1
Introduction

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1.1 INTRODUCTION

In the Sun's necklace of planets, one gem outshines the rest: Jupiter. Larger than all other planets and satellites combined, Jupiter is a true giant. If intelligent beings exist on planets circling nearby stars, it is probable that Jupiter is the only member of our planetary system they can detect. They can see the Sun wobble in its motion with a twelve-year period as Jupiter circles it, pulling first one way, then the other with the powerful tug of its gravity. If astronomers on some distant worlds put telescopes in orbit above their atmospheres, they might even be able to detect the sunlight reflected from Jupiter. But all the other planets – including tiny inconspicuous Earth – would be hopelessly lost in the glare of our star, the Sun.

Jupiter is outstanding among planets, not only for its size, but also for its system of orbiting bodies. With fifteen satellites, and probably more too small to have been detected, it forms a sort of miniature solar system. If we could understand how the jovian system formed and evolved, we could unlock vital clues to the beginning and ultimate fate of the entire solar system.

..... Morrison and Samz, *Voyage to Jupiter*, 1980

Thus begins Morrison and Samz' (1980) review of results from the *Voyager* mission. Two decades later Jupiter remains supreme amongst planets in our solar system: the largest, the most massive, the fastest rotating, the strongest magnetic field, the greatest number of satellites (the tally passed 60 in 2003), and its moon Europa, some would say, is the most likely place to find extraterrestrial life. Moreover, we now know of at least 100 Jupiter-type planets that orbit other stars. Our understanding of the various components of the Jupiter system has increased immensely with recent spacecraft missions. But it is the knowledge that we are studying just the local example of what may be ubiquitous throughout the universe that has changed our perspective. Studies of the jovian system have ramifications that extend well beyond our solar system.

The previous book that comprehensively addressed the whole jovian system is *Jupiter* edited by Gehrels (1976). The Gehrels book presented results from the two *Pioneer* flybys. It was pre-*Voyager* and pre-Hubble Space Telescope. The *Galileo* mission was but a distant dream. Yet, Gehrels' *Jupiter* is a substantial book. It reminds us of the vast heritage of the careful astronomical observations, meticulous laboratory work and complex theoretical modeling on which modern space-era investigations are based.

After the spectacular *Voyager* flybys came books that concentrated on a specific topic (sometimes expanded to include all four giant planets): *Satellites of Jupiter* edited by Morrison and Matthews (1982); *Satellites* edited by Burns and Matthews (1986); *Planetary Rings* edited by Greenberg and Brahic (1984); and *Physics of the Jovian Magnetosphere* edited by Dessler (1983). Belton, West and Rahe (1989) edited a compendium of papers *Time-Variable Phenomena in the Jovian System* which pursued how components of the system work through examining how they vary with time.

Rogers (1996) *The Giant Planet Jupiter* is an impressive volume that presents, from the viewpoint of an avid Jupiter observer, the history of jovian astronomy and a detailed digest of observations made over the past century. The emphasis is on atmospheric phenomena – their classification, variability and implications for underlying physical causes.

Most notable amongst books on Jupiter of a less technical nature, written for a general audience, are: *Galileo's Planet: Observing Jupiter Before Photography* by Hockey (1999) which provides a fascinating history of Jupiter observations up to 1900; *Jupiter: The Giant Planet* by Beebe (1994); and *The New Solar System* (4th ed.) edited by Beatty, Petersen and Chaikin (1999).

The purpose of this book is to document our scientific understanding of the jovian system after six spacecraft flybys and *Galileo*'s 34 orbits of Jupiter. Each chapter appraises what we have learned from this major epoch of exploration about component parts of the planet, satellites or magnetosphere and describes the outstanding questions that remain. The purpose of this chapter is to provide general information about spacecraft explorations of Jupiter, to briefly introduce the jovian system and to point to chapters where further details can be found.

1.2 EXPLORATIONS OF JUPITER

1.2.1 *Pioneers 10* and *11*

As the era of space exploration blossomed in the late 1960s, engineers expanded their horizon past Mars to Jupiter and beyond. Ambitious plans were made for a Grand Tour of the outer solar system (see next section). But before investing in sending a vast array of expensive and delicate equipment two potential hazards needed to be evaluated. No spacecraft had ventured across the asteroid belt and while few were concerned about the very improbable collision with the large (but sparse) known asteroids, the distribution of dust and pieces of collisional debris was completely unknown. At orbital speeds in the inner solar system even microscopic particles can cause substantial damage. The second potential hazard to a spacecraft passing close to Jupiter was its radiation belt. A couple of years before Van Allen's historic discovery of the radiation belts around the Earth, Burke and Franklin (1955) discovered powerful radio emissions from Jupiter. By the late 1960s it was clear that Jupiter's radio emissions were being generated by energetic electrons trapped in a strong magnetic field. Damage to spacecraft electronics passing through the terrestrial radiation belts raised concerns about whether a spacecraft could survive the higher fluxes at Jupiter suggested by the radio emissions.

The *Pioneer 10* and *11* spacecraft, intended as trailblazers to subsequent missions, were designed for economy and durability. Having the spacecraft spinning (usually around an axis that is pointed roughly towards Earth, and in the *Pioneers*' case at 4.8 rpm) makes it easier to maintain stability and allows particle detectors to sweep through a range of directions in the sky. But taking pictures is much harder from a spinning spacecraft. Each *Pioneer* spacecraft was equipped with six separate instruments for detecting charged particles of various kinds and energies plus a magnetometer (two on *Pioneer 11*) to measure the radiation environment of interplanetary space as well as near Jupiter. There were also three instruments that measured light plus two instruments that detected meteoroid particles, one via direct impact and the other via scattered sunlight.

Pioneer 10 and *11* were launched in spring of 1972 and 1973 respectively, passed uneventfully through the asteroid belt (measuring only a minor increase in meteoroid flux) and flew past Jupiter almost exactly a year apart on November 27, 1972 and December 10, 1973. *Pioneer 10* passed 130 000 km above Jupiter's cloud tops measuring record fluxes of energetic ions and electrons, but with only minor electronic hiccups. So, *Pioneer 11* was targeted even closer, 42 000 km above the clouds, the first of several spacecraft to use Jupiter's gravity to get a boost to Saturn and the outer solar solar system. For further description of the *Pioneer* missions see particularly *Pioneer Odyssey* by Fimmel *et al.* (1977) as well as shorter discussions in Morrison and Samz (1980) and Rogers (1996). Their trajectories through the Jupiter system are shown in Figures 1.1 and 1.2.

Details of the scientific measurements by the *Pioneer* missions are described in Gehrels (1976). Below we summarize the significant results:

- Images of Jupiter (constructed from sweeps of the photopolarimeter) showed detailed cloud structure, particularly at the boundaries between the (dark) belts and (light) zones, hinting at convective motions but there were insufficient images to allow tracking of individual features.
- Observations of infrared emission from Jupiter's nightside compared to the dayside confirmed that the planet is radiating 1.9 times the heat received from the Sun. And that heat is evenly distributed within the atmosphere, the poles being close to the temperature of the equator.
- The abundance of helium was measured for the first time and found to be similar to that of the Sun.
- By accurately tracking the Doppler shift of the spacecraft's radio signal, the gravitational field of Jupiter was more precisely determined (revealing the planet to be 1% more massive than previously thought), constraining models of Jupiter's deep interior.
- Similarly, the masses of the Galilean satellites were corrected by up to 10%, establishing a radial decline in the density of the four satellites with distance from Jupiter.
- Magnetic field measurements confirmed the strong magnetic field of Jupiter, putting tighter constraints on the magnitude, tilt and offset of the dominant dipole component and providing estimates of the higher order components.
- Occultation of Io by *Pioneer 10* revealed a substantial ionosphere, indicative of a significant atmosphere.
- The magnetosphere of Jupiter was found to be highly variable in size, extending up to distances of $\sim$100 jovian radii.
- Bursts of energetic particles are periodically ejected from the jovian magnetosphere and penetrate as far as Earth into the inner solar system.
- The multiple particle detectors confirmed that the inner magnetosphere of Jupiter is dominated by very high fluxes of energetic particles and that these particles are absorbed by the satellites as they drift inwards towards Jupiter.

At Jupiter the *Pioneer* missions were important less for revolutionary discoveries but more for precise measurements of quantities that could previously only be guessed at. Moreover, they proved that the asteroid and radiation belts could be survived. Despite receiving 1000 times the lethal radiation dose for humans, the *Pioneer 10* spacecraft continued communicating with Earth for 30 years, out to a distance of $\sim$80 AU.

1.2.2 *Voyagers 1* and *2*

The idea of using the gravity of a planet to change a spacecraft's trajectory had been around for a while and considered for the inner solar system. For his 1965 summer break from engineering studies at Caltech, Gary Flandro was assigned to apply the principle to the outer solar system. The initial goal was to use Jupiter's gravity to shorten travel times to the farthest planets. But in plotting the locations of the outer planets for the next 20 years Flandro (1966) realized that in the 1980s the planets would all be in the same quadrant of the solar system, providing a special opportunity to fly past all of the planets with a single spacecraft. With a gravity-boost at each planet a spacecraft would get to Neptune in 12 years instead of the minimum-energy flight time of 30 years. Thus, the planetary syzygy of the 1980s gave birth to the Grand Tour – probably the best ever outcome of a graduate student summer project. It was just the right discovery at just the right time.

Table 1.1. *Voyager* scientific investigations.

Investigation	Principal Investigator / Team Leader	Primary Objectives at Jupiter	Range
ISS Imaging science	B. A. Smith, Univ. Arizona	High resolution reconnaissance over large phase angles; atmospheric dynamics; satellite geology; search for rings, new satellites.	0.33–0.62 μm
IRIS Infrared interferometer spectrometer	R. A. Hanel, NASA Goddard Space Flight Center	Atmospheric composition thermal structure, and dynamics; satellite surface composition and thermal properties.	2.5–50 μm
UVS Ultraviolet spectrometer	A. L. Broadfoot, Kitt Peak Observatory	Upper atmospheric composition and structure; auroral processes; distribution of ions and neutral atoms in the jovian system.	40–160 nm
PPS Photopolarimetry	C. F. Lillie/C. W. Hord, Univ. Colorado	Atmospheric aerosols; satellite surface textures.	235–750 nm
PRA Planetary radio astronomy	J. W. Warwick, Univ. Colorado	Polarization and spectra of radio emissions; Io radio modulation; plasma densities.	20 kHz–40 MHz
MAG Magnetic fields	N. F. Ness, NASA Goddard Space Flight Center	Magnetic field of Jupiter, magnetospheric structure.	2×10^{-3}–2×10^{6} nT
PLS Plasma science	H. S. Bridge, MIT	Ion and electron distribution; solar wind – magnetosphere interaction; ions from satellites.	4 eV–6keV
PWS Plasma waves	F. L. Scarf, TRW	Plasma electron densities; wave–particle interactions.	10Hz–56kHz
LECP Low energy charged particles	S. M. Krimigis, Johns Hopkins Univ. Applied Physics Lab.	Distribution, composition, and flow of energetic ions and electrons.	10keV–30MeV
CRS Cosmic ray particles	R. E. Vogt, Caltech	Distribution, composition, and flow of energetic trapped nuclei; energetic electrons.	0.15–500 MeV
RRS Radio science	V. R. Eshleman, Stanford Univ.	Atmospheric and ionospheric structure, constituents, and dynamics (occultations); satellite masses (celestial mechanics).	X-, S-Band

Much has been written about the *Voyager* mission to the outer planets, one of the great exploratory journeys of all time. In *Pale Blue Dot*, Carl Sagan wrote, "*Voyager 1* and *Voyager 2* are the ships that opened the Solar System for the human species, trailblazing a path for future generations." The navigational challenge is described by Hall (1992). The *Voyager* missions are described in *Voyage to Jupiter* by Morrison and Samz (1980) and *Voyager's Grand Tour* by Dethloff and Schorn (2003). Textbooks around the world show *Voyager* pictures.

The two identical *Voyager* spacecraft (each a total of 2 tons, over half the weight in fuel) carried the best technology of the 1970s. Unlike the *Pioneers*, the *Voyager* spacecraft were stabilized (3 axes) to facilitate taking images. A steerable platform allowed the imaging experiments (IS, IRIS, UVS, PPS, see Table 1.1) to point at targets. Each *Voyager* took ~20 000 images at each Jupiter encounter. Six additional instruments (see Table 1.1) measured particles and fields (both electric and magnetic).

Voyagers 1 and *2* were launched in late summer 1977 and passed closest to Jupiter on March 5 and July 9, respectively, in 1979. The *Voyager* trajectories through the Jupiter system are shown in Figures 1.1 and 1.2. The spectacular pictures made headline news around the world. Movies of Jupiter's atmosphere showed turbulent eddies, dramatic wind shears, and clouds swirling around the Great Red Spot. Images of the Galilean moons revealed each to be a totally bizarre, different world – craters on Callisto, grooves on Ganymede, volcanic plumes on Io and mysterious lines across Europa. Carl Sagan commented on first seeing images of Europa: "At the moment of discovery, the vaulted technology has produced something astonishing. But it remains for another device, the human brain, to figure it out." (*Cosmos*, p. 151)

The preliminary scientific results were published in special issues of *Science* (vols. 204 and 206, 1979), followed with more detailed reports in a special issue of the *Journal of Geophysical Research* (vol. 86, 1981) and of *Icarus* (vol. 44, Nov. 1980). The books edited by Burns and Matthews (1986), Greenberg and Brahic (1984) and Dessler (1983) review *Voyager* results on satellites, rings and the magnetosphere. Below we present an abbreviated list of scientific findings (adapted from Stone and Lane 1979a,b):

Atmosphere

- Clouds of very difference sizes appear to move together, suggesting motion due to bulk winds rather than wave motions, and in a systematic pattern of zonal winds that was basically the same for both flybys.
- The pattern of alternating eastward and westward wind jet streams extends to high latitudes. The jet profiles are much sharper than simple shear-instability theory predicts.
- Clouds in the Great Red Spot exhibit anticyclonic motion with a period of about six days.
- The eddies or "spots" interact with each other, occasionally merging.
- Powerful bolts of lightening penetrate the cloud tops.
- High temperatures are measured in the upper atmosphere and ionosphere.

• Ultraviolet observations indicate the presence of a high-altitude absorbing haze in the polar regions.
• Strong ultraviolet and visible aurora are detected around Jupiter's magnetic poles.

Satellites and Rings

• At least eight active volcanoes were observed by *Voyager 1* on Io, with plumes extending up to 250 km above the surface, six of which were still active when *Voyager 2* flew by six months later.
• Spectral signatures indicate the presence of SO_2 as frost on the surface and gas in the atmosphere.
• The remarkably smooth surface of Europa, with few impact craters, indicates a geologically-young surface.
• Numerous intersecting, linear features on Europa suggest crustal cracking.
• Two distinct types of terrain (cratered and grooved) on Ganymede suggest that the entire ice-rich crust was once under tension.
• The heavily cratered crust on Callisto indicates a geologically-ancient surface.
• First images of Amalthea reveal an elongated body (270 × 160 km) with an irregular shape and reddish surface.
• A faint, narrow ring of material was detected.

Magnetosphere

• An electrical current system of more than a million amps flows through Io and along magnetic field lines linking Jupiter and Io.
• Strong ultraviolet emissions and in situ plasma measurements reveal a dense torus of electrons, sulfur and oxygen ions, presumably the result of ionization of Io's outer atmosphere.
• Plasma flows throughout most of the magnetosphere are largely in the direction of corotation with Jupiter (rather than dominated by influences of the solar wind).
• Hot plasma in the magnetosphere comprises protons, sulfur and oxygen ions.
• Measurements of high energy oxygen suggest that these nuclei are diffusing inwards towards Jupiter.
• A wide range of plasma waves and radio emissions indicate extensive wave–particle interactions.

From Jupiter, *Voyager 1* went on to fly past Saturn and to have a close encounter with its major satellite, Titan. Exploring Titan came at a great expense because it required the spacecraft to leave the Grand Tour path. In fact, Titan was given such a high priority that, had the *Voyager 1* encounter failed, the backup plan was to steer *Voyager 2* off the Grand Tour as well and make a second attempt at Titan. *Voyager 2* continued past Saturn to make the first encounters with Uranus and Neptune. As of September 2003, *Voyagers 1* and *2* continue to measure the interplanetary medium at 89 and 71 AU respectively.

1.2.3 *Ulysses*

The European Space Agency and NASA collaborated on a mission to explore the interplanetary medium at high solar latitudes in order to understand the structure and dynamics of the heliosphere. Such a mission entails escaping the ecliptic plane – the orbital plane of the Earth and planets. Once again, the gravity of Jupiter was called upon to change a spacecraft's trajectory. The *Ulysses* spacecraft was primarily equipped to measure the solar particles and fields. Concerned about the high radiation doses in Jupiter's intense radiation belts, several of the instruments did not operate during the encounter. The outbound passage through the previously unexplored dusk region of the magnetosphere and the high latitudes reached by the spacecraft made the measurements of those instruments that continued to take data particularly useful.

The *Ulysses* spin-stabilized spacecraft carried a range of scientific instruments, many of them international collaborations (see Table 1.2). *Ulysses* was launched in October 1990 and flew past Jupiter in February 1992. The *Ulysses* trajectory is shown in Figures 1.1 and 1.2. The scientific results from the *Ulysses* flyby of Jupiter are presented in special issues of *Science* (vol. 257, 11 September 1992), *Planetary and Space Science* (vol. 41, November/December 1993) and the *Journal of Geophysical Research* (vol. 98, December 1993). The major scientific findings of the *Ulysses* flyby of Jupiter are:

• The shape of the magnetosphere and structure of magnetic field measured on the first pass through the high latitude dusk region suggests that the influence of the solar wind penetrates much deeper into Jupiter's giant magnetosphere than previously expected.
• Beams of particles streaming both from and to the planet indicated localized and/or transient regions of particle acceleration at high latitudes.
• Perturbations of the magnetic field revealed narrow but strong field-aligned currents flowing between the planet's ionosphere and the magnetosphere.
• The first correlative studies of in situ magnetospheric measurements with Hubble Space Telescope observations of Jupiter's aurora were made during the *Ulysses* flyby.

The *Ulysses* observations of the magnetosphere of Jupiter are incorporated in Chapters 24 and 25.

1.2.4 *Galileo*

The *Voyagers* gave glimpses of the varied, strange worlds of the Galilean satellites. Five flybys had indicated the magnetosphere of Jupiter to be vast, energetic, full of ionized material stripped from Io's atmosphere, and highly variable. Obviously, the next step was to send an orbiter that could make extended observations. Moreover, major issues of the jovian atmosphere begged for a probe to measure directly the basic atmospheric properties (pressure, wind speed, temperature, composition, etc.) suggested by remote measurements and theoretical modeling.

The *Galileo* mission to Jupiter had a very long and tortured gestation (discussed briefly by Harland 2000 and in detail by Meltzer 2004). While the mission was fraught with political, financial and technical problems (most notable being a crippled high-gain antenna), the eventual outcome was spectacular scientifically.

The *Galileo* spacecraft consisted of a main body (that became the orbiter) and a probe. The orbiter ingeniously comprised both spinning (at ~3 rpm) and de-spun sections,

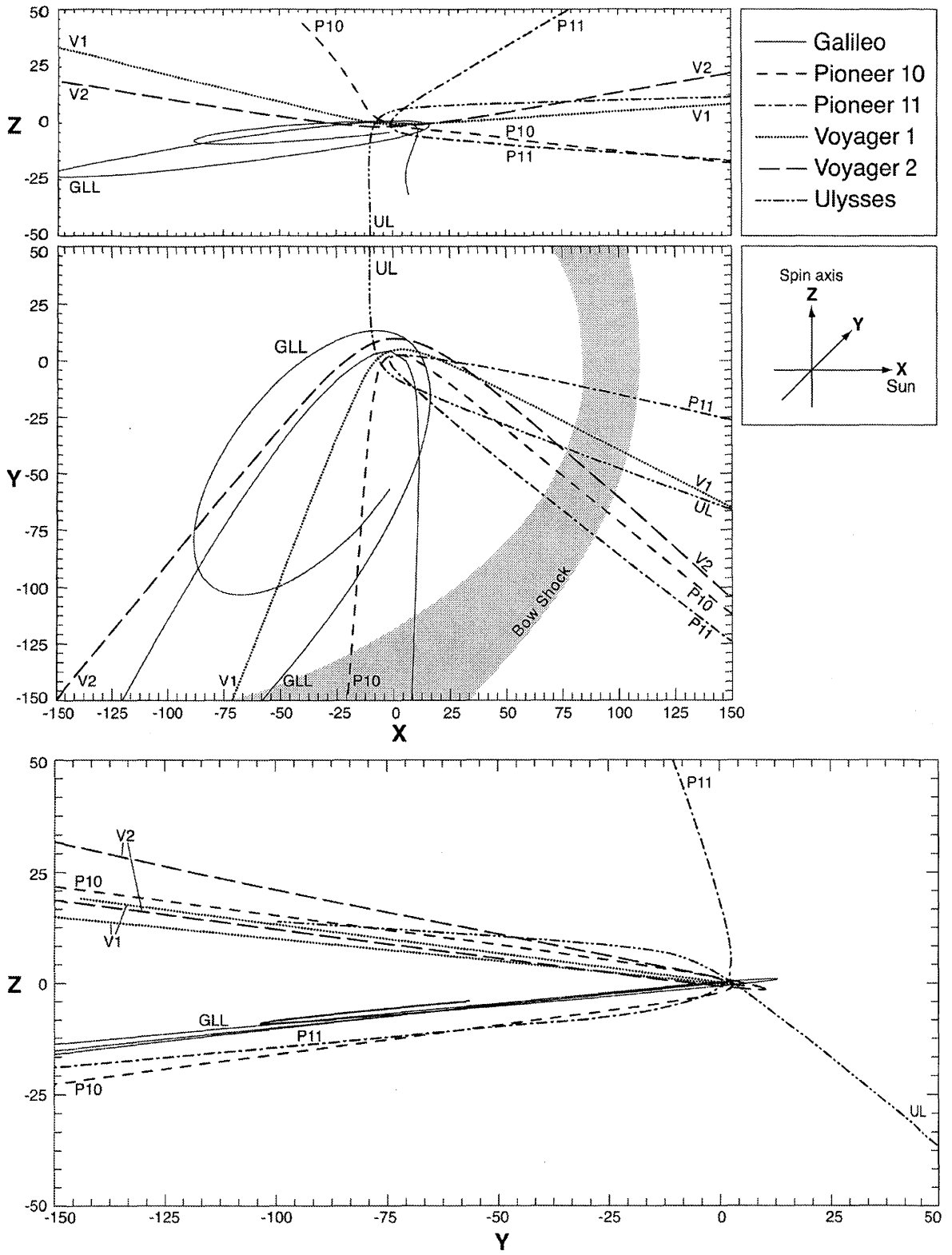

Figure 1.1. Trajectories of the five spacecraft flybys and the first orbit by *Galileo*. The co-ordinate system is centered on Jupiter and has the x axis pointed towards the Sun, the z axis is pointed along Jupiter's spin axis and the y axis makes a right-handed set (and points towards Jupiter's dusk side). The units are in jovian radii. (Courtesy of S. Joy, UCLA.)

Table 1.2. *Ulysses* scientific investigations.

Investigation	Principal Investigator	Objectives at Jupiter	Range
Magnetic field	A. Balogh, Imperial College	Magnetic field	0.01–44 000 nT
Solar wind plasma	S. J. Bame, Los Alamos National Lab.	Solar wind interaction with magnetosphere	Ions 0.26–35 keV Electrons 1–900 eV
Solar wind composition	J. Geiss, Univ. Bern G. Gloeckler, Univ. Maryland	Composition, temperature, flow of ions	0.6–60 keV
Unified radio and plasma waves	R. G. Stone, Goddard Space Flight Center	Plasma waves and radio emissions	B 0.1–500 Hz E 0–60 kHz Radio 1–940 kHz
Energetic particles and interstellar neutral gas	E. Keppler, Max-Planck Institut fur Aeronomie	Composition of energetic ions	80 keV–15 MeV/nuc.
Low-Energy Ions and Electrons	L. J. Lanzerotti, Bell Labs	Energetic ions and electrons	Ions 0.05–5 MeV Electrons 40–300 keV
Cosmic rays and solar particles	J. A. Simpson, Univ. Chicago	Energetic ions and electrons	Ions 0.5–600 MeV/nuc. Electrons 2.5–6000 MeV
Cosmic dust	E. Grun, MPK, Heidelberg	Fluxes of sub-micron particulates	10^{-16}–10^{-6} g

allowing stable pointing for imaging from the de-spun section while the spinning portion maintained stability of the spacecraft as a whole and allowed particle and field instruments to scan the sky. The *Galileo* mission (Johnson *et al.* 1992), trajectory design (D'Amario *et al.* 1992) and all of the science instruments are described in a special issue of *Space Science Review* (vol. 60, May 1992). The *Galileo* science investigations are listed in Table 1.3.

The 2.7 ton *Galileo* spacecraft was launched from Space Shuttle Atlantis on October 18th, 1989. After an extensive tour of the inner solar system, getting gravity assists from Venus and Earth (twice), it reached Jupiter on December 7, 1995. About six months prior to arrival at Jupiter the probe was detached and allowed to free-fall into the planet. The 331 kg probe entered at 6.5° N latitude, sending data up to the orbiter for ~60 minutes, by which time it had reached a depth of ~22 bars, ~150 km below the clouds. Soon after the probe data were received, powerful German-built engines fired to slow down the main spacecraft to allow it to be captured by Jupiter's gravity.

Figure 1.1 shows *Galileo*'s first, highly extended orbit. Figure 1.2 shows the subsequent orbits, principally aimed to make a close flyby of a satellite on each orbit and, in the process, use the satellite's gravity to tune the orbit to rendezvous with another satellite on the next orbit. Information about each of the satellite flybys are given on the accompanying CD. As the very final pages of this book were being written the *Galileo* orbiter plunged into Jupiter's atmosphere having completed 34 orbits in nearly eight years.

Further descriptions of the *Galileo* mission can be found in *Jupiter Odyssey: The Story of NASA's Galileo Mission* by Harland (2000) and *History of the Galileo Mission to Jupiter* by Meltzer (2004). Scientific results from the *Galileo* mission are published in special issues of *Icarus* (vol. 135, 1998) and *Journal of Geophysical Research* (vol. 103, E10, 1998 and vol. 105, E9, 2000). And throughout this book, of course. Below is a list of some of the mission's scientific accomplishments at Jupiter:

- The descent probe measured atmospheric elements and found that their relative abundances were different than in the Sun.
- *Galileo* made a first direct observation of ammonia

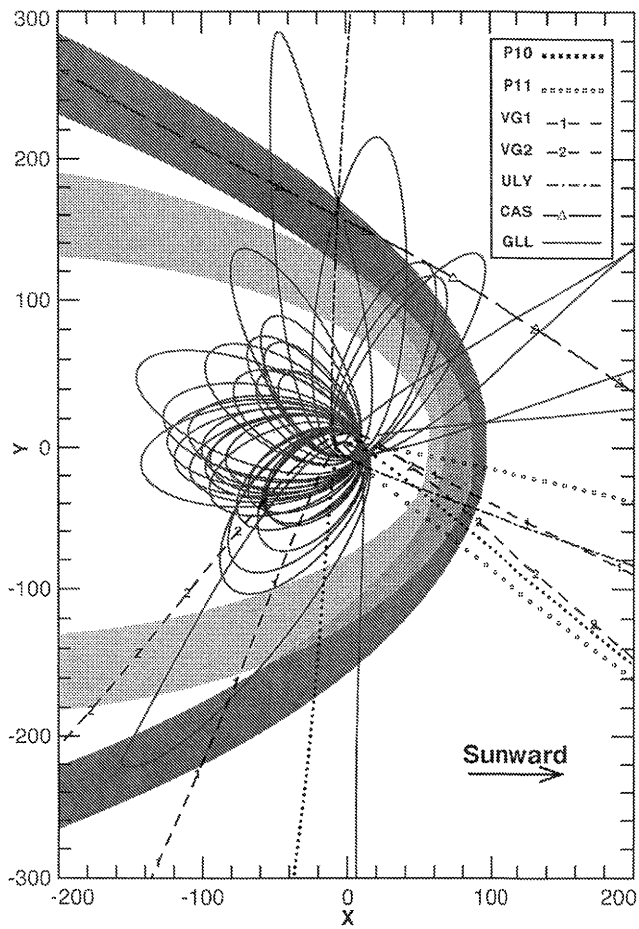

Figure 1.2. Trajectories of the the five spacecraft flybys and all 34 orbits of *Galileo* in the x–y plane of the co-ordinate system shown in Figure 1.1 (units in jovian radii). The bow shock and magnetopause locations are shown as shaded regions and are derived from models based on statistical fluctuations of the solar wind and observed boundary locations. Light gray is the 25–75% probability magnetopause region and dark gray is the 25–75% bow shock. The medium gray shows the region of overlap in the two probability distributions. (Adapted from Joy *et al.* 2002)

Table 1.3. *Galileo* scientific investigations.

Experiment/Instrument	Principal Investigator / Team Leader	Objectives	Range
PROBE			
Atmospheric structure	A. Seiff, NASA Ames Research Center	Temperature, pressure, density, molecular weight profiles.	0–540 K 0–28 bar
Neutral mass spectrometer	H. B. Niemann, NASA Goddard Space Flight Center	Chemical composition.	2–150 amu
Helium abundance interferometer	U. von Zahn, Bonn Univ.	Helium/hydrogen ratio.	Accuracy = 0.1%
Nephelometer	B. Ragent, NASA Ames Research Center	Solid/liquid cloud particles.	0.2–20 μm
Net flux radiometer	L. A. Sromovsky, Univ. Wisconsin	Thermal profile, heat budget.	0.3–500 μm
Lightning/energetic particles	L. J. Lanzerotti, Bell Laboratories	Lightning flashes. Lightning radio bursts. Energetic charged particles.	White light 0.1–100 kHz 3–900 MeV
ORBITER (De-spun)			
Solid-state imaging camera	M. J. S. Belton, NOAO	High-resolution imaging of Jupiter, moons and ring.	0.37–1.1 μm
Near-infrared mapping spectrometer	R. W. Carlson, JPL	Atmospheric and surface compositions; thermal mapping.	0.7–5.2 μm
Ultraviolet spectrometer (EUV sensor on spun section)	C. W. Hord, Univ. Colorado	Emissions from atmospheric gases, aerosols, aurora, plasma.	115–430 nm 54–128 nm
Photopolarimeter/ radiometer	J. Hansen, Goddard Institute for Space Studies	Polarimetry: cloud, suface reflection. Radiometry: Surface, atmosphere temperatures.	410–945 nm 15–100 μm
ORBITER (Spinning)			
Magnetometer	M. G. Kivelson, UCLA	Magnetic field strength, fluctuations.	32–16 384 nT
Energetic particles	D. J. Williams, John Hopkins Univ. Applied Physics Lab.	Fluxes of energetic electrons, protons, heavy ions.	Ion 0.02–55 MeV Elec. 0.02–11 MeV
Plasma	L. A. Frank, Univ. Iowa	Composition, energy, distributions of ions and electrons.	0.9 eV–52 keV
Plasma wave	D. A. Gurnett, Univ. Iowa	Electromagnetic waves and wave–particle interactions.	E 5 Hz–5.6 Mhz B 5 Hz–160 kHz
Dust	E. Grun, Max Planck Inst. für Kernphysik	Mass, velocity, charge of sub-micron particles hitting spacecraft.	10^{-16}–10^{-6} g 2–50 km s^{-1}
Radio science: celestial mechanics	J. D. Anderson, JPL	Masses and motions of bodies from spacecraft tracking.	X- and S-Band
Radio science: propagation	H. T. Howard, Stanford Univ.	Satellite radii, atmospheric structure from radio propagation.	X- and S-Band
Heavy ion counter	E. C. Stone, Caltech	Fluxes and composition (carbon–nickel) of energetic heavy ions.	6–200 MeV/nuc.

clouds in another planet's atmosphere. The atmosphere seems to create ammonia ice particles of material from lower depths, but only in "fresh" clouds.

- Lightning activity was definitively tied to large-scale moist convection of water clouds.
- Io's extensive volcanic activity may be 100 times greater than that found on Earth. The high temperatures and frequency of eruption may be similar to early Earth.
- Io's complex plasma interactions in Io's atmosphere include support for currents and coupling to Jupiter's atmosphere.
- Ganymede is the first satellite known to possess an internally-generated magnetic field.
- *Galileo* magnetic data provide evidence that Europa, Ganymede and Callisto each have a conductive (i.e., salty) hidden ocean.
- Geologic evidence supports a theory that an ocean exists under Europa's icy surface layer (the thickness of which remains a major topic of debate, but is probably less than 30 km).
- Europa, Ganymede, and Callisto all provide evidence of thin atmospheres.
- Jupiter's ring system is formed by dust kicked up as interplanetary meteoroids smash into the planet's four small inner moons. The outermost ring is actually two rings, one embedded within the other.
- *Galileo* was the first spacecraft to dwell in a giant planet magnetosphere long enough to identify its global structure and to investigate its dynamics.

To avoid any possible contamination of Earth or a conceivable biosphere on Europa by plutonium from *Galileo*'s

Table 1.4. The *Cassini* experiments that obtained data at Jupiter.

Experiment/Instrument	Principal Investigator / Team Leader	Objectives at Jupiter	Range
CAPS Cassini Plasma Spectrometer	D. Young, Southwest Research Institute	Plasma properties in the solar wind – magnetosphere interaction region	Ions and electrons 1 eV–50 keV
CDA Cosmic Dust Analyzer	E. Grün, Max Planck Inst. für Kernphysik	Fluxes, composition of dust particles from jovian system and interplanetary space	10^{-16} to 10^{-6} g
CIRS Composite Infrared Spectrograph	V. Kunde, NASA Goddard Space Flight Center	Composition and temperature of Jupiter, rings and satellites	10–1400 cm^{-1} 7–1000 microns
ISS Imaging Science Subsystem	C. Porco, Space Sciences Institute	Jovian atmosphere, rings, and satellites	200–1100 nm
MAG Dual Technique Magnetometer	D. Southwood, Imperial College, London	Magnetosphere and its interaction with the solar wind	Up to 44 000 nT
MIMI Magnetospheric Imaging Instrument	S. Krimigis, Johns Hopkins Univ. Applied Physics Lab.	Image energetic neutral atoms; Energetic electrons and ions in solar wind and magnetosphere; Upstream pickup ions	Image neutrals, ions 10 keV–8 MeV/nuc. Ions 10–130 MeV Elec. 15 keV–11 MeV
RADAR Cassini Radar Instrument	C. Elachi, JPL	Map Jupiter's synchrotron emission	13.78 GHz Ku-band
RPWS Radio and Plasma Wave Science	D. Gurnett, Univ. Iowa	Magnetosphere response to solar wind; Survey jovian radio emissions	E 10 Hz–2 MHz B 1 Hz–20 kHz
UVIS Ultraviolet Imaging Spectrometer	L. Esposito, Univ.Colorado	Io plasma torus, jovian atmosphere and aurora	56–190 nm
VIMS Visible and Infrared Mapping Spectrometer	R. H. Brown, Univ. Arizona	Cloud motions and morphologies; composition of minor atmospheric constituents; jovian aurora, surface composition of Galilean satellites	0.35–5.1 microns

radioactive thermoelectric generators or any terrestrial microbes that might still be lurking on the spacecraft, the trajectory was adjusted to send the spacecraft into Jupiter on September 21, 2003.

1.2.5 *Cassini*

The *Cassini* mission, following the fine tradition of *Pioneer 11* and *Voyagers 1* and *2*, used Jupiter for gravity assist to get to Saturn. At 5.6 tons, this "Battlestar Galactica" of NASA's fleet of spacecraft carries the best of late 1980s to early 1990s technology and, while it did not pass very close to Jupiter (136 jovian radii), the high quality of its scientific instrumentation and working high gain antenna allowed *Cassini* to obtain important new measurements. The scientific instruments that gathered data on the Jupiter flyby are listed in Table 1.4 and described in a 2004 special issue of *Space Science Reviews*.

The *Cassini* spacecraft passed Jupiter on its dusk side (trailing side of Jupiter's orbit), just skimming inside the flank of the magnetosphere (see Figure 1.2). The closest approach to Jupiter occurred on December 30, 2000 but remote sensing instruments observed Jupiter over $\sim$ six months. Approximately 26 000 images were obtained of the jovian system during the flyby. Moreover, as the *Cassini* spacecraft approached Jupiter, the *Galileo* spacecraft was inside Jupiter's magnetosphere. This provided the first ever opportunity to simultaneously measure variations in the upstream solar wind conditions while measuring the internal response of the magnetosphere. Naturally, Hubble Space Telescope took advantage of this unique opportunity to also observe the ultraviolet emissions from Jupiter's aurora.

The first results from the *Cassini* flyby of Jupiter are published in special issues of *Science* (vol. 299, 7 March 2003) and *Nature* (vol. 415, 28 Feb. 2004) and further papers are expected in special issues of *Icarus* and *Journal of Geophysical Research* in 2004. Below is a brief list of scientific highlights:

- The global profile of winds showed the same pattern as recorded by *Voyager*, and the east–west alternations were seen to extend to the poles, even though the polar regions lack belt–zone striping.
- The most important eastward jet is 60% faster than previously estimated. This is the North Equatorial jet, which carries some of the most conspicuous weather systems on the planet ("hot spots" and "plumes"), and is the region into which the *Galileo* probe descended. As the probe descended below the cloud-tops it accelerated to a speed 60% faster than the cloud-top speed observed from Earth. Now the same speed has been observed all around that latitude (especially in the *Cassini* movie in near-infrared light that came from below the visible cloud-tops). This shows that the major North Equatorial weather systems are waves within this jet; and they are thus analogous to less frequent but well organised disturbances on two other eastward jets with similar peak speeds (the South Equatorial and North Temperate). All three jets have peak speeds of 170 km s^{-1}, and weather systems that move at 50–70% of this speed.
- Observations of the rings at difference phases and wavelengths further constrain the size distribution of particles.
- *Cassini* images in the near ultraviolet showed a dark spot at high latitudes which may be a result of magnetospheric particles bombarding Jupiter's upper atmosphere in the auroral zone.
- Spectral imaging of the Io plasma torus over six months revealed both long-term (weeks) variations in composition

as well as short-term (hours) intensity bursts, perhaps related to similar brightening of the auroral emissions.

- Imaging of energetic neutral atoms confirmed that a major loss process of energetic radiation belt ions is charge exchange with clouds of neutral oxygen and sulfur atoms in the vicinity of Io and Europa.
- Energetic ions of sulfur and oxygen were detected up to 5 AU from Jupiter, produced by re-ionization of extended neutral clouds.
- The *Galileo/Cassini* combination made the first direct measurement of the change in size of the magnetosphere in response to a pressure increase of the solar wind.

As studies of Jupiter have evolved from exploration to deeper investigations, missions do not just make "discoveries" but their detailed measurements begin to test models or hypotheses.

1.2.6 Telescopes and Supporting Research

The Hubble Space Telescope (HST), launched in 1990, has made a major impact on jovian science, particularly through UV imaging and spectroscopy but also with high resolution imaging at visible wavelengths. HST has made critical measurements of satellite atmospheres, radically improved our characterization of the jovian aurora, and made substantial contributions to studies of the Io torus. Infrared observations of jovian targets from ISO have recently joined a long history of UV observations from space-based telescopes (IUE, EUVE, HUT and now FUSE).

The last 25 years have also seen major advances in ground-based studies. These were largely due to the invention and continuing improvement of electronic detectors, at both visible and infrared wavelengths, which have revolutionized imaging. Amateur astronomers have been using CCDs since the mid-1990s, and now regularly produce images that could previously be produced only by large professional telescopes. The internet allows amateur organizations to monitor and report changes on the planet continuously at high resolution, and to collaborate with space scientists, as happened during the *Galileo* mission. As well as visible wavelengths, the 0.89 micron methane band is now used by several amateurs and permits the tracking of novel types of disturbance (such as little red spots in high latitudes, and the South Equatorial Disturbance). Professional observatories have also continued monitoring in both visible and methane bands, especially the Observatoire du Pic du Midi and the New Mexico State University Observatory. As a result of these observations, long-term patterns of atmospheric activity are still being revealed. Major patterns have been discovered or rediscovered.

Perhaps the most important development in ground-based observations has been in infrared imaging. These observations have been made at several observatories and most regularly, during the *Galileo* mission, at the NASA Infrared Telescope Facility on Mauna Kea. High-resolution images are produced at wavelengths ranging from 1.6 microns to 4.8 microns, which are sensitive to a range of altitudes from the ionosphere (where bright auroral ovals are always visible), through the stratosphere (where the most elevated reflective hazes are picked out in methane absorption bands), to the deep troposphere (where thick cloud layers are seen dark against the thermal emission from deeper in the planet). Images are also made at longer infrared wavelengths, which reveal the contrasted temperature/pressure profiles in the belts and zones, some of which were found to vary with a 4-year period. Io has only recently been resolved from the ground, spectacularly, using adaptive optics at the Keck facility. Monitoring of Io's thermal emissions with smaller telescopes in the infrared has been an important component of measuring changes in Io's volcanic activity.

In the summer of 1994 Jupiter had the public limelight for days as the Shoemaker–Levy 9 comet fragments impacted the planet and every piece of glass around the globe or orbiting the Earth was trained on Jupiter. The observations told us much about the comet, Jupiter and impacts (see Chapter 8) and provided a substantial quantity of data.

Finally, we mention the tools for studying Jupiter that get the least publicity: theoretical and laboratory studies. It is sometimes easy to get caught up in the excitement of glamorous space missions and forget the careful hard work that showed which quantities are the most useful to measure or the models that allow interpretation of spacecraft observations in terms of meaningful physical quantities. Some might go so far as to say that theorists are the unsung heroes of the space age. Similarly, measurements of fundamental properties of materials under planetary conditions are often underappreciated. While the laboratory equipment necessary for, say, ultra-high pressure measurements certainly requires extensive investment, it must be considerably cheaper than deep space missions. Yet, we are just as hampered in our understanding of Jupiter's interior by the lack of data on the behavior of hydrogen as by the lack of space measurements. In fact, we cannot interpret our expensive space measurements without the lab data. Unfortunately, laboratory measurements with planetary or astrophysical applications often fall into the gulf between funding agencies.

1.3 THE JOVIAN SYSTEM

Daunted by the idea of summarizing 700 pages of detailed material spanning the entire jovian system, below we merely outline the structure of the book and mention a few issues – a personal precis of particulars. For simplicity, references to original sources are omitted. Readers are guided to the relevant chapters and their bibliographies. The old fogeys of planetary science will probably not read this section (they will not see their names referenced). Our aim is to show future bright sparks that there are important and interesting challenges to work on – and that this book is *by no means* the last word on Jupiter.

After a review of observational constraints and current theories of the origin of the jovian system (Chapter 2), the book marches from the inside of Jupiter outwards (roughly). Chapter 3 presents observational constraints and quantitative models of the interior structure of Jupiter. Discussions of atmospheric chemistry, structure and dynamics of the jovian atmosphere – from the troposphere to the ionosphere – are presented in Chapters 4 to 9 (including Chapter 8 on the lessons learned from the impacts of Comet Shoemaker–Levy 9). There follows three chapters (10–12) on the "small stuff" of the jovian system: dust, ring material, small satellites

close to Jupiter, the swarms of tiny irregular satellites in the outer reaches of the system as well as their cousins, the Trojan asteroids. The middle third of the book discusses the Galilean satellites. A chapter on their interior structures (Chapter 13) is followed by discussions of the surface properties and geology of each (Chapters 14–17). These latter chapters involve particularly large author teams whose opinions generally span the range of viewpoints on controversial issues. In the case of Europa, the arguments in favor of a very thin, continuously fracturing crust have recently been reviewed by Greenberg *et al.* (2002) and are not prominent in this book. All four satellites are compared in overviews of cratering processes and implications for geological ages of satellite surfaces (Chapter 18). There follows reviews of the satellites' tenuous atmospheres (Chapter 19) and of the consequences for surface chemistry of the satellites being immersed in the intense radiation belts (Chapter 20). The remaining third of the book discusses the vast magnetosphere of Jupiter. The environment surrounding each satellite and the general physical principles of plasma–satellite interactions are presented in Chapter 21, followed by a detailed discussion of the particularly complicated case of Io's interaction with the magnetosphere in Chapter 22. The main features of the magnetosphere – the plasma torus, overall structure, dynamics and aurora – are covered by Chapters 23–26. Chapter 27 reviews the topic of the radiation belts of the inner magnetosphere with a view to quantifying the radiation hazard faced by future low-altitude orbiters necessary for probing the deep interior of Jupiter and the polar magnetosphere, a next phase of Jupiter exploration. Finally, the book ends with two appendices which present spectra, maps and tables of physical parameters.

1.3.1 Interior

Chapter 3 wins the editors' pick of the book. Understanding the interior of Jupiter is of such profound importance that it is worth extracting and repeating chunks of this particular chapter.

"Jupiter mostly contains hydrogen and helium (more than 87% by mass), and as such bears a close resemblance to the Sun. However, the Sun has only 2% of its mass in elements other than hydrogen and helium (the *heavy elements*), whereas Jupiter has between 3 and 13%. The exact amount of these heavy elements in the planet and their distribution are keys to understanding how the solar system formed.

To first order, Jupiter's interior can be described by simple arguments. Jupiter is a hydrogen–helium planet in hydrostatic equilibrium. Its interior is warm ($\sim$20 000 K) because it formed from an extended gas cloud whose gravitational energy was converted into heat upon contraction. (It is still contracting at the rate of $\sim$3 cm per year (30 km per million years) while its interior cools by $\sim$1 K per million years.) This has several important consequences: The relatively warm conditions imply that Jupiter's interior is *fluid*, not solid. The cooling and contraction yield a significant intrinsic energy flux (revealed by the fact that Jupiter emits more energy than it receives from the Sun) that drives convection in most parts of the interior. Convection ensures the planet's homogeneity and generates the observed magnetic field through a dynamo mechanism.

Were the above description entirely true, one would be able to derive the planet's composition directly from the determination of the atmospheric abundances. However, several factors contribute to a more complex picture of Jupiter's interior. Observation of the planet's atmosphere indicates that several major chemical species (such as helium, and water) are partly sequestered into the interior. In the interior, the degenerate nature of the electrons and the Coulomb interactions between ions can be responsible for phase transitions and/or phase separations, synonymous of chemical inhomogeneities. Energy transport is complicated by the possibility of radiative transport of the intrinsic heat flux in some regions, while convection itself is complicated by the presence of molecular weight gradients and by intricate coupling with rotation and magnetic fields. Finally, interior models based on the measurements of the planet's gravity field generally (but not always) require the presence of a central, dense core of uncertain mass and composition."

A simple picture of Jupiter's interior is given in Figure 1.3. The circulation in the lower atmosphere/upper core is terra incognito. For greater detail see Figure 3.5 and the full discussion of methods, data and models presented in Chapter 3, a fascinating mixture of basic geophysics (but arguably simpler than for Earth) blended with astrophysics (but more complicated than a star).

"Despite numerous space missions that have flown past Jupiter, the planet has kept many of its secrets: we do not know what quantities of heavy elements it contains, we do not know if it possesses a central core, and we still have to guess how and where its magnetic field is generated. Progress concerning these key questions will be partly addressed by better experimental results on hydrogen compression to ultra-high pressures. However, improvement in our knowledge of Jupiter's interior will eventually require three key measurements: (i) a determination of the bulk abundance of water; (ii) mapping the planet's gravity field with high accuracy and spatial resolution; (iii) mapping the planet's magnetic field with high accuracy and spatial resolution."

Models give a range in Jupiter's heavy element abundance between 3 and 13% by mass. This is a huge uncertainty. Oxygen is the third most abundant element in the universe and is assumed to comprise half the mass of heavy elements in Jupiter. Up to 20 Earth-masses of oxygen unaccounted for seems a bit of an embarrassment. Pinning down the jovian water abundance – the single most important datum missing in our understanding of solar system formation – needs either a deep probe into Jupiter or careful measurement plus modeling of emission at millimeter wavelengths.

The gravitational and magnetic fields have been mapped for Earth (and to some extend Mars and Venus) using low-altitude orbiters. The strong gravity, radiation hazard, and farther distances from Sun and Earth all make such missions harder at Jupiter, but just a score of passes with low-altitude perijoves would put Jupiter on a par with our 1960s knowledge of Earth (probably enough to keep the modelers busy for another decade). Jupiter has the second most powerful magnetic dynamo in the solar system (after the Sun's). The workings of Jupiter's dynamo probably bears little more than superficial resemblance to Earth's

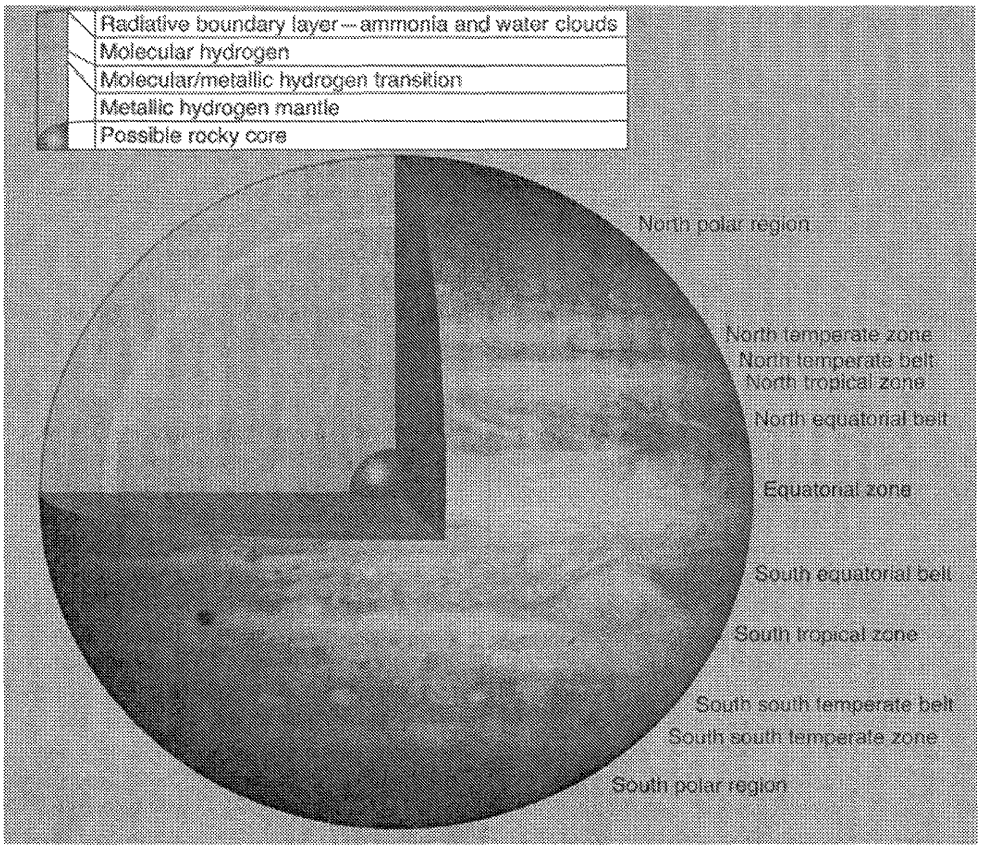

Figure 1.3. Cut-away view of Jupiter showing the internal structure (see Chapter 3). The cloud bands of Jupiter are labeled on an image of Jupiter taken by *Cassini* in November 2000. At the time of going to press a colour version of this figure was available for download from http://www.cambridge.org/9780521035453.

small, iron-core dynamo, but is it necessarily like the Sun's dynamo (confined to a shell in a boundary layer)?

The swirling clouds on the exterior of Jupiter get all the public attention. But some of the keenest cutting-edge issues of planetary science are hiding inside the planet.

1.3.2 Atmosphere

Jupiter is much easier to observe than Saturn, Uranus, and Neptune from Earth, and we knew generations before the first *Pioneer* spacecraft encounter that Jupiter's atmosphere has fast jet streams, dramatic changes in cloud brightness, and in particular a very old circulation pattern in its southern hemisphere called the Great Red Spot (GRS). Even when the first crystal-clear images from *Voyager* came back in 1979 showing elegant, Earth-sized turbulence turning in slow motion alongside jet streams that run so true one can predict jovian weather with just a clock and a ruler, there was the sense that the GRS was special, perhaps unique, because there was no obvious analog on Earth or anywhere else. But, by the end of *Voyager*'s Grand Tour, Neptune's Great Dark Spot was discovered and the status of the GRS changed overnight from one-of-a-kind to ubiquitous. Today, we even find analogs in Earth's oceans, called meddys, which are long-lived anticyclones that persist from one season to the next under the surface of the Atlantic Ocean, and making a GRS in the laboratory or in computer models turns out to be as easy as giving it a try.

Now, the planet itself has reached the status of ubiquity with new extrasolar giant planets being discovered each year. The chemistry and dynamics of Jupiter's atmosphere take on special significance. We do not have to go outside the solar system to benefit directly from detailed analysis – in Chapters 4 through 9 you will see informative comparisons made between the atmospheres of Jupiter and Earth. Some themes jump out on the topic of similarities. A common theme regarding atmospheres is that they have a minimum temperature somewhere in their middle-altitude region, and they are warmer *everywhere* else, reaching extremely high temperatures in the thermosphere, and for a giant planet, extremely high temperature in their interior. Thus, if the minimum temperature happens to be too warm for a particular vapor to condense, then clouds of that species will not form anywhere in the atmosphere, no matter how high or how low one looks. This is the case for methane vapor in Jupiter's atmosphere, and the fact is exploited to give remote-sensing instruments control over what depth they are sampling. Observe Jupiter with a filter that passes only light associated with a methane absorption line and you will see only structure that is above most of the methane and therefore high in the atmosphere; look between the lines and you will probe deeply. Remote-sensing techniques are not described for their own sake in this book, but they are intertwined throughout and especially can be appreciated in practice in Chapters 4 and 5 on the chemical composition of Jupiter's atmosphere and on the structure of the clouds

and haze, and in Chapter 9 on the thermosphere and ionosphere. Interestingly, the remote-sensing techniques and the data from the one in situ probe to date, the *Galileo* probe, both reach down to about 20 bars. Not surprisingly, a recurring refrain from the authors of all the atmospheres and interior chapters is a wish to send a probe down to 50 or even 100 bars.

A major theme that one finds in this book is Jupiter's helium abundance, because it contains information about the formation of the solar system itself as well as history about the planet. Another is the importance of water. It is understood by school children that the weather on Earth is strongly affected by the action of condensing and evaporating water, but it was not until *Galileo* that we had definitive proof that the same holds true on Jupiter. On Earth, maritime barometers are labeled "Stormy" on their low-pressure side, and so it may not come as a surprise that the lightning activity on Jupiter occurs predominantly in the cyclonic regions, so named because they turn in the same direction as the sense of the planetary rotation and hence are low-pressure regions (the other way is anticyclonic, implying high pressure), but nevertheless it *is* somewhat of a surprise, as you will read in Chapter 6. For most of the trace species in Jupiter's atmosphere, except water, the rule of thumb is that their abundance is about three times that seen spectroscopically in the Sun (three times solar), whereas the best one can say for water on Jupiter is that it is extremely heterogeneous – but that is just like on Earth. One gets the sense when reading the atmospheres chapters that Jupiter's meteorology is quite a bit like Earth's in many respects, certainly there is 120 times as much surface area on Jupiter and no surface to stand on (or to collect rain on), but for the most part, Jupiter and Earth are on the same page meteorologically.

One of the major differences that is just now being investigated in numerical weather models for Jupiter is the fact that water vapor is much heavier than jovian dry air (hydrogen and helium), whereas on Earth water vapor is slightly lighter than dry air (nitrogen and oxygen). Consequently, rain should drop like lead shot on Jupiter and after it stops raining, the remaining air is much lighter than before, an effect that is not experienced on Earth. Regarding precipitation, the best terrestrial analog may be rainstorms that occur over deserts in conditions that are so dry that the rain evaporates before it hits the ground. Some of the mystery of Jupiter's dynamic meteorology has lifted like a morning fog. For example, the fact that jovian storms tend to merge on contact is a mathematical consequence of two-dimensional turbulence that has now been well documented in theoretical meteorology and statistical physics. Essentially any source of small eddies will result in large, long-lived vortices, but there remains the fundamental question of how the small eddies are generated – by convection? Shear instability? Both? Other enduring puzzles include what controls the size and shape of the alternating jets streams and the nature of the abyssal circulation.

Most of planetary science relies on passive, remote investigations. In contrast, modern physics is extremely interested in the workings of atomic nuclei, and one of the most successful means of inquiry into the subatomic realm is the not-too-subtle technique of colliding nuclei together as hard as can be managed. We do not usually have the luxury in planetary science of subjecting our objects of interest to such controlled laboratory investigations, but occasionally Mother Nature herself provides such an experiment. For Earth, the June 1991 explosion of Mt. Pinatubo, and, not diminishing the subsequent human tragedy, the rich stratospheric data set that resulted comes to mind. In the context of Jupiter, we refer to the events of July, 1994 when the fragments of Comet Shoemaker–Levy 9 collided at precisely known times and positions with Jupiter, the first ever such planetary collision witnessed by humankind. Chapter 8 is devoted to a summary of what happened and what can been made of it, the effects the collisions bear on topics in chemistry, impact and explosion physics, magnetospheric perturbations, and long-term atmospheric transport and mixing, not to mention a heightened awareness of Earth's vulnerability, especially to uncharted comets.

The region of Jupiter's atmosphere most accessible to remote-sensing techniques is the stratosphere, and in particular the photochemistry of the stratosphere (sneak a peek at Fig. 7.3 and count the "hν" symbols). A central theme that emerges in the discussion of the middle and upper atmosphere is temperature. In Jupiter's stratosphere, the temperatures and composition are now known to be intimately connected. In the thermosphere, a top question is about the temperature itself, why it is hundreds of degrees hotter than was anticipated based on a theory that is adequate for Earth and Titan, namely, a balance between heating by solar extreme ultraviolet radiation and downward thermal conduction. Chapter 9 explores this question and the chemistry of the upper atmosphere in detail. For those interested in the interaction of Jupiter's powerful magnetic field with its atmosphere, this interplay is central to Chapter 9 and the discussion of stratospheric haze in Chapter 5. The million amps coming into the atmosphere along the circuit that threads through Io literally lights up Jupiter's polar sky. That is to say, if you like your hydrocarbons fricasseed and you like to dance under a strobe of X-rays, then Jupiter's middle and upper atmosphere is the place to be.

1.3.3 Satellites

Each of the Galilean satellites exhibits unique characteristics in terms of its surface features, interior structure and evolution. The surface features (discussed in Chapters 14–18) are revealed by images, surface composition comes from spectroscopy and Earth-based radar, while the interior characteristics are inferred from gravity and magnetic field measurements by the *Galileo* spacecraft (Chapter 13). In order to piece together the history of how these bodies derived their current characteristics one needs to "look backward from the present or forward from an assumed past" (to quote Chapter 18). Or, most likely, do some schizophrenic combination of both. And, quite reasonably, one has to make bold assumptions about such things as the composition of the hidden parts of the satellite (e.g., it should comprise the abundant elements of the solar system, i.e., metal, rock, and water are the main constituents of the interiors, though Io has no water) or that the impact flux on the Galilean satellites should not be radically different from that on other objects in the solar system.

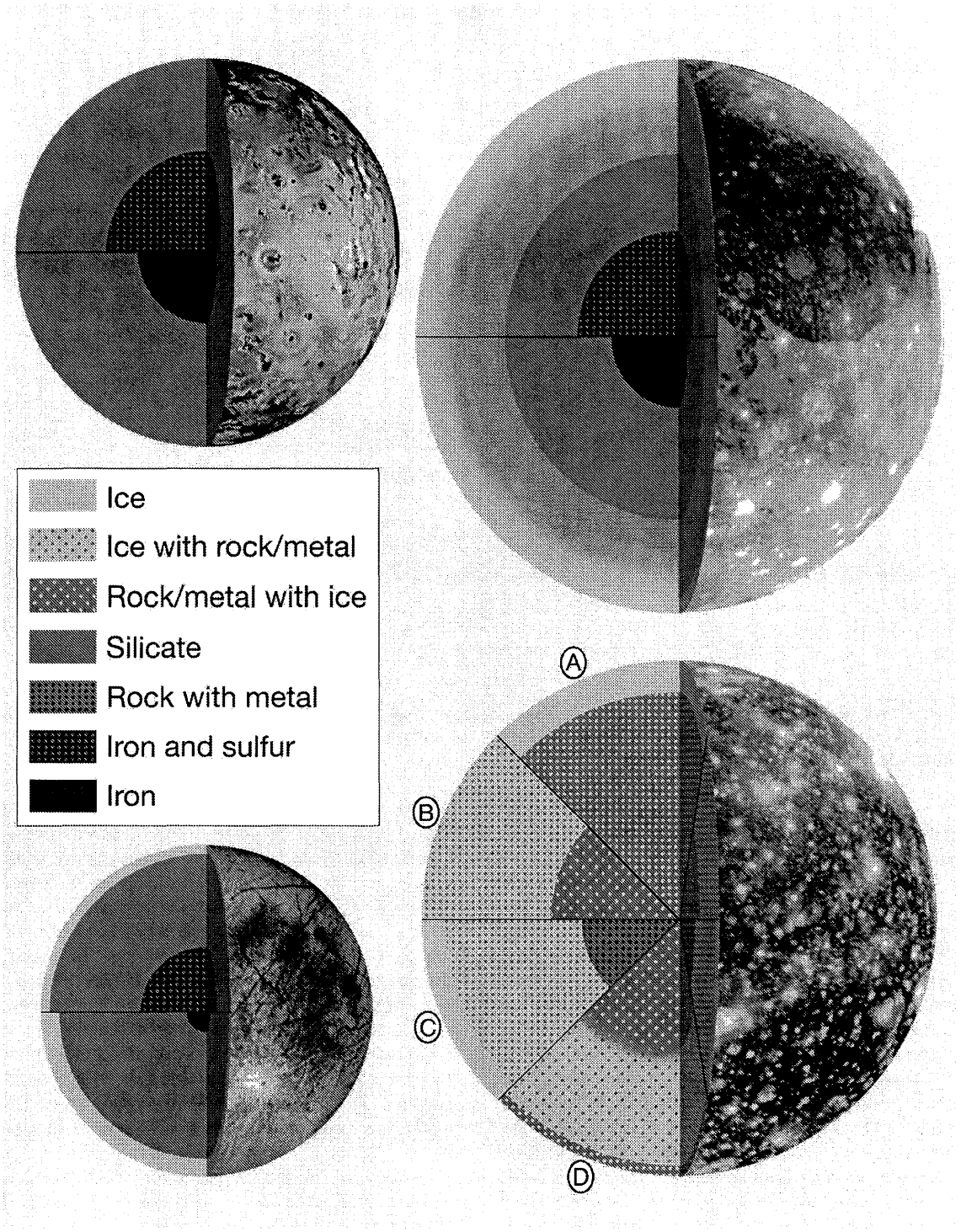

Figure 1.4. Satellite interiors. The satellites are shown at their relative sizes. For each of Io, Europa and Ganymede the upper and lower cases illustrate the range in reasonable models consistent with gravity field and magnetic field measurements by the *Galileo* spacecraft. For Callisto the upper two models (A) and (B) show the range in 2-layer models (Anderson *et al.* 2001), the bottom two (C) and (D) are sample 3-layer models (Mueller and McKinnon 1988, Nagel *et al.* 2003). (See discussion in Chapter 13.)

Io is distinguished as a rocky moon and is the most volcanically active object in the solar system. The current eruption rates are equivalent to the entire body recycling tens of times over the age of the solar system. The high temperatures and eruption rates of lava on Io suggest an analogy to the early Earth. Rock and metal have separated inside Io to form a metallic core and silicate mantle. The high temperature surface lavas (revealed by near-IR spectra), and the density inferred for the mantle are consistent with a mantle comprised of magnesium-rich (mafic) silicates, broadly similar to the mantles of the terrestrial planets. The exact size and composition of Io's core are unknown. The limiting

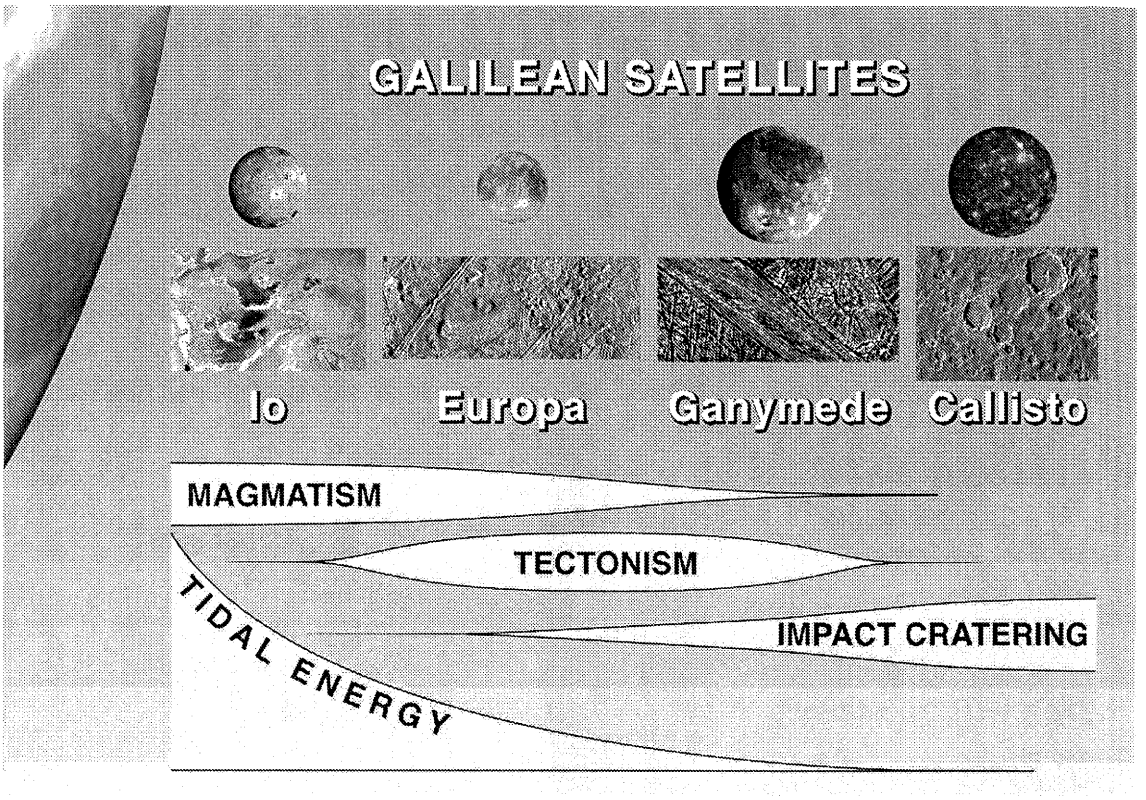

Figure 1.5. Satellite geology. The surfaces of the satellites are revealed by mosaics of images obtained from NASA's *Voyager* and *Galileo* spacecraft. In this view, the sizes of the satellites are scaled to their relative sizes, but the radial distance from Jupiter is not to scale. (Adapted from a figure provided by Ron Greeley, ASU.)

cases of a small, pure iron core and a larger, less-dense core of iron–sulfur mixture are shown in Figure 1.4. The later *Galileo* flybys over polar regions of Io dampened earlier suggestions of Io having a substantial internal magnetic field. Thus, there is no evidence whether or not Io's core is liquid or solid. Of greater importance is the thermal state of the mantle: what is the degree of melting of the mantle, where is the tidal heating dissipated and what is the extent of mantle convection? Io has huge mountains (nearly as high as Mars' Olympus Mons). Yet, the high eruption rate implies large amounts of silicate melt. From what depth and how does the melt reach the surface? How thick is the crust? What is driving the mountain-building on Io? Here we have the most dramatic active geology in the solar system, perhaps related to early terrestrial geology, and we have little idea of how it actually works inside. This is not to imply that scientists studying Io are numbskulls – far from it – Io is proving to be a hard nut to crack.

Europa is primarily a rocky object but has an outer shell of water and a solid surface layer of mostly ice. Mg-rich (mafic) silicates are again assumed to form Europa's mantle, because of internal heating and differentiation. But the size and composition of Europa's metallic core are undetermined as is the case for Io's core. It is interesting that the gravity field measurements can be matched with models of Europa's interior that range from an ~80 km water shell and a larger, Fe+S core to an ~170 km water shell and a much smaller, denser pure Fe core (though the core composition and ice shell thickness are not as linked (causally) as this statement implies). Europa's surface, laced with linear features, indicates a history characterized by tectonic deformation of the ice and local resurfacing by melted and/or ductile ice. The relative paucity of preserved impact craters on Europa suggests a geologically rapid rate of resurfacing. Europa's water shell is mostly ice, but because an induced magnetic field was detected, there must be an inner layer of liquid water, though its depth and thickness are not well constrained. *The* critical issue that everyone wants to resolve, both scientifically in terms of understanding how Europa works as well as practically in terms of the difficulty of reaching liquid, potentially-life-bearing water with exploratory equipment, is the thickness of the solid surface layer. Arguments bearing on this are presented in Chapter 15, briefly in Chapter 18 and in Greenberg *et al.* (2002), but it remains an outstanding question how close to the surface liquid water could be found today.

The interior of Ganymede seems in some ways the best constrained of the four Galilean satellites. The strong magnetic field is (most probably) generated by a dynamo in a liquid iron-rich core. The range of possible core radii (dependent on the proportion of the major likely lighter element, sulfur) is relatively small in terms of total satellite radius (Figure 1.4). Analogy to Earth's dynamo would lead one to guess that the necessary convective motions are driven by condensation of denser, pure iron on to a smaller solid inner core. But the story at Ganymede could well be different. Interior models seem to converge on a thickness of about 900 km (~1/3 radius) for the ice layer above the

(cosmochemically demanded) Mg-rich silicate mantle. Similarly, the liquid water layer necessary for a possibly observed induction signature is of unknown thickness. The pressures deeper in the thick shell imply that the deeper ice is in higher-pressure phases. Ganymede, composed of somewhat less than half water and somewhat greater than half rocky material, shares some attributes with Europa by having extensive tectonic resurfacing of its ice-rich surface, but also has substantial terrains that preserve the record of early cratering in the Jupiter system. Thus, the rate and intensity of internal activity of Ganymede is less than that of Europa.

Interestingly, if the water shells could be removed from Europa and Ganymede, all three inner Galilean satellites would, to first order, seem very much alike in terms of overall size and internal structure. One has to ignore, however, the different levels of tidal heating, and the likely effect of core structure and dynamo generation. With further information, important second-order differences will no doubt alter this simple picture as well.

Finally, Callisto's surface is dominated by impact craters of all sizes; yet, a magnetic signature of induction requires a deep-seated "ocean" of liquid water. However, the large depth of such a liquid layer and low amount of internal energy release have apparently precluded processes leading to resurfacing. Much, perhaps all, of Callisto's deep interior is presumed to be a mixture of rock (with some metal) and ice. The distribution of these materials is not well constrained and there is a wider range of interior models for the interior of Callisto than for the other satellites (Figure 1.4). If one assumes a simple 2-layer model, the gravity data are consistent with a range of models (see Figure 13.7) between (A) a thick (300 km) layer of pure ice over a mixture of ice and rock (density $\sim$2200 kg m^{-3}) to (B) a deep (1250 km) "dirty ice" layer (density $\sim$1500 kg m^{-3}) above a dense ($\sim$3800 kg m^{-3}) rock+metal core. The daring may venture into the arena of poorly constrained 3-layer models, but specific scenarios suggest an interesting range of structures. In Figure 1.4 we show two cases: (C) a small rocky core, ice/rock mantle with ice shell; (D) a primordial rock/ice shell below which rocky "boulders" have "drifted" downward through the ice, leaving a largely ice mantle.

Turning to the relationship between the observed surface features and their implications for current and past geologic processes, Figure 1.5 attempts to show the qualitative relationship of the surface histories of the Galilean satellites to the amount of internal energy generated (primarily) by tidal friction, plus contributions from radioactive decay. Since tidal heating decreases steeply with distance from Jupiter, Io experiences the maximum tidal flexing and is the most active, while tidal energy generated in Europa is substantially less, yet apparently sufficient to produce geologically rapid resurfacing. Ganymede experiences relatively little tidal flexing today, but shows extensive tectonic resurfacing in its early history. Its resurfacing could have been driven primarily by short-lived tidal heating events. Although Callisto apparently had a relatively thin icy lithosphere underlain by water or slush early in its history (as suggested by the presence, albeit in sparse quantity, of palimpsests and large, shallow multi-ringed structures), internal energy was insufficient to lead to subsequent resurfacing. Although this scenario is undoubtedly over-simplified, it provides a unifying theme for the surface histories of all four satellites, and a basis for moving on to more complicated scenarios.

There are plenty of puzzles to work on: in addition to the mechanics of Io's prolific activity and the state of Europa's H_2O layer, there is the issue of how the satellites were formed and evolved to their present states, particularly the conundrum of why Ganymede and Callisto have ended up so different.

The conservative approach is to look at the observational evidence and carefully, slowly piece together a picture of the past based on what is observed at present (and there are huge quantities of important details describe in the chapters of this book, and many more in data only partially analyzed). An alternative approach is to take a stab at what the past might have looked like and test if model predictions lead to anything resembling the present. Temporal variability is the great monkey-wrench in the workings of planetary science. Models of Laplace-like resonances have already shown that at least Ganymede could have moved in and out of resonance (and by implication tidal heating rates have varied wildly with time). The formation and evolution of the Galilean satellites is a major frontier of planetary science. Bright minds are encouraged to be creative.

Some might dismiss the visible skin and tenuous atmospheres of the satellites as the mere icing on the cake. But the processing of volatiles, through volcanism, sublimation, radiolysis, etc. is critical for interpreting the chemical composition of the outer layers and a key part of each satellite's evolution. In Io's case its chemical composition (through loss of sulfur dioxide) is still evolving. Chapters 19 and 20 review the current understanding from observations and modeling of these processes.

1.3.4 Magnetosphere

While particle detectors were originally added to *Pioneer 10* and *11* spacecraft to measure the radiation environment as a safety measure, as we began to explore the giant magnetosphere of Jupiter, it soon became clear that the space environment of the planet had an importance beyond the health of spacecraft. The strong magnetic field of Jupiter links the planet to its moons and rings, taps the rotational energy of the planet, accelerating charged particles, which then bombard the surfaces of satellites and rings or deposit their energy into the atmosphere of the planet, exciting intense aurora. Moreover, the *Galileo* mission has demonstrated how magnetic field measurements can provide critical pieces of information about the internal structure of planetary objects e.g., the giant and tiny dynamos of Jupiter and Ganymede, induction signatures at the other satellites (see Chapters 3, 13 and 21).

The most dramatic magnetospheric phenomenon is the interaction of Io with Jupiter's magnetosphere, which generates a million amps of current, a million megawatts of power, removes about a ton of sulfur and oxygen atoms per second from Io's atmosphere, drives powerful electron beams, and triggers intense radio and ultraviolet emissions (discussed in Chapters 22 and 23). Several decades of study and at least a dozen PhDs have yet to properly model this interaction. The problem is inherently circular: the extent to which the impinging plasma flow is deflected around Io depends

on the amount of collisional ionization of Io's atmosphere, and the extension of Io's atmosphere out into the magnetosphere depends on collisional heating by the impinging plasma. Numerical calculations have been moderately successful in simulating the electrodynamics (Chapter 22) and in modeling the neutral atmosphere (Chapter 23), separately. The coupled problem remains an untamed computational multi-headed monster.

There is considerable debate about how much plasma is produced very close to Io or farther away via ionization of Io's extended neutral clouds (and Chapter 23 discusses how the two cases have important consequences for the interaction process and for torus energetics). But there is no question that Io is the underlying source of the ~ton per second of sulfur/oxygen plasma that fills the giant magnetosphere of Jupiter, stretching for ~100 jovian radii in the solar direction and out to at least the orbit of Saturn, >4 AU downstream in the solar wind. Figures 24.1 and 25.1 illustrate what this enormous, tenuous object looks like, Chapter 24 describes its structure and Chapter 25 discusses its dramatic variability. Figure 27.1 includes a close-up view of the inner magnetosphere and hazardous radiation belts.

The first-order description of the dynamics of Jupiter's magnetosphere entails magnetic field coupling of the iogenic plasma in the magnetosphere to Jupiter's ~10-hour rotation rate. Stresses on the magnetosphere (such as production of new ionization or radial transport of plasma) drive electrical currents along the magnetic field to Jupiter's ionosphere. If the coupling were perfect between the magnetosphere and the ionosphere, the momentum of Jupiter's flywheel would be transferred to the plasma which would then be accelerated to full corotation. The measurement of deviations from full corotation in the magnetosphere, currents flowing to/from the planet, and the auroral emissions are all indications of imperfect coupling. This paramount issue of ionosphere–magnetosphere coupling is discussed from different angles in Chapters 24, 25 and 26. From spacecraft sitting close to Jupiter's equator and images of the aurora in Jupiter's upper atmosphere we can only speculate how these regions are connected. The only way we will really begin to understand ionosphere–magnetosphere coupling at Jupiter is the way we have tackled it at Earth – by measuring the particles and fields over the polar regions.

The second fundamental issue of Jupiter's magnetosphere is what drives its variability. Certainly the outer regions "breath" in and out in response to changes in the solar wind. But are the observed disruptions driven internally (say, by increase plasma production at Io) or are they driven by the solar wind interaction with the magnetosphere (the cause of major magnetic storms at Earth)? The reason why 6 spacecraft flybys and 34 *Galileo* orbits have not decided this basic question is that with a single spacecraft flying through a structure, it is ambiguous whether an observed change in a local property is due to temporal or spatial variability (or both). At Earth this issue is being addressed with multiple spacecraft, 3, 4 or more, piecing together the jigsaw. There is even discussion of putting a constellation of 100 mini-spacecraft throughout the Earth's magnetosphere. Just a couple, or maybe 5 (small ones), at Jupiter would move us a long way forward.

Finally, it should be remembered that the magnetosphere has important effects on more substantial, more tangible bodies – the planet's atmosphere, satellites and debris:

- The energy deposited in the auroral regions of Jupiter has dramatic atmospheric effects. The local changes in temperature, composition and electrical properties of the upper atmosphere produced by auroral precipitation drive large-scale winds that affect the upper atmosphere (discussed in Chapter 9). Similarly, changes and motions in the atmosphere are physically coupled back to the magnetosphere via electric fields generated by these winds and through the generation of energetic plasma scattered or accelerated back into the magnetosphere.
- All objects orbiting Jupiter are subject to substantial radiation doses, and the closer to Jupiter the more intense the dose. When ices and rocks are bombarded by energetic particles the molecular structures can be rearranged, chemical bonds changed, and material sputtered from the surface (Chapter 20). Thus, surfaces of materials in the jovian system have been altered over the history of the solar system by the radiation environment in which they are embedded.
- Dust grains become electrially charged when embedded in a plasma. Electrodynamic forces on charged dust grains compete with gravity for control of the dynamics of dust grains. Chapter 10 discusses how dust generated in meteoroid impact of satellites, ring particles or even Io's giant volcanic plumes is transported by electrodynamics through the jovian system and out in streams into interplanetary space.

1.3.5 Origin of Jovian Planetary Systems

The main content of this book begins with a discussion of the origin of Jupiter in Chapter 2 (and quotes in this section are from that chapter). Perhaps it might be better left to the end. First tackle all the details of how the system *is* and then consider how it got to be that way. Naturally, we have the least information about the past. But, as Chapter 2 elaborates, tightening observational constraints will ultimately eliminate models of giant planet formation. To eventually combine information about Jupiter's interior (Chapter 3), satellite interiors (Chapter 13), satellite histories (Chapter 18) and the evolution of "small stuff" (Chapters 10–12) into computational simulations of solar system formation remains a formidable interdisciplinary challenge.

To put a major debate of the past decade into a nutshell, two theories for giant planet formation have been competing for supremacy: gravitational disk instability vs. nucleated instability. The version of nucleated instability for Astronomy 101 goes as follows: As the disk of solar nebula material cooled, materials began to condense, clump together and "snow ball" into substantial objects, let's call them protoplanets; with oxygen being the third most abundant element, H_2O was the most important ice and the corresponding "frost line" in the nebula disk was at about 3 AU, beyond which giant protoplanets formed; as the mass of these snow balls accreted to a critical mass of a few Earth-masses, they began to gravitationally attract hydrogen; since hydrogen is by far the most abundant element, they quickly became giant planets. For comparison, gravitational disk instability is where "protoplanetary disks undergo self-compression in a dynamically unstable situation." That is, the solar nebula

forms homogeneous, gaseous clumps held together by self-gravity, and quickly enough that they do not shear apart under orbital motion of the disk material around the central star. The problem is that models that add hydrogen and helium to the total mass of current planets (bringing the mix up to solar composition) are gravitationally stable. Adding more mass brings the nebula to the threshold of instability, but the disk must be cold. And if the disk is cold, we are back to snow, and snowlines, and protoplanets.

Chapter 2 concludes "both the interior modeling and compositional data have proceeded to the point where we can probably rule out the gravitational disk instability mechanism in favor of the nucleated instability mechanism for Jupiter, and by reasonable extension, for Saturn." Three dense pages of discussion and the tentative wording of this conclusion indicate that the debate was not a slam-dunk. And some may not think it completely over.

But over the past few years attention has been intensifying on how to make not just Jupiter but also the satellites. There are reasons (described in Chapters 2 and 13) to consider the satellites were formed from a disk nebula around, more or less, the tail end of planet formation. The big problem has been that if you take a minimum mass nebula (adding solar-abundance quantities of hydrogen and helium to total mass of current satellites), the timescale for the cloud to cool (via radiation) and condense is too long (~million years). That is, the timescale for a satellite-sized body to accrete from condensed matter is much shorter (~1000 years) than timescales for the material to condense. Furthermore, any small clumps of material that managed to form would suffer the gas drag of the nebula against their orbital motion and they would tend to be swept up into Jupiter. (For simple calculations of these timescales see textbooks such as Lissauer and dePater 2002, Hartmann 1999.) Various ingenious schemes to overcome this obstacle are described in Chapters 2 and 13. But the current trend is to favor the idea of initially having a much less massive disk (which can radiate, cool and condense rapidly enough to beat the (reduced) gas drag) and bringing in more material, bit by bit, from the solar nebula. But alternative views exist and the matter is far from settled.

The devil is always in the details, and these are far from worked out. As Chapter 2 concludes, "The hydrodynamical modeling of the accretion of Jupiter, of the evolution of the surrounding nebular environment, and of the formation of satellites – all separate efforts – seem to be pointing in promisingly parallel directions, but the highly desirable coupling of these to each other and to the details of the chemistry probably will have to await the next generation of enhanced computational power and speed." Moreover, there is the issue (mentioned in Chapter 13) of whether one can make all the Galilean satellites in their current location, or do their varied characteristics and checkered histories require substantial orbital evolution?

Furthermore, as if the theoretical challenges of forming our own solar system were not enough, "the detection of over 100 extrasolar giant planets has created a new conundrum. Are these bodies the result of the same formation process that created Jupiter and Saturn, an essentially *planetary formation* that involved the accretion of solids prior to and throughout the relatively slow capture of gas? Or are these bodies the low-mass end of a *stellar formation* mechanism in which direct disk collapse rapidly produces dense self-gravitating clumps throughout the disk, some destined for ejection, others to survive the resulting disruption of the massive disk?"

There is perhaps a tendency amongst those of us who were involved in the heady discoveries of *Voyager* and *Galileo* to think of Jupiter as our special planet, our piece of turf to be defended, our own sand box to play in. As we write this book, summing up the early exploratory phase, we recognize that new talent is needed to tackle the much harder task of explaining not only how Jupiter got to be this way but also the similarities and differences between our Jupiter in our solar system and the hundreds of other jovian planets in our cousin solar systems. We may have been the early birds that got the worms but the next generation should remember that it's the second mouse that gets the cheddar.

1.4 OUTSTANDING QUESTIONS

Most chapters conclude with a list of outstanding questions, intended to summarize the open issues and stimulate future research. From these lists we have distilled the following über-questions:

- What is the interior structure of Jupiter? Is there a core? Where exactly is the magnetic field rooted and how does the dynamo operate?
- How is water distributed in Jupiter's atmosphere? In its interior? What is the total amount?
- What shapes and limits the jet streams?
- How do the cloud-top circulations transition into the abyssal circulation? How do the fluid motions behave across the molecular–metallic transition of hydrogen?
- What is the range of possibilities for atmospheric chemistry and dynamics of extrasolar giant planets?
- What are main geological structures and processes on Io? Where is the tidal energy dissipated? How does molten lava reach the surface? What makes the high blocky mountains? How deep are the mantle motions that drive the geology?
- How thick is Europa's solid, outer layer and what is the composition of the global ocean underneath? How close does liquid water get to the surface?
- What drives Ganymede's magnetic field? Why don't the other satellites have internal magnetic fields?
- Why is Callisto so different from Ganymede? Should we assume that the reason Callisto and Ganymede had divergent histories is solely the consequence of the role of tidal heating, or are there viable alternative explanations (such as accretion dynamics)?
- What happens in the polar regions of the magnetosphere? This is not just exploring "terra incognita" for its own sake but critical for understanding the coupling of the planet's abundant angular momentum to the vast surrounding volume dominated by Jupiter's strong magnetic field (and how many astrophysical objects likewise shed their momentum).
- How did the jovian system form? How did the four very different Galilean satellites form? How close to/far from their current locations were they formed? At what stage in formation of jovian system did the satellites form?

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