# Chapter 2
# Astrophysical Factors

$$N_{civ} = N_{gal} f_{star} f_{planet} f_{life}$$
$$\uparrow$$

To understand something of the elements which determine $f_{star}$ we must review some aspects of the current understanding of the history of the universe. Evidence arising from observations of the rate at which stars and galaxies are receding from the earth indicates that, approximately 14 billion years ago (the exact time remains in some dispute) the universe as we observe it was confined to a very small region of space and has been expanding from that confined space ever since (the 'Big Bang') (More precisely, the space itself has been expanding, but this distinction need not concern us.) Some details of the very early history of that expansion remain in some dispute. However, there is strong evidence that, roughly one second after the expansion began, the initial material cooled sufficiently to leave mainly electromagnetic radiation, two kinds helium nuclear isotopes, two kinds of hydrogen nuclei (protons and deuterons) and electrons. At about 300,000 years after the initial explosion, the electrons combined with the nuclei to leave mainly electrically charge neutral atoms of helium and hydrogen as well as electromagnetic radiation.

The fact that the universe is expanding was first established in the 1920s, mainly by observations of Edwin Hubble of the Doppler shifts in the spectra of light emitted by stars in galaxies (see Appendix 2.1). The galaxies of stars outside the solar system were all found to be receding (redshifted spectra) from us with velocites v which increase with the distance r of the galaxies from us according to the relation $v = Hr$. H is called the Hubble constant. If the galaxies have been moving at a constant velocity then it is easy to see (Fig. 2.1) that this relation is consistent with convergence of all the galaxies at a common point at a time 1/H ago: Consider two galaxies 1 and 2 observed at distances $r_1$ and $r_2$ from us and moving at velocities $v_1$ and $v_2$. If the velocities obey the Hubble relation then $r_1 = (1/H)v_1$ and $r_2 = (1/H)v_2$ which are

J. W. Halley, *How Likely is Extraterrestrial Life?*, SpringerBriefs in Astronomy,
DOI: 10.1007/978-3-642-22754-7_2, © The Author(s) 2012

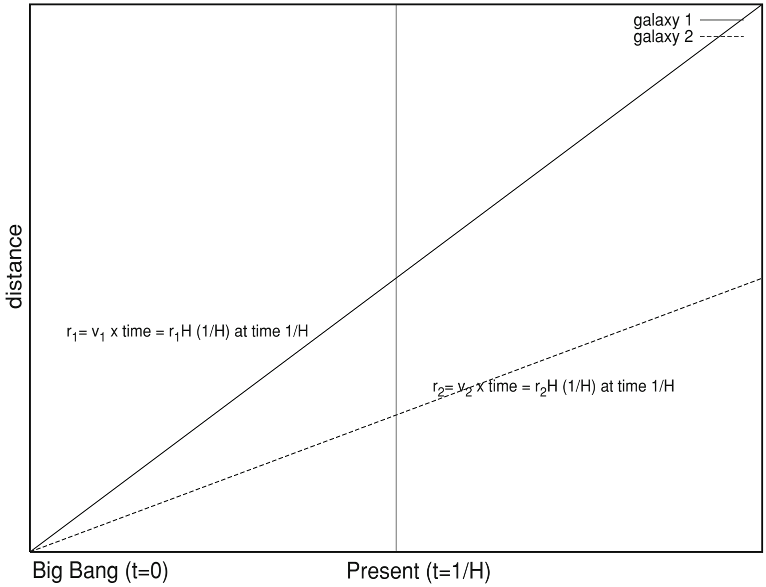


**Fig. 2.1** Illustration of the relation of the Hubble constant to the age of the universe

equations describing two points moving at their respective velocities starting at a common point a time 1/H ago.

It has recently been discovered that the picture is complicated by indications that the galaxies are *accelerating* away from us, but the basic idea that the universe has been expanding from a common point for about 14 billion years is retained. There are two additional kinds of experimental evidence for this 'big bang' picture of the evolution of the universe: It predicts correctly the abundance of the helium and hydrogen as observed today and it accounts in considerable detail for the distribution of electromagnetic radiation observed in the universe.

For our purposes a very important point here is that in the scenario sketched so far, no carbon, oxygen or any of the other elements except hydrogen which are essential for life on earth have appeared. While it might be possible to imagine behavior of condensed hydrogen and helium which was complex enough to be characterized as 'life', nothing of that sort has ever been observed and we will suppose that a more complete collection of atoms from the periodic table is required for life. For example, a summary of those elements of the periodic table which are believed to be essential for human life appears in Table 2.1.

The rest of the atoms of the periodic table are known to have arisen from processes occuring in the natural 'nuclear furnaces' in the interiors of stars. This occurred in the following way. After the formation of the helium and hydrogen as described in the last paragraph, the resulting gas cloud gradually separated into clumps as a result of the mutual gravitational attraction that the atoms exerted on one another. These

**Table 2.1** Periodic table, with elements required for human life underlined

**Periodic Table of the Elements**

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 H [redacted] | | | | | | | | | | | | | | | | | 2 He 4.00 |
| 3 Li 6.94 | 4 Be 9.01 | | | | | | | | | | | 5 B [redacted] | 6 C [redacted] | 7 N [redacted] | 8 O [redacted] | 9 F [redacted] | 10 Ne 20.18 |
| 11 Na [redacted] | 12 Mg [redacted] | | | | | | | | | | | 13 Al [redacted] | 14 Si [redacted] | 15 P [redacted] | 16 S [redacted] | 17 Cl [redacted] | 18 Ar 39.95 |
| 19 K [redacted] | 20 Ca [redacted] | 21 Sc 44.96 | 22 Ti [redacted] | 23 V [redacted] | 24 Cr [redacted] | 25 Mn [redacted] | 26 Fe [redacted] | 27 Co [redacted] | 28 Ni [redacted] | 29 Cu [redacted] | 30 Zn [redacted] | 31 Ga 69.72 | 32 Ge [redacted] | 33 As [redacted] | 34 Se [redacted] | 35 Br [redacted] | 36 Kr 83.80 |
| 37 Rb 85.47 | 38 Sr 87.62 | 39 Y 88.91 | 40 Zr 91.22 | 41 Nb 92.91 | 42 Mo [redacted] | 43 Tc (97.91) | 44 Ru 101.07 | 45 Rh 102.91 | 46 Pd 106.42 | 47 Ag 107.87 | 48 Cd [redacted] | 49 In 114.82 | 50 Sn [redacted] | 51 Sb 121.75 | 52 Te 127.60 | 53 I [redacted] | 54 Xe 131.29 |
| 55 Cs 132.91 | 56 Ba 137.33 | 57 La 138.91 | 72 Hf 178.49 | 73 Ta 180.95 | 74 W [redacted] | 75 Re 186.21 | 76 Os 190.23 | 77 Ir 192.22 | 78 Pt 195.08 | 79 Au 196.97 | 80 Hg 200.59 | 81 Tl 204.38 | 82 Pb 207.2 | 83 Bi 208.98 | 84 Po (208.98) | 85 At (209.99) | 86 Rn (222.02) |
| 87 Fr (223.02) | 88 Ra (226.03) | 89 Ac (227.03) | 104 Rf (261.11) | 105 Ha (262.11) | 106 Sg (263.12) | | | | | | | | | | | | |
| | | | | 58 Ce 140.12 | 59 Pr 140.91 | 60 Nd 144.24 | 61 Pm (144.91) | 62 Sm 150.36 | 63 Eu 151.97 | 64 Gd 157.25 | 65 Tb 158.93 | 66 Dy 162.50 | 67 Ho 164.93 | 68 Er 167.26 | 69 Tm 168.93 | 70 Yb 173.04 | 71 Lu 174.97 |
| | | | | 90 Th 232.04 | 91 Pa 231.04 | 92 U 238.03 | 93 Np (237.05) | 94 Pu (244.06) | 95 Am (243.06) | 96 Cm (247.07) | 97 Bk (247.07) | 98 Cf (251.08) | 99 Es (252.08) | 100 Fm (257.10) | 101 Md (258.10) | 102 No (259.10) | 103 Lr (262.11) |

clumps became denser and denser until eventually a very high pressure developed at the center of each clump, resulting in the combination of the nuclei of the constituent atoms and the release of large amounts of (kinetic) energy resulting in heat and radiation. Thus radiating stars were born (Some of the processes involved have been artificially induced to occur in thermonuclear weapons.). Stars formed (and continue to form) with a variety of masses. In the interior of stars which are not very massive (such as our own sun and lighter stars) the nuclear 'burning' associated with the combination of atomic nuclei only continues up to the formation iron and then stops (The fusion reactions occurring in stars are summarized in Fig. 2.2). The star then dies slowly and in a relatively uneventful way as a white dwarf. As we are interested in how the chemical elements of life form, and become available for planets, this sequence of events is not very relevant, because the heavier elements in Table 2.1 were not formed and what elements were formed remained mainly within the interior of these low mass stars.

However, for more massive stars (5 times as massive as our sun or more), something more spectacular happens: When the pressure inside the star has induced nuclear fusion up to iron nuclei and the star thus runs out of 'fuel' it implodes very fast (in a few seconds) and then a lot of material bounces off the core and explodes into space.

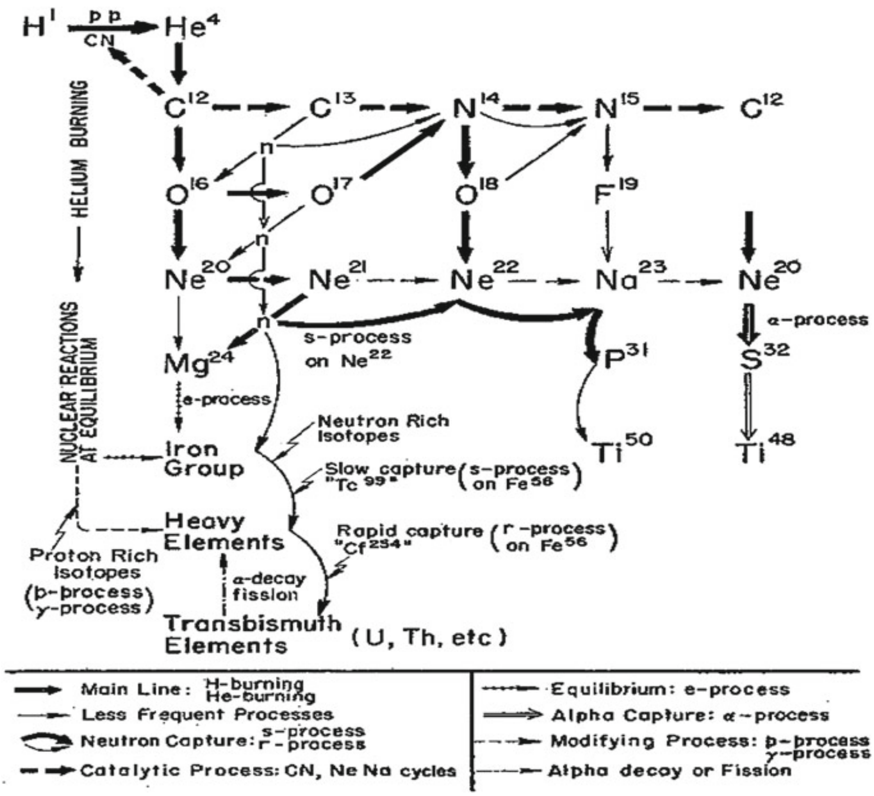


**Fig. 2.2** Nuclear reactions occurring inside stars to make the elements of the periodic table, starting with hydrogen. Moving from *left* to *right* in the diagram, one usually adds neutrons to the nuclei, though in some cases, protons are added. The *superscripts* on the symbols indicate the number of protons plus the number of neutrons in the nucleus. Moving *down* the table one adds 'alpha particles' to the nuclei. These reactions are helium nuclei with 2 protons and 2 neutrons. The reactions *down* to iron all occur inside stars, but the reactions leading to the elements *above* iron are believed to require stellar explosions (*supernovae*) to occur. Aspects of the nature of the reactions leading to the higher atomic number elements above iron are still under study. From Ref. [1]

This is a 'supernova'. It results in a flash of light in the sky. The changes in color and brightness which occur during the lifetime of such a massive star are illustrated in Fig. 2.3. Supernovae big enough and close enough to earth to be observed without a telescope have been observed every few hundred years by humans and were recorded as long ago as 1054 by Chinese astronomers.

Many more supernovae are observed, in our own and other galaxies, with telescopes. (There are two types of supernovae. This is a description of type II supernovae. Type I supernovae are basically similar but occur in slightly less massive stars, between 1.4 and 5 times the mass of our sun and require accretion of mass from some outside source to implode. We will not be concerned with the distinction

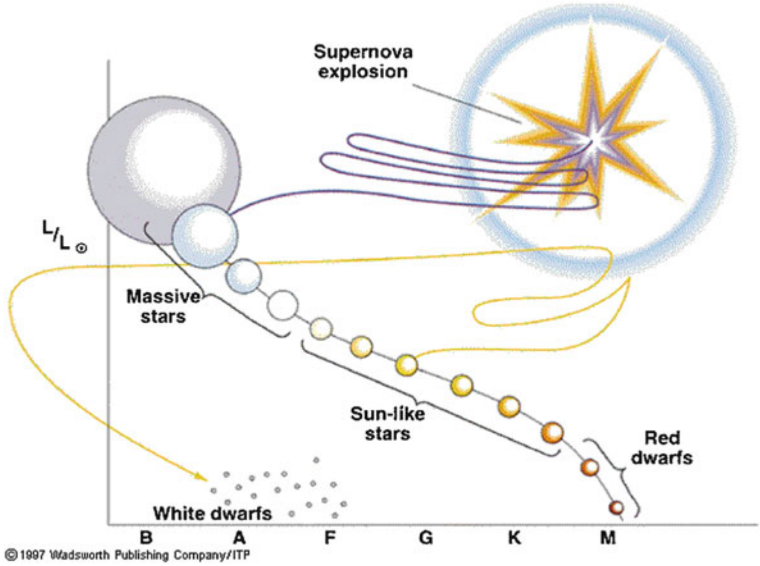


**Fig. 2.3** The path which the theory of stellar evolution says that a star of mass more than 5 solar masses will follow in the so called HR diagram used by astronomers to classify stars. The *vertical axis* is the luminosity (brightness of the light) and the *horizontal axis* is the surface temperature (inferred from the color). These high mass stars live about $10^7$ years. A star like our sun has luminosity 1.0 and is of type G and is on the main sequence. It is expected to live about $10^{10}$ years and to end as a white dwarf star, not as a supernova. From Ref. [2]

between type I and type II supernovae any more here.) The glowing remanents of a supernova which occurred in 1054 and was observed by Chinese astronomers can still be seen in the Crab nebula, of which a picture appears in Fig. 2.4.

The supernovae are significant because they produce the elements above iron in the periodic table and because they spread the products of nuclear burning in the interior of stars into the interstellar medium. Assuming that, like life on earth, other life would require that these heavier elements be present, we will expect to find life originating only on planets formed from the debris of these supernovae explosions. Such planets exist because there is evidence that, after the explosions, the material from the explosion again starts to clump up under the action of the mutual gravitational attraction of the atoms in the gas of the debris. New, ‘second generation’ stars are formed (and around them, at least sometimes, planetary systems which we discuss later). Such stars, of which our sun is one, reveal that they are second generation because the atoms in the gas of the stars emit light characteristic of the heavy elements which can only be formed in supernovae explosions.

With this picture and a little quantitative information about the stars we can get an estimate of the factors $N_{gal} f_{star}$ in the Drake equation. The average number $N_{gal}$ of stars per galaxy is roughly known (this is just a matter of counting) and we will use the number $10^{11}$ for it. To find the rate at which matter is released by supernovae

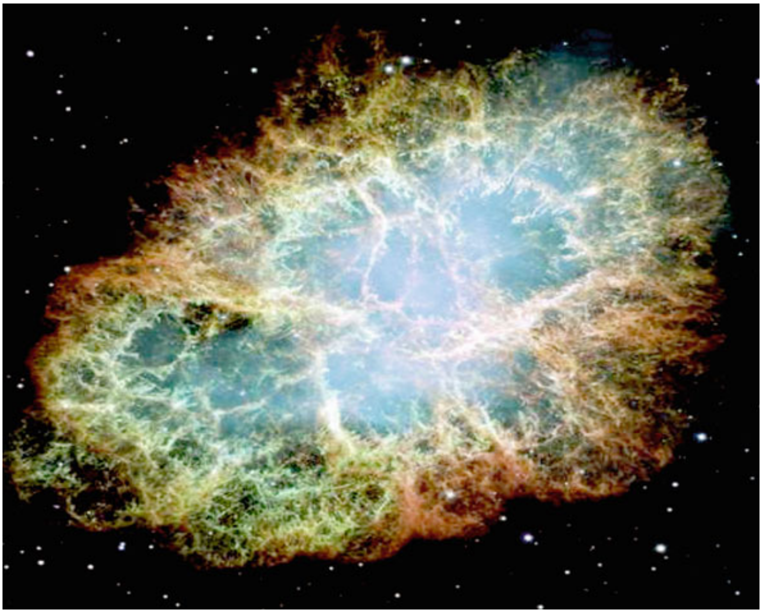

**Fig. 2.4** The Crab nebula, identified as the remanent of the supernova observed by Chinese astronomers in 1054. It lies about 6,300 light-years and is expanding at an average speed of 1,800 km/s. The image is a composite taken with the Hubble space telescope [3]

explosions in a galaxy we use the fact that supernovae occur roughly every $10^2$ years per galaxy. (In our own galaxy, supernovae have been definitely observed in 1006, 1054, 1572 and 1604. However, some may have been missed and others obscured from view by the dense material at the center of the galaxy. The estimate of one every century takes into account observations of supernovae in many other galaxies as well.) Here, as in most other quantitative arguments in this book, we will only cite numbers up to the nearest power of 10. This is justified by the fact that many of the quantities we need are not known to much better accuracy than this and also by the interesting fact that estimates made using such numbers usually give better results than one might expect. Errors made in one factor of a calculation by rounding off to the nearest power of 10 tend to be compensated by errors in the other direction in other factors in the calculations. The theory of stellar evolution, amply confirmed by extensive calculations and observations, gives a lifetime for stars in the mass range leading to supernovae (more than five times the mass of the sun) which is of order $10^7$ years. From these numbers we can estimate the average number $N_{big}$ of massive stars in a galaxy which will become supernovae:

$$N_{big}/(10^7\, yr) = 1/10^2\, yr$$

so that $N_{big} \approx 10^5$. Since each of these stars contains at least 5 solar masses of mass, one is producing at least $5 \times 10^{-2}$ solar masses of material for second generation stars per year. Once formed, these second generation stars, which are mainly of 1 solar mass each or less, live about $10^{10}$ years. We can estimate the number of second generation stars $N_2$ by equating their death rate to their birth rate:

$$N_2/10^{10}\,year = 5 \times 10^{-2}\,per\,year$$

so that $N_2 \approx 5 \times 10^8$ and the fraction $f_{star}$ of stars in the galaxy which are second generation and of a mass similar to that of our sun is $f_{star} \approx 5 \times 10^8/10^{11} = 5 \times 10^{-3}$. This estimate is about 10 times lower than a similar one due to Hart [4]. Our considerations neglect some effects. For example, the gas from a supernova could all coagulate into another giant star which could in turn explode and so on. During the lifetime of the universe ($14 \times 10^9$ *year*) there could in principle be enough time for more than 100 generations of stars if this process repeated itself. However, because only one in a million stars is big enough to make a supernova, this multiple generation process is very unlikely and most stars will be first or second generation. Also, we have restricted attention to second generation stars with lifetimes of order $10^{10}$ *year*. Less massive stars than the sun will live longer and more massive ones will have shorter lives. There are reasons associated with need for a habitable climate to restrict attention to the stars with masses close to that of the sun, as we will discuss in the next part. Notice that though the lifetime of the universe ($14 \times 10^9$ *year*) seems very long, it is not much longer than the estimated lifetime of our sun. On the time scales which interest us, our universe will turn out to appear to have lived quite a short time from several points of view.

In summary our estimates for the first two, astrophysical, factors in the Drake equation are

$$N_{gal} \approx 10^{11}$$

and

$$f_{star} \approx 10^{-2}.$$

## References


1. E. Margaret Burbidge, G.R. Burbidge, W.A. Fowler, F. Hoyle, Synthesis of the elements in stars. Rev. Mod. Phys. **29**, 547 (1957) Copyright (1957) by the American physical society used by permission
2. Image from Michael Seeds, Horizons: Exploring the Universe, 5th Edition, Wadsworth Publishing Co. (1997), Fig. 10-1 by permission
3. Image by NASA, ESA and Allison Loll and Jeff Hester (Arizona State University) by permission
4. M.H. Hart, in *Extraterrestrials, Where are they*? 2nd edn. ed. by B. Zuckerman, M.H. Hart (Cambridge Press, Cambridge, 1982), p. 218

Springer

http://www.springer.com/978-3-642-22753-0

How Likely is Extraterrestrial Life?
Halley, J.W.
2012, IX, 151 p. 49 illus., 27 illus. in color., Softcover
ISBN: 978-3-642-22753-0