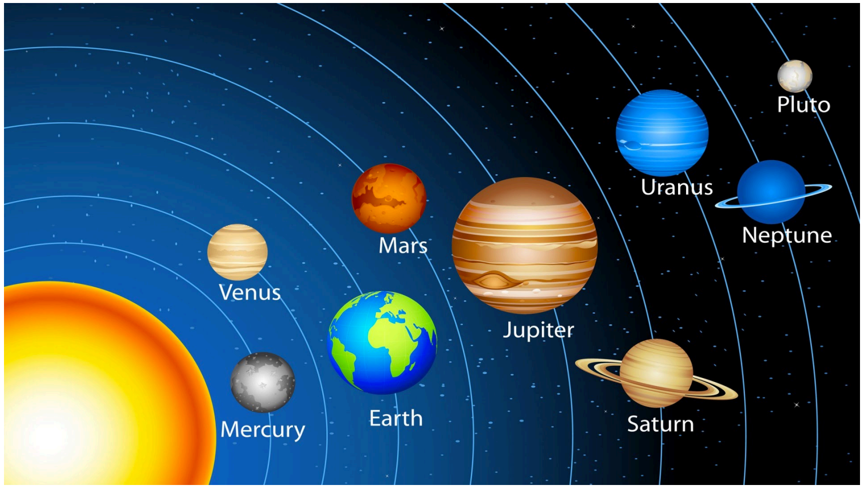
THE ORIGIN AND EARLY HISTORY OF THE UNIVERSE

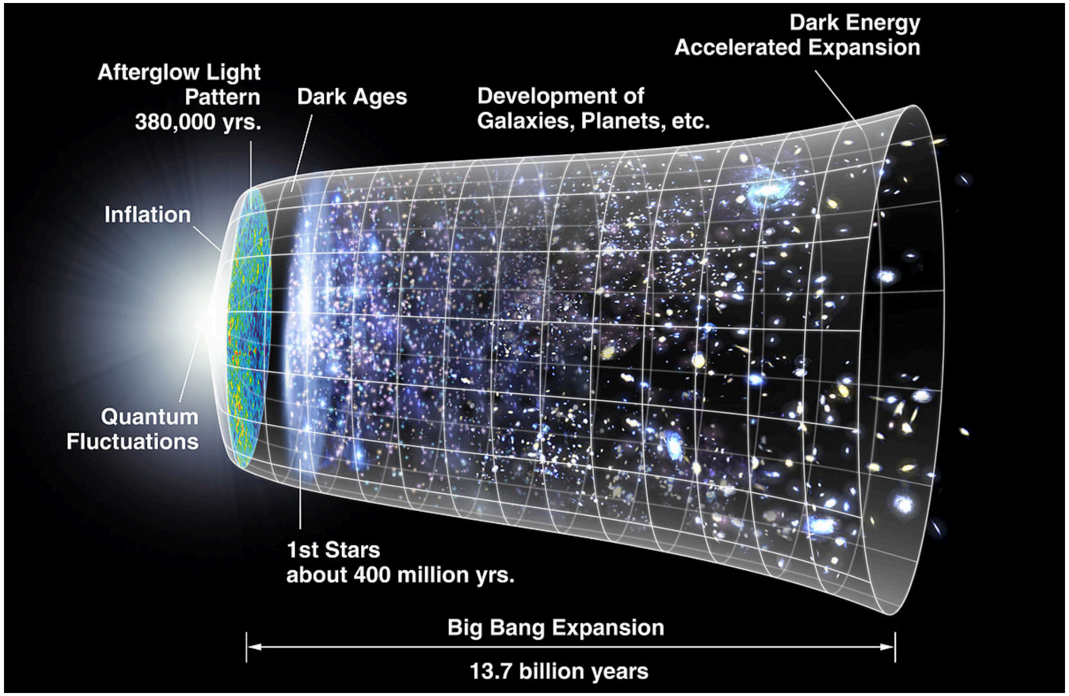
1) the elemental abundances in the early solar system are a function of its setting within the galaxy and this “cosmic geography” ultimately determines the “raw materials” of the terrestrial planets.



2) a planetary view of the Earth provides insight into the ultimate Earth system, in which there was profound, dynamic interaction between what are now the different components of the modern Earth system.

The Big Bang theory

The prevailing theory of the origin and evolution of the Universe is the **Big Bang theory**. According to this theory, about 14 billion years ago the Universe expanded to its present enormous volume from an initial volume, which was effectively zero.



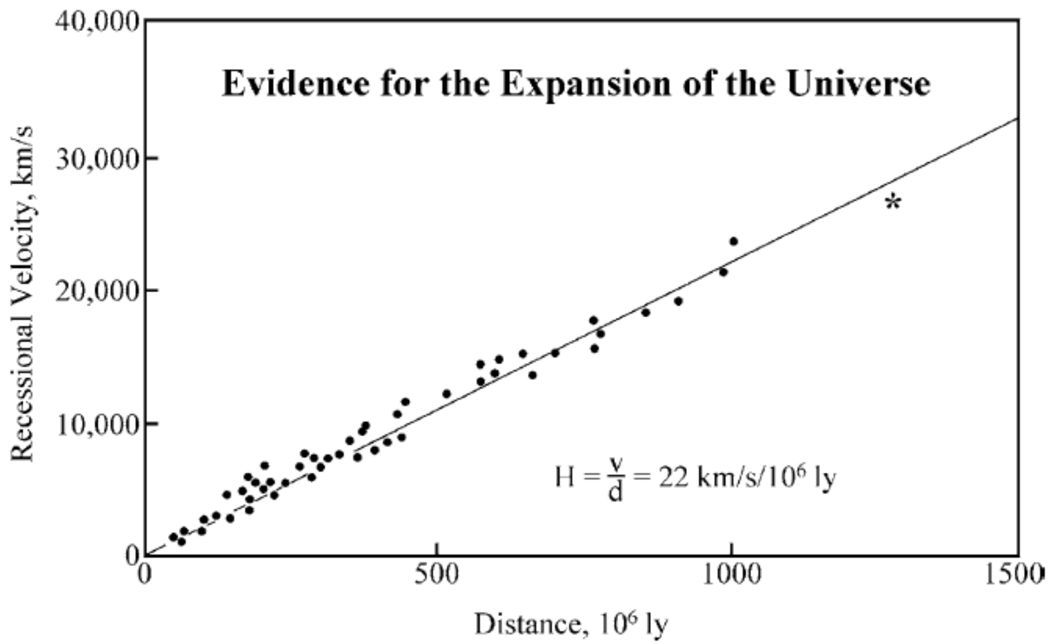
Three sets of observations have profoundly shaped the way in which we think about our Universe and led to the Big Bang theory:

1) First was the discovery that our Universe is expanding.
2) Second, there were predictions about the abundances of the light elements H, He, and Li in the Universe,
3) third was the discovery made by Penzias and Wilson (1965) that our part of the Universe is filled with microwave radiation.

Evidence for the Big Bang theory

An expanding Universe

Hubble (1929) discovered that there is a simple, linear relationship between the distance to a remote galaxy and the cosmological redshift – the redshift in the spectral lines from that galaxy (Hubble, 1929).

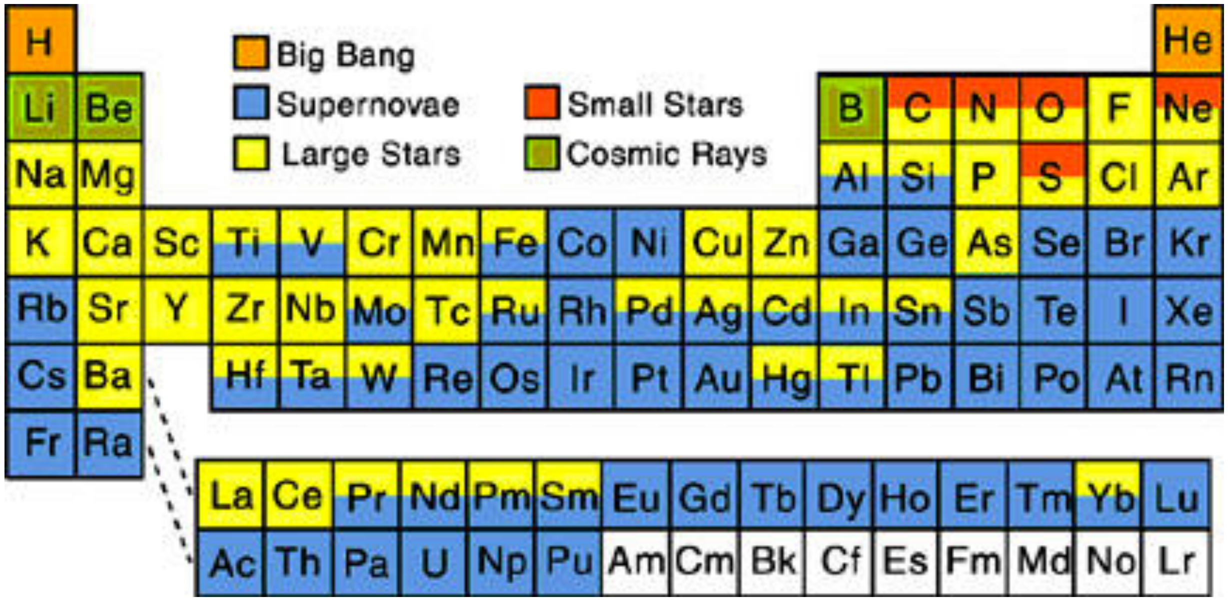


The measurements of the recessional velocities (v) and the distances (d) between the Earth and distant galaxies define a straight line whose slope is the Hubble constant (H) defined by the relation: $H = v/d$ or $v = H \times d$ as stated in equation 4.1. A statistical interpretation of these data yields a value of 22 ± 2.2 km/s/10^6 ly for the Hubble constant. The asterisk identifies the most distant galaxy included in this survey, which is located at almost 1300 ± 10^6 ly from Earth (1.22×10^{22} km) and which has a recessional velocity close to 26,500 km/s (8.8% of the speed of light). These modern measurements extend and confirm the results Edwin Hubble published in 1929. Adapted from Hester et al. (2002, Figure 19.6)

Hubble's observations showed that the greater the distance to a galaxy, the greater the redshift in its spectral lines. These measurements strongly indicated that galaxies appear to be moving away from us with speeds proportional to their distance.

The net effect of this motion is that, as time goes on, the galaxies are getting further and further apart. A very important consequence of these observations is that at some point in the past all matter must have been concentrated in one place. Astronomers define this point in time as the beginning of the Universe. At
this time all the matter of the Universe was concentrated in an infinitely small volume with a state of infinite density.

The abundance of the light elements



The Big Bang theory predicts that the early universe was very hot. In the early stages of the formation of the Universe the light elements H (and its isotope deuterium), He, and Li were formed during the “Big Bang nucleosynthesis.”

The deuterium found today in the interstellar medium could only have formed at the beginning of the Universe (Songaila et al., 1994). Calculations based upon the initial ratio of protons and neutrons suggest that if the Big Bang theory is correct then about 24% of the ordinary matter in the Universe will be He and the rest hydrogen (Schramm & Turner, 1998). This value is in good agreement with recent observations indicating that the Big Bang theory passes one of its key “tests.”

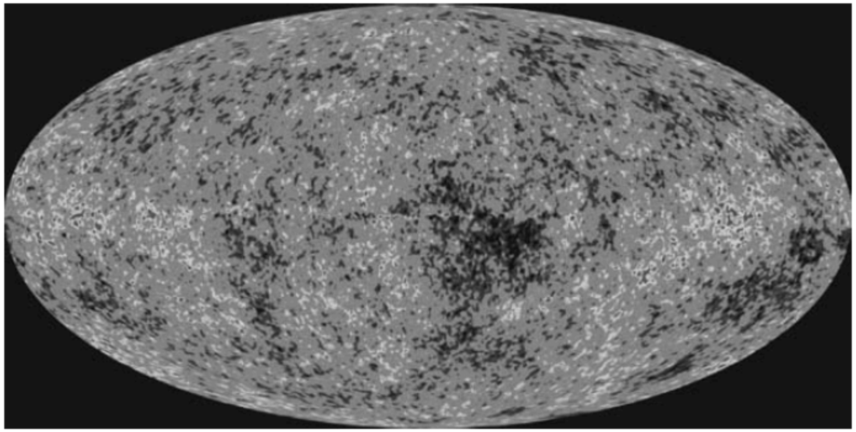
The Cosmic Microwave Background

If the early Universe was extremely hot, it is possible that, even today, the remnants of this initial fireball might be detected. Support for this hypothesis came from the discovery by Penzias and Wilson (1965) of what came to be known as the Cosmic Microwave Background.

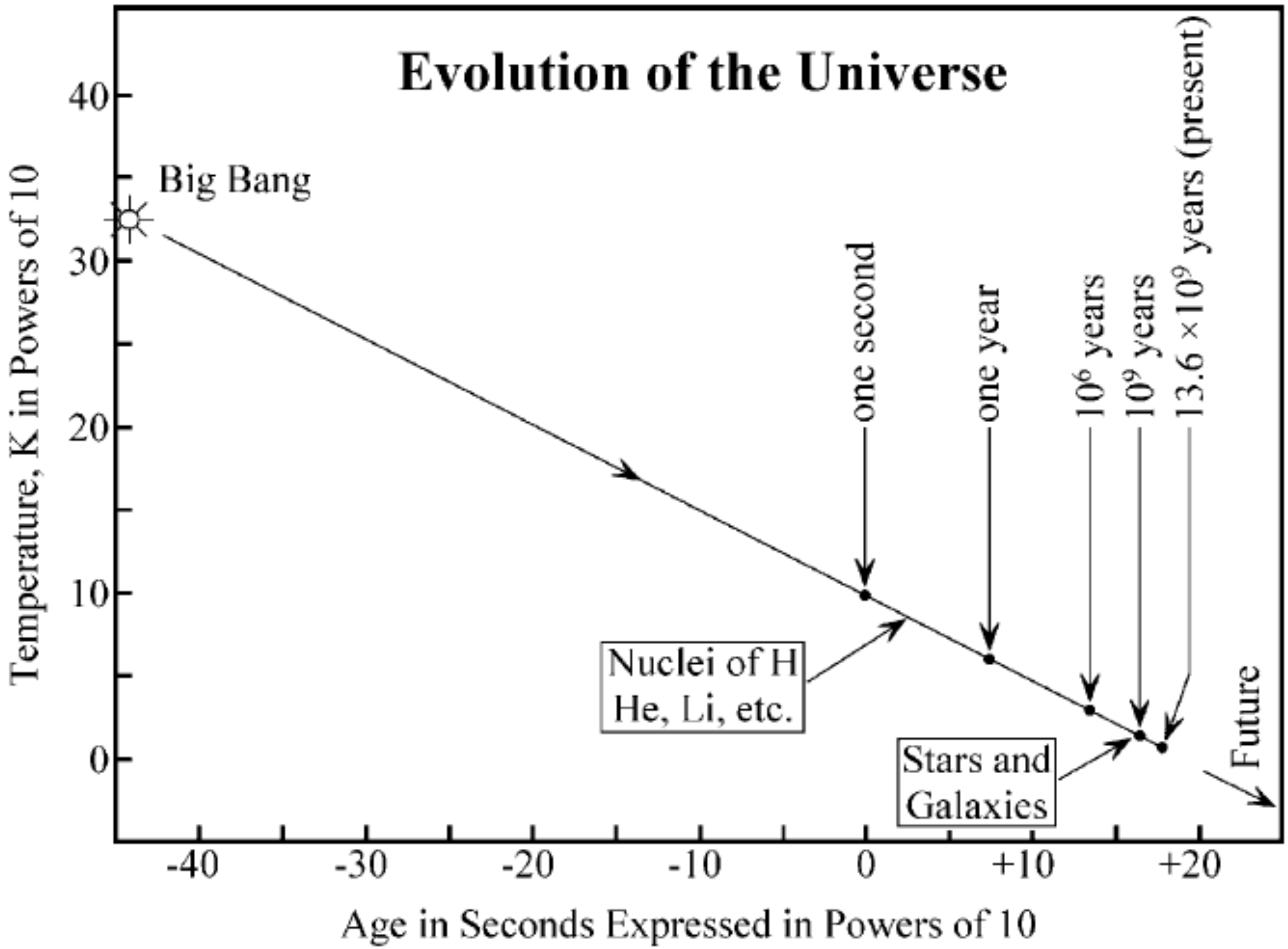
This discovery coincided with the work of theoretical physicists who showed that if the Universe began with a hot Big Bang, then the Universe should be filled with electromagnetic radiation cooled from the early fireball to a temperature of around a few Kelvin.

Wilkinson microwave anisotropy probe (WMAP) was launched to map the fine detail of the Cosmic Microwave Background.

A WMAP image of the infant universe showing 14 billion year old temperature fluctuations (shown as differences in grey shading) that correspond to the seeds of galaxies (from http://map.gsfc.nasa.gov/m_or.html, courtesy of NASA/WMAP Science team).



In subsequent years a large number of direct measurements of the Cosmic Microwave Background at different wavelengths yielded an intensity– wavelength plot which had the characteristics of black body radiation at 2.73 K. This is the remnant of the initial fireball of the Big Bang.



The temperature of the Universe decreased from greater than 10^{32} kelvins only a tiny fraction of a second after the Big Bang to 2.73 kelvins at the present time about at 13.6×10^9 years later. The age of the Universe and its temperature are both expressed in powers of 10 meaning that the age "–20" is equal to 10^{-20} seconds and that a temperature of "20" represents 10^{20} kelvins. Several milestones in the evolution of the Universe are identified for reference. Data from Hester et al. (2002, Figure 20.14)

The Big Bang. At the Big Bang there was a huge expansion of matter, an expansion that has continued ever since.

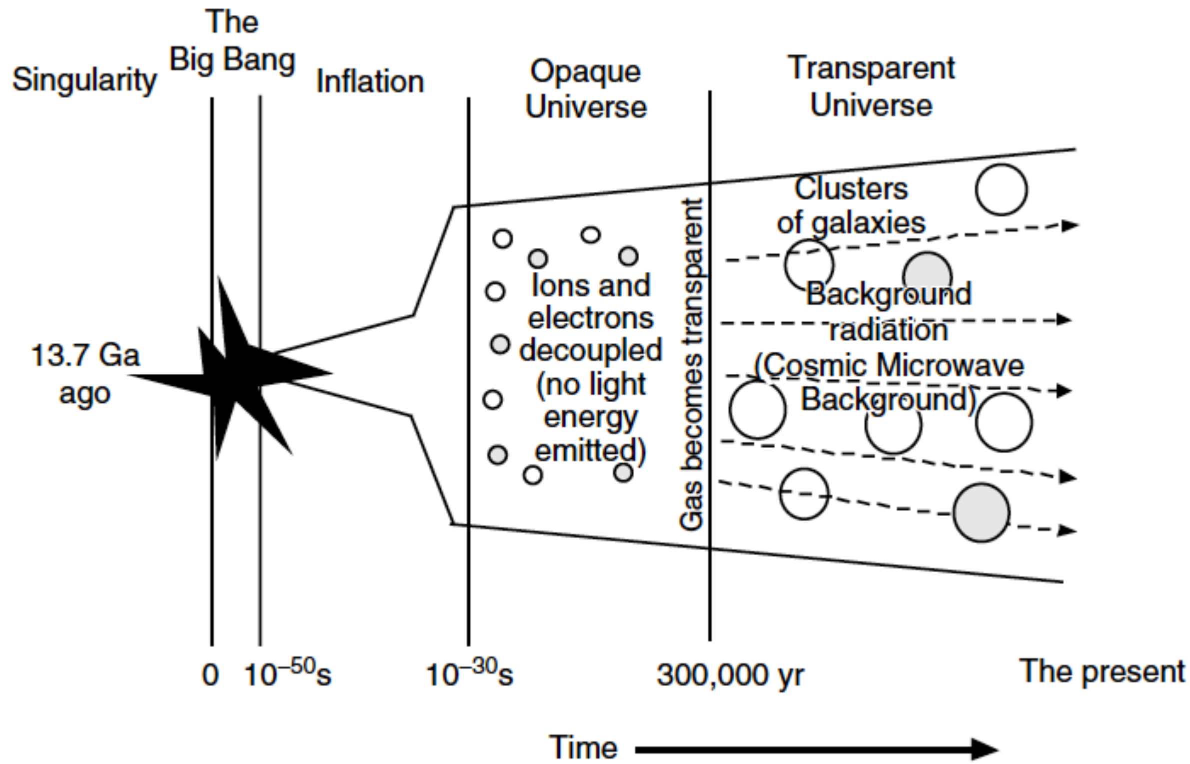


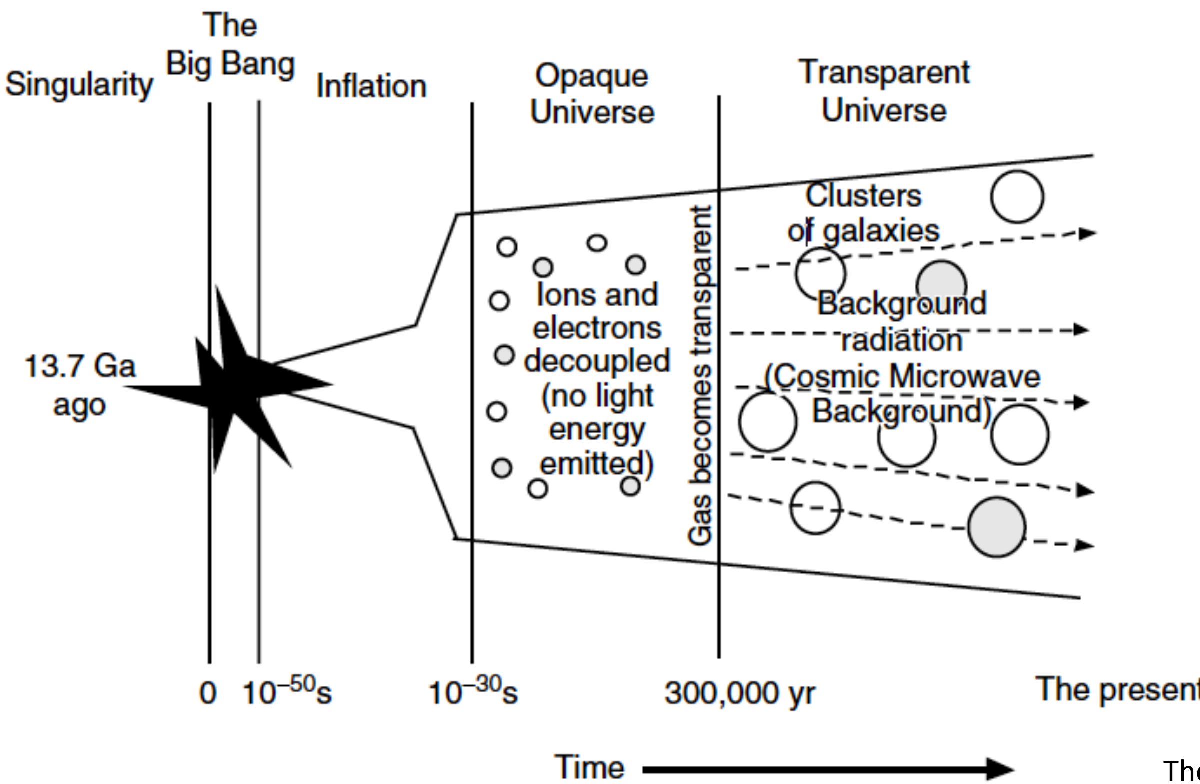
FIGURE 2.2 The origin, inflation, and expansion of the Universe from the initial singularity to the present.

An initial singularity. At the beginning of the Universe, 13.7 billion years ago, all matter was in one place at a single instant; this event in cosmological parlance is known as a "singularity." This term describes the inference that an infinitely large amount of matter is gathered at a single point in space-time.

Inflation. Between 1050 and 1030 s after the Big Bang there was a particularly rapid expansion of the Universe. This process is known as the inflation of the Universe and represents the first burst of growth of the Universe. During inflation the part of the Universe that we see today expanded by a factor of 10^{60}.

An opaque Universe. An almost uniform plasma of electrons, hydrogen, and helium ions filled the Universe. At this time the free electrons acted as a block to photons – generated from the light energy generated in the Big Bang, and prevented them escaping, rendering the early Universe opaque.

A transparent Universe. After 300,000 yr temperatures dropped to 4,500 K and gave rise to the formation of atomic matter, and atoms of hydrogen, helium, and deuterium were formed. Because electrons were removed from the plasma through the formation of atoms, radiation streamed out and the Universe became transparent. Initially the Universe contained abundant ultraviolet and X-rays, now cooled down to microwave wavelengths. This is what is recorded as the Cosmic Background radiation.



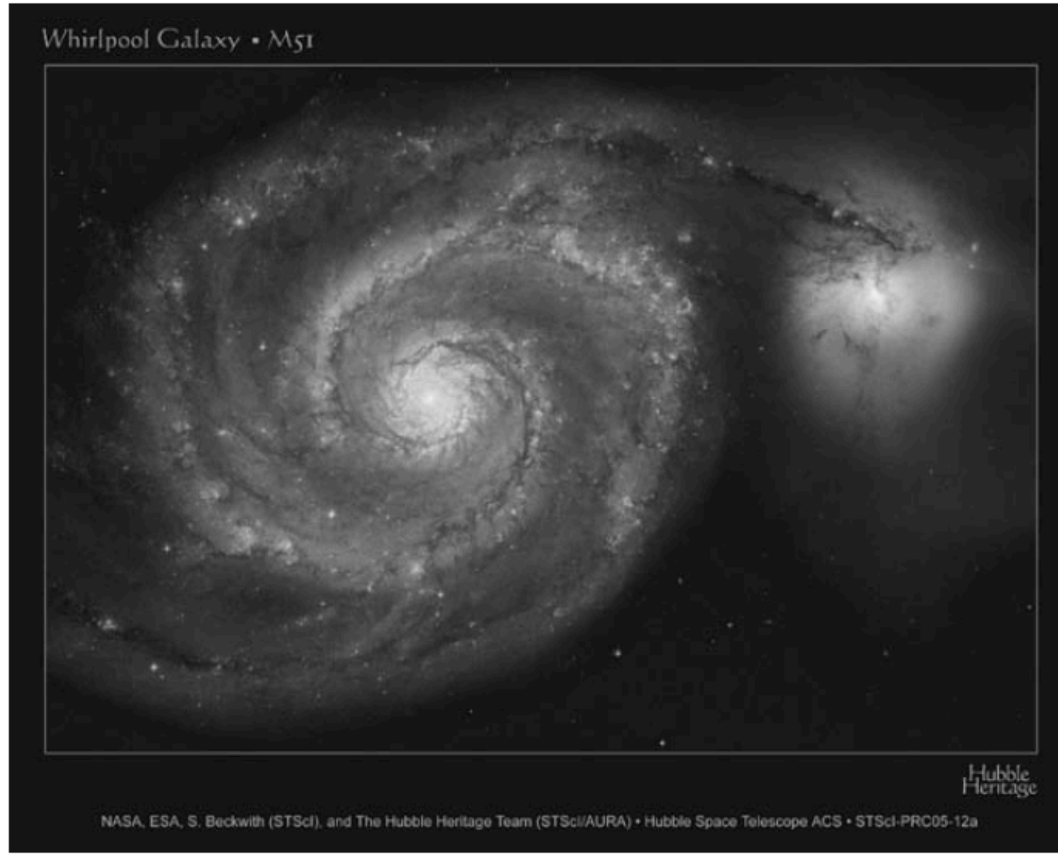
The origin, inflation, and expansion of the Universe from the initial singularity to the present.

The present Universe. As the universe continues to expand the initial radiation will appear to be derived from a much cooler body. Hence today the Cosmic Background radiation is 2.73 degrees above absolute zero.

STAR FORMATION

As cosmologists began to accumulate measurements of the Cosmic Background radiation at the edge of the Universe they were impressed by the uniformity of the results. However, many theorists predicted that in detail the results should not be uniform, leading to a search for microscale variability in the cosmic background radiation. This was first discovered using a differential microwave radiometer on the COBE space probe and demonstrated that the Cosmic Microwave background was very slightly variable on the scale of one part in 100,000.

The significance of this variation in the intensity of the Cosmic Microwave Background is that it shows how matter and energy were distributed when the Universe was still very young. It is thought that these early inhomogeneities subsequently developed into the regions in the present Universe where there is matter, that is, galaxies and galaxy clusters, and those regions from which matter is, absent – space. The early inhomogeneous distribution of matter also reflects an inhomogeneous distribution of density, and it is these initial density differences that gave rise to small differences in gravitational forces which began to draw matter together.



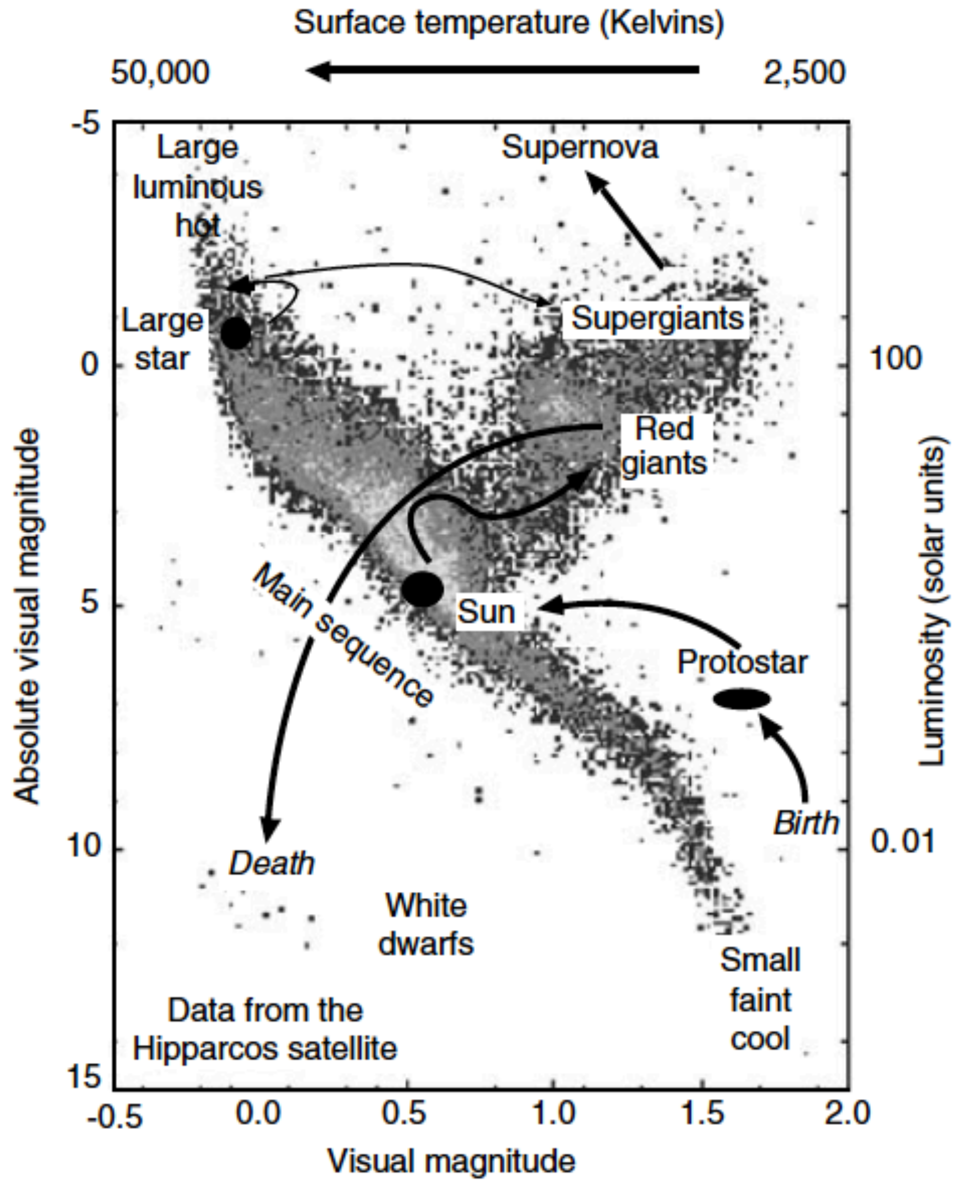
A typical spiral galaxy – the Whirlpool Galaxy, M51 and companion galaxy (from the HubbleSite picture gallery http://hubblesite.org/, Credit NASA, http://www.nasa.gov/, ESA, http://www.spacetelescope.org/, S. Beckwith (STSci), http://www.stsci.edu/, and the Hubble Heritage team (STSci/AURA), http://heritage.stsci.edu (http://www.stsci. edu/and http://www.aura-astronomy.org/)).

Primordial gas clouds, composed of hydrogen and helium, are thought to be the beginnings of galaxies and represent the first large-scale structures to form in the evolving Universe.

These huge gas clouds with masses 1015–1016 greater than that of the sun (that is, 104–105 times greater than our own galaxy, the Milky Way), formed due to gravitational forces working against the expansion of the Universe.

The process of star formation

As large molecular clouds fragment and collapse, star formation can take place. This process is triggered by density inhomogeneities in the gas cloud, producing regions which become gravitationally unstable and contract.



Hertzsprung–Russel diagram for the classification of stars. The data in this diagram are taken from the Hipparcos satellite which measured the properties of more than 10,000 nearby stars. Key variables are the relationship between the luminosity of the star (relative to the sun) or absolute visual magnitude, and its color index – the inverse of the surface temperature. The data in this diagram show the relative importance of the different types of star. The arrows show a typical birth to death cycle of a small star (lower part of diagram) and of a large star with a mass 25 times that of the sun (upper part of diagram).

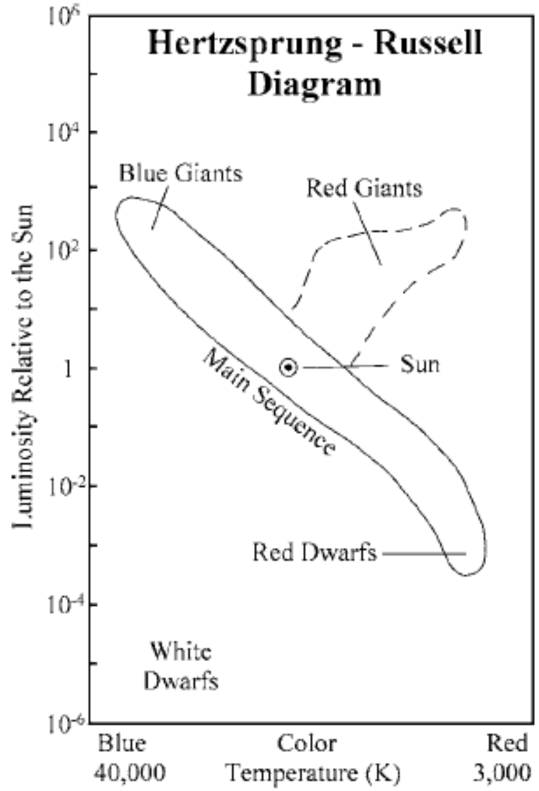
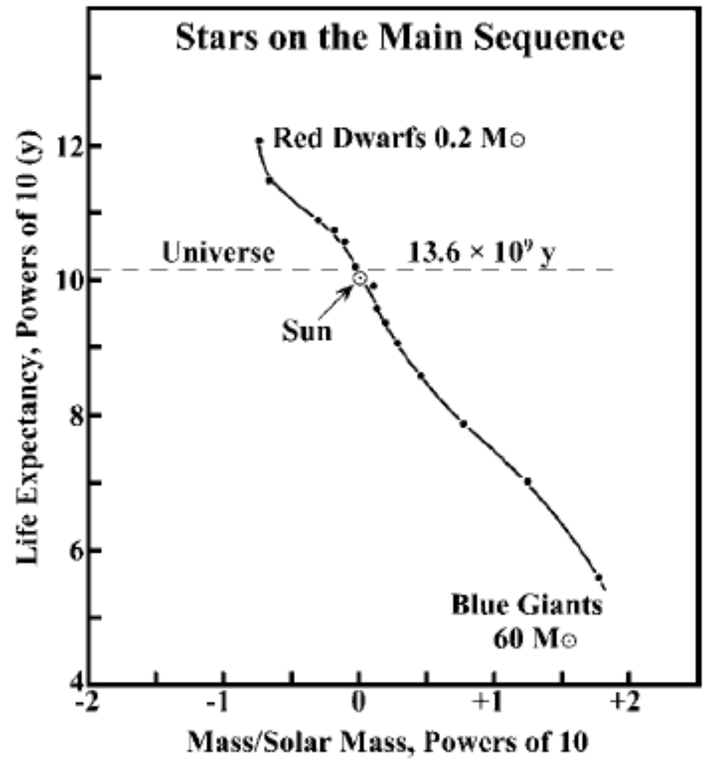
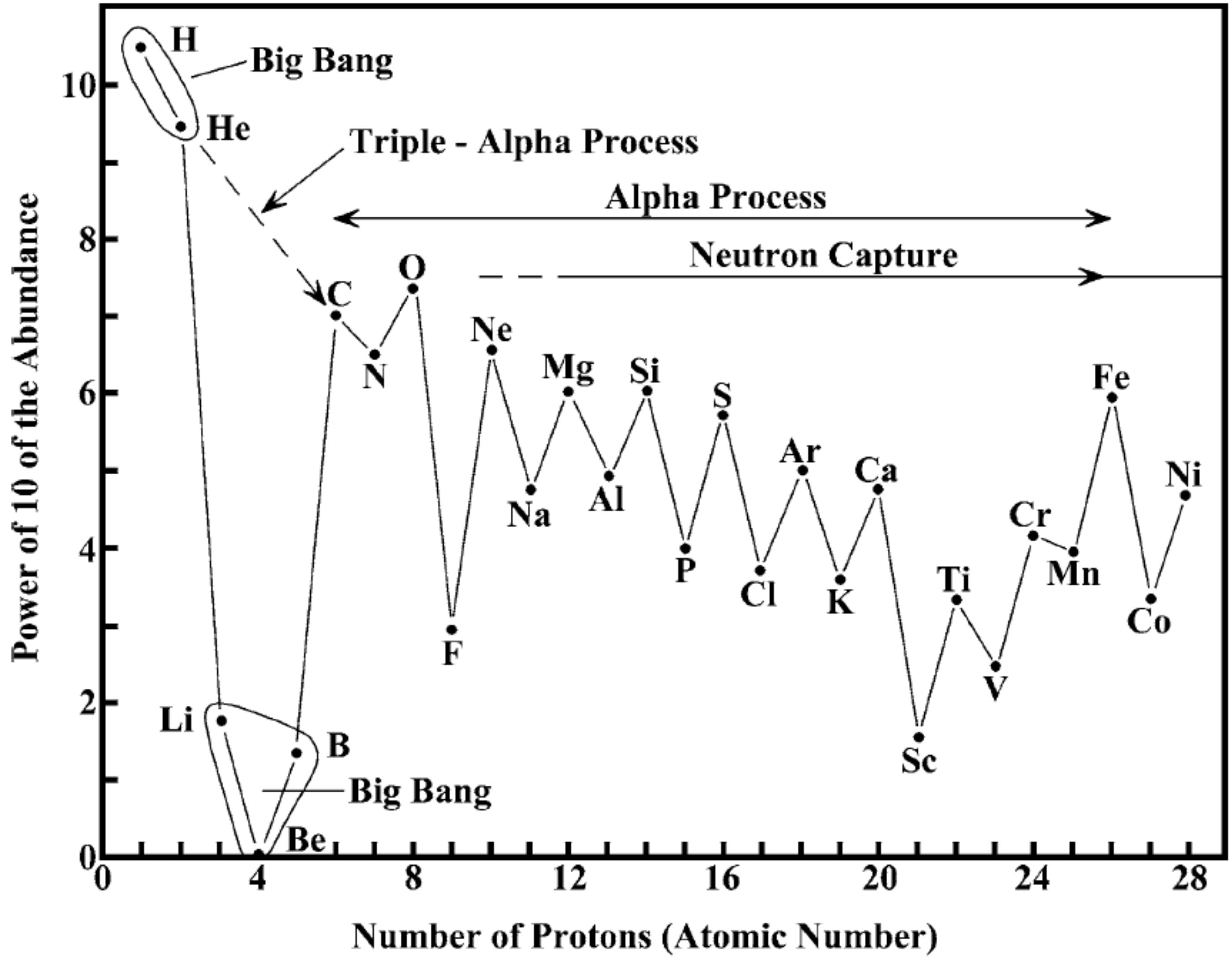


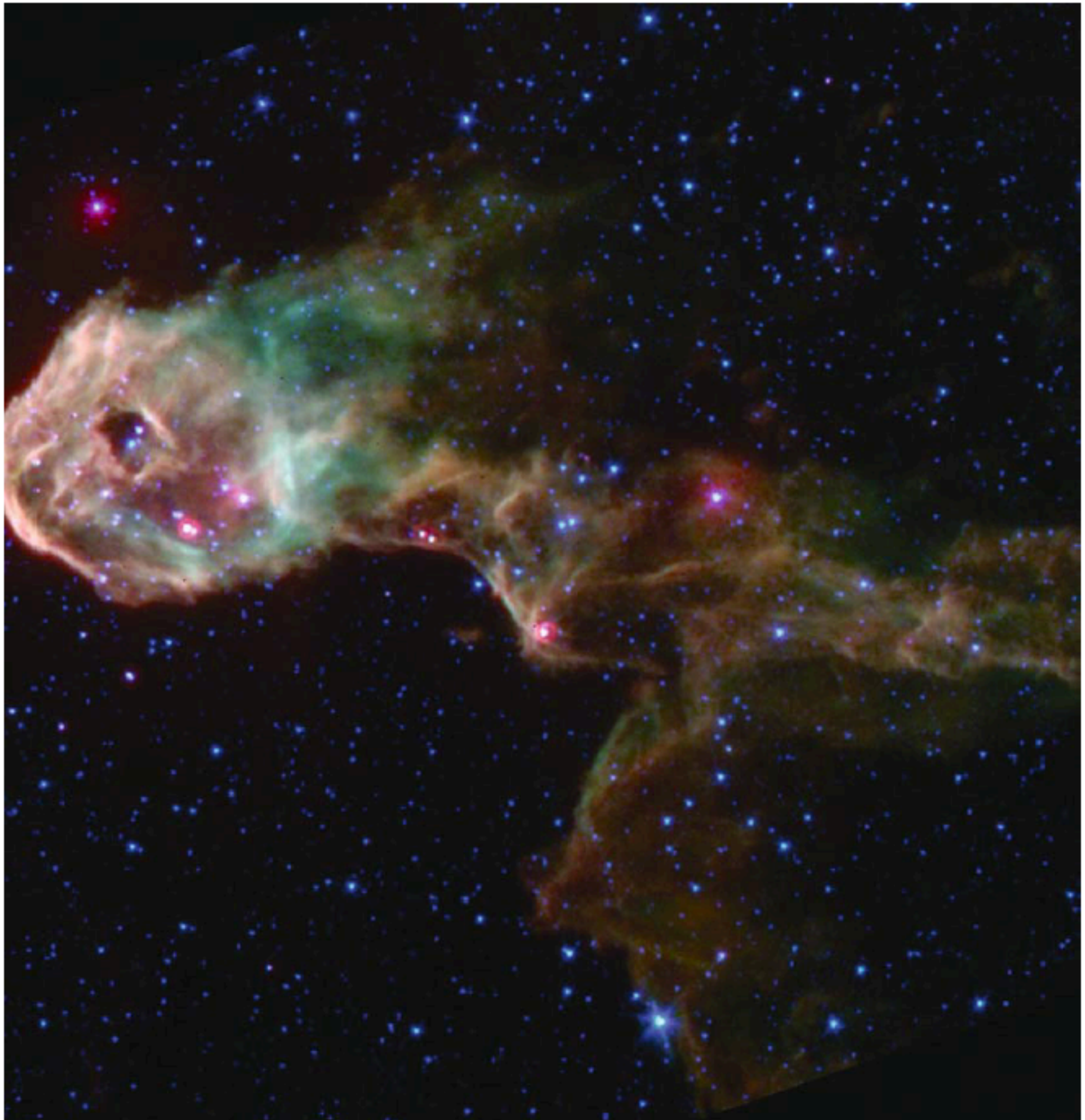
Figure 4.3. The Hertzsprung-Russell diagram is constructed by plotting the luminosity of stars (divided by the luminosity of the Sun) in powers of 10 versus their surface temperature (or color). Most of the stars of an active galaxy plot in the area labeled main sequence. The blue giants are the largest stars with about 60 solar masses, whereas red dwarfs have less mass than the Sun. Stars on the main sequence generate energy in their cores by a nuclear reaction that fuses two protons (nuclei of hydrogen atoms) with two neutrons to form a nucleus of helium. After the hydrogen in the core is exhausted, stars leave the main sequence and become red giants which ultimately eject their gas envelopes leaving their cores, which take the form of white dwarfs, neutron stars, or a black holes depending on the original mass of the star. Adapted from Hester et al. (2002, Figure 12.15)



The life expectancies of stars on the main sequence depend strongly on their masses. The most massive stars (60 solar masses) "burn" the hydrogen in their cores in less than one million years and complete their life cycle soon thereafter. The least massive stars (less than one solar mass) spend up to one thousand billion years on the main sequence. As a result, the red dwarfs are the oldest and most abundant stars in the Milky Way and other galaxies, whereas blue giants are the youngest and least abundant stars. The life expectancy of the Sun on the main sequence is ten billion years. We also know that the Sun is 4.6 billion years old which means that it will continue to shine for about another 5.4 billion years before it becomes a red giant. Data from Hester et al. (2002, Table 12.3)



The abundances of the chemical elements in the solar system are expressed in terms of numbers of atoms per million atoms of silicon and were plotted in this diagram in powers of 10. The abundances of hydrogen and helium are up to 1000 times higher than those of carbon and other elements of higher atomic number (i.e., number of protons). The chemical symbols used to identify the elements are: H = hydrogen, He = helium, Li = lithium, Be = beryllium, B = boron, C = carbon, N = nitrogen, O = oxygen, F = fluorine, Ne = neon, Na = sodium, Mg = magnesium, Al = aluminum, Si = silicon, P = phosphorus, S = sulfur, Cl = chlorine, Ar = argon, K = potassium, Ca = calcium, Sc = scandium, Ti = titanium, V = vanadium, Cr = chromium, Mn = manganese, Fe = iron, Co = cobalt, and Ni = nickel. Only the first 28 of the 92 naturally occurring chemical elements are included in this diagram. Data from Anders and Grevesse (1989)



The Elephant's Trunk nebula in the Milky Way galaxy, seen here in false-color infrared light by the Spitzer Space-Telescope. The nebula is a stellar nursery in which several young stars glowed brightly when the light was emitted about 2450 years ago. This nebula also contained dust particles and molecules of hydrogen and of complex polycyclic aromatic hydrocarbons (PAHs). (Courtesy of NASA/JPL-Caltech/W. Reach (SSC Caltech). (http://ipac.jpl.nasa.gov/media_images/ssc2003-06b1.jpg)

Cosmological nucleosynthesis. The elements H, and its isotope D, He, and Li were created in the first few moments of the Big Bang. These are the essential ingredients of the cosmos and the starting composition for all other elements. The ratio of He/H, in terms of the number of atoms, is about 25% as a consequence of this event, and although some additional He has been created in stellar nucleosynthesis (see below) the ratio in the Universe as a whole has remained essentially unchanged since the beginning of time.

Stellar nucleosynthesis. Elements with atomic masses up to that of iron (56Fe) are created in stars through a variety of different reactions, taking place over a wide range of temperatures.

Hydrogen burning and helium production. Hydrogen burns in the core of a star to form ^{4}He through either the proton–proton chain reaction, which takes place at $5x10^{6}$ K or at higher temperatures ($20x10^{6}$ K) through the carbon cycle (the C–N–O cycle) in which carbon acts as a nuclear catalyst in the production of He. This process is also known as the quiescent burning phase of a star and is a slow process which takes billions of years and covers much of the life of a star. Our sun is currently in this phase.

Helium burning to form carbon and oxygen. As the hydrogen in a star is used up, the star contracts and its temperature rises to greater than 10^{8} K. At this stage nuclear reactions take place which permit the synthesis of the elements carbon, nitrogen, and oxygen, from helium. ^{12}C forms from ^{4}He, through what is known as the triple alpha reaction, and when sufficient ^{12}C is present, further reaction leads to the formation of ^{16}O.

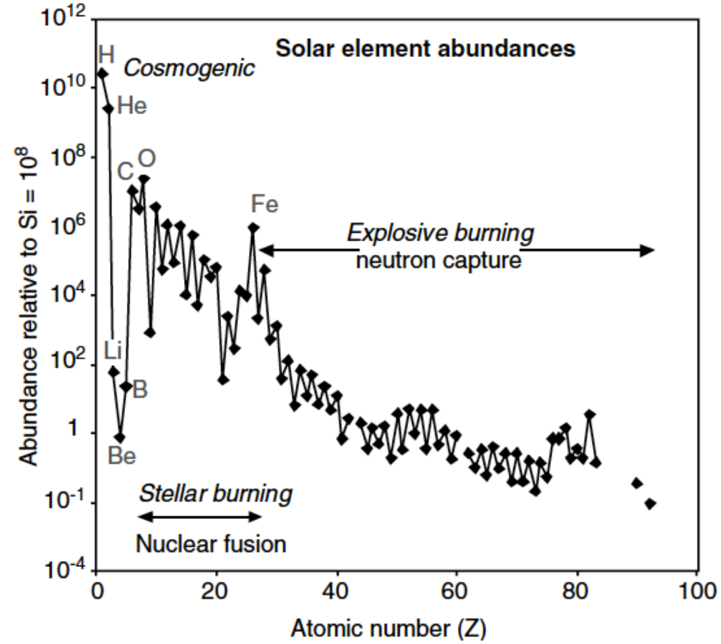
Carbon and oxygen burning. When the helium is almost completely consumed then the carbon and oxygen can be transformed into elements with masses up to that of silicon. This takes place after the stellar core has contracted further and increased in temperature. In detail carbon fusion reactions (^{12}C) lead to the formation of ^{24}Mg, ^{23}Na, and ^{20}Ne at about 6×10^8 K. Oxygen fusion reactions lead to the formation of ^{32}S, ^{31}P, ^{31}S, and ^{28}Si at about 10^9 K.

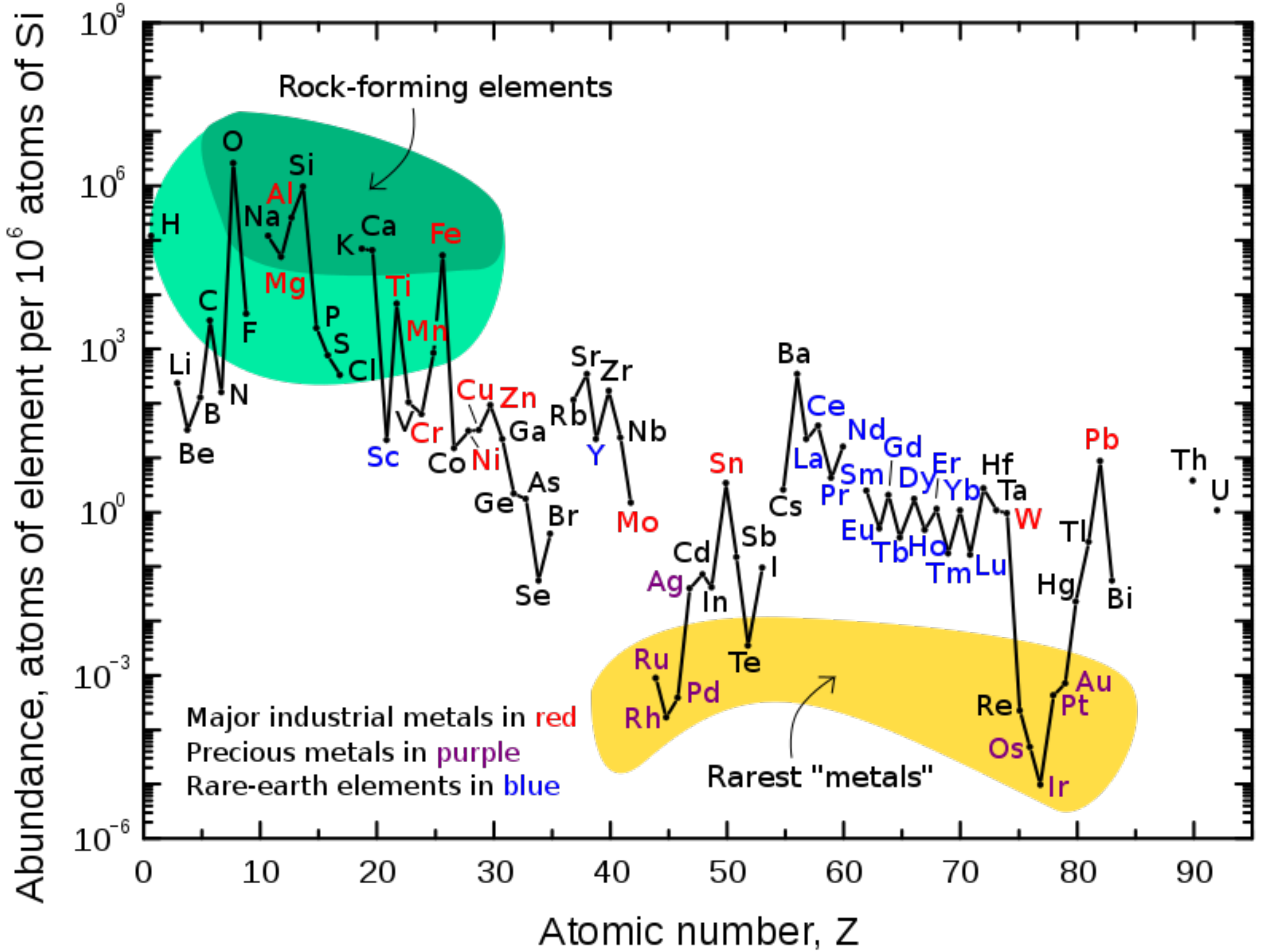
Silicon burning. As carbon and oxygen burning proceeds the stellar core becomes enriched in Si and is at temperatures of about 10^9 K. At these temperatures nuclear reactions in the stellar core induced by photons lead to the formation of elements with masses up to that of iron. Elements heavier than Si cannot be formed by the process of nuclear fusion because beyond this point the nuclear reactions cease to be an energy source.

The most energetic fusion reaction is hydrogen burning;

a lesser amount of energy is produced by He-burning, even less from C and O, and progressively less until Fe is reached at which point no energy is released at all.

Explosive burning in a supernova. In contrast to the nuclear reactions thus far described, the formation of elements beyond the mass 56 (Fe) consumes energy. This process is that of neutron capture and involves the absorption of neutrons by the atomic nucleus. Hence heavier elements such as silver, gold, or lead can only be formed in a highly energetic environment within a star, such as found in a supernova explosion, because only in this environment is sufficient energy released to allow the energy-inefficient process of heavy-element formation to take place. Supernovae explosions are the endpoint of large stars and represent the violent collapse of a Fe-rich stellar core, during which neutrons, produced in the core collapse, are captured by other nuclei. They are built into heavy nuclei, through rapid neutron capture, up to the elements Th and U. Hence, the reason that the heavy elements are so rare is because the process by which they are formed is rare – approximately only one in a million stars is massive enough to go supernovae.





Rock-forming elements
Rarest "metals"
Major industrial metals in red
Precious metals in purple
Rare-earth elements in blue
Abundance, atoms of element per 10^6 atoms of Si
Atomic number, Z
10^9
10^6
10^3
10^0
10^-3
10^-6
0
10
20
30
40
50
60
70
80
90
H
Li
Be
B
C
N
O
F
Na
Mg
Al
Si
P
S
Cl
K
Ca
Sc
Ti
V
Cr
Mn
Fe
Co
Ni
Cu
Zn
Ga
Ge
As
Se
Br
Rb
Sr
Y
Zr
Nb
Mo
Ru
Rh
Pd
Ag
Cd
In
Sn
Sb
Te
I
Cs
Ba
La
Ce
Pr
Nd
Sm
Eu
Gd
Tb
Dy
Ho
Er
Tm
Yb
Lu
Hf
Ta
W
Re
Os
Ir
Pt
Au
Hg
Tl
Pb
Bi
Th
U

Major elements are those chemical elements which make up the principal part of rocks. These are the elements which make up the main rock-forming minerals. They are normally reported as metals, but, since oxygen is also an important part of the Earth, by convention they are presented as percentages by weight of the metal oxide. They tend to be listed in the order – SiO_2, TiO_2, Al_2O_3, FeO, MnO, MgO, CaO, Na_2O, K_2O, and P_2O_5. Sometimes structurally bound water (listed as H_2O) may also make up several percentages by weight of the rock. Major element analyses should sum to about 100 wt%.

Trace elements are those elements which do not normally make up rock-forming minerals in their own right, and are present at the part per million level (ppm) or lower. Over the past 50 years methods of determining the concentrations of trace elements in rocks have improved dramatically, so that determinations with precision at the parts per billion (ppb, 10^{-9}) level are not uncommon.

Minor elements are those elements which have concentrations between 1.0 and 0.1 wt%. They include elements such as Ti, Mn, K, and P. These elements may behave either as a major element or a trace element. For example, K may be present as several wt% in granite and may be part of a major rock-forming mineral (K-feldspar). In a basalt however, K may be present only at the ppm level, substituting for Na in plagioclase feldspar.

A geochemical classification of trace elements according to their position in the periodic table

It is useful in geochemistry to recognize particular groups of elements on the basis of their position in the periodic table. This is because their chemical similarities lead us to expect some similarity in their geochemical behavior in natural systems. In this text, reference will be made to:

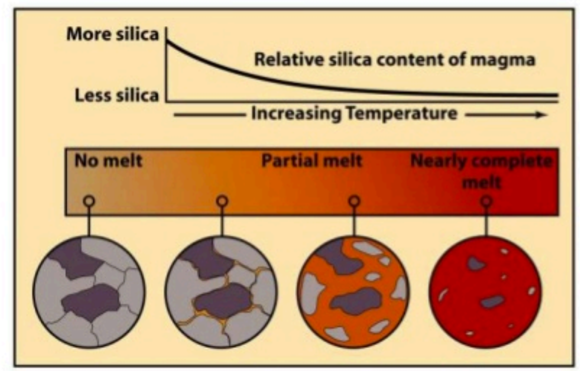
- the *noble gases* (rare gases or inert gases) Ne, Ar, Kr, and Xe;
- the lanthanide series, or the *rare Earth elements (REE)*, as they are more normally known – elements 57 to 71 – La, Ce, Pr, Nd, (Pm), Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, and Lu;
- the *platinum group elements (PGE)*, Ru, Rh, Pd (elements 44–46), Os, Ir, and Pt (elements 76–78) and sometimes including Au (79);
- the *transition metals*, that is, the first transition series, Sc to Zn, elements 21 to 30.

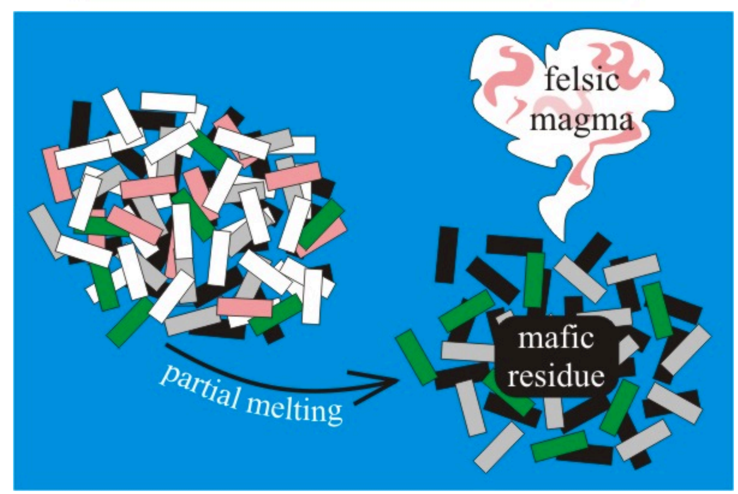
A geochemical classification of trace elements according to their behavior during partial melting

During partial melting trace element behavior is governed by the preference of a particular element for its host (a mineral phase) or the melt phase. Elements which tend to become part of the melt are known as *incompatible elements*, and those which prefer to remain in the mineral phase are known as *compatible elements*. In detail this is governed by relationships between the particular element and the structure of the relevant mineral phase. The degree of incompatibility of a specific element in a particular mineral phase is expressed as the mineral–melt partition coefficient. Incompatible elements have mineral–melt partition coefficients < 1.0 and highly incompatible elements have partition coefficients $\ll 1.0$, whereas compatible elements have partition coefficients of > 1.0.

Partial Melting

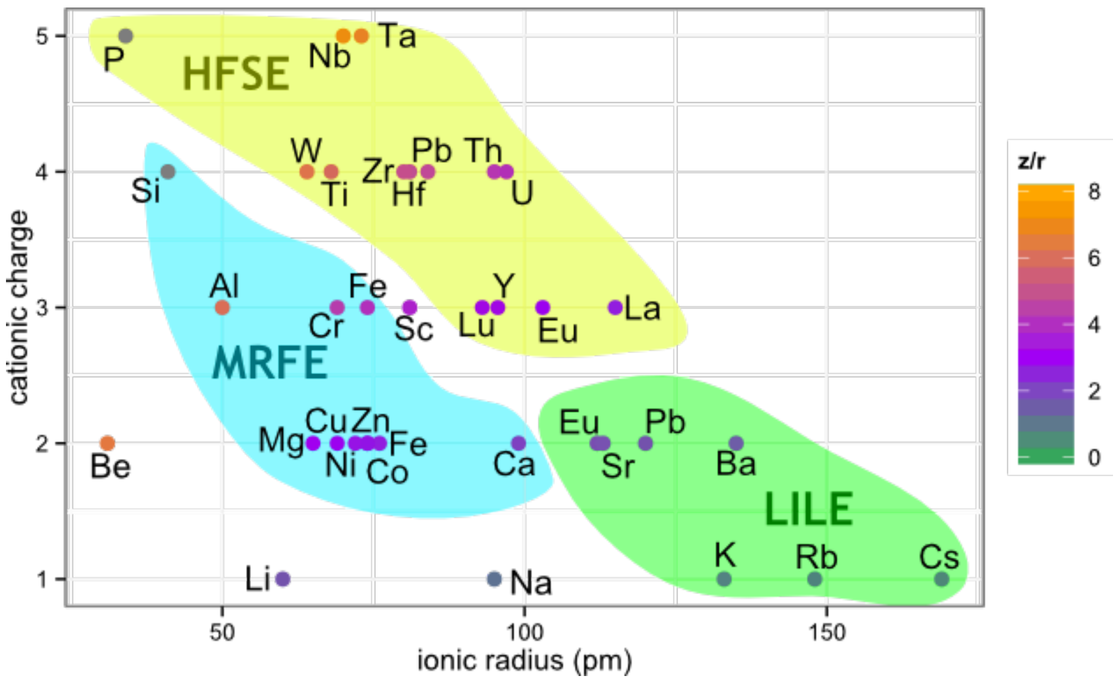
- Upon heating, silica-rich minerals melt first.
- Thus, partial melting yields a silica-rich magma
- Removing a partial melt from its source creates:
- -felsic magma
- -mafic residue left behind





A geochemical classification of trace elements according to their ionic charge and size ratio

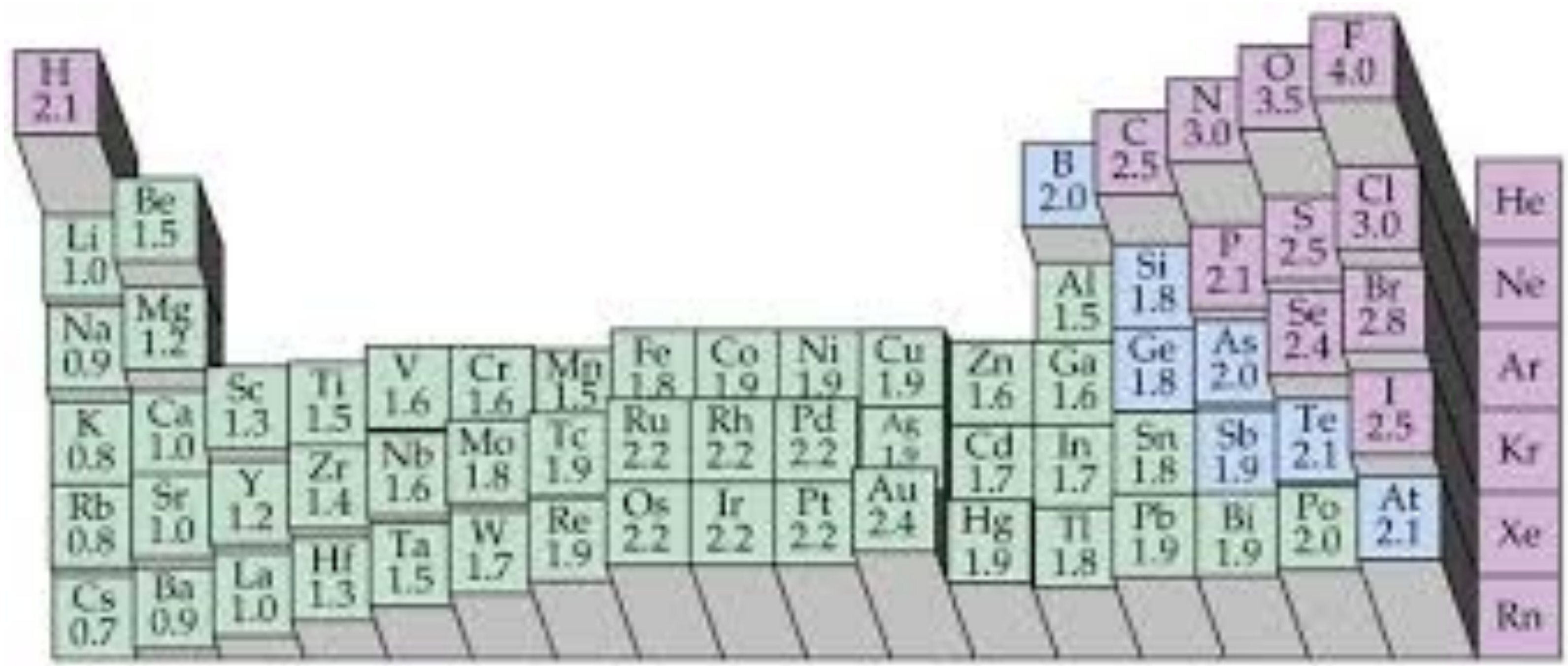
Small, highly charged ions behave differently from large ions with a low charge during geochemical processes. Small highly charged ions include metals such as Ti, Hf, Nb, and Zr and are known as the *high field strength elements (HFSE)*. These are elements which tend to be immobile when hydrous fluids react with a rock. Examples of larger ions carrying a low charge are Ba, Sr, and K. These are known as the large ion lithophile elements (LILE) or *low field strength elements*. These elements tend to be mobile in hydrous fluids.



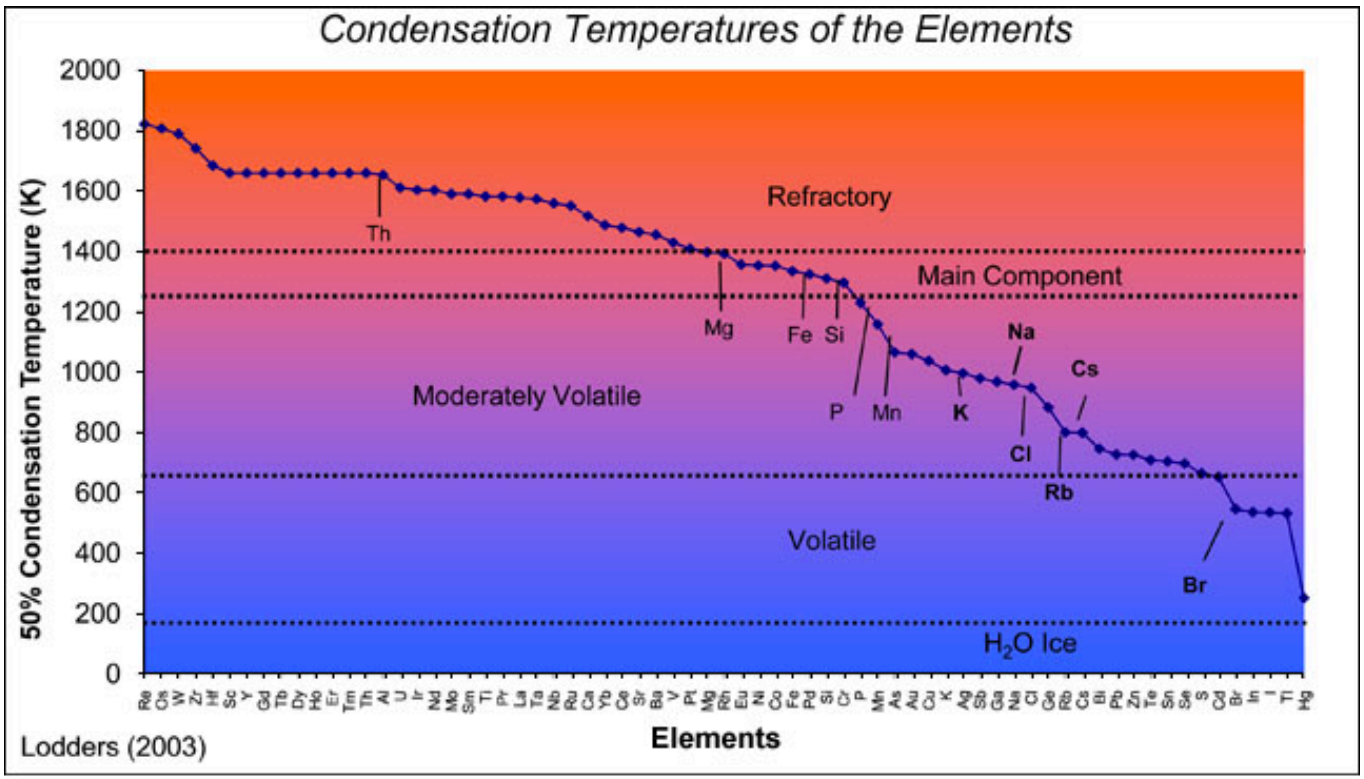
MRFE = mantle rock forming elements)

A geochemical classification of the elements based upon their electronegativities

Lithophile elements are those which have a preference for a silicate host, whereas chalcophile elements have an affinity for sulfur and so will most frequently be found in sulfides. Siderophile elements are those which will partition preferentially into a metallic iron phase and so are enriched in the Earth's core and in iron meteorites. Atmophile elements prefer the gaseous phases of the Earth atmosphere.



A cosmochemical classification of the elements based upon the solar condensation sequence
During the condensation of a solar nebula different mineral phases condense as the nebular temperature decreases. It is an understanding of this process which has led to an appreciation of the mineralogy of meteorites. Phases which condense at high temperatures (1850–1400 K) are known as *refractory*, whereas phases which cool at lower temperatures are know as *volatile*. Highly volatile phases condense below 640 K (see Section 2.3.2.1).



(PSRD graphic based on calculations done by Katarina Lodders, Washington University in St. Louis.)

A cosmochemical and geochemical classification of the elements based upon their Lithophile/siderophile/chalcophile affinities and their refractory or volatile character (after Palme and O'Neill, 2003).

	Lithophile (silicate)	Siderophile and chalcophile (metal and sulfide)
Refractory *(T_c 1,850–1,400 K)*	Al, Ca, Ti, Be, Ba, Sc, V, Sr, Y, Zr, Nb, Ba, REE, Hf, Ta, Th, U, Pu	Mo, Ru, W, Re, Os, Ir, Pt
Main component *(T_c 1,350–1,250 K)*	Mg, Si, Cr, Li	Fe, Ni, Co, Pd
Moderately volatile *(T_c 1,230–640 K)*	Mn, P, Na, B, Rb, K, F, Zn	Au, As, Cu, Ag, Ga, Sb, Ge, Sn, Se, Te, S
Highly volatile *(T_c < 640 K)*	Cl, Br, I, Cs, Tl, H, C, N, O, He, Ne, Ar, Kr, Xe	In, Bi, Pb, Hg

Condensation temperature T_c is at a pressure of 10^{-4} bars.

A rather different approach to understanding the condensation of the solar nebula came from the work of the geochemist **V.M. Goldschmidt** carried out in the **1920s**. Goldschmidt proposed, what has now become, a widely used geochemical classification of the elements. This work was in part based upon the study of meteorites, and so his classification is very relevant to the understanding of planetary processes. Chemical elements display different chemical affinities, explained largely by their differing electronegativities, and may be classified into **lithophile elements** – those with an affinity for silicates and oxygen, **chalcophile elements** – those with an affinity for sulfur, **siderophile elements** – those with an affinity for metallic iron, and **atmophile elements** – those with an affinity for the gaseous atmosphere. Initially Goldschmidt's classification of the elements was helpful in understanding two rather different subjects – the differences between the major meteorite groups and the differentiation of the Earth.

However, Goldschmidt's scheme only relates to the condensation of major elements into mineral phases.

Goldschmidt's Classification