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Introduction

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1.1 Comparative heliophysics

Our knowledge of conditions – past, present, and future – throughout the solar system is rapidly advancing. We can specify the details of the evolution of the Sun, and can represent the conditions of its magnetic activity over time with fair certainty. We have explored – both remotely and in situ – many of the "worlds" throughout the solar system, from Mercury to Pluto, including asteroids and comets. Along with an appreciation of the diversity of conditions in space around all these environments comes the realization that the conditions here on Earth are remarkably just right for the only world that we know to sustain life. Specifically, Earth is in an orbit that has kept it within the range in orbital distances within which the planet has maintained liquid water at its surface throughout the past several billions of years. It orbits far enough from the Sun that tidal forces could not lock Earth's rotation to its orbital motion, thus allowing solar irradiance to be effectively distributed over the sphere on the relatively short time scale of the terrestrial day. Moreover, since the Late Heavy Bombardment some 4 billion years ago, Earth has received limited environmental debris (asteroids, comets, ...). The impacts of the Sun's magnetic activity on the Earth have also been relatively benign, without overly detrimental effects of flares and coronal mass ejections. Moreover, the Earth is shielded well enough from galactic cosmic rays by both solar wind and terrestrial magnetism. And then there are the added conditions related to the internal properties of the planet that contribute to its ability to sustain life, including plate tectonics and dynamo action. In short, the Earth's characteristics are "just right" (see, e.g., Ch. 4 in Vol. III, and Ward and Brownlee, 2000, and also Vidotto *et al.*, 2014, and references therein, for select topics on cool stars and space weather and planetary habitability).

All of these circumstances conspire to a relatively stable environment, both in terms of the terrestrial climate and in terms of what we nowadays call "space weather". In order to understand the processes that create these environmental conditions, and to appreciate the influences of space weather on the planet that is our only known compatible habitat, we need to advance a field of science called "heliophysics". Heliophysics is the field that encompasses the Sun–solar system connections, and that therefore concentrates on the Sun and on its effects on Earth, the other planets of the solar system, and the changing conditions in space. As such, heliophysics has to cover an extraordinary range of topics, essentially being equivalent to ecology in attempting to describe a complex web of often non-linear interactions that certainly do not stop at the boundaries of the traditional scientific (sub-)disciplines or at the perimeters of domains maintained by funding agencies.

Heliophysics tackles the workings of an interconnected system of magnetic field and plasma that couples the Sun with her entourage that forms the solar system. Indeed, it is the commonality of plasma physics of this solar system family that has enabled the amalgamation of solar physics, cosmic ray physics, solar wind physics, magnetospheric physics, ionospheric physics, and more into heliophysics. What plasma physics does on the Sun to generate huge bursts of energy as photons, solar wind structures, and energetic particles, plasma physics also does on the planets, in effect protecting them from these energetic outbursts via magnetospheres and ionospheres, whose activity at times interferes with our technological tools on and near Earth.

The "habitable zone" of a planetary system is commonly defined loosely as the range of distances of planets relative to their parent star within which water can exist at the planet surface as a liquid. But from a heliophysics point of view, the definition of "habitable" also includes how well the planet is shielded from what the nearby star or the surrounding galaxy throws at it. In that sense, a habitable planet is one that provides a magnetic shield that stalls and deflects the energetic solar wind structures and cosmic rays respectively. The upper atmosphere of a habitable planet similarly plays the role of absorbing harmful radiations, in the process creating the planet's ionosphere. The ionospheric shield also safely dissipates the energy carried by huge currents generated in the magnetosphere as the planet's magnetic field stalls the solar wind structures. Heliophysics can thus be viewed as the integrating science that will determine which exoplanets are habitable to a technologically advanced life form. In fact, the aspects of this definition of "habitable planet" require understanding of space weather.

This is the fourth volume in a series that introduces the rich spectrum of topics covered in heliophysics (see Table 1.1 for the volume titles and Table 1.2 for thematically sorted chapter titles). Where the preceding three volumes focus on describing and understanding the conditions in our local cosmos, particularly where the Sun and its planets are concerned, here we take a somewhat different perspective. The focus of this volume is what we can learn from other stars, from

Table 1.1 *Titles of the volumes in the Heliophysics series. References in this volume to chapters in other volumes use the numbering as in this table.*

Volume	Title and focus
I	Plasma physics of the local cosmos
II	Space storms and radiation: causes and effects
III	Evolving solar activity and the climates of space and Earth
IV	Active stars, their astrospheres, and impacts on planetary environments
V[a]	Space weather and society

[a] Available online at http://www.vsp.ucar.edu/Heliophysics/science-resources-textbooks.shtml

Table 1.2 *Chapters and their authors in the Heliophysics series sorted by theme (continued on the next page), not showing introductory chapters.*

Universal and fundamental processes, diagnostics, and methods	
I.2. Introduction to heliophysics	*T. Bogdan*
I.3. Creation and destruction of magnetic field	*M. Rempel*
I.4. Magnetic field topology	*D. Longcope*
I.5. Magnetic reconnection	*T. Forbes*
I.6. Structures of the magnetic field	*M. Moldwin* et al.
II.3 In-situ detection of energetic particles	*G. Gloeckler*
II.4 Radiative signatures of energetic particles	*T. Bastian*
II.7 Shocks in heliophysics	*M. Opher*
II.8 Particle acceleration in shocks	*D. Krauss-Varban*
II.9 Energetic particle transport	*J. Giacalone*
II.11 Energization of trapped particles	*J. Green*
IV.11 Dusty plasmas	*M. Horányi*
IV.12 Energetic-particle environments in the solar system	*N. Krupp*
IV.13 Heliophysics with radio scintillation and occultation	*M. Bisi*
Stars, their planetary systems, planetary habitability, and climates	
III.3 Formation and early evol. of stars and proto-planetary disks	*L. Hartmann*
III.4 Planetary habitability on astronomical time scales	*D. Brownlee*
III.11 Astrophysical influences on planetary climate systems	*J. Beer*
III.12 Assessing the Sun-climate relationship in paleoclimate records	*T. Crowley*
III.14 Long-term evolution of the geospace climate	*J. Sojka*
III.15 Waves and transport processes in atmosph. and oceans	*R. Walterscheid*
IV.5 Characteristics of planetary systems	*D. Fischer & J. Wang*
IV.7 Climates of terrestrial planets	*D. Brain*

Table 1.2 *(Continued from the previous page)*

The Sun, its dynamo, and its magnetic activity; past, present, and future	
I.8. The solar atmosphere	*V. Hansteen*
II.5 Observations of solar and stellar eruptions, flares, and jets	*H. Hudson*
II.6 Models of coronal mass ejections and flares	*T. Forbes*
III.2 Long-term evolution of magnetic activity of Sun-like stars	*C. Schrijver*
III.5 Solar internal flows and dynamo action	*M. Miesch*
III.6 Modeling solar and stellar dynamos	*P. Charbonneau*
III.10 Solar irradiance: measurements and models	*J. Lean & T. Woods*
IV.2 Solar explosive activity throughout the evol. of the solar system	*R. Osten*
Astro-/heliospheres, the interstellar environment, and galactic cosmic rays	
I.7. Turbulence in space plasmas	*C. Smith*
I.9. Stellar winds and magnetic fields	*V. Hansteen*
III.8 The structure and evolution of the 3D solar wind	*J. Gosling*
III.9 The heliosphere and cosmic rays	*J. Jokipii*
IV.3 Astrospheres, stellar winds, and the interst. medium	*B. Wood & J. Linsky*
IV.4 Effects of stellar eruptions throughout astrospheres	*O. Cohen*
Dynamos and environments of planets, moons, asteroids, and comets	
I.10. Fundamentals of planetary magnetospheres	*V. Vasyliūnas*
I.11. Solar-wind magnetosphere coupling	*F. Toffoletto & G. Siscoe*
I.13. Comparative planetary environments	*F. Bagenal*
II.10 Energy conversion in planetary magnetospheres	*V. Vasyliūnas*
III.7 Planetary fields and dynamos	*U. Christensen*
IV.6 Planetary dynamos: updates and new frontiers	*S. Stanley*
IV.10 Moons, asteroids, and comets interact. with their surround.	*M. Kivelson*
Planetary upper atmospheres	
I.12. On the ionosphere and chromosphere	*T. Fuller-Rowell & C. Schrijver*
II.12 Flares, CMEs, and atmospheric responses	*T. Fuller-Rowell & S. Solomon*
III.13 Ionospheres of the terrestrial planets	*S. Solomon*
III.16 Solar variability, climate, and atmosph. photochemistry	*G. Brasseur* et al.
IV.8 Upper atmospheres of the giant planets	*L. Moore* et al.
IV.9 Aeronomy of terrestrial upper atmospheres	*D. Siskind & S. Bougher*
Technological and societal impacts of space weather phenomena	
II.2 Introduction to space storms and radiation	*S. Odenwald*
II.13 Energetic particles and manned spaceflight	*S. Guetersloh & N. Zapp*
II.14 Energetic particles and technology	*A. Tribble*
V.2 Space weather: impacts, mitigation, forecasting	*S. Odenwald*
V.3 Commercial space weather in response to societal needs	*W. Tobiska*
V.4 The impact of space weather on the electric power grid	*D. Boteler*
V.5 Radio waves for communication and ionospheric probing	*N. Jakowski*

other planetary systems, and from non-planetary bodies within the solar system. With this, we attempt to open up a view of what could be termed "comparative heliophysics" that aims to learn about our local cosmos by looking beyond it, and in doing so also enables the converse.

Where experimental physics offers researchers the possibility to set key parameters to desired values, albeit to a range of values generally limited by the instrumental setup, heliophysics does not offer that valuable option to study the dependence of processes on any one of the environmental parameters. We cannot change the mass, age, spin rate, or chemical composition of the Sun or of the Earth. Nor can we change the distance at which our home planet orbits its parent star. This is a major complication not only in quantifying how these and other parameters affect the Sun–Earth connections, but even in determining which parameters are of critical importance in shaping the climate of space throughout the solar system.

As our observational technologies advance, and as our observational archives grow, however, even heliophysics can approximate an experimental science by looking not only at the present-day Sun, Earth, and other planets, but by studying conditions of a multitude of Sun-like stars, of the other bodies within the solar system, and increasingly of other planetary (or exoplanet) systems.

1.2 Exoplanets

Until the mid 1990s, no planets were known to orbit Sun-like stars other than those orbiting the Sun. Within the following two decades, our capabilities and knowledge advanced to the estimate – using statistical arguments based on the observed sample – that most stars that we see in the sky have a planetary system with one or more planets; even binary stars show evidence of circumbinary planets in at least 1 in 10 cases (note that roughly 1 in 2 "stars" in the sky is actually a binary system composed of two, often quite dissimilar, stars). Chapter 5 outlines the observational instrumentation and techniques that enabled this dramatic shift in our knowledge.

Instrumental limitations and the properties and orbital parameters of exoplanets have thus far kept the number of detected exoplanet systems at several thousand. But that number suffices to enable us to learn much about the formation and evolution of planetary systems and their planets, as discussed in Ch. 5.

For example, the combination of observations and numerical experiments suggests that gas giants accumulate up to a few hundred Earth masses of material – first the solids and then increasingly rapidly gases – within a matter of a few million years. This process is aided in its efficiency by the migration of growing planets within the young planetary system: planets are not bound to their initial orbits, but can migrate either inward or outward, subject to gravitational interactions, thus having access to a large volume of the primordial disk from which to collect material. Interestingly, it appears that it is the very collection process of matter onto the growing planet that causes mass redistributions within the disk so that their tidal effects can make planets migrate, particularly if other planets are forming elsewhere in the system, while the gravitational coupling between multiple young planets in eccentric orbits can scatter bodies around (both in distance from their central star and in orbital inclination).

Planets may form into three distinct categories: terrestrial planets with radii up to about $1.7R_\oplus$, dwarf gas planets up to about $4R_\oplus$, and giant gas planets beyond that. Their radii and their atmospheric constituents appear to reflect their migration history within the primordial disk, but the details of these dependencies continue to be uncovered. The lower-radius group looks to be mostly rocky, while the intermediate-radius group shows evidence of an increasingly large gaseous envelope with increasing radius.

1.3 Cool stars and their space weather

Many stars exhibit signatures of stellar magnetism resembling what we see on the Sun. Even if spectroscopy does not provide direct evidence for a complex, evolving surface magnetic field, many stars do display one or more of a variety of tell-tale signatures: cool starspots that modulate the brightness as the stars rotate and the spots evolve, a warm chromosphere enveloping the star, a hot corona glowing in the EUV or in X-rays, or flaring. All this activity is rooted in the stellar dynamo process (see, e.g., Chs. 3 and 4 in Vol. I, and Chs. 2, 5, and 6 in Vol. III) that converts mechanical energy in 3D convective plasma motions of sufficient complexity into electromagnetic energy, directed into large-scale organization by the Coriolis forces acting within the rotating star.

Magnetically dominated phenomena in the atmospheres of stars bear similarities to what we observe on the Sun in a class of stars that we refer to as "cool stars". Whether old or young, more or less massive than the Sun, these stars have two characteristics that set them apart from other stars. The first, as can be inferred from their name, is that they all have surface temperatures that are relatively low, making them yellow, orange, or red in appearance. It is another, related common characteristic that is directly responsible for making all cool stars exhibit solar-like magnetic activity: they all have a zone that extends up to their surfaces – i.e., an envelope – in which convective energy transport (through overturning bulk plasma motions) carries most of the energy outward.

This convection zone may be a shallow layer (as in mid-F type main-sequence stars of 1.2 solar masses) around a "radiative interior" (in which energy is transported primarily by a random walk of photons) or it may reach all the way to the very center (for main-sequence stars much cooler than the Sun, of spectral type late-M or cooler, around 0.3 solar masses or less). In the long-lived phase of stellar adulthood – when we characterize them as "main-sequence stars" – stellar mass may be used as differentiator: stars with masses below roughly 1.2 solar masses are cool stars. But stars in their infancy (prior to reaching hydrostatic stability that follows initiation of nuclear fusion of hydrogen) or in their old age (after running out of most of the fusible hydrogen) have convective envelopes regardless of their mass, making it unambiguously clear that it is the convection that powers the stellar dynamo. We know from stellar population studies that the characteristics of the convective motions and their response to stellar rotation (through the Coriolis force) are the controlling parameters that set stellar magnetic activity levels.

The evolution of stars like the Sun and of their magnetic activity was summarized in Chs. 2 and 3 of Vol. III (for other introductory discussions of solar and stellar magnetism, see, e.g., Schrijver and Zwaan, 2000, and Reiners, 2012). In this volume, Ch. 2 uses observations of stellar flaring to piece together the history of impulsive activity of the Sun from its pre-main-sequence phase to old age. Observations of many stars and with different instruments sensitive to different energy ranges along the electromagnetic spectrum suggest that observable stellar flares (which are typically much more energetic than even the largest solar flares simply because smaller ones hide below present-day detection thresholds or within the quiescent background glow of the corona) have many properties in common, supporting the assumption that stellar and solar flares share the basic picture that was developed for magnetically driven, reconnection-powered solar impulsive events. Although that general picture appears to be widely applicable, we note that observations of stellar flares, and indeed also of solar flares, generally occur in narrow spectral bands that can range from hard X-rays to radio, or in broad spectral windows without spectral information. The result is that it remains a challenge to put solar and stellar flare observations on a common energy scale (preferably the bolometric scale that measures all of the temporary, sudden increase in photon output from stars that is the definition of flaring; see, e.g., Schrijver *et al.*, 2012).

The young Sun, in the first hundreds of millions of years of its main-sequence life, would most likely have exhibited flaring with energies exceeding 100 up to perhaps 1000 times the total energy involved in the largest recent flares, and would have displayed even these major events as frequently as roughly once a week. Over time, the frequency of flaring dropped sharply as the Sun lost angular momentum through the magnetized solar wind, a process that continues today albeit at a much reduced rate. This decrease in flare frequency would have been rapid over the first billion years or so of solar history, likely having slowed considerably over the most recent few Gyr. Whether there is an upper cutoff energy to solar flares that might also have dropped over time remains to be established: we do not know if the present-day Sun can still generate such enormous flares, albeit at vastly reduced frequency. On the one hand, we have no evidence that it did so in any available record, be it written or geological. On the other hand, there are observations of stars that look to be quite like the Sun in terms of internal structure and rotation rate that have been observed to produce flares with energies hundreds of times larger than the largest flare recorded for the Sun in the past half century (see Sect. 2.2.3, and Schrijver and Beer, 2014).

Binary stars (in particular the tidally interacting compact ones) provide yet another experimental environment, both on dynamo activity and on flaring: in such stars, flare energies can reach up to 100 000 times those seen for the most energetic solar flares, possibly through tidal effects on dynamo action or through magnetic coupling between the stars. Although such large flares attract observers for the obvious reason that they stand out from the background emission of the stellar system and that they occur so often that they are readily captured within the limits of observing windows, it remains to be seen whether such enormous energies could ever have been released from flaring from the single star that we call the Sun at any phase of its evolution.

Although energetic flares can be observed on other stars throughout the electromagnetic spectrum, there are no unambiguous indicators of coronal mass ejections or energetic particle populations in the astrospheres of those stars; for those properties, we need to rely on solar and solar-system observations combined with numerical experimentation at least until detection techniques are developed that are far more sensitive than we have access to today.

1.4 Astrospheres, stellar winds, and cosmic rays

The interaction of the solar wind and the interstellar medium is discussed in Ch. 3. One of the effects of the solar wind is that Galactic Cosmic Rays (GCRs) are held at bay fairly effectively (e.g., Ch. 9 in Vol. II, and Ch. 9 in Vol. III). Changes in the solar wind and its embedded magnetic field over evolutionary to short-term time scales are associated with changes in the spectrum of the GCRs that can penetrate into the solar system to reach Earth orbit, because they affect the propagation of the GCRs into the inner solar system and also because these changes move the very boundary of the solar wind from where GCRs start their random-walk diffusive penetration of the solar system.

Over the billions of years in the history of the Sun, the solar system will have encountered very different interstellar medium (ISM) environments. ISM density contrasts reach up to a factor of a million, with densities ranging from some $0.005\,\mathrm{cm}^{-3}$ in tenuous, warm clouds to $10^4\,\mathrm{cm}^{-3}$ in dense, cool molecular clouds. Increasingly dense ISM environments would decrease the size of the heliosphere by pushing the heliopause – that separates the solar wind from the ISM with its GCRs – inward. Chapter 3 discusses how the heliosphere would vary with the properties of the solar wind and of the interstellar medium. Models suggest that the Earth would be shielded from the full effect of GCRs under almost all circumstances. Even at an ISM density 100 times higher than in the local interstellar cloud (LIC), the termination shock (TS) would still be at about 10 Sun–Earth distances (astronomical units, or AU). Only at a density of multiple hundreds of times that in the LIC would the TS move inside of the Sun's present-day habitable zone (cf., Ch. 4 in Vol. III), exposing Earth to the full intensity of GCRs as well as to interstellar dust. A nearby supernova would do the same, plus expose Earth to the remnants of the stellar explosion themselves; this may have happened a mere 3 Myr ago, leaving a signature in the ^{60}Fe radioisotope in the Earth's crust (see Sect. 3.5).

When the Sun was younger, it most likely had a larger mass loss. How much larger remains to be established, but observations of Sun-like stars (Sect. 3.7.2) suggest the mass-loss rate may have been at least some 50 times higher than at present. For the present ISM conditions, that would have meant a heliosphere some seven time larger, with correspondingly much lower GCR intensities (cf., Ch. 11 in Vol. III). In the distant future, with weakening solar activity, the Sun's mass-loss rate is expected to decrease by a factor somewhere between 4 and 7 prior to the beginning of the subgiant and giant phases (Eq. (3.2)), and the heliosphere will correspondingly gradually shrink to about half its present size (to roughly Pluto's orbital radius; assuming present-day ISM conditions), and the GCR population in the inner solar system will thereby gradually increase.

Chapter 4 shows how models suggest that the GCR intensity around 1 GeV has likely increased by more than a factor of 100 since the Archean era (ending some 2.5 billion years ago) after the Late Heavy Bombardment when evidence for single-celled life is first seen on Earth (cf., Ch. 4 in Vol. III). Whether energetic particles originating from the more active young Sun would have compensated for the low GCR intensities around the young Earth remains to be seen: although young stars flare much more intensely and frequently (Ch. 2), we simply do not know enough about any associated coronal mass ejection (CME) activity to usefully constrain "SEP" events for the young Sun: whereas radio observations of stars may give some information on energetic particles trapped within coronae, no techniques are currently available to reveal energetic particles moving outward through astrospheres.

1.5 Astrophysical dynamos and space weather

Computer simulations provide us with glimpses of what space-weather phenomena may be like if the orbit of the planet is changed, or if the level of activity of the star is changed. Chapter 4 discusses, among other things, the effect of a variable stellar wind on a hypothetical magnetized planet at about a fraction of only a few tenths of the Sun–Earth distance. First, the rapid orbital motion would cause the planet's magnetotail to persistently be driven away from the essentially radial direction relative to the Sun–planet line that it has for Earth, by many tens of degrees. When coronal mass ejections (CMEs) would hit this planet, the magnetotail would be forced into the near-radial direction, thus shifting the associated auroral zones and the range of impacts of magnetospheric storms.

Planetary magnetism appears to be an important ingredient in the evolution of a planetary atmosphere, in part by setting the stripping effects of stellar winds. It also keeps energetic particles largely away from these atmospheres. As in the case of stellar dynamos, planetary dynamos require the combination of overturning motions in a conducting fluid and a deep-seated driver of such motions (see Ch. 6). The fluid in this case is indeed a liquid, of a viscosity that is considerable compared to that of the stellar gaseous plasma. The driver of the flows can be heat from impacts onto the planet (or smaller body), or released from nuclear fission of radio-active elements deep inside the planet, or from tidal forces. Or the driver of the flow may be a gradient in chemical composition maintained by a chemically differentiating phase transition from fluid to solid as the planet cools.

Astrophysical dynamos persist for a long time in bodies of sufficient size. Earth's magnetic field, for example, although variable in its detailed pattern and dominant directionality (i.e., polarity), appears to have maintained a roughly constant net strength over at least the past 3 billion years (Ch. 6) despite the fact that the dominant driver of the internal convective motions switched from thermal (nuclear decay) to compositional (chemical differentiation driven by Ni and Fe condensation onto the core, releasing lighter elements including Si, S, and O) about a billion years ago.

Astrophysical dynamos appear to generate structures in the magnetic field on a wide range of scales. This is immediately evident on the Sun, where we see bipolar regions emerge and evolve that span a range from the observational resolution limit (of order 100 km) up the full solar diameter (1.4 million km). For Earth, we cannot directly measure the small-scale structures, because the top of the dynamo region is deep inside the Earth, so that only the lower orders are readily measurable at the surface (see, e.g., Ch. 7 in Vol. III). If we look away from the solar surface by the same relative distance, we see a similarly "simple" structure, dominated by the dipole and quadrupole terms that shape the heliospheric magnetic field.

In smaller bodies, one key problem for exciting and maintaining a magnetic field is simply that their size lowers the magnetic Reynolds number by making the diffusion of magnetic field more effective relative to the motions shaping that field, all other things being equal (cf., Eq. (6.3)). In those smaller bodies with limited available primordial thermal energy or nuclear fission energy, and larger surface-to-volume ratios that speed up cooling, dynamos that do manage to operate should shut down sooner than in larger bodies (a process that may take only millions of years in planetesimals with radii above some 100 km, see Ch. 6). This is likely to be what happened on Mars in which no current global dynamo is functioning. But chemical composition may lead to exceptions: Ch. 5 describes the possibility that a sulfur-rich interior of Ganymede might lead to iron snow or FeS "hail" to maintain the only dynamo known to work in a satellite. Earth's Moon has no current dynamo, but it appears it sustained one longer than would be expected. Planetary dynamos, despite fairly successful modeling of Earth's dynamo (e.g., Ch. 7 in Vol. III) and Jupiter's dynamo (Ch. 6), have quite some secrets to disclose. There, study of solar system objects will help us figure out what happens in exoplanets where (as discussed in Sect. 6.3.2) there is a great deal of variability to be anticipated related to composition, size, and orbit.

1.6 Heliophysics of planetary atmospheres

The evolution of planetary systems, the structure and dynamics of the formed planets and the impacts of asteroids, comets, and dust on them, and even the properties of planetary dynamos, all contribute to the conditions in planetary atmospheres. Chapter 7 describes this for the terrestrial planets Venus, Earth, and Mars. The atmospheric conditions at the surfaces of these three planets differ greatly in composition, pressure, temperature, relative humidity, and types of (or even absence of) precipitation (see the summary in Table 7.1). Even the general patterns of atmospheric circulation differ greatly, leading to very different "seasons" and latitudinal climate zones on the terrestrial planets. The slow rotation of Venus enables effective exchange of thermal energy between poles and equator, greatly weakening the effects of different insolation at different latitudes relative to the pole–equator climate contrasts we see at Earth. The small tilt angle of Venus' rotation axis means that the small pole–equator differences are weakened even more in any seasonal activity. On Mars, despite a current tilt of its rotation axis relative to its orbital plane that is similar to that of Earth that contributes to seasonal changes, the main seasonal variations (including the occasional planet-encompassing dust storms that form during the austral summer season when Mars is near perihelion) are associated with Mars' orbital eccentricity that modulates the solar power input by some 44% from perihelion to aphelion.

Climates are set by a combination of stellar irradiance (i.e., by the properties of the central star and of the planet's orbit), planetary albedo, and atmospheric greenhouse gases (Ch. 7 and Ch. 11 in Vol. III). The latter two combine to elevate the surface temperatures by some 500 K, 30 K, and 5 K for Venus, Earth, and Mars, respectively, relative to the equilibrium mean surface temperatures set by orbital radius and solar irradiance in the absence of planetary atmospheres.

On Earth, the global mean temperature has changed by 10–15 °C and the surface pressure by a factor of two over its history. This has to do with geochemical changes, evolving life, and gravitational interactions with the other planets. Evidence for climate change on Venus is largely masked by a makeover of its surface within the past several hundred million years, but the chemistry of its atmosphere (notably the D/H ratio) suggests that it has lost much of at least the water content of its atmosphere. Mars' largely transparent atmosphere provides easier access to that planet's climate history. It appears that Mars has had liquid water and a much thicker atmosphere with a surface pressure exceeding 0.5 bar to account for many of its surface features; by now, it may have lost somewhere between half to 90% of its original atmosphere. Chapter 7 discusses the variety of processes involved in the erosion of atmospheres: thermal escape, photochemical escape, and sputtering for neutral atoms and molecules, and ion outflow, ion pickup, and bulk plasma escape for ions.

On geological time scales, climates are influenced by the processes that power planetary dynamos, both through bulk chemical evolution driven by internal processes and atmospheric losses driven from outside the planet: internal fluid motions are associated with volcanic activity (which releases various gases into the atmosphere – for Earth's life forms, most importantly CO_2) and continental drift, that either change or maintain greenhouse gases and albedo. And they are coupled to the evolution of the stellar dynamo: both the output of high-energy X-ray and EUV photons that can dissociate molecules and energize or ionize atoms, and the efficacy of the stripping effects of the stellar wind, decrease over time as the star loses its angular momentum causing its dynamo action to weaken.

Estimates for present-day atmospheric escape rates are uncertain to about two orders of magnitude. Chapter 7 points out that the uncertainty range is rather intriguing from the perspective of heliophysics: at the lower end of the range of estimates, heliophysical drivers are unimportant for each of the three terrestrial planets considered, while at the upper end, heliophysical drivers of the atmospheric losses are dominant. Estimates for past conditions are even more uncertain, being subject to changes in solar and solar-wind conditions, atmospheric composition, and planetary dynamo action. It is fascinating to see that the atmospheric escape rates for Venus, Mars, and Earth are comparable within their uncertainties, despite the differences in their atmospheres, surface gravity, and dynamo action. The latter distinction in the magnitude of the planetary magnetic fields has caused speculation that whereas these fields may protect a planetary atmosphere by keeping the solar wind at a distance, it may also add to atmospheric losses by harnessing some of the solar-wind energy in heating and ionization effects within its topmost atmospheric regions, making it ambiguous at present what planetary magnetism does to planetary atmospheric losses as driven by solar activity. There is clearly a lot to be learned in this arena.

1.7 Aeronomy and magnetospheres

The study of comparative aeronomy involves understanding differences in the aeronomy processes occurring in a planet's upper atmosphere where the lower neutral atmosphere transitions to a mixture of ions plus neutrals in which plasma processes contribute significantly to the energetics (Vol. I, Ch. 12 provides an introduction to ionospheres). In our solar system not only are there examples of terrestrial planets as well as of gas giants, but within each group there are quite different aeronomy processes at work. These differences are partly due to significantly different chemistry of the neutral atmospheres. A planet with an intrinsic magnetic field will also provide additional plasma processes that couple the planet's ionosphere, via the magnetosphere, to the solar wind in dramatically different ways to that of an unmagnetized ionosphere.

The distance of a planet from the Sun provides yet another aeronomy difference concerning the energy deposition and effectiveness of ionization in generating the ionosphere. Where the terrestrial thermosphere is predominantly heated by solar irradiance, the temperatures in the thermospheres of the gas giants appear to require more: particle precipitation from their magnetospheres (by Joule heating) provides likely at least an order of magnitude more energy than solar input, while an as yet unknown contribution by dissipation of wind shear and waves is also being considered (Ch. 8).

Aeronomy focuses on the energetics that drive neutral–ion processes. On a micro-scale, these processes involve chemical reactions of both neutral and charged particles. On a macro-scale, the dynamics of the neutral and ion populations is driven from the atmosphere below and the mostly ionized region above. In this volume, Chs. 8 and 9 describe comparative aeronomy for the gas giants and terrestrial planets respectively. How the terrestrial atmosphere evolves and hence impacts the planet's aeronomy is presented in Ch. 7. Chapter 12 discusses the energetic particle environment of the solar system that, together with solar irradiance, creates the ionosphere and is an aeronomy driver. The gap between our aeronomy knowledge based on our solar system versus what we currently know about exoplanets can be inferred from how we detect exoplanets, as discussed in Ch. 5.

The major commonality of the terrestrial upper atmospheres is the dominance of atomic oxygen, O, at the expense of molecular species (N_2, O_2 for Earth, CO_2 for Mars and Venus) above ~150–200 km for all three planets (cf., Chs. 7 and 9 in this volume, and Chs. 13 and 14 in Vol. III). These are the altitudes where the densities are low enough for orbiting satellites (hence the importance of aeronomy for spaceflight, see Vol. III, Ch. 14) but also where solar photons are absorbed, heating and ionizing the upper atmosphere. Chapter 9 shows the steep temperature gradients in all three terrestrial atmospheres above 120–150 km with factors of ~ 2 differences between minimum and maximum solar activity. But the true value in comparative aeronomy of the terrestrial planets comes less from their similarities than from their differences. The very different magnetic field structures, tides, and planet-wide atmospheric circulations of the terrestrial planets provide opportunities to test the detailed models developed for the Earth under contrasting conditions at Mars and Venus.

The giant planets of our solar system, Jupiter, Saturn, Uranus, Neptune as well as Jovian exoplanets of other systems, all have upper atmospheres dominated by hydrogen chemistry. One might easily expect the ionization of molecular H_2 to produce H_2^+ and H^+, but infrared (IR) observations of Jupiter in 1988 gave the first detection of H_3^+ outside the lab (Drossart *et al.*, 1989), produced by dissociative charge exchange of H_2^+ and H_2. Chapter 8 discusses the chemistry of neutral and ion species in the upper atmospheres of the giant planets and compares the relative importance of solar UV, dissipation of magnetospheric currents, and auroral precipitation for heating and ionization at the different planets. While the upper atmospheres of Jupiter and Saturn are fairly well described (as measured using stellar occultations in the UV, or at radio wavelengths by spacecraft communicating with Earth as they move behind the planet), the upper atmospheres of Uranus and Neptune are very poorly understood (as are their magnetospheres, see Vol. I, Ch. 13). Chapter 8 describes how observations of auroral emission (in the UV from excited H_2, from thermal IR emissions of H_3^+, X-rays from precipitating energetic ions, or auroral radio emissions from non-thermal electrons) provide an important diagnostic of magnetospheric processes. While the UV and radio emissions indicate immediate responses to changes in auroral precipitation, the thermal IR from H_3^+ has a slower response and indicates long-term deposition of energy into the ionosphere-thermosphere via Joule heating. Thus, observations at different parts of the spectrum provide diagnostics of different aspects of ionosphere–magnetosphere coupling, a valuable tool for understanding the giant planets of our solar system and may prove to be useful for exploring processes at exoplanets.

1.8 Dimensionless heliophysics: from heliosphere to dust

The variety of conditions under which bodies in the solar system interact with the surrounding plasma (either the solar wind or magnetospheric plasma) is described in Ch. 10, focusing in particular on the interactions with moons, asteroids, and comets. That chapter presents a wonderful example of what we can learn by looking at "universal processes" that occur throughout the solar system, and indeed the universe. Here, we see how to partition conditions depending on the relative strengths of effects through the use of dimensionless numbers that express ratios of flow or wave speeds: the Alfvénic Mach number, M_A (which measures flow speeds in terms of the Alfvén speed, v_A); M_{ms} (which measures flow speeds in terms of the magnetosonic fast mode speed $(c_s^2 + v_A^2)^{1/2}$, with c_s the sound speed); and the plasma β (which compares gas pressure to magnetic pressure; note that $\beta^{1/2}$ is the ratio of sound to Alfvén speeds), are particularly useful when grouping interactions of magnetized plasma flows into similar classes (cf., Table 10.1; see also Ch. 13 in Vol. I). Other important factors include whether the object has an atmosphere (either a gravitationally bound gas or one that may be sustained only as a result of the interaction with the solar wind, or may be maintained against losses by geysers or volcanoes). Does the body have an intrinsic magnetic field or not? Does it allow electrical currents to flow through it or does it not, i.e., does it behave as a conductor or as a non-conducting object? Is the body larger or smaller than the gyration radius of the solar-wind particles, or – alternatively phrased – is magnetohydrodynamics a valid approximation?

With just these few dimensionless numbers and properties of the solar-system bodies we are already looking into a six-dimensional space in terms of interactions, creating $6! = 720$ potentially distinct types of interactions to explore (leaving geometrical distinctions aside). These include the non-magnetized, non-conducting Moon when outside of the terrestrial magnetosphere, where the solar wind slams onto the lunar surface with little to stop it. Another example is the magnetized Earth with its conducting upper atmosphere and interior where the magnetic fields of solar wind and Earth field conspire to form a bowshock that deflects essentially all of the solar wind to flow around an extended, highly asymmetric volume that we call the magnetosphere. Beyond these six dimensions lie factors that differentiate by temporal behavior and by the directions of the flows and fields. Here, we see contrasts between the steady sub-Alfvénic plasma flow with field opposite to that of the body around which it flows as in the case of Ganymede moving through Jupiter's magnetosphere, or Earth embedded in the solar wind with its variable strength, direction, and speed. And yet (as discussed in Sect. 10.6.1) we see that the reconnection between the body's field and that in the inflowing solar wind or the Jovian magnetospheric "headwind" in both cases is intermittent, despite the near-perfectly steady and symmetric conditions around Ganymede.

When we extend the size spectrum of bodies under consideration downward well beyond that of asteroids and comets, at some point another transition occurs: when we reach the scale of "dust" (at roughly a micron, or 10^{-11} g, and below), the dust particles interact in such a way with the surrounding medium that in effect they become part of the plasma or are at least strongly affected by it and the magnetic field that it carries (see Ch. 11).

One example in which dust is used as a probe of heliospheric conditions is the effect of the solar cycle, through the heliospheric magnetic field, on the population of interstellar dust grains moving through the heliosphere. Their electrical charge causes them to respond as a population depending on the direction of the heliospheric magnetic field, as do galactic cosmic rays. But their low velocity (of some 26 km/s rather than near light speed) means that they probe the state of the heliospheric field (which they spend up to two decades traversing) with a very different response time, resulting in a phase lag of order half a sunspot cycle. Another population of dust has its origin in the destruction of comets in the inner solar system, after which radiation pressure pushes this dust outwards, on near-hyperbolic pathways away from the Sun, even as it serves as a source of neutrals and ions (through sputtering, sublimation, or collisional vaporization) that join the solar wind as pickup (atomic and molecular) ions. Within planetary magnetospheres, where volcanism of moons is another source of dust, a population of small, positively charged dust grains may even migrate outwards, to be expelled by a combination of their electrical charge subject to the apparent electric field associated with the rotating planetary field. Such evicted particles likely contribute to dust streams observed about Jupiter and Saturn (Sect. 11.3.2).

1.9 Energetic particles as diagnostic tools for heliophysics

Charged particles interact with magnetic fields in a wide variety of ways, some being accelerated to higher energies in the process. Chapter 12 discusses how detection of energetic particles in different regions of the heliosphere can act as diagnostic for such acceleration processes. For example, reconfiguration of the Sun's strong magnetic field produces expulsion of coronal plasma and entwined magnetic flux as a coronal mass ejection (CME). Particles are accelerated both during the initial reconnection and at the shock front as the CME travels through the heliosphere. Within the roughly dipolar magnetic fields of planetary magnetospheres charged particles exhibit gyro, bounce, and drift motions on increasing time scales. Perturbations of the local fields on these time scales can accelerate particles and populate the radiation belts within planetary magnetospheres (see also Vol. II, Ch. 11). Further acceleration processes within planetary magnetospheres result from large-scale motions (e.g., the Dungey cycle at Earth driven by reconnection at the day-side magnetopause and within the magnetotail) or via more diffusive processes during centrifugally driven flux tube interchange motions in rotation-driven magnetospheres of the outer planets (Vol. II, Ch. 10). The most energetic particles are generated well outside the heliosphere as galactic cosmic rays (GCRs) penetrating first across the heliopause and then into magnetospheres where they interact both with atmospheres (where further energetic particles are produced via cosmic-ray albedo neutron decay) and solid surfaces of moons (where radiolysis of ices can produce hydrocarbon compounds, perhaps pre-biotic materials). The tracking of energetic particles is important, therefore, not only as tracers of magnetic topology (i.e., open versus closed magnetic flux) and as an indication of acceleration processes, but also key for habitability perhaps below icy surfaces (e.g., Europa, Enceladus) as well as for human activity in space (Vol. II, Chs. 13 and 14).

1.10 Radio signals as diagnostic tools for heliophysics

The vast area of heliophysics is probed by analyzing the properties of light and particles: the glow of the various domains of the solar atmosphere help us understand its properties, and the reflection of sunlight or the intrinsic glow from planets and other bodies in the heliosphere enable us to diagnose conditions without sending probes to explore these conditions in situ. Where observations of light invariably integrate along the line of sight, in-situ measurements enable determination of local properties of chemical compositions, ionic and energetic particle populations, dust, and electromagnetic fields, although providing only a local snapshot along their migration pathways. In-situ measurements of energetic particles ultimately inform us about their origin and their interactions with the medium through which they propagated to wherever they are measured. In-situ probes are sampling conditions around Earth, other planets and their moons, near or on comets and asteroids, throughout the heliosphere and – with the Voyager spacecraft – even beyond that cavity carved out of the interstellar medium by the solar wind. Chapter 3 in Vol. II describes how particle measurements can be made, and the chapters that describe what they tell us include Ch. 12 in this volume, and Chs. 8–11 in Vol. II, and Ch. 9 in Vol. III.

Similarly, photons can tell us about the source regions (Ch. 4 in Vol. II) and the regions through which they propagate. Even almost entirely transparent media can be probed by photons by using the way that light is diffracted and scattered by density irregularities of the constituent particle populations. Chapter 13 focuses on a particular wavelength range, namely radio waves. It tells us what we can learn by looking at distant radio sources, both within the galaxy and far beyond its bounds, about the properties of the solar corona and the solar wind. Frequent or even continuous measurements of radio sources such as quasars and pulsars across the background sky enable three-dimensional (3D) tomography of coronal mass ejections throughout the inner heliosphere.

These same observations also contain information about the properties of the interstellar medium through which the signals propagated, and about the terrestrial ionosphere as the final refractive pathway through which extraterrestrial radio waves propagate prior to reaching the radio telescopes around the globe. Observing distant radio sources or using man-made radio transmitters during occultations can also tell us about planetary ionospheres and neutral atmospheres (e.g., Ch. 8 in this volume; as do occultations at UV and IR wavelengths) as well as about the Sun's corona (for which Faraday rotation of polarized signals offer the means to also sense the properties of the magnetic field, in addition to the scintillation signal that is sensitive to density contrasts).

1.11 Chapter outlines

Chapter 2 discusses explosive events on the Sun and on stars like the Sun in temperature and internal structure. These involve the changing of magnetic configurations and subsequent liberation of energy. The chapter reviews how flares manifest themselves differentially across the electromagnetic spectrum – from hard X-rays to radio – and the difficulty in observing any associated energetic particles and coronal mass ejections that propagate into astrospheres. The sections in this chapter discuss key stellar and wavelength-dependent parameters important to a discussion of explosive events. The examination of explosive events proceeds as a function of the star's age, from birth to beyond the current age of the Sun, with energies of over a thousand times that of the largest solar flares down to flares that disappear in the background atmospheric emission of the Sun-like "cool stars".

Chapter 3 discusses interactions of stars with their galactic environment, in the context of how that might affect orbiting planets. The characteristics of astrospheres depend on the properties of the stellar winds and on those of the interstellar medium (ISM) into which the winds are expanding. The chapter therefore includes a discussion of what is known about stellar winds and how they evolve with time, and a discussion of different sorts of ISM within the galaxy. Particular attention is given to our own Sun and to the surrounding heliosphere as it is carved out of the ISM by the solar wind. Observational studies of global heliospheric structure are reviewed, and speculation is offered as to how this heliospheric structure might change in response to different ISM environments and long-term solar-wind evolution.

Chapter 4 reviews how changes in stellar magnetic activity of Sun-like stars throughout their evolution translate into changes in their stellar winds, the structure of their interplanetary space, as well as of their astrospheres, the transport of particles, and the propagation and evolution of CMEs. Young, rapidly spinning stars have strong high-latitude fields and substantial effects of rotational forces in their winds. Old, slowly spinning stars have winds with fields wound up into the Parker-spiral pattern characteristic of the heliospheric structure. All stars likely exhibit coronal mass ejections (CMEs) that contribute in different degrees to stellar angular momentum loss. CMEs and the background stellar winds affect the evolution of planetary atmospheres, and the activity of planetary magnetospheres, depending also on the planet's orbital radius. The strength, pattern, and dynamics of astrospheric fields changes the GCR population that penetrates deep into astrospheres; Earth has been subjected to the associated changes in GCR intensities and energy spectra over its 4.5-billion year history.

Chapter 5 focuses on exoplanet systems. Search techniques for exoplanets include Doppler measurements, transit photometry, microlensing, direct imaging, and astrometry. Each detection technique has some type of observational incompleteness that imposes a biased view of the underlying population of exoplanets. With such partial information, we must piece together an understanding of exoplanet architectures by counting planets in the regimes where techniques are robust and then estimating correction factors when possible. This chapter therefore begins with a review of the exoplanet detection techniques with particular consideration of the observational biases. Only then can we discuss the implications of the rapidly growing multitude of exoplanet systems for planet formation with an eye toward how our solar system compares. We can begin to address questions about how planetary systems form and evolve. How do planetary systems – including gas and debris disks, and planetary migration by mutual gravitational interactions – evolve over time? In what ways do exoplanetary systems mirror our solar system? How are they different? Does the presence of a binary star affect planet formation? What are the formation histories of "terrestrial" planets and of gas giants? Are Earth analogs common?

Chapter 6 reviews planetary dynamos, which produce the magnetospheres that are a crucial component of the study of heliophysics and the interactions of solar and stellar winds with planets. This chapter reviews the current understanding of planetary dynamos, including theoretical foundations, and our knowledge of planetary magnetic fields from spacecraft data. It discusses planetary interior structure and processes responsible for the different magnetic fields seen in the solar system, focusing on recent findings. It also discusses the possibilities of extrasolar planet magnetic fields and what we can learn about exoplanets from them.

Chapter 7 addresses how a planet's atmosphere and surface habitability are inextricably linked. Life at Earth's surface has been made possible by atmospheric conditions, and has modified them. Planetary climates are not static, but instead change as energy or particles are added or removed from the atmosphere. The Sun plays a large role in shaping climate in a variety of ways. Of particular interest for this volume are heliophysical processes that remove particles from the upper layers of terrestrial planet atmospheres. This chapter describes the present-day climates of Venus, Earth, and Mars, and evidence for how their atmospheres have changed over time. The present understanding of the role of heliophysical processes in driving these changes is summarized. Special attention is paid to how atmospheric escape varies with changes in solar photon fluxes, solar wind, and the interplanetary magnetic field, and the role of global-scale planetary magnetic fields in inhibiting escape. We discuss the importance of applying lessons from the terrestrial planets to exoplanetary atmospheres.

Chapter 8 reviews how the upper atmospheres of planets represent a key transition region between a dense atmosphere below and a tenuous space environment above. An array of complex processes from below and from above lead to a highly coupled system, with neutrals, plasmas, and electromagnetic processes linking surfaces to magnetospheres and to the solar wind, and ultimately to the Sun itself. Evidence of these coupling processes includes various upper-atmospheric emissions, such as dayglow and nightglow, resulting from the absorption of solar photons, and aurorae, produced from the energy deposition of energetic particles from the space environment. The chapter gives an overview of the current state of knowledge of giant-planet atmospheres, first focusing on thermospheres and ionospheres, next on the processes coupling planetary atmospheres and magnetospheres, and finally on the auroral emissions resulting from those coupling processes. Giant-planet aurorae are spectacular displays of magnetosphere–atmosphere coupling, the most powerful in the solar system. Furthermore, by studying the giant planets in our own neighborhood we can lay a solid foundation for understanding the rapidly accumulating zoo of exoplanets.

Chapter 9 reviews how upper atmospheres of terrestrial planets are affected by processes from above and from below. One of the new paradigms in solar–terrestrial research is that meteorological forcing from the lower atmospheres of planets can affect planetary upper atmospheres and drive space weather. Concurrently, general circulation models of planetary lower atmospheres are being coupled with planetary thermospheres and ionospheres. We are thus witnessing the beginning of the era of whole-atmosphere modeling of space weather. Ultimately, these whole-atmosphere models will be linked to heliophysics models to produce true solar–terrestrial simulation systems. This chapter focuses on the specific phenomena that have been recently identified to couple the lower atmospheres of terrestrial planets, mainly Earth and Mars, with their respective upper atmospheres and ionospheres. It describes the basic state of terrestrial planetary upper atmospheres and ionospheres and how they depend upon atmospheric composition. It also discusses specific differences between the two worlds such as Martian dust storms or effects from the differing magnetic-field environment of both planets.

Chapter 10 explores couplings between smaller bodies in the solar system and their space environment. A body such as a planet, a moon, an asteroid, or a comet, typically enveloped in a tenuous neutral gas, perturbs its surroundings in a flowing, magnetized plasma. The structure of field and plasma resulting from the interaction depends on properties of the ambient plasma, of the atmosphere and internal structure of the body onto which the plasma flows, and on the relative speeds expressed in terms of propagation velocities of acoustic and magnetohydrodynamic waves. This chapter addresses the interaction of solar-system plasmas with a number of small bodies of the solar system by exploring magnetohydrodynamic couplings as a function of several dimensionless numbers. The interaction regions surrounding the small bodies of interest vary in global geometric configuration, in spatial extent relative to the size of the central body, and in the nature of the plasma disturbances.

Chapter 11 starts with an introduction of selected heliospheric observations that indicate dusty plasma effects on the flow of interstellar dust through the heliosphere, the effects of dust impacts on electric-field measurements on spacecraft, and on the ion composition of the solar wind. After describing the basic dust-charging processes, the chapter describes the unusual dynamics of charged dust particles in planetary magnetospheres, and the possible role dusty plasma waves might play in cometary environments. Dust particles immersed in plasmas and UV radiation collect electrostatic charges and respond to electromagnetic forces in addition to all the other forces acting on uncharged grains. Simultaneously, dust can alter its plasma environment as it can act both as a sink and a source of ions, and electrons. Dust particles in plasmas are unusual charge carriers. They are many orders of magnitude heavier than any other plasma particles, and they can have time-dependent (positive or negative) charges that are many orders of magnitude larger. Their presence can influence the collective plasma behavior, for example, by altering the traditional plasma wave modes and by triggering new types of waves and instabilities. Dusty plasmas represent the most general form of space, laboratory, and industrial plasmas.

Chapter 12 argues that energetic-particle environments in the solar system are fundamental to understand the plasma-physics processes in our universe. Energetic ions and electrons are found everywhere in the heliosphere and beyond. The knowledge of their composition, energy, and spatial distributions in different plasma environments provides an enormous source of information to investigate the origin, evolution, and current state of our solar system. Originating outside and inside the heliosphere the distribution of energetic particles is widely used to study acceleration phenomena in space near shocks, to study the configuration and dynamics of planetary magnetospheres, atmospheres, rings, neutral gas and dust clouds in the vicinity of planets and moons. They are also very important to study the interaction processes between planets/moons and their local plasma environment and can help to discover formerly unknown objects.

Chapter 13 explores how remote sensing can tell us about tenuous environments, primarily by focusing on radio waves as diagnostics. The density irregularities in the solar wind can be observed by remote sensing techniques using ground-based or space-based coronagraphs for the inner solar wind as it emerges from the Sun corona, by space-based white-light heliospheric imagers, and by radio observations of distant compact radio sources to indirectly observe the solar wind through scintillation and Faraday rotation in the radio signal received from distant astronomical or artificial radio sources. This chapter focuses on the development of radio scintillation methods since the middle of the twentieth century, from localized observations of irregularities along particular source directions with a single antenna, to large-scale, three-dimensional, evolving tomographic modeling of outflow velocities and density structures throughout large parts of the inner heliosphere including the inclusion and determination of magnetic fields, that can utilize multi-antenna, multi-wavelength observational methods.