CHAPTER 1

PLANETARY UPPER ATMOSPHERES

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Earth and most planets in our solar system are surrounded by permanent atmospheres. Their outermost layers, the thermospheres, ionospheres and exospheres, are regions which couple the atmospheres to space, the Sun and solar wind. Furthermore, most planets possess a magnetosphere, which extends into space considerably further than the atmosphere, but through magnetosphere-ionosphere coupling processes closely interacts with it. Auroral emissions, found on Earth and other planets, are manifestations of this coupling and a mapping of distant regions in the magnetosphere into the upper atmosphere along magnetic field lines. This article compares planetary upper atmospheres in our solar system and attempts to explain their differences via fundamental properties such as atmospheric gas composition, magnetosphere structure and distance from Sun. Understanding the space environment of Earth and its coupling to the Sun, and attempting to predict its behaviour ("Space Weather") plays an important practical role in protecting satellites, upon which many aspects of todays civilisation rely. By comparing our own space environment to that of other planets we gain a deeper understanding of its physical processes and uniqueness. Increasingly, we apply our knowledge also to atmospheres of extrasolar system planets, which will help assessing the possibility of life elsewhere in the Universe.

1. Introduction

Earth, like most planets in our solar system, is surrounded by a permanent layer of gas, an atmosphere. When following the changes of temperature with altitude, as shown in Figure 1, we may identify regions of negative and positive temperature gradient which define layers in the atmosphere. From the surface to top these are the *troposphere* (0 - ∼12 km), *stratosphere* (∼12 - 45 km), *mesosphere* (∼45 - 85 km) and *thermosphere* (above ∼85 km). Part of the thermosphere is ionized, forming an *ionosphere*. The upper boundary of any "∼*sphere*" is denoted by the similar word ending in "∼*pause*", so the top of the mesosphere and bottom of the thermosphere is the *mesopause*. The upper thermosphere/ionosphere regime is the *exosphere*, a region (above ∼700 km on Earth) where collisions between gas particles become rare and upward moving atoms can escape. The lower boundary of the exosphere is the *exobase*. While the bottom of the thermosphere is characterized by a sharp rise of temperature with height it becomes isothermal above a certain altitude. This height-independent temperature value is often referred to as the *exospheric temperature*.

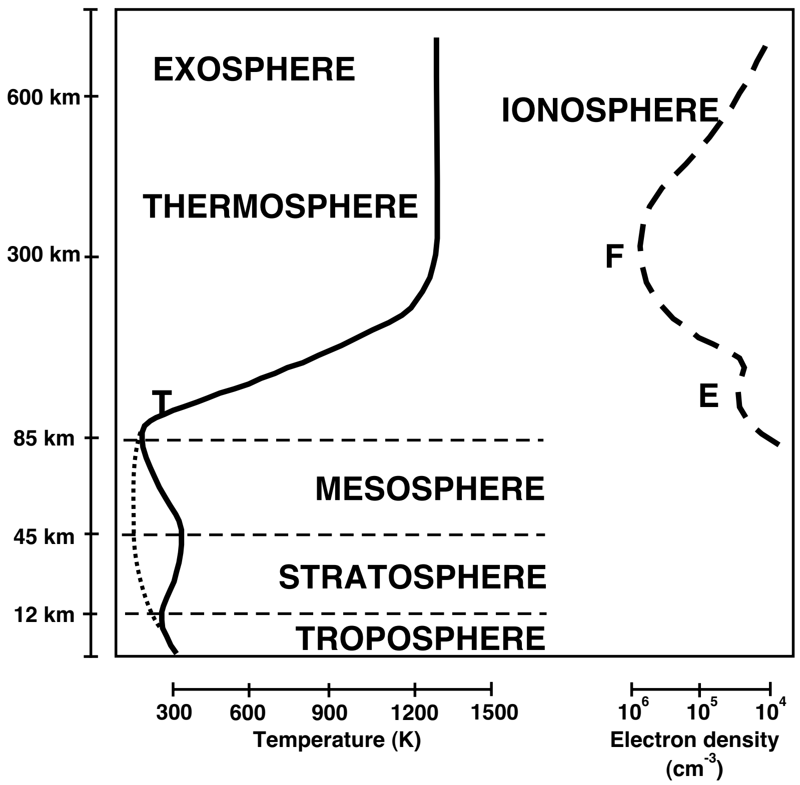

Fig. 1. The vertical thermal structure of the Earth's atmosphere and density structure of its ionosphere. Note that electron densities increase from right to left.

What generates this distinct layer structure in our atmosphere? The main reason lies in the fact that our atmosphere consists of a variety of gases which not only each absorb different parts of the solar spectrum, but are also distributed non-uniformly with altitude, thus giving a height structure to the solar absorption and thereby heating rates. This along with the ability of some gases (eg., CO_2) to radiate in the infrared, cooling their surroundings, gives rise to the distinct atmospheric layer structure. As an example, the occurrence of a stratosphere on Earth is due to the presence of ozone which absorbs solar radiation between around 200 and 300 nm wavelength, heating that region. So, without ozone the vertical temperature profile would in that altitude regime instead adopt the dotted line (see Figure 1) and there would be no stratosphere. While we may identify the atmospheric layers of Figure 1 in many atmospheres of our solar system (Earth, Gas Giants, Titan), others (Venus, Mars, Triton, Pluto) are believed not to have a stratosphere, due to the lack of an "ozone-equivalent" constituent heating that region and causing a temperature profile inversion. Dominant physical processes differ between layers and one can at times study one region in isolation, but it is important to remember that all atmospheric layers are coupled through vertical transport of gases, energy or momentum. This adds considerable complexity to the study of atmospheres.

On the basis of dominant physical processes scientists generally distinguish between two broad domains, the lower and upper atmospheres, and the studies of these regions also carry separate names. For the case of Earth, the lower atmosphere consists of the troposphere and stratosphere, and the discipline exploring these is *meteorology*, while the upper atmosphere consists of the mesosphere, thermosphere, ionosphere and exosphere, which are studied in the discipline called *aeronomy*. The name "aeronomy", created by Sidney Chapman, was officially introduced in 1954, a few years before the launch of the first artificial satellite. The purpose of this interdisciplinary field is to study any atmospheric region (earth, planet, satellite, comet) where ionization and photodissociation processes play a role. Aeronomy examines processes that couple the atmospheres of planets and moons to the solar wind and ultimately to the Sun itself. This implies that any concept, method or technique developed for the terrestrial atmosphere can be adapted to other bodies of the solar system. Sometimes in the literature the stratosphere is seen as part of the upper atmosphere and thus included in aeronomy studies, but we will not consider stratospheric processes here. This article will highlight some of our current understanding of aeronomy, with an emphasis on comparison between different solar system bodies (”*comparative aeronomy*”). By seeing Earth or any other planet or moon in context with the rest of the solar system, we understand better their differences and may identify any features unique to a particular atmosphere. Testing our theories of atmospheric behaviour under the different environments of other planets not only enables us to learn about those worlds, but also urges us to revise some of our understanding of our own planet.

Recently, Mendillo et al.[1] identified the following as some of the key questions posed in solar system aeronomy: (1) What are the constituents of each atmosphere? (2) How do they absorb solar radiation? (3) What thermal structures result from heating versus cooling processes? (4) What types of ionospheres are formed? (5) What are the roles of atmospheric dynamics? (6) Does a planetary magnetic field shield the atmosphere and ionosphere from solar wind impact? (7) How do trapped energetic particles and electrodynamics affect the atmospheric system? Some of these questions will be reviewed in this article.

2. Methods of exploring planetary atmospheres

The techniques for acquiring information about our own as well as other bodies' atmospheres have reached a high level of ingenuity and accuracy and merit a discussion far beyond the scope of this brief review. Readers are therefore referred to more comprehensive descriptions in the literature, discussing both historical and current techniques [2,3,4,5,6,7]. On a broad scale, we may distinguish between *remote sensing* and *in situ* observations, where an instrument either measures from a distance or within the environment itself. While in-situ measurements often give us more detailed information about specific processes, they are confined to the location of the instrument (path of the spacecraft carrying it), whereas remote sensing techniques give information on a broader spatial and temporal scale, and may often be easier and cheaper to accomplish. Most remote sensing measurements are made by detecting and spectrally analyzing radiation, whereas in-situ measurements can sample atmospheric particles directly in addition to detecting radiation. Instruments can measure in an *active* or *passive* way, in which they either detect emissions from the region of interest or send out a signal (eg., radar) and measure its return. By spectrally analyzing the radiation we learn about the atmospheric gas composition, its dynamics and the planet‘s magnetic environment.

Once observations have been made, sophisticated *data analysis* needs to be carried out since in most cases the parameters of interest (eg., temperature or composition of atmospheric gases) are not detected directly, but derived from instrument signals by making assumptions about the atmosphere or environment. Often, data analysis is a complex procedure which may take years and cause much controversy since different analyses make different assumptions and may obtain diverging results. One recent example for the range of possible results is the analysis of Voyager observations of Saturn's exospheric temperature; while the analysis of a stellar occultation experiment yielded a value of 800 K[8], a solar occultation experiment on board the same spacecraft gave 400 K[9].

Space probes which made important contributions to aeronomy in the solar system include Mariner (Venus, Mars), Venera (Venus), Pioneer Venus, Pioneer (Jupiter, Saturn), Voyager (Jupiter, Saturn, Uranus, Neptune), Galileo (Jupiter, Venus) and the on-going or future missions Ulysses (Sun, Jupiter), Mars Global Surveyor, Cassini (Saturn, Jupiter, Venus), Mars Express and Venus Express. Thanks to these spacecraft and a vast range of ground based observations exploring our own and other aeronomic systems over the past 3 decades, today we have an unprecedented understanding of atmospheres in our solar system. Observations are accompanied by detailed theoretical modelling work which takes advantage of the increasing computing capabilities to simulate the physics of planetary atmospheres. Such numerical models play a crucial role in helping us understand the observations and predict other, yet unobserved, features.

3. Atmospheres in the solar system

In order for a planet or moon to possess an atmosphere, its solid body or dense inner core need to bound gravitationally the gas particles, preventing the bulk of them from escaping into space. By contrast, bodies such as comets possess what is called a coma, where gas particles escape into space continuously but are replenished, thus giving these bodies a transient atmosphere which will disappear as soon as the gas source vanishes. Other examples of bodies with transient atmospheres are our Moon, the planet Mercury and Jupiter's moons Io, Ganymede, Europa and Callisto. The exact composition of an atmosphere depends on the available gases at the time when the solar system was formed as well as the evolution under the influence of geology (via outgassing), impacts of other bodies, solar radiation and the solar wind. On Earth, the presence of life has also considerably influenced the atmospheric composition. Broadly, we may on the basis of their composition divide the non-transient atmospheres in our solar system into three categories, the Nitrogen atmospheres (Earth, Titan, Triton, Pluto), Carbon dioxide atmospheres (Venus, Mars) and Hydrogen atmospheres (Jupiter, Saturn, Uranus, Neptune). Mercury is the only planet not to have a permanent atmosphere, while Saturn's Titan and Neptune's Triton are the only moons with permanent atmospheres. Titan's atmosphere is particularly thick, with surface pressure values comparable to those on Earth. Pluto, the outermost planet, is thought to have an atmosphere similar to that of Triton, which partly condenses out when Pluto on its elliptical orbit is sufficiently far from the Sun and temperatures are low enough.

3.1. *Thermospheres*

As illustrated in Figure 1, a thermosphere is one of the outermost layers of an atmosphere, characterized by a steep vertical temperature gradient in its bottom region and height-independent temperatures further up. These large temperatures are a result of the highly energetic (Ultraviolet and X-ray) parts of the solar spectrum being absorbed by gases in a low density environment. Another feature of the thermospheric environment is the importance of vertical molecular conduction, as first pointed out for Earth in 1949 by Spitzer[10]. Energy is transferred by collisions between molecules, a process which is particularly important in regions of large temperature gradients, as that in the lower thermosphere. Energy deposited in the thermosphere by solar absorption or magnetospheric sources (see sections 4, 5) is conducted down into the mesosphere. From there it is largely lost back into space by radiative cooling through vibrational transitions in polyatomic molecules, giving the mesopause its cold temperatures[11].

Infrared cooling is also found to be important within the thermospheres of some planets, in particular Venus, Titan and Jupiter. On Venus, the high abundances of CO_2 causes strong cooling at 15 μm[12] and explains the cold exospheric dayside temperatures of below 300 K[13]. While Venus is the planet with an atmosphere located closest to the Sun, the energy is thus effectively radiated back into space, keeping exospheric temperatures relatively low. Infrared cooling on Titan is caused by HCN, a byproduct of ionospheric chemistry which has strong rotational bands and despite its low fractional abundance of less than $\sim$0.1 % causes significant thermospheric cooling[14]. Molecular conduction on Titan only becomes important in the upper regions of the thermosphere[14,15]. In Jupiter's thermosphere an effective radiative coolant is H_3^+, the main ionospheric constituent. Since its

Table 1. Key properties of upper atmospheres on planets and moons in our solar system.

Body	Heliocentric distance [AU]	Siderial rotation period	Main neutral gases	Exospheric Temperature [K]	Main ions	Peak ion density [cm^{-3}]	Magnetic dipole moment (Earth=1)/tilt	Solar EUV, particle/Joule heating [10^9 W]
Venus	0.72	-243 days	CO_2, CO, N_2, O	100-300	O_2^+, CO_2^+, O^+	10^5	$<10^{-4}$/?	300, 0
Earth	0.98-1.02	23^h22^{min}	N_2, O_2, O	800-1400	O^+, O_2^+, NO^+	10^6	$1/10.8^o$	500, 80
Mars	1.4-1.7	24^h15^{min}	CO_2, CO, N_2, O	200-350	O_2^+, CO_2^+, O^+	10^5	$<10^{-4}$/?	25, 0
Jupiter	5.0-5.5	9^h55^{min}	H, H_2, He*	940	H^+, H_3^+	10^5	$20{,}000/9.6^o$	800, 10^5
Saturn	9.0-10.1	10^h39^{min}	H, H_2, He	420	H^+, H_3^+	10^4	$600/< 1^o$	200, 200
Titan	9.0-10.1	15.95 days	N_2, CH_4	180	$C_xH_y^+$	10^3	0?	3, < 0.2
Uranus	18.3-20.1	17^h15^{min}	H, H_2, He	800	H^+, H_3^+	10^4	$50/58.6^o$	8, 100
Neptune	29.8-30.3	16^h7^{min}	H, H_2, He	600	H^+, H_3^+	10^3	$25/47^o$	3, 1
Triton	29.8-30.3	-5.87 days	N_2, CH_4	102	N^+?	10^4	?	0.05, 0.1
Pluto	29.7-49.3	-6.38 days	N_2, CH_4	100?	$HCNH^+$?	10^3?	?	0.05, ?

Values either unknown or estimated are marked with a "?". Negative rotation periods denote retrograde rotation. The table is adopted from Strobel[31].

discovery on Jupiter in 1989[16], H_3^+ has been imaged on several occasions with ground based telescopes, such as NASA's Infrared Telescope Facility on Mauna Kea, Hawaii[17], and emissions were found to be concentrated in the auroral regions. H_3^+ emissions have also recently been discovered near the poles of Saturn[18], but are less pronounced than on Jupiter. The principal gases in the Earth's thermosphere are O, O_2 and N_2, and the small amounts of CO_2 and NO there are insufficient on a global scale to cause significant infrared cooling under normal conditions, but locally and during geomagnetic storm conditions on Earth they have to be taken into account.

Table 1 summarizes key properties of upper atmospheres in the solar system, such as exospheric temperatures, major gas composition and heating rates. Apart from the variations in composition between the planets, note the exospheric temperatures and how their values change with distance from the Sun. The average exospheric temperature values, as well as their diurnal and solar cycle ranges, are also plotted in Figure 2 versus location in the solar system. While one might initially expect planets located closer to the Sun to be hotter, the trends in Figure 2 and Table 1 show that this is not generally the case. One important current topic of research in aeronomy is to understand this unexpected trend, and this will be discussed further in section 5. The earlier discussion of infrared cooling in Venus' thermosphere already gave a reason for the low exospheric temperatures there.

Solar heating of the dayside thermosphere sets up day-night pressure gradients, which drive horizontal winds and thereby a system of global circulation. The nature of thermospheric winds depends amongst other things on the magnitude of day-night pressure gradients as well as the planet's rotation rate. On fast rotating planets (such as Gas Giants, see Table 1), there is too little time to build up substantial day-night temperature gradients, and the direction of thermospheric winds is furthermore influenced by the well known *Coriolis forces*. Thermospheric winds can furthermore be affected by the motion of ions, which respond to the presence of electrical fields (see section 3.2), adding considerable complexity to thermospheric circulation. Thermospheric winds, in turn, transport gases, affecting the distribution of individual constituents. Thermospheric dynamics are studied in detail using *General Circulation Models*, and we now have such models for most planets in the solar system.

As noted previously, any atmospheric region should be seen not as an isolated regime, but coupled to its surroundings. What makes the thermosphere particularly complex is the variety of its coupling to surrounding areas. Forming one of the the outermost regions of an atmosphere, it "sits"

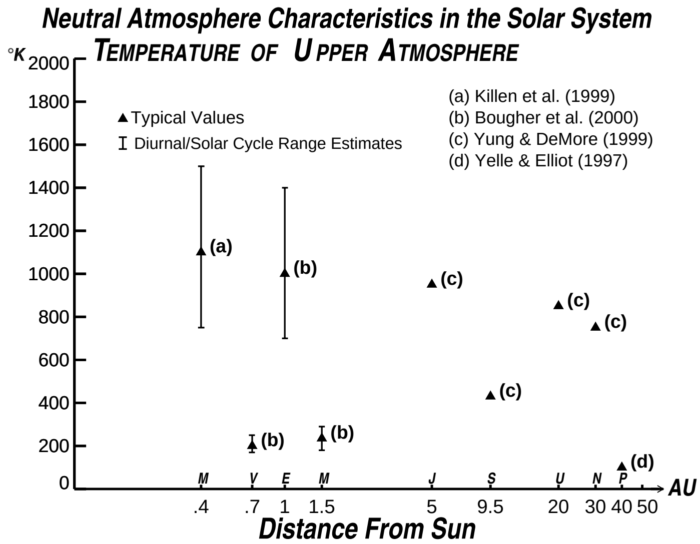

Fig. 2. Exospheric temperatures in the solar system versus distance from the Sun (from Mendillo et al.[20]).

on the entire atmosphere below and is subject to phenomena such as upward propagating waves. These waves have a profound influence on the Earth's lower thermosphere, accelerating winds there and thus also affecting the structures of temperatures and densities. Recently, observations have shown the possibility of phenomena such as global warming, which appear primarily in the lower atmosphere, to be detectable in the Earth's thermosphere and ionosphere as a result of vertical chemical and dynamical coupling[19]. The thermospheric environment is also coupled to interplanetary space through the magnetosphere which can generate substantial winds and heating (see discussions in 4 and 5). The coupling of thermospheres to regions as vastly apart as the lower atmosphere and solar wind or Sun itself via simultaneously occurring processes like chemistry, neutral gas and plasma dynamics as well as electromagnetism make them some of the most complex and fascinating environments to study.

3.2. *Ionospheres*

Energetic photons entering the upper atmosphere of Earth or other planets not only heat neutral gases (see 3.1), but are capable of ionizing them as well, generating a layer of plasma embedded in the thermosphere, called the ionosphere. The same process which causes the neutral atmosphere's vertical thermal structure is often also responsible for the creation of ionospheres with several separate layers of enhanced plasma density. Depending on the distribution of neutral gases with height, different parts of the solar spectrum ionize at varying altitudes, creating separate layers of ionization. The dashed curve in Figure 1 shows the structure of the Earth's ionosphere in terms of electron densities. Two distinct layers can be identified, namely the "*E-layer*" and "*F-layer*" which peak near 90 and 300 km altitude, respectively. Historically, these names derive from the fact that the first ionospheric layer to be discovered was named the "E-layer", where "E" stands for "electric", and other layers discovered subsequently below and above the E-layer were given names of letters before or after the letter "E" in the alphabet. The basic difference between these regions, apart from their electron densities and altitudes of occurrence, is that E-layer plasma is largely in photochemical equilibrium, whereas the F-layer is controlled both by photochemistry and plasma transport and thus not in photochemical equilibrium[20]. Dominant ions in the terrestrial E-layer are molecular ions such as O_2^+ and NO^+, whereas the F-layer near its main peak consists mainly of the atomic ion O^+. Molecular ions in the E-layer are in an environment of larger neutral particle densities than F-layer plasma, so they rapidly recombine after sunset and the E-layer largely disappears during the night. In the F-layer recombination of ions is far more inefficient and additional plasma is supplied from other regions by transport, so the F-layer survives through the night. Peak ion densities in the F-layer are usually less than 0.1 % of the ambient neutral gas densities, but we will show later (section 4) that the ionosphere often plays a crucial role in thermospheric properties and provides the coupling between the thermosphere and magnetosphere. Note that not all ionospheres in the solar system contain all the layers identified on Earth.

Figure 3 along with Table 1 summarize some key ionosphere properties in the solar system, and we may identify two important features. Firstly, the Earth's is according to our current knowledge possibly the only ionosphere in which the main peak density (F-layer) ion is atomic (O^+), whereas on Venus and Mars it is O_2^+, on the Gas Giants H_3^+ and on Titan a hydrocarbon molecule ($C_xH_y^+$). The dominant ion on Triton may also be atomic (N^+ or C^+), but there is as yet too little observational evidence to confirm this unambiguously. Secondly, peak ion densities tend to decrease with distance from the Sun, except for the value on Earth, which is a factor of 5 larger than that of any other ionosphere in the solar system. It seems, therefore, that the Earth's ionosphere stands out amongst the planets. This difference appears unrelated to properties of its magnetic field, as listed in Table 1.

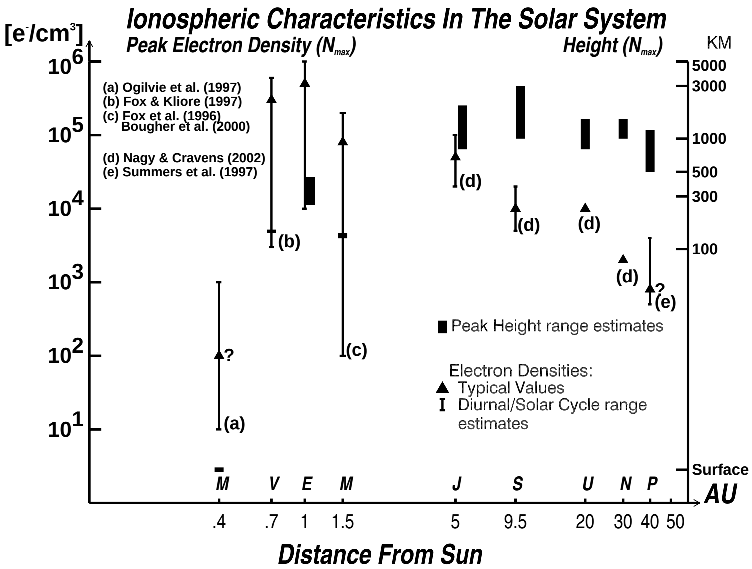

Fig. 3. Ionospheric characteristics in the solar system versus distance from the Sun. On the Gas Giants (Jupiter, Saturn, Uranus, Neptune), "surface" is defined as the 1 bar pressure level in the atmosphere. (from Mendillo et al.[20]).

Recent observations have shown day-to-day variations in the Earth's E-layer to correlate well with those of the main ionospheric peak on Mars, and both these to reflect changes in the solar EUV flux during the same period[21]. The significance of this observation is that it demonstrated similarities between the Martian ionosphere and terrestrial E-layer, indicating that Mars has an "E-layer type" ionosphere which is controlled by photochemical equilibrium, as expected from an ionosphere dominated by molecular ions. The importance of molecular ions (Table 1) indicates that most other ionospheres in the solar system, like that of Mars, are likely to be of "E-layer type" and in photochemical equilibrium, with Earth being a special case where the E-layer is in photochemical equilibrium, but the main peak, the F-layer (being atomic), is not. While this statement is a reasonable description of the global behaviour of ionospheres in the solar system, it does not capture more detailed properties. Locally, winds or other magnetospheric coupling processes may disrupt photochemical equilibrium, and on most planets the ionosphere above the peak (the *topside ionosphere*) is not in photochemical equilibrium.

4. The space environment of magnetized bodies

4.1. *What is a magnetosphere?*

The thermospheres and ionospheres, as described in 3.1 and 3.2, are coupled to space, the Sun and solar wind by vast regions beyond the atmospheres which surround magnetized bodies, called *magnetospheres.* Caused by the presence of magnetic fields, they form cavities which protect the planet or moon from the direct influence of the solar wind. In fact, life on Earth may not have evolved without the presence of our protecting magnetosphere. Figure 4 illustrates schematically the structure of the Earth's space environment. The internal magnetic dipole field without the presence of the solar wind would form field lines similar to those of a bar magnet. However, the solar wind, a stream of high energetic particles ejected from the Sun, affects the global shape of magnetic field lines surrounding Earth, compressing them on the sunward side (left half of Figure 4) and streching them out on the anti-sunward side into a *tail* (right half of Figure 4). The boundary layer where solar wind pressure and magnetic field pressure balance is the *magnetospause* (dashed line in Figure 4). The environment inside the magnetopause is the magnetosphere, so the magnetic field shields Earth from the bulk of the solar wind particles. While Figure 4 highlights some features specific to Earth, the schematic equally applies in principle to any magnetized body in the solar system. The eighth column in Table 1 compares magnetic dipole moments ("strengths") and magnetic field tilts between the various bodies in the solar system. A tilt of 0^o would imply the "bar magnet" to be aligned with the rotational axis of the planet. We see from the values in Table 1 that the bodies in the solar system with significant magnetic fields, and thus magnetospheres, are Earth, Jupiter, Saturn, Uranus and Neptune. Titan and Triton are special cases - they do not possess intrinsic magnetic fields, but their orbits lie within the magnetospheres of Saturn and Neptune, respectively, so they have *induced* magnetospheres.

4.2. *Aurora*

One particular manifestation of the Earth's coupling to the solar wind via the magnetosphere are the spectacular Northern/Southern Lights or *aurora*

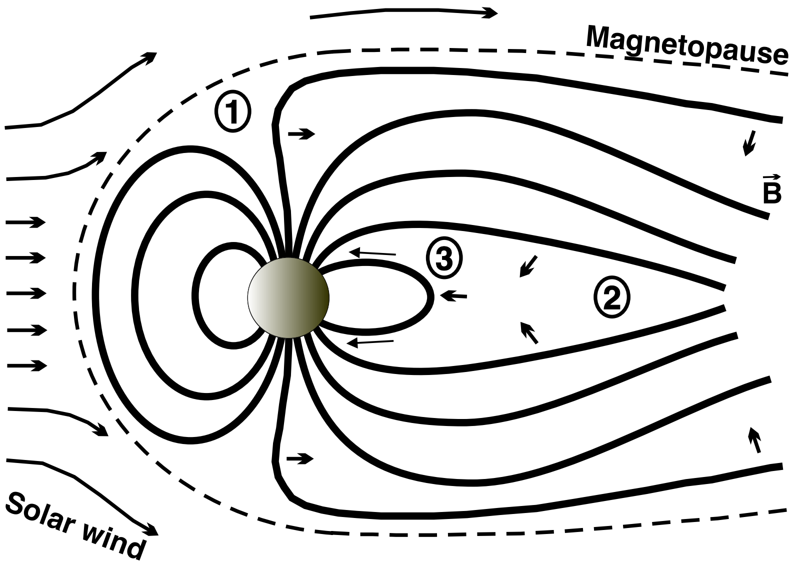

Fig. 4. Schematic of the Earth's magnetosphere and its interaction with the solar wind.

borealis/australis which, seen at night from the ground, are vast curtains of light changing rapidly their shape and intensity (Figure 5). These auroral emissions appear to the naked eye in green and red colours and seem so violent and mysterious that they have captured human curiosity and fear throughout history, being given an almost mythological status and interpretation. Overall, aurora appear in the form of ring shaped bright regions roughly centred around the north and south magnetic poles of a planet, the *auroral ovals*. A scientific exploration into the origins and nature of the Earth's aurora began in the 18th and 19th centuries[22,23], and more powerful observational techniques led to the discovery of auroral emissions also on other planets, such as Jupiter[24] (Figure 6) and Saturn[25]. Other forms of atmospheric emissions that appear less spatially defined and less bright than the polar, highly variable aurora are summarized as *airglow*. Based on differences in the creation mechanisms one may define an aurora as being *any optical manifestation of the interaction of extra-atmospheric energetic electrons, ions and neutrals with an atmosphere*[26]. What distinguishes airglow from aurora is the primary process causing them: airglow is generated by solar photons, whereas aurora is generated by energetic particles from outside the atmosphere (which excludes photoelectrons, a by-product of some chemical processes inside the atmosphere). Auroral emissions can be observed at visible, infrared, UV and, for Jupiter and Earth, at X-ray wavelengths.

Fig. 5. Auroral emissions, as seen from the ground (Photo courtesy of Jouni Jussila).

4.3. *Magnetosphere-Ionosphere coupling*

The processes which lead to auroral emissions on Earth and other magnetized bodies form part of a field referred to as *Magnetosphere-Ionosphere* *coupling*. What distinguishes planets are the atmospheric composition and the processes accelerating the energetic particles entering an atmosphere. So, the study of auroral emissions gives us important information about a planet's atmosphere and magnetosphere, which will be reviewed below. This comparison will show that aurora on Earth originates from coupling to the solar wind, while on Jupiter they originate primarily from the fast rotation of the planet and the effect this has on the magnetosphere. Not enough is known yet about the origins of Saturn's aurora, but the planet may be an "in-between case" between Earth and Jupiter[27]. Realizing differences such as these is an important step towards a more comprehensive understanding of the planets in our solar system.

4.3.1. *Earth*

On Earth, changes in auroral brightness and shape are related to disturbances in the geomagnetic field which are induced by its interaction with the solar wind, triggered for example by solar flares or coronal mass ejections. At times, these disturbances are particularly violent and lead to *geomagnetic storms*, which manifest themselves as periods (from below an hour to a day) of particularly bright auroral displays and an expansion of the auroral oval, making it visible at times from mid latitudes. The nature of solar wind-magnetosphere interaction on Earth during such events is illustrated in Figure 4. The solar wind "drags" magnetic field lines across the poles (marked as "1" in Figure 4) towards the tail region, where these contract into the tail ("2") and recombine into loops (closed field lines), which convect inward towards the nightside of the planet, accelerating plasma along the field lines ("3") mapping into the high latitude regions of the atmosphere and causing auroral emissions. Enhanced aurora on Earth is thereby a direct result of Sun-Earth coupling via the solar wind.

Understanding this response of the Earth's upper atmosphere to solar disturbances is an active field of research called *Space Weather* and has important practical applications. The strong currents, electric fields and fluxes of incident energetic particle in the upper atmosphere during geomagnetic storms are capable of severely disrupting satellites and even power grids on the ground, so it has become desireable to be able to predict these events in order to switch off satellites or otherwise protect sensitive electrical equipment.

4.3.2. *Jupiter*

Jupiter's magnetosphere is the largest structure in our solar system after the Sun's own atmosphere, extending out by up to 100 Jupiter radii (R_J) into space. If it were visible with the naked eye in its entirety from Earth, it would have a radius in the sky larger than the Moon, despite its much larger distance from Earth. Earth based observations of Jupiter's aurora as well as in-situ measurements of field strength by the Pioneer, Voyager, Ulysses, Galileo and, most recently, Cassini spacecraft have given many clues about its structure and processes, suggesting Jupiter's magnetosphere to be different in many ways to that of the Earth. While plasma in the Earth's magnetosphere originates mainly from the atmosphere and partly from the solar wind, that in Jupiter's magnetosphere originates primarily from the Galilean moons, in particular the volcanic moon Io which injects > 1 tonne of material (mainly SO_2) per second into space. This is then ionized by solar EUV radiation or energetic particle collisions. The moon Europa, through bombardment of its surface ice by energetic magnetospheric particles, ejects around 50 kg of atomic oxygen per second, while only the light ions (H^+, He^{++}) originate from Jupiter's upper atmosphere. The dominant mechanism accelerating plasma in Jupiter's magnetosphere is not the solar wind (like for Earth), but a break-down of the magnetosphere's co-rotation and the disturbance that this breakdown generates[28]. Jupiter rotates once every 10 hours and up to a distance of around 20 Jupiter radii the plasma co-rotates at the same angular velocity. Beyond that distance, however, co-rotation cannot be maintained and the outer regions of Jupiter's magnetosphere "lag behind" the inner ones. The co-rotation break-down leads to acceleration of plasma which along magnetic field lines travels towards the planet and enters the atmosphere, generating auroral emissions. The exact morphology of these complex interactions is currently an active subject of study, with numerous theoretical models being developed to understand the latest observations[28,29]. Figure 6 shows an artist's impression of Jupiter's magnetosphere and illustrates the plasma flow along magnetic field lines between the Galilean satellites, in particular Io, and Jupiter's upper amosphere, where it creates "foot prints" of the moons in the auroral emissions.

Both on Earth and Jupiter, as well as other magnetized bodies, it is important to realize that the horizontal structures observed in auroral emissions in the atmosphere along magnetic field lines map to different regions in the magnetosphere. As can be seen from the schematic in Figure 4, field lines crossing the equatorial plane closer to the planet map into more

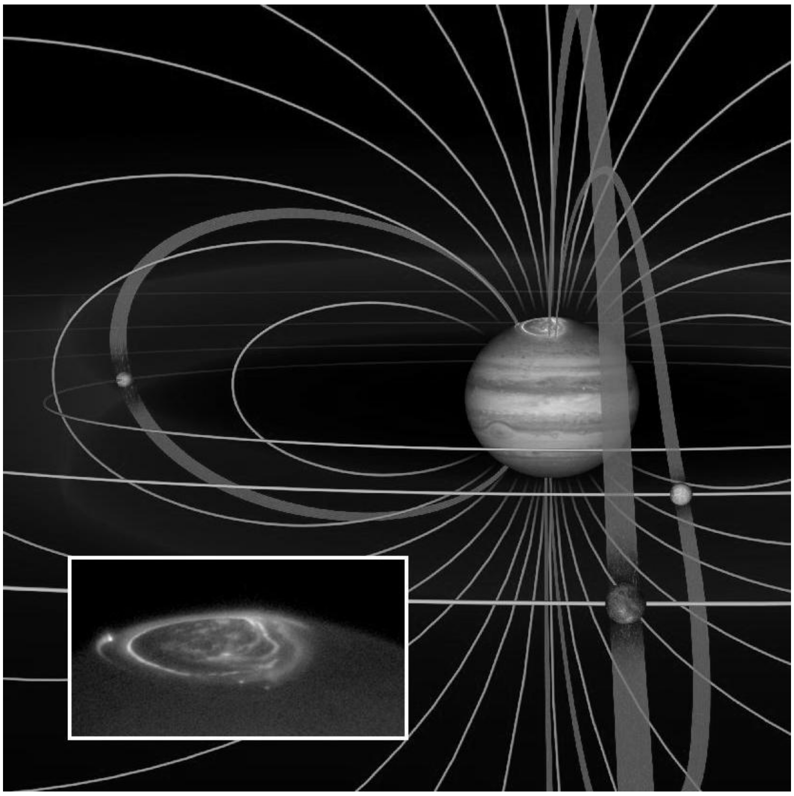

Fig. 6. Jupiter's space environment, with moons Io, Europa and Ganymede (insert: Jupiter's aurora, as seen in the UV). Illustration courtesy of John Clarke.

equatorial regions, whereas those extending out to larger distances map into higher latitudes. The auroral emissions are thus a direct projection of magnetospheric processes into the atmosphere. One striking example can be seen in the auroral maps of Jupiter, such as those derived from Hubble Space Telescope (HST) observations in the UV (insert in Figure 6): we can clearly identify bright patches in the aurora which are magnetic footprints of the Galilean satellites Io (above the left hand limb), Europa and Ganymede (bright dots near the central meridian)[30]. These are striking examples of how seemingly uncoupled regions, such as moons and the planet's atmosphere, are indeed closely linked through the presence of the seemingly invisible magnetosphere.

5. Energy crisis in the solar system

Another important on-going field of research in solar system aeronomy is to understand the exospheric temperatures on planets. As discussed earlier (see 3.1) and shown in Figure 2 and Table 1, exospheric temperatures do not generally decrease with distance from the Sun. Venus is colder than expected from its location close to the Sun, whereas Gas Giants are far hotter than we would expect them to be. It is evident that the intensity of solar radiation alone is insufficient to understand this. In section 3.1, CO_2 cooling was found to explain Venus' cold temperatures, but what processes explain the hot thermospheres of Gas Giants, in particular Jupiter? This is an outstanding problem in our understanding of the outer planets. The two currently most favoured processes which could additionally heat the upper atmospheres of Gas Giants are (1) deposition of energy from the solar wind and magnetosphere into the upper atmosphere, (2) heating due to upward propagating waves[33].

Magnetosphere-Ionosphere coupling on Earth (section 4.3.1) not only creates the spectacular auroral emissions, but also deposits significant amounts of energy into the upper atmosphere through the precipitating particles themselves and, secondly, a process called *Joule heating*. Essentially, Joule heating is equivalent to the creation of thermal energy by a current flowing through a resistor. The currents on Earth are driven by electric fields generated by the interaction between the solar wind and magnetosphere (see section 4.3.1) and mapped into the auroral latitudes. Joule heating is particularly effective during geomagnetic storms, at times doubling local temperatures. Furthermore, the collisions of fast ions with slower ambient neutrals act to accelerate the neutral gas, creating strong thermospheric winds. Could similar processes play a role on other planets?

The right column in Table 1 compares heating rates in the upper atmospheres of Earth and other planets due to solar EUV absorption, particle precipitation and Joule heating. The given values are global averages and the balances of these heating processes may vary locally, in particular in the regions of precipitation and Joule heating. The absence of induced electrical fields, and thereby Joule heating on unmagnetized planets (Venus, Mars) makes solar heating the dominant energy source. Titan and Triton with their induced magnetospheres are special cases and magnetospheric energy sources are thought to play a role primarily on Triton. The moon is exposed to Neptune's magnetosphere which, due to the large tilt of 47^o between magnetic and rotational axes, is particularly dynamic[34]. The interaction between Titan's atmosphere and Saturn's magnetosphere will be examined in detail with the forthcoming Cassini observations between 2004 and 2008. The planets in Table 1 where particle precipitation and Joule heating clearly play an important role from a global perspective are Jupiter and Uranus, followed by Saturn, Neptune and Earth. On Jupiter, magnetospheric energy sources are thought to exceed solar EUV heating rates by a factor of ∼100, on Saturn the two rates are comparable in magnitude and on Earth, being closer to the Sun, solar EUV heating is on average ∼6 times stronger. The outer planets where magnetospheric heating processes are most important are also those with the largest exospheric temperatures, so this trend clearly suggest one important "missing link" in our understanding of the temperature trends of Figure 2 throughout our solar system to be these magnetospheric energy sources. Many detailed questions remain unresolved, in particular how this magnetospheric energy, deposited at high magnetic latitudes, can be globally distributed on planets like Jupiter and Saturn, whose fast rotation hinders such transport by winds.

Heating from below by upward propagating waves would solve the problem of energy transport into equatorial regions, and much work has gone into investigating the possibility of waves as an energy source for the upper atmosphere. While for planets Earth, Venus and Mars the importance of waves as a source of momentum in their upper atmospheres has been demonstrated, wave dissipation on these planets releases only insignificant amounts of thermal energy. For Jupiter, some studies have suggested wave heating to play a key role, while others have contradicted this finding[33]. Further observations and more accurate calculations are necessary to solve this issue.

6. Looking beyond: extrasolar planets

One fundamental question that has long intrigued humans on Earth is whether other forms of life are present in our solar system and beyond. Within our solar system, the search for life has concentrated on Mars and will advance to Europa an possibly Titan. The first discoveries in 1992 of a planet orbiting a pulsar, and in 1995 of a planet orbiting a "normal" star (51 Pegasi) have given the question of life outside our solar system a new dimension. If other planets exist in other solar systems, what is the likelihood of finding life on these? In this context much effort has gone into determining whether some of the now more than 100 observed extrasolar planets possess atmospheres and, if so, then how these compare to the atmospheres in our solar system, and whether they could support forms of life. In 2000, a pioneering observation discovered for the first time spectroscopically lines of Na and H during the transit of planet HD209458b in front of its star, and thereby detected for the first time directly the atmosphere of an extrasolar planet[35]. Most of the extra-solar planets which we can currently detect, including HD209458b, are Jupiter-like, but orbiting close to the star, with semimajor axes below 0.1 A.U. These properties not only pose new challenges to our theories of solar system formation, but also to our understanding of their atmospheres. Will these atmospheres be similar to those of Gas Giants in our solar system? What exospheric temperatures will they have, and what controls their energetics? What chemical and dynamical processes will occur, and what is the nature of their coupling to internal or induced magnetospheres? While these questions cannot yet be answered through observations, first calculations are now being carried out to understand the aeronomy of such planets[36]. While still struggling to understand the aeronomy of planets in our own solar system, we may already apply our current knowledge and experience to extrasolar planets, predicting some key properties and working towards more accurate observations to help us understand not only Earth in context with other planets of our solar system, but our solar system in context with others. Aeronomy thus promises to capture our curiousity, inspire our imagination and demand our efforts for many decades to come.

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