminosity of a star like Sun	3.8×10^{26}
3.0	Galactic	10^{36}	Luminosity of a galaxy like Milky Way	1.2×10^{37}
4.0	Observable Universe	10^{46}	Luminosity of observable universe	$\sim 10^{48}$

Table 3
Terrestrial Power Consumption, Past and Projected

Year	Power (W)	Type (K_P)	Reference
1800	6.4×10^{11}	0.58	1
1900	1.4×10^{12}	0.61	1
1965	4.9×10^{12}	0.67	2
2000	1.3×10^{13}	0.71	2
2015	1.7×10^{13}	0.72	2
2654	1.0×10^{16}	1.00	3
4968	1.0×10^{26}	2.00	3

References. (1) Smil (2017); (2) BP (2018); (3) 1% growth rate.

(Criswell 1985). The approximate output of a Sun-like star seems most useful for present purposes, and the decimal scale supports distinctions such as $K_P = 1.8$ for capturing 1% of the categorical stellar 10^{26} W or producing the power in other ways.

Human energy production would reach the Type 2.0 stellar scale in the year 4968 at a 1% annual growth rate from 2015, from Table 3. Kardashev projected 3200 years from 1964 at that rate, which would be the year 5164; the 196-year difference in projections is due to adopting Sagan's value for the stellar level, using 2015 as the base year, and Kardashev rounding to the nearest century.

Isotropic broadcasts detectable across the Galaxy become possible between the planetary and stellar scales, requiring for example $\sim 10^{18}$ W for 50,000 ly assuming a 100 m search system comparable to one used at the GBT. A few searches for evidence of infrared signatures from stars possibly due to Dyson-like structures have been carried out, including one covering 96% of the sky with sensitivity sufficient to detect a Dyson sphere with the luminosity of the Sun out to 300 pc (Carrigan 2009). Searches for evidence of megastructures are also possible in transit data from exoplanet searches (Wright et al. 2016).

2.5. Type 3.0: Galactic Scale

The value 10^{36} W is taken as a Galactic-scale power level, following Sagan's suggestion. One estimate of the total luminosity of the Milky Way Galaxy is 2.3×10^{10} times solar luminosity (Freudenreich 1998) or 8.8×10^{36} W, and another estimate is 6.7×10^{10} times solar luminosity (Kent et al. 1991) or 2.6×10^{37} W. A civilization commanding power equivalent to the luminosity of the Milky Way would be Type 3.1 using either estimate (rounding to one decimal place) rather than Type III on the original scale. Taking the Galactic scale as approximately one order of magnitude smaller than the Milky Way estimate fits the 10^{10} intervals, and seems reasonable because the Milky Way is larger than most galaxies—second largest in the Local Group of dozens.

This category does not assume any particular scenario such as a single civilization colonizing a galaxy rather than multiple independently evolved civilizations, or Dyson structures surrounding all or many stars, or power being generated from a supermassive black hole (Inoue & Yokoo 2011), but the waste heat of energy use at such a large scale might be detectable regardless of how it is produced. One search of $\sim 10^5$ other galaxies for galaxy-spanning civilizations found no evidence of "an alien civilization reprocessing more than 85% of its starlight into the MIR" (mid-infrared) in data from the Wide-field Infrared Survey Explorer (WISE) telescope survey (Griffith et al. 2015, p. 25), with one problem being the need to identify and exclude intrinsically dusty galaxies with infrared signatures. Another analysis found no obvious evidence of a civilization using the bulk of a galaxy's starlight for its own purposes in a sample of 137 galaxies (Annis 1999).

2.6. Type 4.0: Observable Universe Scale

Kardashev did not define a Type IV for power comparable to the luminosity of the observable universe, but adding such a level at 10^{46} W is consistent with the other 10^{10} intervals and is within two orders of magnitude of current estimates for the luminosity of the observable universe. One such estimate is 10^{48} W, assuming 10^{11} galaxies each averaging 10^{11} stars with an average luminosity of a few times 10^{33} erg s^{-1} like the Sun (Wijers 2005). The Hubble Ultra Deep Field observations reported more than 10^4 galaxies in a $11'$ field (Beckwith et al. 2006), which is consistent with a total of 10^{11} galaxies, and a more detailed analysis reported the "number of galaxies currently detectable within the universe with a hypothetical all-sky *Hubble Space Telescope* survey at UDF-Max depth" as 2.47×10^{11} (Conselice et al. 2016, p. 16). Not all galaxies can be detected with current instruments; an estimated 2×10^{12} galaxies "in principle could be observed" (Conselice et al. 2016, p. 12). The type for a civilization spanning the observable universe might very well exceed 4.0.

Sagan wrote "there is no provision for a Type IV civilization, which by definition talks only to itself" (Sagan 1973a, p. 234), but the decimal scale accommodates more complex scenarios such as one or many civilizations spanning various fractions of the observable universe whose radio, optical, or infrared emission we might detect if any exist.

3. Kardashev-like Scales for Information, Population, and Mass of Constructions

Civilizations can be classified by characteristics in addition to power, such as the amount of information stored and mass of constructions (both mentioned in Kardashev 1985 and Sagan 1973a) and population (noted in Ćirković 2018). Classification by power is the main topic of this paper, but minor variations in Equation (1) can be applied to these other characteristics. No model is advanced regarding the relationships among energy production, information store, population, or mass of construction.

3.1. Information Scale

Sagan proposed using the 26 letters of the English alphabet to classify the amount of information stored by a civilization, with $A = 10^6$ bits, $B = 10^7$ bits, and so on, and he wrote that terrestrial civilization circa 1973 could be "well characterized by something like 10^{14} or 10^{15} bits" based largely on estimated holdings of the largest libraries (Sagan 1973a, p. 237). He described a composite terrestrial power and information type as 0.7 H (H actually corresponds to 10^{13} bits).

An equation similar to the one used for power can be used for an information scale K_I,

$$K_I = \log_{10}(I/10^6)/10, \tag{5}$$

where I = information in bits ($\neq 0$). Sagan's estimate of 10^{14} or 10^{15} bits circa 1973 yields $K_I = 0.8$ or 0.9.

The constant 10^6 is the same as in the power equation and yields $K_I = 0.0$ for 10^6 bits, which is also the value Sagan chose for his category "A," saying that 10^6 bits were less than "any human society that we know well—and a good beginning point" (Sagan 1973a, p. 237). Robertson (1998) estimated 10^7 bits as available to individual humans before language and writing were developed, and Landauer estimated the "functional information content of human memory" as 10^9 bits at midlife based on testing of text and image retention (Landauer 1986, p. 491).

Estimates of the information store of human civilization vary depending on what is counted and when. Kardashev (1964) estimated 10^{14} bits circa 1964 counting 10^8 publications at 10^6 bits each. Lesk (1997) estimated 10^{18} bits in 1997 including books, maps, films, and sound recordings. Robertson (1998) estimated 10^{17} bits available in books and other publications in 1998 and 10^{25} bits including computers. Lyman & Varian (2000) estimated 10^{18}–10^{19} bits being added annually around 2000, including paper, film, optical, and magnetic storage with a growth rate of 50%. Taking the terrestrial value as 10^{18} bits in 1998 and using a modest 1% growth rate results in approximately 1.2×10^{18} bits in the year 2015 and $K_{\mathrm{I}} = 1.2$; using the 50% growth rate results in approximately 10^{21} bits in the year 2015 and $K_I = 1.5$.

3.2. Population Scale

A similar equation can be used to classify the population of a civilization K_{N},

$$K_N = \log_{10}(N)/10, \tag{6}$$

where N = population ($\neq 0$), omitting the 10^6 scaling because population is a count of individuals. A population of 1 yields $K_{\mathrm{N}} = 0.0$, and the world population of 7.38×10^9 in 2015 (U.N., 2017) yields $K_{\mathrm{N}} = 0.99$.

World population forecasts for the year 2100 are 7.3, 11.2, and 16.5 billion for low, medium, and high variants (U.N., 2017) yielding $K_N = 0.99$, 1.00, and 1.02, respectively. A value of $K_{\mathrm{N}} = 2.0$ would correspond to a population of 10^{20}, which could describe a galactic-scale civilization with 10^{10} planets each having a population of 10^{10}, or many other scenarios.

3.3. Mass of Constructions Scale

A similar equation can be used to classify the mass of a civilization's constructions K_C,

$$K_C = \log_{10}(C/10^6)/10, \tag{7}$$

where C is mass of constructions in metric tonnes ($\neq 0$). One estimate for total human construction is 3×10^{13} t (Zalasiewicz et al. 2017), which yields $K_C = 0.75$, a mass comparable to a solid sphere approximately 30 km in diameter with the density of aluminum or concrete. Type 1.0 would correspond to 10^{16} t, comparable a solid sphere several hundred kilometers in diameter like the asteroid Juno. Kardashev (1985) speculated about the possibility of extremely large "superstructures" that might be detectable but did not suggest a classification scheme.

3.4. Composite Type

The Earth's composite type classified by power, information, population, and mass of constructions in 2015 could be expressed as $K_{P,I,N,C} = 0.72$, 1.50, 0.99, 0.75.

The power available to a civilization has obvious implications for the detectability of extraterrestrial intelligence, because power is required for signaling, and because very large-scale power consumption might be detectable as thermal emission without intentional signaling. The large mass of constructions might be relevant, because very large structures might be detected by astronomical observations, as in speculation that variations in brightness of KIC 8462852 might be due to large-scale engineering (Boyajian et al. 2018), Dyson spheres or swarms, and Kardashev's superstructures. Population might be relevant as driving growth, although not directly observable over interstellar distances. The information store of civilizations would not be directly observable over interstellar distances, but conceivably could be detected if transmitted, because as Kardashev (1964) noted the $\sim 10^{14}$ bits of a terrestrial 1964 civilization could be transmitted across the Galaxy using a 10^9 bit s^{-1} bandwidth channel for approximately one day.

4. Conclusions

This paper describes a numeric scale for classifying civilizations according to the amount of power produced, replacing the original Kardashev Types I, II, and III corresponding to 4×10^{12}, 4×10^{26}, and 4×10^{37} W, respectively, with Types 0.0, 1.0, 2.0, 3.0, and 4.0 corresponding to 10^6, 10^{16}, 10^{26}, 10^{36}, and 10^{46} W, respectively, where each whole number is the power available at approximately biological, planetary, stellar, galactic, and observable universe physical scales.

Arabic numbers and 10^{10} intervals were first suggested by Sagan to accommodate decimal fractions for finer resolution than Kardashev's Roman numerals. The original scale defined Type I as 1964 terrestrial power production; on this updated scale the 1964 power production would yield $K_{\mathrm{P}} = 0.67$, and the 2015 power production would yield $K_{\mathrm{P}} = 0.72$.

The scale provides a framework for describing terrestrial energy production in the past and in the future from an astronomical perspective, and for thinking about possible technosignatures of hypothetical extraterrestrial civilizations.

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References

Annis, J. 1999, JBIS, 52, 33
Beckwith, S. V. W., Stiavelli, M., Koekemoer, A. M., et al. 2006, AJ, 132, 1729
Boyajian, T. S., Alonso, R., Ammerman, A., et al. 2018, ApJL, 853, L8
BP 2018, Statistical Review of World Energy—All Data 1965–2018, https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html
Campbell, D. B., Hudson, R. S., & Margot, J-L 2002, in Review of Radio Science 1999–2002, ed. W. R. Stone (New York: John Wiley & Sons), 869, http://www2.ess.ucla.edu/~jlm/publications/CampbellHudsonMargot02.rrs.advances.pdf
Carrigan, R. A. 2009, ApJ, 698, 2075
Ćirković, M. M. 2015, SerAJ, 191, 1
Ćirković, M. M. 2018, The Great Silence (Oxford: Oxford Univ. Press), 208
Conselice, C. J., Wilkinson, A., Duncan, K., & Mortlock, A. 2016, ApJ, 830, 83
Criswell, D. R. 1985, in Interstellar Migration and the Human Experience, ed. B. R. Finney & E. M. Jones (Berkeley, CA: Univ. California Press), 50
Dyson, F. J. 1960, Sci, 131, 1667
Freudenreich, H. T. 1998, AJ, 492, 495
Griffith, R. L., Wright, J. T., Maldanodo, J., et al. 2015, ApJS, 217, 25
Inoue, M., & Yokoo, H. 2011, JBIS, 64, 58
Kardashev, N. S. 1964, SvA, 8, 217
Kardashev, N. S. 1967, SvA, 8, 217
Kardashev, N. S. 1985, in IAU Symp. 112, The Search for Extraterrestrial Life: Recent Developments, ed. M. D. Papagiannis (Dordrecht: Reidel), 497
Kent, S. M., Dame, T. M., & Fazio, G. 1991, ApJ, 738, 131
Landauer, T. K. 1986, Cognitive Science, 10, 477
Lemarchand, A. 1994, SETIQuest, 1, 3, https://www.researchgate.net/profile/Guillermo_Lemarchand/publication/314151939_Dectectability_of_extraterrestrial_technological_activities/links/58b74371aca27261e51a435c/Dectectability-of-extraterrestrial-technological-activities.pdf?origin=publication_detail
Lesk, M. 1997, How Much Information Is There in the World?, http://www.lesk.com/mlesk/ksg97/ksg.html
Lockyer, C. 1981, Mammals in the Seas, Vol. III, General Papers and Large Cetaceans (Rome: Food and Agriculture Organization), 465
Lyman, P., & Varian, H. R. 2000, How Much Information? A Study Produced by Faculty and Students at the School of Information Management and Systems, Univ. California at Berkeley, http://www2.sims.berkeley.edu/research/projects/how-much-info/how-much-info.pdf
O'Neill, G. K. 1979, Space Resources and Space Settlements, ed. J. Billingham & W. Gilbreath, NASA SP-428, https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19790024054.pdf
Piotelat, E., & Cerceau, F. 2013, IJAsB, 12, 208
Prša, A., Harmanec, P., & Torres, G. 2016, AJ, 152, 41
Rebane, K. K. 1993, in ASP Conf. Ser. 47, Third Decennial US-USSR Conference on SETI, The Search for Extraterrestrial Intelligence and Ecological Problems, ed. S. Shostak (San Francisco, CA: ASP), 219
Robertson, D. S. 1998, The New Renaissance: Computers and the Next Level of Civilization (Oxford: Oxford Univ. Press)
Sagan, C. 1973a, The Cosmic Connection: An Extraterrestrial Perspective (New York: Doubleday)
Sagan, C. 1973b, Icar, 19, 350
Smil, V. 2017, Energy Transitions: Global and National Perspectives (2nd ed.; Santa Barbara, CA: Praeger) Appendix A
U. N. 2017, World Population Prospects: The 2017 Revision, United Nations, Department of Economic and Social Affairs, Population Division, https://population.un.org/wpp/Download/Standard/Population
Wijers, R. A. M. J. 2005, arXiv:astro-ph/0506218
Wright, J. T., Cartier, K. M. S., Zhao, M., Jontof-Hutter, D., & Ford, E. B. 2016, ApJ, 816, 17
Wright, J. T., Griffith, R. L., Sigurdsson, S., Povich, M. S., & Mullan, B. 2014, ApJ, 792, 27
Zalasiewicz, J., Williams, M., Waters, C. N., et al. 2017, Anthropocene Review, 4, 9
Zubrin, R. 1999, Entering Space: Creating a Spacefaring Civilization (New York: Tarcher)