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 ∼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 ∼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 $\times$ 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,

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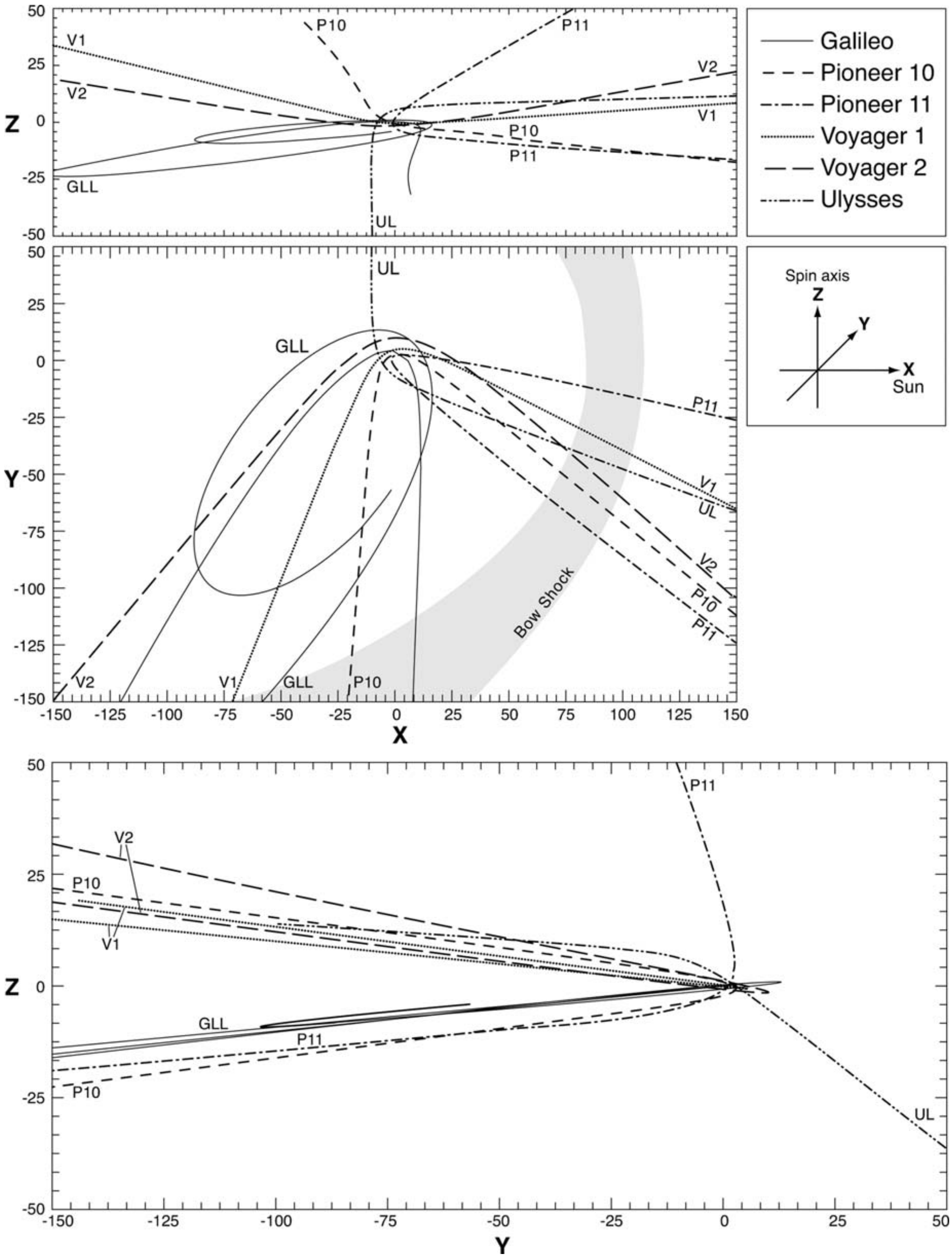

Figure 1.1. Trajectories of the five spacecraft flybys and the first orbit by *Galileo*. The co-ordinate system is centered on Jupiter and has the x axis pointed towards the Sun, the z axis is pointed along Jupiter's spin axis and the y axis makes a right-handed set (and points towards Jupiter's dusk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

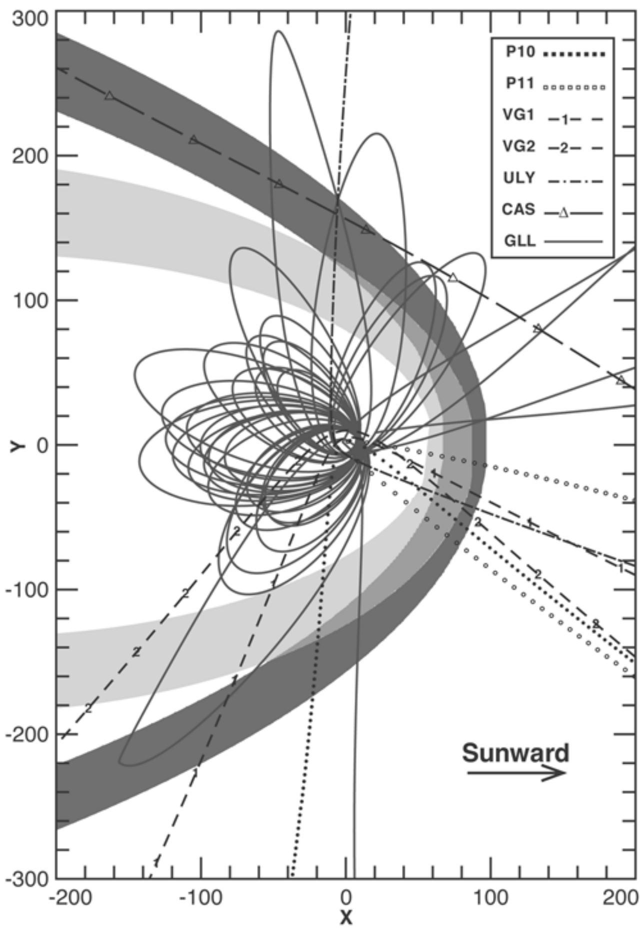

Figure 1.2. Trajectories of the the five spacecraft flybys and all 34 orbits of *Galileo* in the x–y plane of the co-ordinate system shown in Figure 1.1 (units in jovian radii). The bow shock and magnetopause locations are shown as shaded regions and are derived from models based on statistical fluctuations 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