12.2.2 Scenario #2, a remanent field

If the magnetic field is a remanent field it loosens the constraint for a presently molten outer iron core. In this case, the core would be completely solid at present and its S content would be less than 0.2%. For a S content of 0.2%, the core takes almost the age of the Solar System (4.6 billion years) to solidify. With less it would solidify much faster, but it would still take well over a billion years to completely solidify because of its very large size. This small amount of S has implications for the origin of Mercury. The problem of the amount of radius decrease does not go away under this scenario. In fact it makes it worse. The amount of radius decrease would be at least 10 km which is not even close to the maximum estimate (2 km) based on the thrust faults. It is unlikely that there are significantly more thrust faults on the unexplored side than on the surface analyzed. Furthermore the onset of compressive stresses also occurs very early in Mercury's history. This alternative scenario produces a somewhat different history, but still presents difficulties with the geology.

12.2.3 No thermal model consistent with the geologic history

In short, there are distinct conflicts with thermal history models and the observed geology. These conflicts are surely due to our lack of data, and, therefore, lack of understanding of both the geological and geophysical processes on Mercury. Future spacecraft exploration of Mercury will hopefully supply the data to resolve these vexing conflicts.

12.3 ORIGIN OF PRESENT DAY MERCURY

Mercury's iron core is much larger in proportion to its rocky mantle than any other planet or satellite in the solar system. The primary problem concerning the origin of Mercury is how it acquired such a large iron core. We are fairly confident that the planets accreted from a solar nebula of gas and dust during the final stages of the Sun's formation. The large compositional difference between the outer jovian planets and the inner terrestrial planets was probably caused by a temperature gradient in this nebula. The inner part of the nebula was at high temperatures where *refractory material* predominated out to about ~4 AU, while the outer part beyond about ~4 AU was at low temperatures where volatile condensates such as ices would predominate. Thus, the outer planets are large bodies consisting predominately of H and He with their satellites mostly consisting of a mixture of rocks with water and other ices. The inner planets are dominated by silicate mantles and crusts, and iron cores. The problem with Mercury is that its iron core is much larger than predicted by solar nebula *chemical equilibrium* condensation models.

12.3.1 Chemical equilibrium models

12.3.1.1 Early condensation models

Early chemical equilibrium condensation models that assumed Mercury formed entirely at its present distance from the Sun could not account for Mercury's large iron core. Furthermore, the models predicted almost the complete absence of S (100 parts per trillion of FeS). Other volatile elements and compounds, such as water, are also severely depleted (<1 part per billion of H). The absence of S is a severe problem if Mercury still contains an outer molten iron core.

12.3.1.2 Turbulence broadened the possibilities

More realistic models, where a significant part of Mercury is formed from material at more distant feeding zones, relax the S problem but still result in an uncompressed density of 4.3 g/cm^3 rather that the observed 5.3 g/cm^3. In other words, no chemical equilibrium condensation model seems to explain Mercury's enormous iron core.

12.3.2 How did the core get so large?

Three hypotheses have been proposed to account for Mercury's large iron core and to explain the discrepancy between the predicted and observed Fe abundance. One hypothesis (selective accretion) involves an enrichment of Fe due to mechanical and dynamical accretion processes in the innermost part of the solar nebula. The other two (post-accretional vaporization and giant impact stripping) invoke removal of a large fraction of the silicate mantle from a once larger proto-Mercury.

12.3.2.1 Differential sorting of iron and silicates

In the selective accretion model, the differential response of Fe and silicates to impact fragmentation and aerodynamic sorting leads to Fe enrichment owing to the higher gas density and the shorter dynamical time scales in the innermost part of the solar nebula. The removal process for silicates from Mercury's present position is more effective than that for Fe, leading to Fe enrichment. Selective accretion requires that Mercury accrete at about its present distance from the Sun in order for these dynamical processes to operate. In this model of the inner solar nebula must have lower temperatures than the equilibrium condensation model mentioned above.

12.3.2.2 Post-accretion vaporization

The post-accretion vaporization hypothesis proposes that intense bombardment by solar electromagnetic and corpuscular radiation in the earliest phases of the Sun's evolution (T-tauri phase) vaporized and drove off much of the silicate fraction of Mercury, leaving the core intact. The lost mantle and retention of the original core results in the large iron/silicate ratio and Mercury's high density.

12.3.2.3 Giant impact stripping

In the giant impact hypothesis, a planet-sized object impacts Mercury and essentially blasts away much of the planet's rocky mantle, leaving a core about the size of the original. This model is essentially the same as the impact model for the formation of the Earth, but in this case the impact is more direct and does not result in a satellite.

12.3.3 Which hypothesis is correct?

Discriminating between these models may be possible from knowledge of the chemical composition of the rocky silicate fraction. John Lewis estimates that for the selective accretion model, Mercury's silicate portion should contain about 3.6 to 4.5% alumina (Al), about 1% alkali oxides (Sodium (Na) and potassium (K)), and between 0.5 and 6% FeO. Post-accretion vaporization should lead to very severe depletion of alkali oxides (~0%) and FeO (0.1%) and extreme enrichment of refractory oxides (~40%). If a giant impact stripped away the crust and upper mantle late in accretion, then alkali oxides may be depleted (0.01 to 0.1%), with refractory oxides between about 0.1 to 1% and FeO between 0.5 and 6%. Unfortunately, our current knowledge of Mercury's silicate composition is extremely poor, but near- and mid-infrared (IR) spectroscopic measurements favor low FeO (~3%) and alkali-bearing feldspars or basalts with similar SiO_2 content. If the exosphere of Na and K is being outgassed from the crust, as seems possible from recent observations, than the post-accretional vaporization model may be unlikely. If FeO abundances are about 3 percent they are too high for this model. Deciding between the other models is not possible with our current state of knowledge about the crustal composition. Since selective accretion requires Mercury to have formed near its present position, then S should be nearly absent unless the solar nebula temperatures in this region were considerably lower than predicted by the chemical equilibrium condensation model. If there were lower temperatures then more FeO would also be supplied. If Mercury's magnetic field is a remanant field and the core is completely solidified, then the required very low core S abundance would be consistent with that model (Figure 12.2).

12.4 CLASHING PLANETS

Support for the giant impact hypothesis comes from three-dimensional computer simulations of terrestrial planet formation for several starting conditions. Since these simulations are by nature stochastic, a range of outcomes are possible (Figures 12.3, and 12.4).

They all suggest that significant fractions of the terrestrial planets may have accreted from material formed in widely separated parts of the inner Solar System. The simulations also suggest that Mercury may have experienced large excursions in its semi-major axis during its accretion. Proto-Mercury may have ranged over distances of 0.4 to 1.4 AU owing to energetic impacts during accretion (Figure 12.5). Consequently, Mercury could have accumulated material originally formed over the entire terrestrial planet range of heliocentric distances. About half of Mercury's mass could have accumulated from material originally formed at distances between about 0.8 and 1.2 AU (Figure 12.6). If so, then Mercury may have acquired a significant amount of S and other semi-volatiles like Na and K from material formed in regions of the solar nebula where S is stable. Plausible models estimate from 0.1 to 3% FeS abundance. However, the most extreme models of accretional mixing result in homogenizing the entire terrestrial planet region, contrary to the observed large systematic density differences.

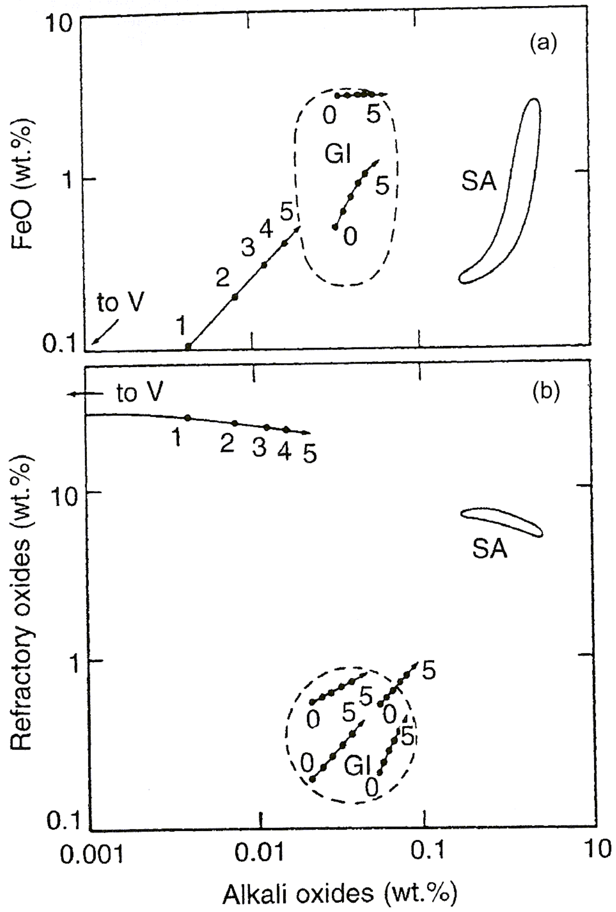

Figure 12.2. This diagram shows the possible bulk composition of the silicate mantle for the three models of Mercury's origin based on an analysis by John Lewis: selective accretion (SA), post-accretion vaporization (V), and giant impact (GI). The composition is parameterized for the FeO content, the alkali content (soda plus potash), and the refractory oxide content (Ca plus Al plus Ti oxides). The modifying effects of late infall of 0 to 5% meteorite material on several regolith compositions are indicated by arrows labeled 0 to 5 (from Lewis, 1988).

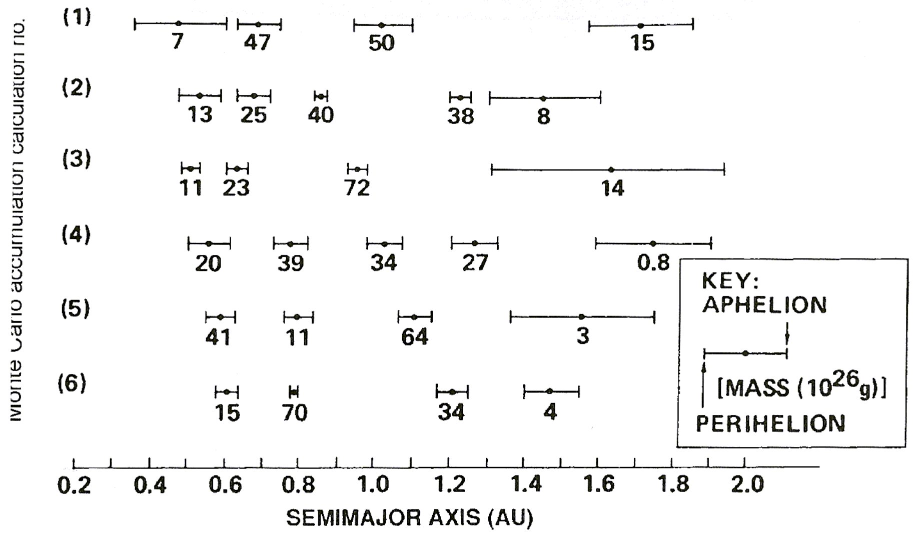

Figure 12.3. This shows the final outcome of six Monte Carlo accumulation calculations using five hundred 2×10^{25} g bodies. The semimajor axes of the final planets are indicated by points; the line through each point extends from the perihelion to the aphelion distances of the planet. The number under each point indicates the final masses of the bodies in units of 10^{25} g (from Wetherill, 1988).

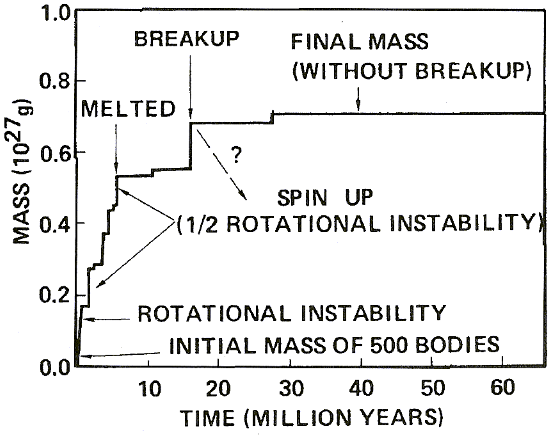

Figure 12.4. The growth on the innermost planet Mercury for case (1) in Figure 12.3 shows that the growth is punctuated by a number of giant impacts, one of which is energetic enough to cause major disruption of the planet (from Wetherill, 1988).

The computer simulations also indicate that the by-products of terrestrial planet formation are planet-sized objects up to three times the mass of Mars that become perturbed into eccentric orbits (mean $e \sim 0.15$ or larger). They eventually collide with the terrestrial planets during their final stages of growth. The final growth and giant

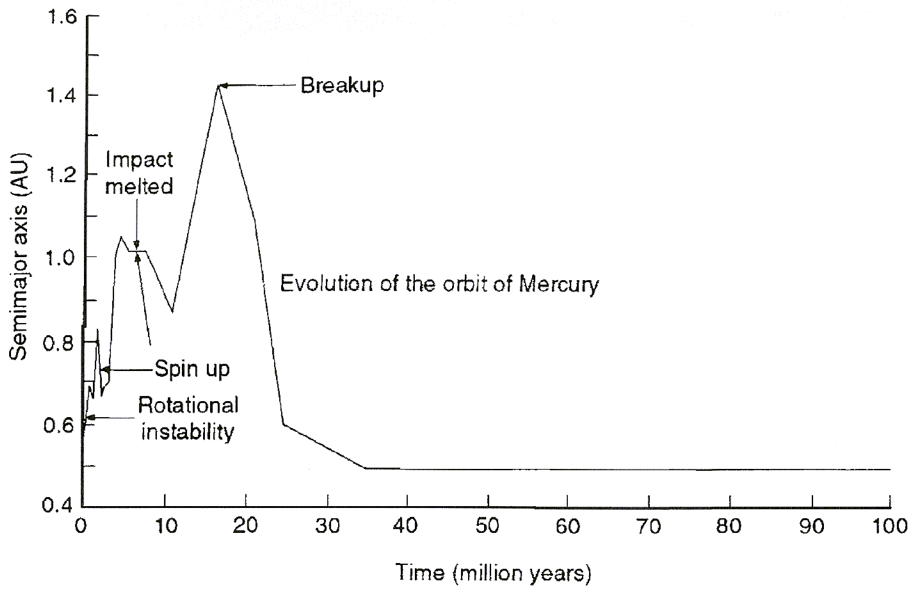

Figure 12.5. This shows the evolution of the semimajor axis of Mercury for case (1) in Figure 12.3. During the course of growth, the heliocentric distance of the body spans the entire terrestrial planet region (from Wetherill, 1988).

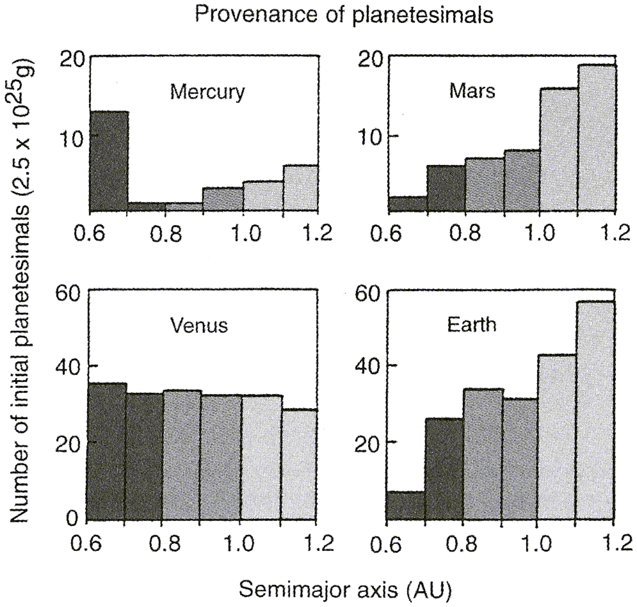

Figure 12.6. This diagram shows the source of the planetesimals as a function of semimajor axes that formed the final bodies for case (1) of Figure 12.3. A significant number of the planetesimals comes from feeding zones in the vicinity of Earth (from Wetherill, 1988).

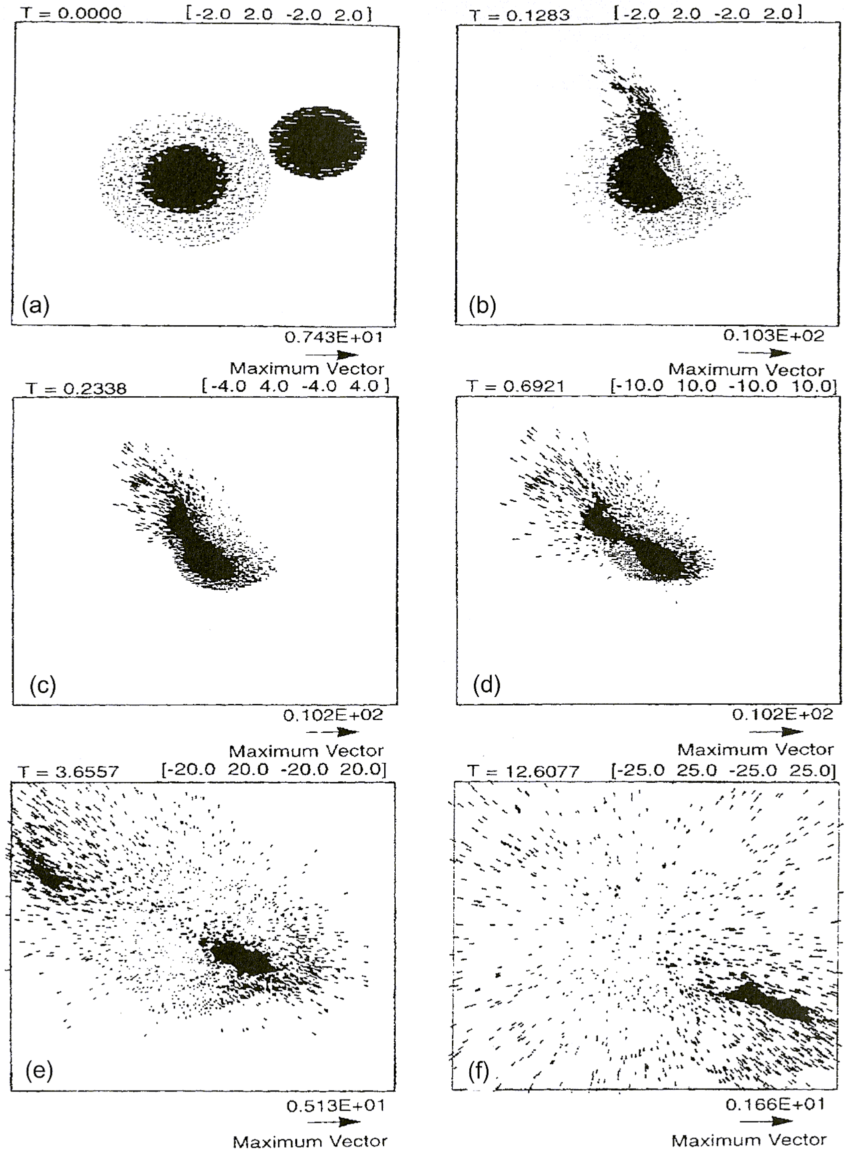

Figure 12.7. Computer simulation of a large off-axis impact with Mercury at 35 km/s by W. Benz. It shows that the mantle separates from the core. At least a portion of the mantle must re-accrete to form the present-day Mercury (from Benz, Slattery and Cameron, 1988).

impacts occur within the first 50 million years of Solar System history. Such large impacts may have resulted in certain unusual characteristics of the terrestrial planets, such as the slow retrograde rotation of Venus, the origin of the Moon, the Martian crustal dichotomy, and Mercury's large iron core.

In at least one computer simulation where proto-Mercury grew to 2.25 times its present mass with an uncompressed density of about 4 g/cm^3, nearly central collisions of large projectiles with iron cores impacting at 20 km/s, or non central collisions at 35 km/s, resulted in a large silicate loss and little Fe loss (Figure 12.7). In the former case, although a large portion of Mercury's iron core is lost, an equally large part of the impactor's iron core is retained, resulting in approximately the original core size. At Mercury's present distance from the Sun, the ejected material re-accretes back into Mercury if the fragment sizes of the ejected material are greater than a few centimeters. However, if the ejected material is in the vapor phase or fine-grained (<1 cm), then it will be drawn into the Sun by the *Poynting–Robertson effect* in a time shorter than the expected collision time with Mercury (about a million years). The proportion of fine-grained and large-grained material ejected from such a large impact is very uncertain. Therefore, it is not known if a large impact at Mercury's present distance would exclude enough mantle material to account for its large iron core. However, the disruption event need not have occurred at Mercury's present distance from the Sun (it could have occurred at a much greater distance, for example, >0.8 AU [see Figure 12.5]). In this case, the ejected mantle material would be mostly swept up by the larger terrestrial planets, particularly Earth and Venus.