Dynamic Planet

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Mercury in the Context of Its Environment

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This book is dedicated to my colleagues, whose unceasing efforts led to a resurgence of interest in the planet Mercury and eventually to reconsideration of return missions to Mercury despite the challenges. I would particularly like to recognize those who supported, encouraged, reviewed, and/or provided material to support our efforts, particularly, Susan McKenna Lawlor, who provided a great deal of initial input for the chapters on Mercury's atmosphere and magnetosphere, as well as Steven Curtis, Rosemary Killen, Martha Leake, Faith Vilas, Ann Sprague, Barbara Giles, Clark Chapman, Joe Nuth, Jim Slavin, Bob Strom, Pontus Brandt, Norman Ness, Drew Potter, Mark Robinson, Ron Lepping, and Bill Smyth. I would also like especially to thank the staff of the NASA Goddard Space Flight Center library and the Café 10 for providing supportive environments.

PREFACE

UNDERSTANDING THE PLANET MERCURY

Thirty years have elapsed since the one and only mission to Mercury, Mariner 10, performed three flybys of the planet, capturing moderate-resolution (100 m at best) images of one hemisphere (45% of the surface) and discovering that Mercury could be the only other terrestrial planet to have a global magnetic field and core dynamo analogous to the Earth's. At the time of this writing, the MESSENGER mission to Mercury has been launched. We are still a couple of years away from the first of the next flybys of Mercury, by MESSENGER, on its way to insertion into a nearly polar, but highly elliptical, orbit, seven years from launch. In the interim, a plethora of ground-based observations has been providing information on hitherto unseen aspects of Mercury's surface and exosphere. Furthermore, Mariner 10 data have been analyzed and reanalyzed as the technology for modeling and image processing has improved, leading to important breakthroughs in our understanding of Mercury and its environment.

Thus, we are writing this book with the realization that we are in a time of transition in our understanding of the planet Mercury. Of particular interest to us in this book is the emerging picture of Mercury as a very dynamic system, with interactions between interior, surface, exosphere, and magnetosphere that have influenced and constrained the evolution of each part of the system. Previous well-written books have compellingly emphasized the results of Mariner 10 and current ground-based measurements, with very little discussion of the nature and influence of the magnetosphere. This book will present the planet in the context of its surroundings, with major emphasis on each sphere, interior, surface, exosphere, and magnetosphere, and interactions between them.

Our organizational scheme for this book is as follows: Chapter 1 will provide an introduction to the solar system, planets, and their subsystems as dynamic interconnected systems, as well as a view of Mercury in the context of the solar system. Following this, Chapter 2 will discuss missions to Mercury, including details of the only deep-space mission to reach Mercury to date, Mariner 10, and brief summaries of the next committed missions to Mercury, including NASA's MESSENGER (launched in 2004) and ESA/ISAS Bepi Colombo (launch anticipated for 2014). Chapters 3 through 6 will include reviews of our current knowledge of and planned observations for Mercury's interior, surface, exosphere, and magnetosphere, respectively. The dynamic interactions between subsystems are also considered. Results already obtained by instruments on the Mariner 10 spacecraft and by multi-disciplinary ground-based observations will be described. Current interpretation of those results will be given, along with response, in the form of anticipated capability and scientific objectives of the planned missions. The final chapter describes the future of Mercury exploration, including a profile for a mission that has the potential to complement and enhance the results obtained from MESSENGER and Bepi Colombo. The final section also contains our overall conclusions.

In this way, we hope to lay the foundation for the next major influx of information from Mercury and contribute to the planning for future spacecraft encounters.

Greenbelt, Maryland *Pamela Elizabeth Clark*

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Chapter 1

MERCURY FROM A SYSTEMS PERSPECTIVE

1.1 MERCURY IN CONTEXT

Less is known about Mercury than about any other inner planet because it is a more challenging target in so many respects. Before 1974, studies of Mercury involved astronomical observations from which its orbit, rotation period, radius and mass were determined. The Mariner 10 Mission in 1974 produced intriguing results, which will be discussed in detail in the next chapters, but provided coverage for only one hemisphere.

Mercury, the innermost member of the Solar System, is never more than 28^0 from the Sun as viewed from the Earth. Consequently, Mercury is relatively difficult to observe: the planet can only by observed with terrestrial telescopes during thirty to forty days per year. Such ground-based observations are made through the Earth's atmosphere via a long path length, either at twilight or close to dawn. At twilight, the effects of atmospheric refraction and turbulence can present a significant 'seeing' problem. Under daylight conditions, the contrast between the bright disk of the planet and the background sky is low.

1.2 PHYSICAL AND ORBITAL MEASUREMENTS

Table 1-1 presents a general summary of current physical and orbital data for Mercury in the context of other terrestrial planets (Weissman et al, 1999; Chamberlain and Hunten, 1987; Langel et al, 1980; Ness et al, 1979; Russell et al, 1974, 1979). This compilation derives from many decades of work by planetary investigators. The data are derived from both Earth-based and in-situ (Mariner 10) observations. Some of the difficulties experienced in arriving at these parameters are outlined below to indicate representative problems experienced in studying Mercury. Only solar system bodies (Mercury and Venus) describe orbits that are located between the Sun and the Earth and these two bodies are referred to as the *Inferior Planets*. Because of their locations of their orbits, the Inferior Planets display phases similar to those of the Moon.

Table 1-1. **Mercury's Planetary Characteristics in Context**

Terrestrial Planets Physical Characteristics Comparison							
planet	Total Mass (g)	Mean density (g/cm^3)	Surface gravity (cm/s^2)	Escape velocity (km/s)	Surface T extremes (K)	Normal albedo (5^o phase angle)	Magnetic dipole moment (J/T)
Mercury	3.3×10^{26}	5.4	370	4.25	90-470	0.06	4.9×10^{19} (1)
Moon	3.3×10^{26}	3.3	162	2.38	50-123	0.07	$<1.3 \times 10^{15}$ (2)
Earth	6.0×10^{27}	5.5	978	11.19	260-310	0.30	7.9×10^{22} (3)
Mars	6.4×10^{26}	3.9	367	5.03	130-20	0.27	$<2.1 \times 10^{18}$ (4)
Refs: 1) Ness et al, 1979; 2) Russell et al, 1974; 3) Langel et al, 1980; 4) Russell et al, 1979.							

Terrestrial Planets Orbital Characteristics Comparison							
planet	Sidereal period (days)	Rotation period (days)	Spin:Orbit Resonance	Perihelion (AU)	Aphelion (AU)	Obliquity (degrees)	Orbital inclination (degrees)
Mercury	87.97[6]	58.65	3:2	0.308	0.467	0.	7.0
Moon	27	27	1:1	0.98	1.02	1.5	5.1 (Earth)
Earth	365	1.0	365:1	0.98	1.02	23	0.0
Mars	686	1.0	686:1	1.38	1.67	25	1.9

1.3 DIFFICULTIES AND ANOMALIES UNCOVERED IN OBSERVING MERCURY

Attempts to determine Mercury's basic physical properties led to the determination of its unexpectedly large mass and implied high density. The mass of Mercury was first derived by a German astronomer Johann Franz Encke in 1841 when he measured the perturbations produced by Mercury on a comet that has since been given his name. The measurement remained controversial until the mass and size of this body were later more accurately determined from combined ground-based and Mariner 10 observations (Lyttleton, 1980, 1981; Branham, 1994; Anderson et al, 1987). A major implication for this measurement was that the density of the planet was much higher than models could explain, implying disproportionately greater iron abundance and core size. This will be discussed in full in Chapter 3 on Mercury's Interior.

Methods of computerized location and tracking have recently increased the probability of successfully observing Mercury from the Earth under daylight conditions. As a direct result of not only these technological advances but of the unanticipated scientific advances made during the Mariner 10 mission in 1974 (NASA Atlas of Mercury), a more vigorous and multi-faceted ground observation program for Mercury has ensued in the last three decades. **Table 1-2** is a summary of findings on the figure, orbital, and surface properties of Mercury made from ground-based measurements.

Table 1-2. **Ground-based Observations Contributions**

Type of Observation/Target	Finding
Visible/Near to Mid IR (Chapters 3, 4) Regolith Compositional Properties	Minimal (1-2%) iron in iron-bearing silicate minerals in regolith
Visible Spectrometer Lines, Images (Chapter 5), Exosphere	Spatial and Temporal characterization of Na, K, Ca exosphere
Thermal, Microwave, Radar Figure and Orbital Properties (Chapter 1) Regolith Physical Properties, Surface topography, morphology (Chapter 4)	Radar ranging for figure and dynamic properties, confirm General Relativity, radar imaging and topography confirm impact, tectonic, polar features Thermal, Microwave reflectivity, polarization ratios indicates lunarlike regolith, polar volatiles

In 1965, on the basis of Doppler radar measurements made at Arecibo Observatory, Colombo and Shapiro (1996) unexpectedly demonstrated that Mercury exhibits a rotation period of 58.6 days, a value that is exactly two thirds of its 88 days orbital period. Yet, previous optical observations apparently indicated that the rotation and orbital periods were the same. Why the apparent difference between the result obtained using radar and that determined optically? The inference was drawn, from the radar based result, that Mercury rotates three times about its axis during every two of its orbits about the Sun, and that after three synodic periods, the same face of Mercury viewed at the same phase, will be presented to Earth based observers. Three synodic periods is also the time interval between the most favorable conditions for viewing Mercury telescopically from the northern hemisphere. An astronomer working in this hemisphere at favorable times would consistently track 88-day passages of characteristic surface markings for up to six consecutive years. An obvious drift in the positions of the markings would thereafter, for geometrical reasons, become apparent. However, because optical maps of Mercury's surface features were typically made at particular observatories within the compass of programs that extended over just a few years, a set of drawings of surface features made at a particular site could, against this background, convincingly, but erroneously, suggest an 88-day rotation period for Mercury.

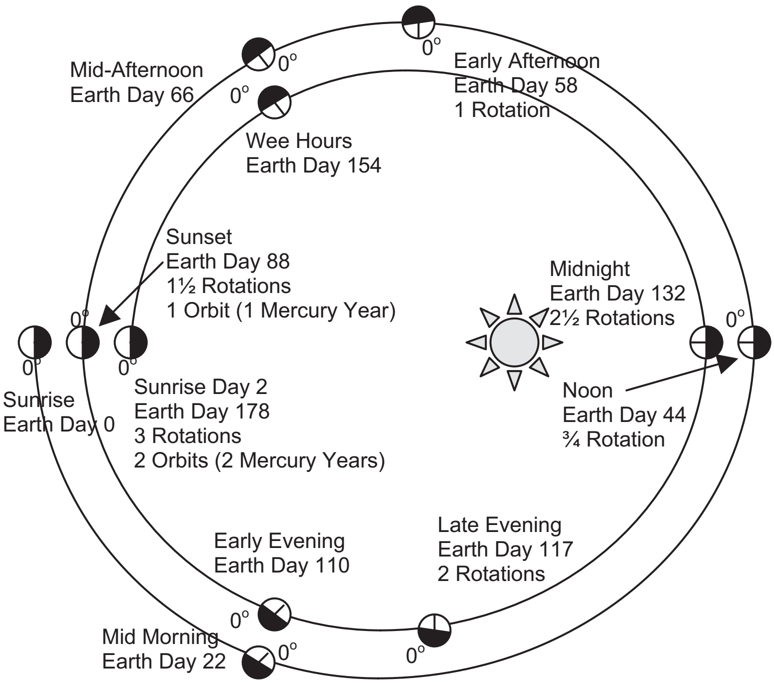

Figure 1-1. Mercury spin-orbit coupling: Mercury's 3:2 spin-orbit coupling is illustrated by this diagram of the planet's illumination as a function of position in its orbit. In the starting position at aphelion, it is sunrise at one of the terminators. After half an orbit, it is noon at that terminator. After a complete orbit, Mercury has rotated 1.5 times, and it's sunset at the same terminator. After two complete orbits, Mercury has rotated three times and it is sunrise again at the same terminator. (After Strom, 1987. Courtesy of Robert Strom.)

Mercury has the most eccentric and inclined orbit of all the terrestrial planets, and, as a result, displays the greatest variation in its heliocentric distance. Spin orbit coupling combined with the pronounced orbital eccentricity of Mercury result in the planet first presenting one particular hemisphere, then the one opposite to it, to the Sun during successive perihelion passages (**Figure 1-1**). Mercury's prime meridian was chosen to pass through the sub-solar point at the first perihelion passage that occurred in 1950; thus, central meridians 0^0 and 180^0 always face the Sun at perihelion.

With an obliquity close to zero degrees, Hermean latitudes experience diurnal, but not seasonal, changes in temperature. Overall, Mercury's proximity to the Sun, lack of an insulating atmosphere and long day cause it

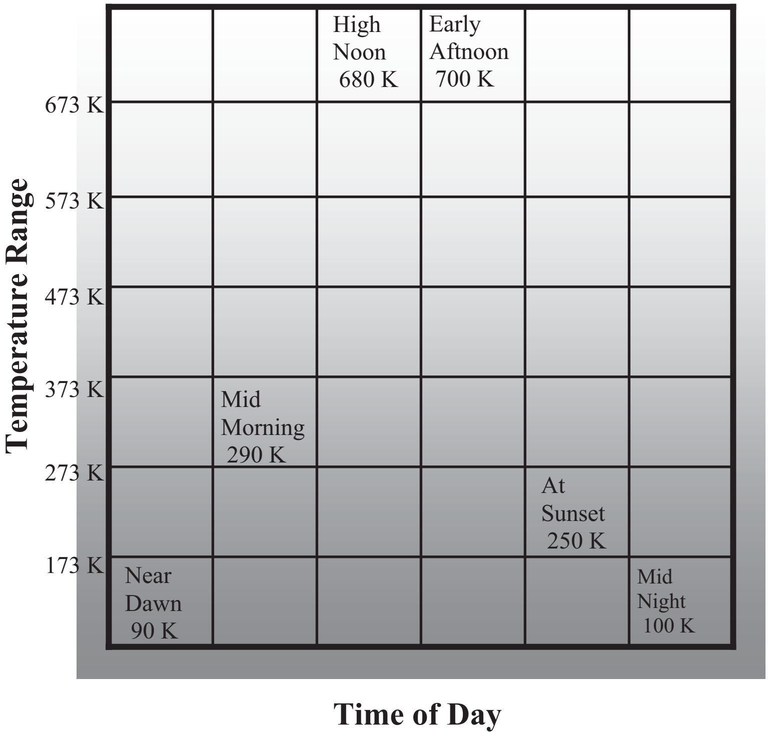

Figure 1-2. Mercury's extreme temperature cycle.

to display the greatest difference among the planets of the Solar System between its day and night temperatures. Diurnal Temperature cycles as a function of a Mercury day (one spin) (Strom and Sprague, 2003) are shown in **Figure 1-2**.

When the planet is closest to the Sun, Mercury's surface temperature reaches about 740 K. The 0^0 and 180^0 longitude meridians are 'hot poles' as a result of the enhanced heating received at these locations as the planet passes through the perihelion of its eccentric orbit. A signature of the temperature enhancement concerned is readily observed from the Earth in microwave radiation. .The central meridians 90^0 and 270^0 face the Sun only at aphelion and the maximum temperature thereby reached is significantly lower (about 525^0 K). On Mercury's night side, the Sun does not shine for months at a time due to the slow rotation of the planet. The surface temperature can thus drop to about 90 K.

1.4 A PLANET AS A SYSTEM OF SUBSYSTEMS

Observations of Mercury in particular have so far allowed us to capture its essence in 'snapshot' fashion, as if the planet is frozen in time. However, observations taken over the last thirty years have indicated that Mercury interacts dynamically with its environment, the magnetosphere and exosphere, and that this environment interacts with the surface. Most likely a dynamo, indicative of ongoing activity in the interior, generates the magnetic field, which results in the presence of the magnetosphere. To understand this active planet, we must see it in terms of temporal as well as spatial variations, in other words, as an interactive system of systems.

A planet is a complex system of subsystems. By using a systematic approach, we can bring order out of the chaos of fascinating idiosyncratic details a particular planet displays (Lewis and Prinn, 1984). This is a challenge. Natural environments are complex. When we observe them, we are not looking at controlled laboratory experiments, where we can carefully vary one parameter at a time, but at many known and unknown simultaneously varying parameters. We must hone in on and capture the most essential ones in order to constrain variation over orders of magnitude. We must be around long enough to observe events that we can't control and that perturb the system, and deal with incomplete or noisy observations in the process. We must be willing not only to abandon old paradigms and formulate new ones, but to consider 'multiple working hypotheses', a very unsettling challenge for most human beings who love certainty.

Energy is transferred between subsystems and the 'work' of the system is done at interfaces where changes of state or phase occur. As described in **Table 1-3**, states include solids, liquids, gases, and, the most ubiquitous state in the universe, plasma. The subsystems include interior, surface, exosphere/atmosphere, and magnetosphere, the origin and generic properties of which are described in **Table 1-4** and in more detail further on.

1.5 TYPES OF SYSTEMS

Systems can be in equilibrium or not in equilibrium. Non-equilibrium models, accounting for most natural systems, range from steady state models where conditions are apparently at equilibrium locally to dynamic models, which exhibit predictable or chaotic variations (Lewis and Prinn, 1984) (**Table 1-5**).

Equilibrium systems are ultimately balanced, in an apparently unchanging non-evolutionary state with no spatial gradients. Nor are there temporal changes or fluxes. Many natural systems that are not actually in this state are treated as equilibrium systems if temporal changes are slow by human standards. State functions are constant, entropy is maximum, and free energy is minimum.

Steady state systems exhibit at least minimal temporal and spatial changes, often at a small enough scale so that, locally, they can be treated as equilibrium systems. However, they do exhibit flow and gradients and non-equilibrium thermodynamics overall. Entropy is no longer maximum and free energy no longer minimum. Temperature variation in the solar system varies across a gradient as a function of distance from the sun. Apparent equilibrium at the top of each planet's atmosphere is governed by its surrounding external state in terms of temperature.

Table 1-3. **States of Matter**

State	Solid	Liquid	Gas	Plasma
Example	Ice H_2O	Water H_2O	Steam H_2O	Ionized Gas H_2>H+ + H++2e-
Description	Molecules Fixed in Crystal Lattice	Molecules not fixed, free to move in confined space	Molecules Free to Move in Large Space	Components (ions and electrons) move independently in large space
Vary Temperature	Coldest ---→ Hottest			
Vary Pressure	Highest ---→ Lowest			

Table 1-4. **General Description of Major Planetary Subsystems**

Subsystem, Structure, Phase Transitions	Sources, Sinks, Processes
Interior Core/Mantle/Crust Boundaries at phase changes Typically liquid to solid	Mixing between layers, Infall meteoritic material, volcanotectonic activity through melting, creep, plastic and elastic deformation
Surface Solid rubble (regolith) Interface between Crust and Exosphere	Interior (volcanic eruption and tectonic displacement) and Exterior (meteoritic, comet, particle) infall, interior-driven resurfacing and cratering (removal and deposition, gardening and space weathering) processes
Exosphere/Atmosphere Interface between surface (neutrals) and plasma (ionized forming ionosphere) layers Typically gas and plasma	Surface molecules, atoms, and ions produced by interaction with plasma, lost through escape and adsorption
Magnetosphere: the somewhat leaky boundary between interplanetary and planetary magnetic field plasmas Magnetopause is Interface with InterPlanetary Field and Magnetotail is Wake	Particles transferred across magnetic field interfaces, in and out of subsystem, by reconnection and across atmosphere and surface boundaries by charge and momentum transfer

Dynamic systems can be cyclical, evolutionary, or catastrophic (Lewis and Prinn, 1984). Cyclical temperature variation cycles, which occur simultaneously, include the diurnal and annual cycles related to a planet's spin and revolution, respectively. Evolutionary systems change slowly due to long-term systematic variations in external conditions superimposed on a steady state. Both cyclical and evolutionary systems are uniformitarian in nature, exhibiting regular, incremental variation in a predictable direction. On the other hand, catastrophic systems exhibit rapid, large-scale, unanticipated changes resulting from major transitions in surrounding environment conditions.

Table 1-5. **System Model Characteristics**

System Type	Thermodynamics	Dynamics	Characteristics
Uniformitarian	Equilibrium	Constant	No spatial or temporal gradients
	Non-equilibrium	Steady State	Locally, approaches equilibrium, Overall incremental temporal and spatial gradients
		Dynamic	Cyclical, repeated patterns in changes induced by changed in external conditions
			Evolutionary, predictable trends in changes induced by gradual changes in external conditions
Catastrophic			Catastrophic, large-scale, unpredictable, unrepeatable changes induced by major shifts in external environment

1.6 IN THE BEGINNING: SOLAR NEBULA SYSTEM FOR PLANET FORMATION

The solar nebula represents a spatial and temporal model for planet formation. The system is powered by nuclear energy. Converted to its gravitational, kinetic, and rotational forms, this energy acts as the ‘mechanical resource’ that can be harnessed to do the work of planetary formation (Elder, 1987). Energy is transferred across interfaces between matter in changed state or phase: e.g., plasma to gas, or high pressure to lower pressure forms of a mineral. Plasma is the most ubiquitous form of matter in the relatively hot and low pressure universe, but, locally in the nebula, conditions get cool and dense enough for matter to coalesce to form solids.

What are the initial conditions for planet formation? (e.g., Lewis and Prinn, 1984; Lewis, 2004; Encrenaz et al, 2003) Recent observations of extra-solar systems in formation have helped to refine the models and constrain the assumptions of these conditions. Planetary systems begin as denser than average gas clouds in hydrogen rich arms of relatively young galaxies (Elder, 1987). Bulk composition, including volatile content and oxidation state, the availability of energy sources (achieving sufficient heat), and the mass of the starting material (achieving sufficient density) are parameters of primary importance in influencing the stability, condensation, and vaporization of small grains in the early nebular phase, as well as the later differentiation and crystallization of larger bodies in the planetary formation stage. Both processes are essential to planet formation.

The planetary formation model initially developed by Safronov (1972) is currently the prevailing paradigm, largely because it best explains the current observations of solar systems outside of our own. In addition, it is the planetary origin model which best accounts for the following observations:

(1) the observed flattening of the nebular disk during planet formation,

(2) distribution and compositional variations between planets including the observed loss of volatiles in the inner solar system and solar abundances among the oldest measured material,

(3) order and duration of events as derived from radiochemical dating measurements (including 10^8 year planet formation period after initial disk formation),

(4) the observed deuterium loss in the sun, where it was used up after nebular disk formation and accretion,

5) the transfer of angular momentum from the sun to planets which, according to recent models, required only small drag and mass loss by the rotating sun,

6) observed small body dynamics including asteroid belt formation.

In Safranov's model (1972), as illustrated in **Figure 1-3**, gas condensed into a diffuse, homogeneous dust cloud which collapsed and accreted heterogeneously relative to the nebular center in response to temperature and pressure gradients. Although temperature varied rapidly with distance, dust, acting as a good insulator, preserved temperature gradients within the accretion disk, and convection transferred heat under steady state conditions. Dust settled toward the midplane with resulting mass distribution inhomogeneities and gravitational instabilities.

Large-scale fluctuations in the output of the early sun brought on the next phase of nebular development (Lewis and Prinn, 1984; Lewis, 2004; Encrenaz et al, 2003). Such events resulted in sudden short energetic pulse or pulses, causing very rapid remelting and solidification of the dust throughout the solar nebula. This event generated the igneous spheroid droplets (chondrules) observed in chondritic meteorites. Chondrules accumulated still-condensing dust layers on their surfaces, and began to coalesce into planetesimals. Subject to drag with the surrounding gas, planetesimals slowed down and spiraled in toward the sun until they grew to a size of about ~1 km in diameter where, due to less surface area per volume, the drag became negligible. There, these coalesced bodies stayed and eventually grew into planetoids, bodies tens of kilometers or greater in diameter.

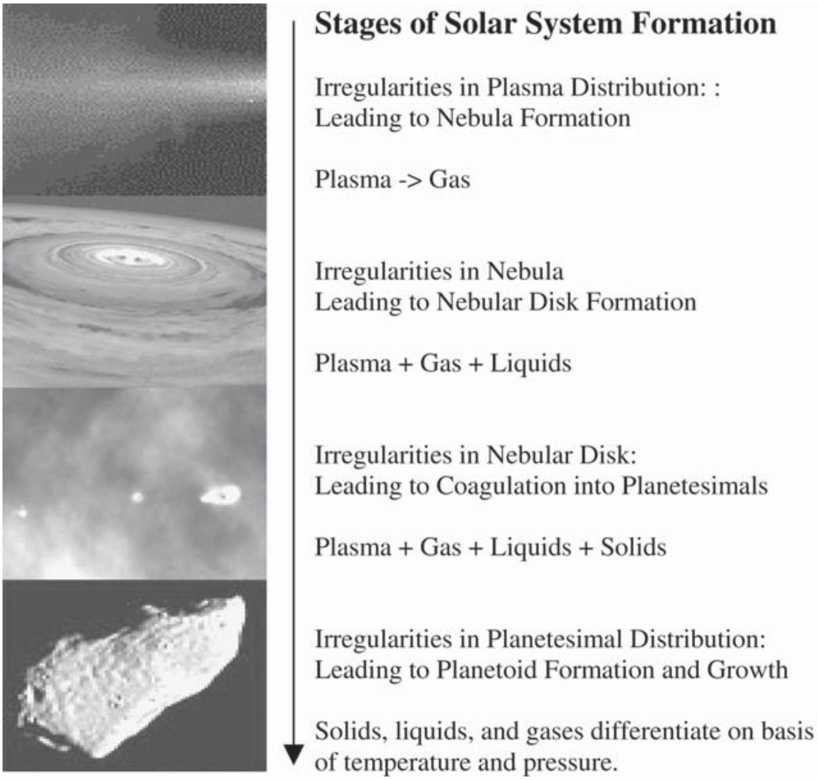

Figure 1-3. Stages of solar system formation, showing systematic changes in distribution and states of matter induced by heterogeneous distribution of matter as discussed in text.

As accretion continued during the planetoid formation stage, compositional boundaries blurred, grains became well-mixed, forming polymict breccias with chondrules, known as chondrites. The sun experienced a sudden, high temperature explosive event known as the T Tauri phase which caused gas to be swept out dragging dust and the smaller bodies along with it.

The larger bodies remained, becoming today's observed planets, but lost their original surrounding gas envelopes, primordial atmospheres, in the process. Closest to the center of the nebula, more severely heated bodies became the differentiated achondrites in which the chondrites had remelted and disappeared. Many bodies remained as chondrites, modified to a degree determined by their distance from the nebular center. On this side of the asteroid belt, chondrites have been subject to some increase of temperature and pressure, metamorphosed to some degree, are coarse grained and low in volatiles. Elsewhere, chondrites remained 'primitive', fine grained, volatile rich, and with low temperature mineral assemblages. Oxygen and other light element isotope ratios are diagnostic for major meteorite classes. Discrete