Chemical composition of the Earth — what is it made of?

We have seen that the Earth has a mean density, corrected for the effects of compression

$$\bar{\rho}_{\oplus} \text{ decompressed} = 4300 \text{ kg/m}^3$$

and a moment of inertia $C/Ma^2 = 0.33$

Similar methods, esp. Kepler's third law, can be used to determine the masses and moments of inertia of other bodies in the solar system

Table 3-3. Characteristics of the planets:*

Planet Name	Radius 10^8 cm	Volume 10^{26} cm^3	Mass 10^{27} gm	Density gm/cm^3	Corrected density† gm/cm^3	
Mercury	2.44	0.61	0.33	5.42	5.4	terrestrial
Venus	6.05	9.3	4.9	5.25	4.3	terrestrial
Earth	6.38	10.9	6.0	5.52	4.3	terrestrial
Mars	3.40	1.6	0.64	3.94	3.7	terrestrial
Jupiter	71.90	15,560	1900	1.31	<1.3	gas giants
Saturn	60.20	9130	570	0.69	<0.7	gas giants
Uranus	25.40	690	88	1.31	<1.3	gas giants
Neptune	24.75	635	103	1.67	<1.7	gas giants
Pluto	1.6	0.17	?	?	?	

*The mass of the Sun is 1.99×10^{33}gm, 1000 times the mass of Jupiter.
†Density a planet would have in the absence of gravitational squeezing.

TABLE 1.1

Physical Characteristics of the Planets and Their Major Satellites

Planetary Body	Semi-Major Axis (AU for Planets, 10^3km for Satellites)	Orbital Period (Days or Years (y))	Rotation Period (Days)	Density (g/cm^3)	Diameter (km)	Surface Composition	Atmosphere Composition
Mercury	0.387	87.97	58.65	5.44	4,800	basaltic	Na (thin)
Venus	0.723	224.7	243.0 R	5.25	12,104	basaltic	CO_2
Earth	1.000	365.26	1.00	5.52	12,756	basaltic & H_2O	$N_2 + O_2$
Moon	384	27.3	27.3	3.34	3,476	basaltic	None
Mars	1.524	686.98	1.03	3.93	6,787	basaltic	CO_2
Largest Asteroids							
Vesta	2.362	3.63 y	0.22	2.9	520	basaltic	None
Ceres	2.768	4.61 y	0.38	?	932	DCS	None
Pallas	2.773	4.62 y	0.33	?	533	D S	None
Jupiter	5.203	11.86 y	0.41	1.3	143,800		H_2 and He
Io	422	1.77	1.77	3.50	3,640	S compounds	SO_2 (thin)
Europa	671	3.55	3.55	3.03	3,130	water ice	None
Ganymede	1071	7.15	7.15	1.93	5,280	water ice D	None
Callisto	1884	16.69	16.69	1.79	4,840	water ice D	None
Saturn	9.54	29.46 y	0.43	0.69	120,660		H_2 and He
Mimas	186	0.94	0.94	1.12	392	water ice	None
Enceladus	238	1.37	1.37	1.00	500	water ice	None
Tethys	295	1.89	1.89	1.00	1,060	water ice	None
Dione	377	2.74	2.74	1.49	1,120	water ice	None
Rhea	527	4.52	4.52	1.24	1,530	water ice	None
Titan	1222	15.94	15.9	1.88	5,150	water ice C	N_2
Hyperion	1484	21.3	?	?	250	water ice	None
Iapetus	3562	79.33	79.33	1.03	1,436	H_2O ice DCS	None
Phoebe	12930	550.4 R	0.4	?	220	H_2O ice DC?	None
Uranus	19.18	84.01 y	0.72	1.28	51,120		H_2 and He
Miranda	130	1.41	1.41	1.35	470	water ice	None
Ariel	191	2.52	2.52	1.66	1,150	water ice	None
Umbriel	266	4.14	4.14	1.51	1,170	water ice	None
Titania	438	8.70	8.70	1.68	1,580	water ice	None
Oberon	586	13.46	13.46	1.58	1,520	water ice	None
Neptune	30.07	164.79 y	0.73	1.64	49,560		H_2 and He
Triton	355	5.88 R	5.88	2.01	2,700	N_2 and CH_4 ice	N_2, CH_4
Proteus	118	1.12	1.12	?	400	D H_2O ice	None
Nereid	5562	359.9	?	?	340	D H_2O ice	None
Pluto	39.44	247.7	6.4	2.06	2,284	nitrogen ice	N_2
Charon	17	6.39	6.4	2.06	1,192	H_2O ice	None

D = dark materials; silicates, carbonaceous, or methane
C = carbonaceous materials
S = silicates
R = retrograde orbit

$\bar{\rho}_{\oplus} = 4300$ kg/m^3 significantly greater than the densities of common rocks found in the Earth's crust

Igneous rocks

- granitic
- andesitic
- mafic (basaltic) — comprise entire oceanic crust
- ultramafic — rare samples of upper mantle

Sedimentary rocks

clastic:
- shale (mudrock) — by far most common
- sandstone
- conglomerate

- chemical — limestone, chert, evaporite

Metamorphic rocks

- metaigneous
- metasediments

Densities: $\rho_{\text{crustal rocks}} = 2500 - 3400$ kg/m^3

What determines the density of a material anyway?

To a large extent, the weight of the atoms it is made up of.

Table 3-4. The relationship between the density of a substance and the average number of nuclear particles in its constituent atoms:

Substance	Formula	Nuclear particles Atom	Density gm/cm^3	Ratio*
Water	H_2O	6.0	1.00	6.0
Calcite	$CaCO_3$	20.0	2.72	7.4
Quartz	SiO_2	20.0	2.65	7.5
Gypsum	$CaSO_4 2H_2O$	14.3	2.32	6.2
Olivine	Mg_2SiO_4	18.3	3.20	5.7
Hematite	Fe_2O_3	32.0	5.26	6.1
Magnetite	Fe_3O_4	33.1	5.18	6.4
Diamond	C	12.0	3.50	3.4
Iron	Fe	56	7.50	7.5
Gold	Au	197	17.10	11.6

*Nuclear particles per atom divided by density. Were the relationship between the average number of nuclear particles per atom and density perfect, this ratio would be exactly the same for all ten compounds. For 8 of the 10 compounds the range is small (5.7 to 7.5). For gold and for diamond the deviation from the mean for the other 8 is sizable (a factor of about 2).

For this reason $\bar{\rho}_{\oplus} = 4300$ kg/m^3 has something to tell us about the $\oplus$'s chemistry

Meteorites – provide our best clue to the bulk chemical composition of the primitive Earth before it differentiated to form an iron core and crustal rocks with densities $\rho \simeq 2500 - 3400$ kg/m^3

TABLE 3.2
Major Meteorite Types

Type	Abundance (percent)	Composition
Stony Meteorites	94	
Chondrites	86	
Ordinary	82	Metamorphosed chondrites
Carbonaceous	4	Carbon- and volatile-rich, undifferentiated
Achondrites	8	Igneous textures, differentiated
Stony-Iron Meteorites	1	Silicate-metal mixtures, differentiated
Iron Meteorites	5	Iron metal, differentiated

Abundances are percentages of each type of meteorite among all meteorites seen to fall on Earth.

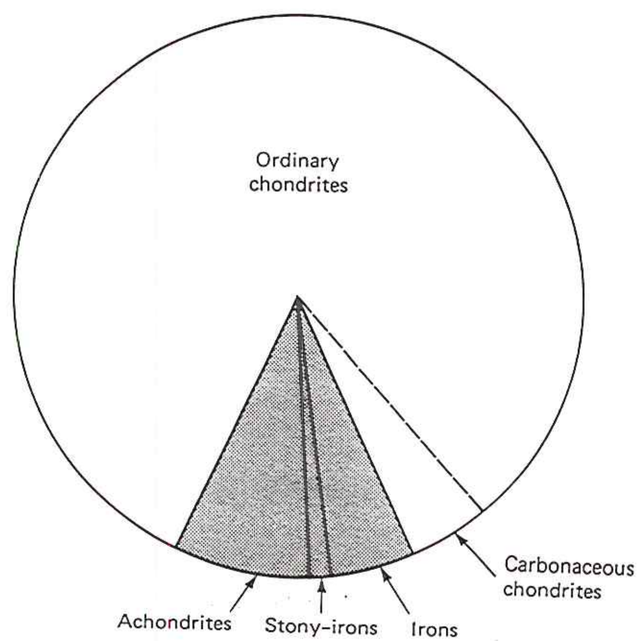


FIG. 5-2 Proportions of major types among meteorites observed to fall to Earth (falls). The enstatite chondrite subtype is included with "ordinary chondrites."

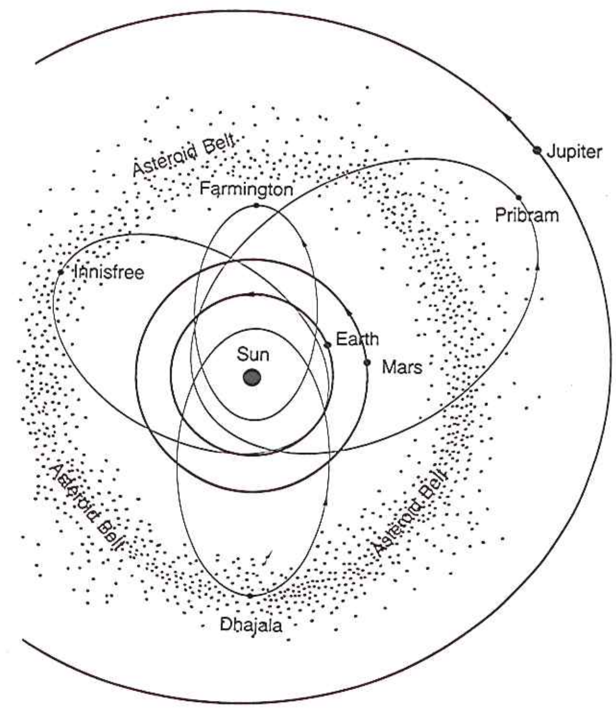
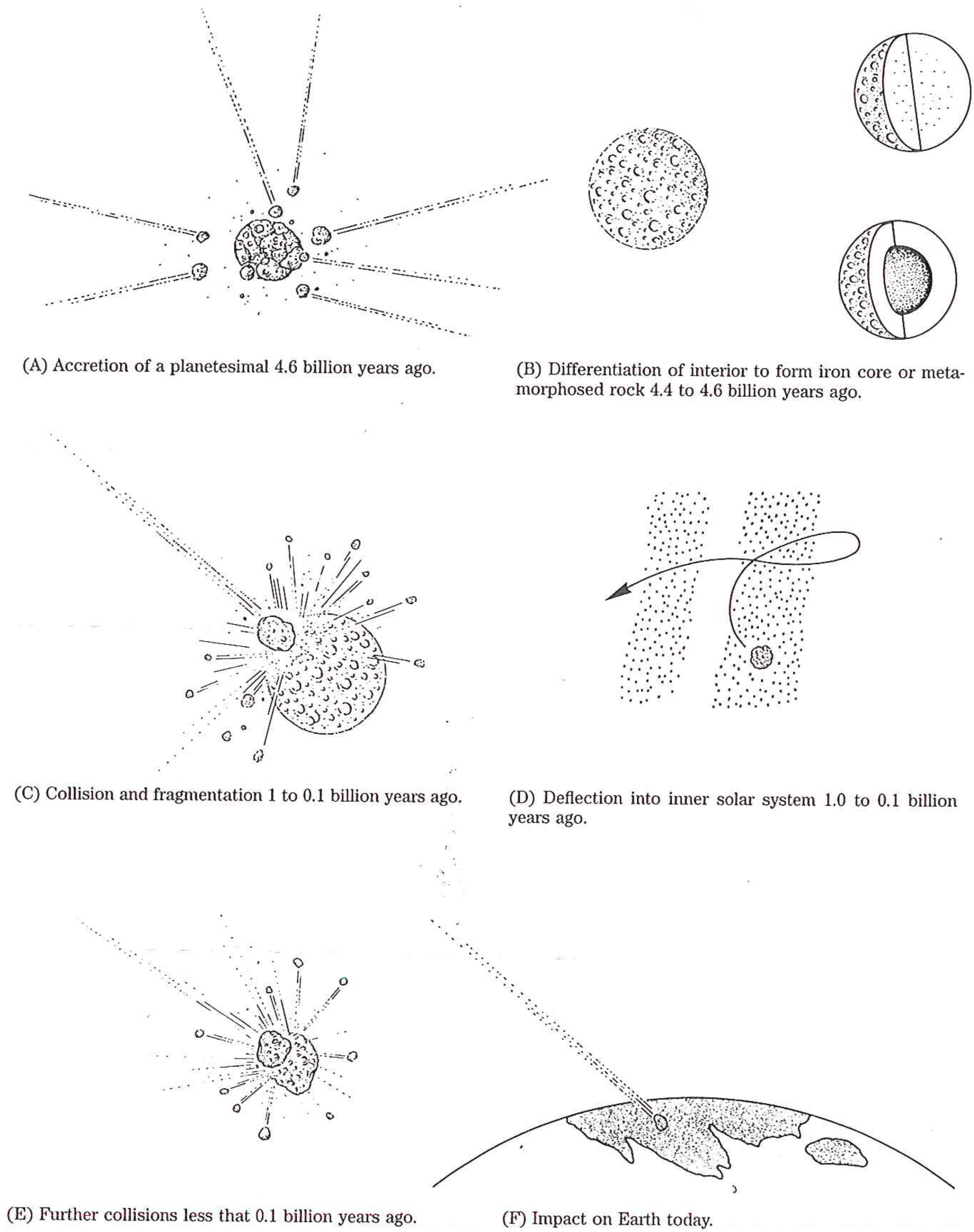


Figure 3.6

Most asteroids have circular orbits that take them between the orbits of Mars and Jupiter in an area known as the asteroid belt. Many other asteroids orbit outside of the main belt—some across Earth's orbit. Asteroids were probably the source of the bodies that impacted Earth and other planets during their early histories.



(A) Accretion of a planetesimal 4.6 billion years ago.

(B) Differentiation of interior to form iron core or metamorphosed rock 4.4 to 4.6 billion years ago.

(C) Collision and fragmentation 1 to 0.1 billion years ago.

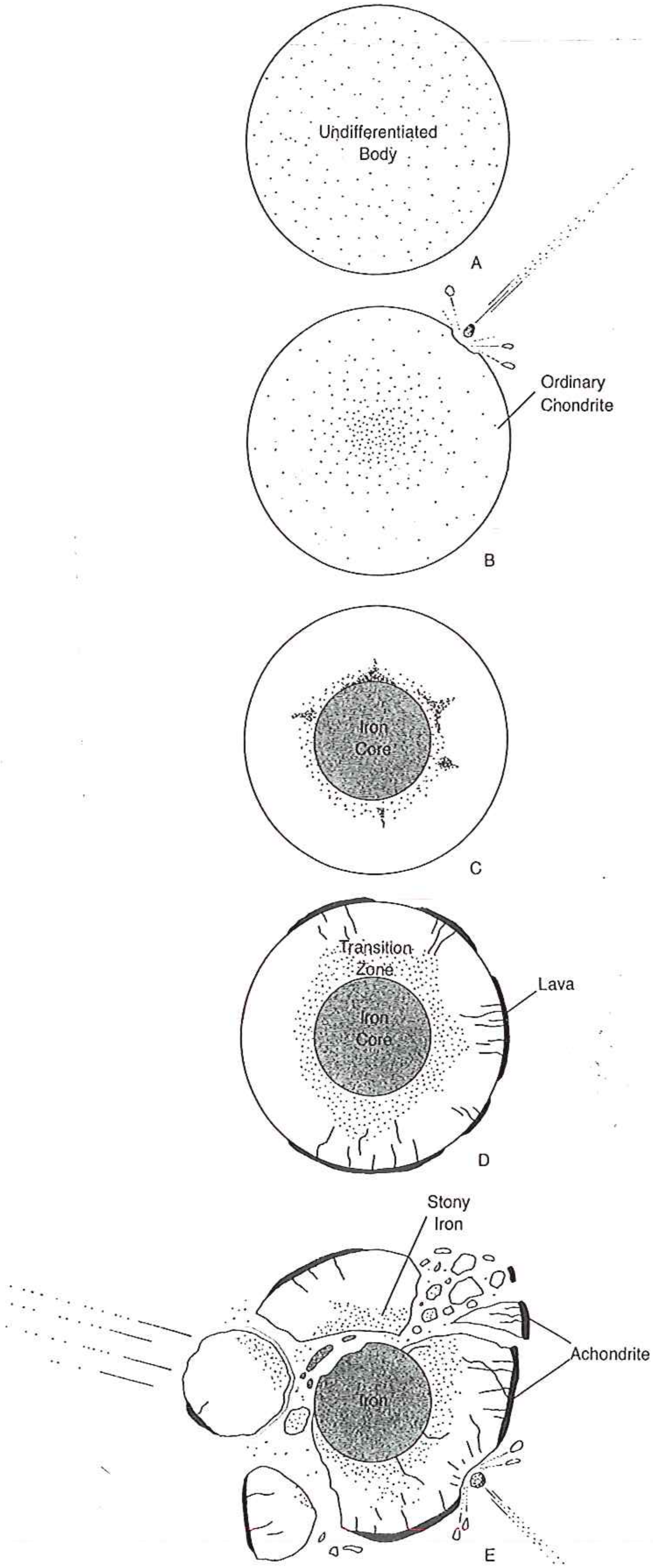
(D) Deflection into inner solar system 1.0 to 0.1 billion years ago.

(E) Further collisions less that 0.1 billion years ago.

(F) Impact on Earth today.

Figure 3.15

The evolution of asteroids as meteorite parent bodies is summarized in this diagram. The events that led to the delivery of fragments of the asteroids to Earth and other inner planets are emphasized.



(A) An original body of primitive composition (carbonaceous, outer belt; ordinary, inner belt) forms by accretion.

(B) This small planetesimal is heated by short-lived radioactivity to the point of mild metamorphism, driving off some volatiles.

(C) Or perhaps it is heated to the melting point of metallic iron. Dense segregations of iron drains toward the center of the body to form a core or several smaller accumulations of metal.

(D) If heating is intense enough, the silicates in the chondritic interior may melt to produce magma, which erupts at the surface to produce a thin veneer of lava and associated intrusive rocks. Eventually, the asteroid cools as heat is radiated away into space; the core and mantle become solid. Depending on (among other factors) size, composition, and distance from the Sun, for a specific asteroid this differentiation process may have ended at any point of the evolutionary scheme.

(E) Fragmentation of such differentiated or undifferentiated bodies could then produce the spectrum of observed asteroid and meteorite types. In fact, a variety of types could come from one body, as illustrated in (E). Most asteroids were not heated beyond the first or second step and only a very few have exposed metallic cores stripped of their silicate cloaks.

Figure 3.14

Stages in the evolution of a meteorite parent body.

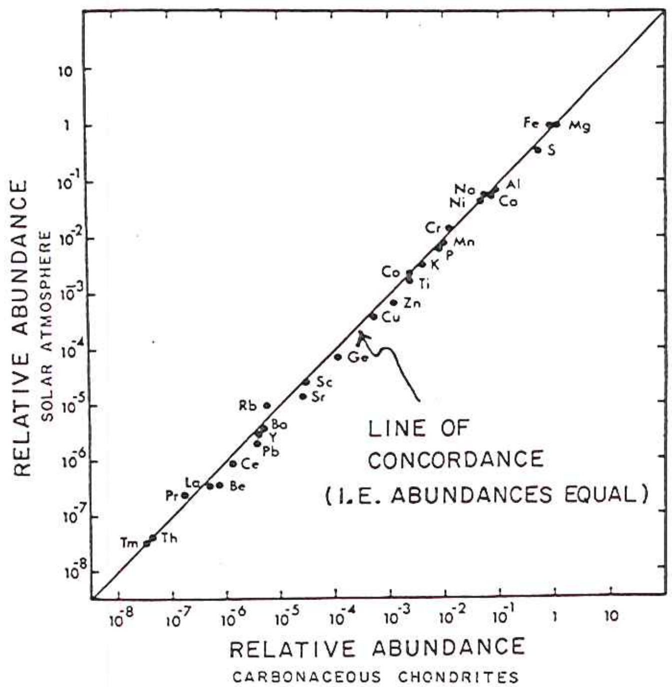


Figure 3-2. Comparison of the relative abundances of elements of low and moderate volatility in the Sun's atmosphere with those in carbonaceous chondrites: Clearly for these elements, carbonaceous chondrites provide a chemically unbiased sample of bulk solar system matter. Because the element silicon is the reference for comparison, it does not appear in the diagram.

Table 3-5. Abundances of metallic elements in chondritic meteorites:

	Percent of total metal atoms
Magnesium (Mg)	32
Silicon (Si)	33
Iron (Fe)	26
Aluminum (Al)	2.2
Calcium (Ca)	2.2
Nickel (Ni)	1.6
Sodium (Na)	1.3
Chromium (Cr)	0.40
Potassium (K)	0.25
Manganese (Mn)	0.20
Phosphorus (P)	0.19
Titanium (Ti)	0.12
Cobalt (Co)	0.10

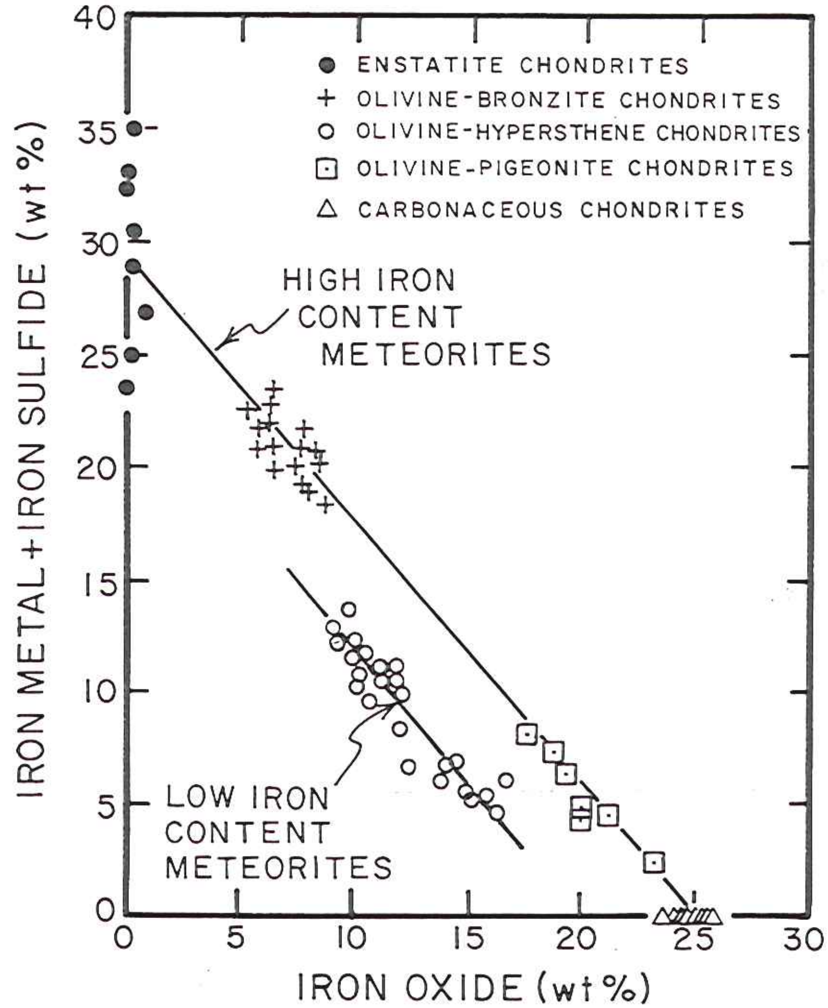


Figure 3-3. Gradations in chemical form of iron in chondrites: The range extends from all oxide in carbonaceous chondrites to all metal (or sulfide) in olivine-hypersthene chondrites. Except for enstatite chondrites, which are depleted in iron, the total iron content remains nearly the same.

Recipe for the Earth

- mix together 4 major elements in ratio
  Fe : Mg : Si : O ≈ 1 : 1 : 1 : 20
- add traces of additional 88 elements for seasoning
- heat to drive off oxygen and form iron core — resulting bulk composition Fe : Mg : Si : O = 1 : 1 : 1 : 3½

Two-layer model of ⊕ :

molten iron core : $\rho_{Fe} = 8000 \frac{kg}{m^3}$

silicate perovskite mantle:
$\rho_{Si} = 3500\ kg/m^3$

$X_{Fe} = \frac{V_{Fe}}{V_\oplus}$, $X_{Si} = \frac{V_{Si}}{V_\oplus}$ volume fractions

$$\boxed{X_{Fe} + X_{Si} = 1}$$

$$\bar{\rho}_\oplus = \rho_{Fe} X_{Fe} + \rho_{Si} X_{Si}$$
$$= \rho_{Fe} X_{Fe} + \rho_{Si} (1 - X_{Fe})$$

$$\boxed{X_{Fe} = \frac{\bar{\rho}_\oplus - \rho_{Si}}{\rho_{Fe} - \rho_{Si}} = \frac{4300-3500}{8000-3500} = 17\%}$$

$$\boxed{\text{Core radius } R_{core} = \sqrt[3]{0.17} \times 6371 = 3500\ km}$$

↙ seismology shows that $R_{core} = 3480$ km

TABLE 2-1

Short Table of Cosmic Abundances (Atoms/Si)

Element	Cameron (1982)	Anders and Ebihara (1982)
O	18.4	20.1
Na	0.06	0.057
Mg	1.06	1.07
Al	0.085	0.0849
Si	1.00	1.00
K	0.0035	0.00377
Ca	0.0625	0.0611
Ti	0.0024	0.0024
Fe	0.90	0.90
Ni	0.0478	0.0493

Table 5-3. Chemical composition (in percent by weight) of the two most important rock types in the Earth's crust compared to the composition of Earth's mantle and to the composition of chondritic meteorites.

	Chondritic meteorites	Earth's mantle	Basalt	Granite
O	32.3	43.5	44.5	46.9
Fe	28.8	6.5	9.6	2.9
Si	16.3	21.1	23.6	32.2
Mg	12.3	22.5	2.5	0.7
Al	1.4	1.9	7.9	7.7
Ca	1.3	2.2	7.2	1.9
Na	0.6	0.5	1.9	2.9
K	0.1	0.02	0.1	3.2
Other	5.9	1.7	2.7	1.6

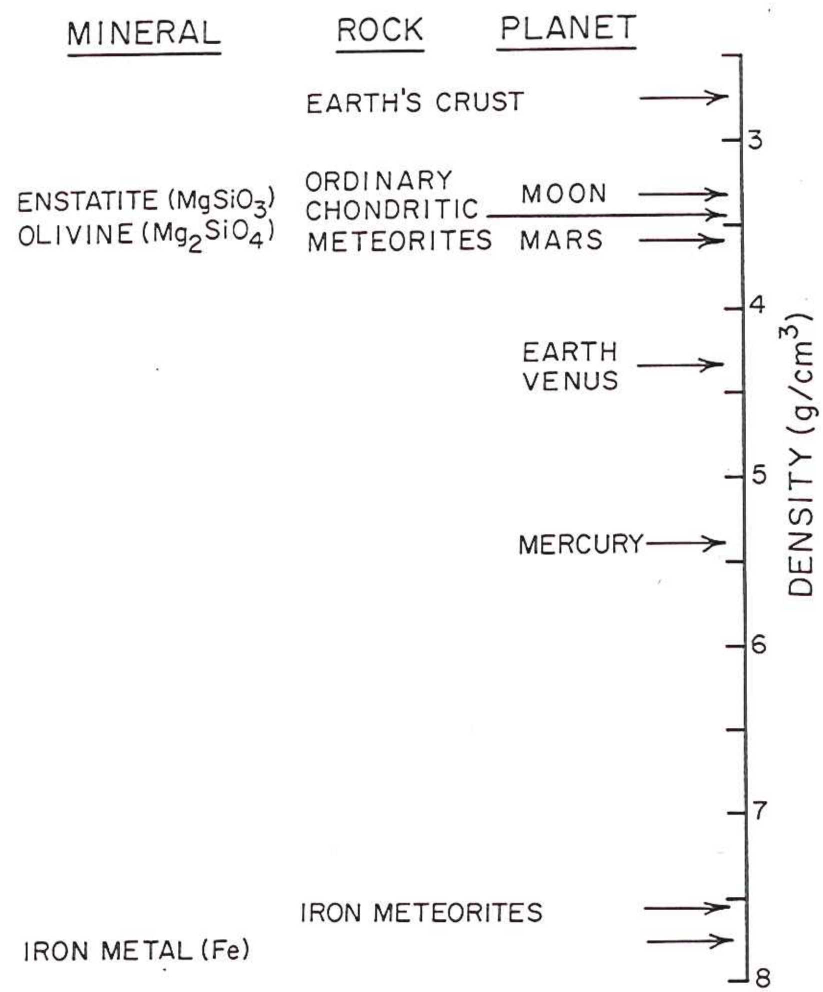


Figure 3-5. Bulk densities of various minerals, rocks, and planets: In the case of the planets, the densities shown have been corrected for gravitational compaction. The planet-to-planet density differences are in part the result of differences in the Fe/Mg+Si ratio and in part the result of differences in the iron/iron oxide ratio.

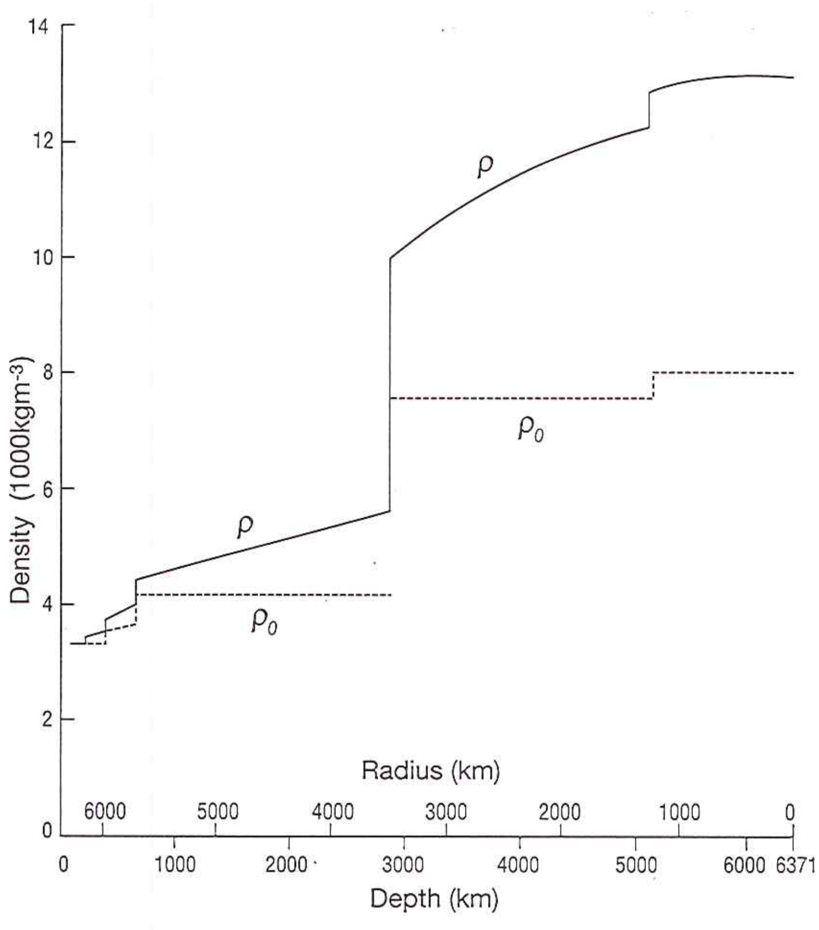


Figure 5.19(a). Profile of density, ρ, through the earth model PREM with corresponding zero pressure, low temperature density, estimated by finite strain theory.

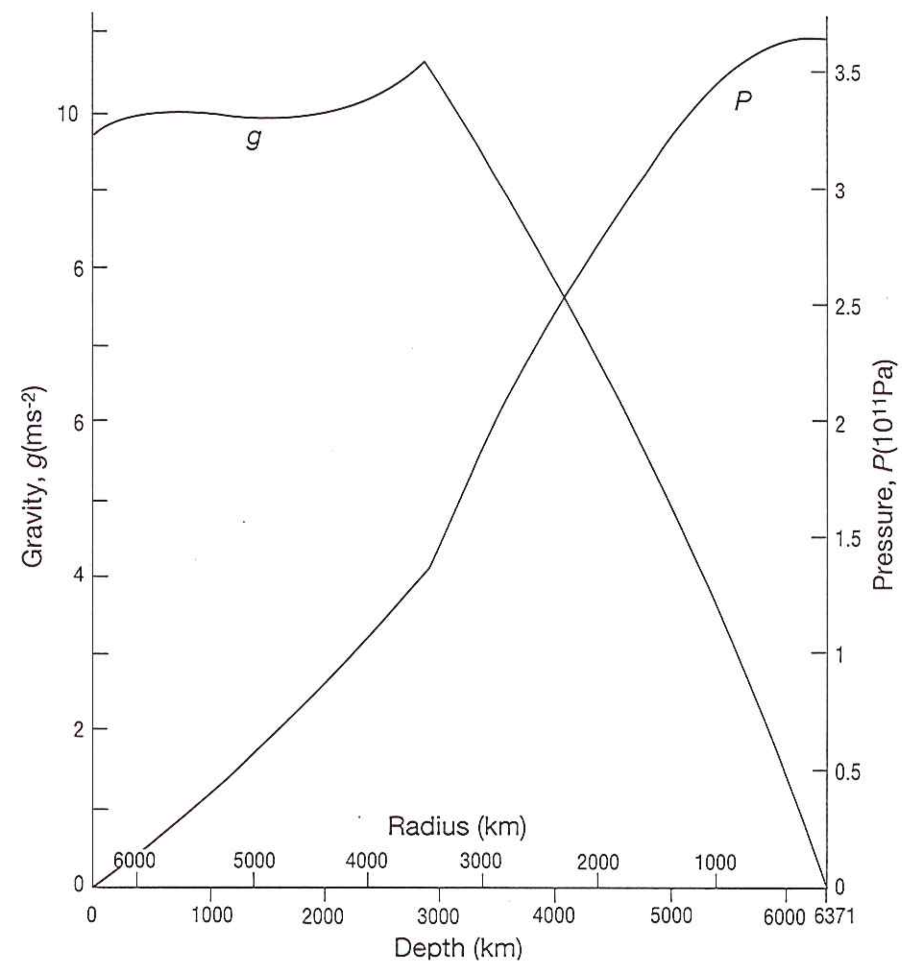


Figure 5.19(b). Profiles of gravity, g, and pressure, P, corresponding to the density profile in Fig. 5.19(a).