Atmosphere (Earth's)

Introduction

Because of the Earth's gravity, atmosphere is horizontally stratified (see, e.g., Kelley, 1989). Its structure can be organized by using the neutral gas temperature, as shown in the figure from mid-latitudes (note the logarithmic altitude scale).
When going upward from the ground within the lowermost atmospheric region, troposphere, the temperature decreases up to about 10 km altitude (tropopause). Above that, in the stratosphere, the ozone (O_3) starts absorbing the ultraviolet solar radiation, and temperature starts rising again. At about 50 km altitude (stratopause) this effect ends, and radiative cooling creates the mesospheric temperature minimum at about 80 km. Above mesopause the temperature starts rising again, now very fast, and we reach the hot thermosphere. The absolute temperature of the thermosphere depends on the solar activity, being between about 700 and 2500 K. The temperature increase is again explained by solar UV radiation. Here the radiation also ionizes the neutral atmosphere, creating the ionosphere.
Because both the ground and ionosphere are better conductors than the atmosphere, a special cavity is formed: see Schumann resonances.

Atmospheric constituents at ground level [%]	
N_2	78.1
O_2	20.9
Ar	0.93
CO_2	0.035
Ne	0.0018
He	0.00052
CH_2	0.0002
Kr	0.00011
H_2	0.00005
Xe	0.00001

There is much less variability in density and composition of the atmosphere than in the temperature. The density decreases monotonously with altitude, and the composition (see table) stays well mixed up to turbopause at about 100 km altitude. Above this turbosphere (or homosphere), heterospheric composition starts showing variability with the altitude, and finally in the upper heterosphere the light helium and hydrogen are the most typical gases.
The upper thermospheric dynamics are typically discussed in terms of **wind** patterns, since the neutral winds there are driven *in situ* by solar heating, Joule heating, and momentum transfer from plasma, and even precipitation (e.g., Killeen et al., 1988; Walterscheid and Lyons, 1989). This means that the coupling to ionosphere is important. On the other hand, the lower thermospheric (corresponding to ionospheric E layer) dynamics are discussed in terms of **tidal modes and gravity waves** originating from below, troposphere and stratosphere (tropospheric weather fronts, tornadoes and thunderstorms, etc.).
There is one important, indirect way the atmosphere is coupled to the Sun's activity via galactic cosmic rays. In addition, man-made atmospheric CO_2 increase can affect thermospheric temperatures. See global change for more information.

Frictional/Joule heating

Introduction

Electric field is a potential heat source for ionospheric particles (Rees, 1989). It is due to the fact that, under the action of an electric field, charged particles drift relative to one another and relative to neutral particles. Collisions between species limit the drift velocities and convert some of the drift energy into thermal energy. This is called frictional heating. The resulting steep gradient between the region of heating (about 200-400 km) and the topside ionosphere leads to upward diffusion with velocities of hundreds of m/s. This mechanism is behind the formation of some ionospheric troughs.
The convection electric field is the main ionospheric source of strong enough electric fields. There are some indications that the whole convection pattern in the midnight sector can vary from minute to minute (Williams et. al., 1990), producing the spiky structure of high time resolution ion temperature. Frictional heating is also very typical near auroral arcs that are related to electric field structures of their own.

Neutrals and electrons

Although the heating rates for neutrals and ions are very comparable, any increase in Tn should be far smaller than the corresponding increase in Ti due to the greater heat capacity of the neutral gas. However, the effect of frictional/Joule heating of neutrals in the auroral electrojet region can lead to upward neutral wind in a region of high electron densities and strong electric fields (Winser et. al., 1986). Also, for a given magnitude of electric field, electron heating is substantially smaller than ion heating in the F - and E - regions of the ionosphere, and becomes comparable only in the D - region. It has been estimated (see, e.g., Schlegel and St.-Maurice, 1981) that the frictional electron heating rate due to 70 mV/m electric field at 110 km would amount to temperature enhancement of only a few degrees or tens of degrees.

Ions

We will concentrate here on ion heating. If we assume the the force per unit mass on the ions due to collisions with neutrals is proportional to the velocity difference between the two species, the rate of frictional heating is
Q = (eE)^2 n/Mv
where n is the ion density, M is the reduced mass, and v is the collision frequency.
Taking into account Earth's magnetic field this can be written as
Q = (eE)^2 Sum((n/M) v/(w^2 + v^2))
where the summation over i and n apply if several ion and neutral species are present. The new term, w, ion gyrofrequency, comes from the fact that ions gyrate about the magnetic lines of force when not traveling parallel to **B**. The other way to describe the frictional heating is **Joule heating due to the Pedersen current** (e.g., Rees et. al., 1983). The last equation can be written as Q = pE^2, where p is the Pedersen conductivity.
Frictional heating rate can be so large at high latitudes, that the ion temperature exceed the electron temperature (usually we had Te > Ti >Tn). In the work by McCrae et. al. (1991) all enhancements in ion temperatures measured parallel to **B** larger than 100 K were identified as frictional heating events. They concluded that a velocity difference of order 1 km/s provides sufficient heat input to double the ion temperature (at about 300 km, when unperturbed Ti was about 900 K). This heating is important both in F - and upper E - region (e.g., Schlegel and St.-Maurice, 1981), i.e., above about 130 km. This is due to the increasing magnetization of the ions with altitude and the consequently higher relative velocities between ions and neutrals (Robinson and Honary, 1990).
It is also possible that the collisions between the drifting ions and neutrals set the **neutral gas in motion**, leading to an equalization of the ion and neutral velocities in a steady state (Kelley, 1989, p. 331). In this case there would be almost no frictional heating although the ion gas can be moving quite rapidly. It has been shown (Baron and Wand, 1983) that the neutral wind speed approaches that of the ions with a time constant t which is inversely proportional to the ion density n,
t = n(neutral)/(nv).
This is the reason for, e.g., the ion temperature structure in the high latitude nightside trough. We can conclude that the best way to measure the effects of frictional heating is to measure directly both the ion drift (using incoherent scatter radars) and neutral wind velocity (using Fabry-Perot interferometers), as is done, e.g., by Hagan and Sipler (1991).
Different kind of frictional heating (and anisotropic ion temperatures) can be produced due to ion-ion collisions as the minor ion species with mass less than the mean ion mass are accelerated through the ion gas (Kelley, 1989, p.316). For example, at high latitudes, both H+ and He++ can be accelerated along field lines through O+ gas and be subjected to this heating process.
Frictional ion heating can also lead ionospheric thermal ion outflow events.

Ionosphere (Earth's)

Introduction

Because of the Sun 's UV radiation, Earth 's upper atmosphere is partly (0.1% or less) ionized plasma at altitudes of 70-1500 km. This region, ionosphere, is coupled to both the magnetosphere and the neutral atmosphere. It is of great practical importance because of its effect on radio waves.
The existense of a conducting layer in the upper atmosphere results also in many other interesting phenomena. Around the plasma density maximum (F-layer, see below) a so-called ionospheric waveguide is formed for magnetosonic waves. In addition, a so-called ionospheric Alfvén resonator (IAR) can be formed between the density maximum and an upper altitude at about 3000 km, where the Alfvén velocity has a maximum. A third natural resonator is

formed between the nearly perfectly conducting terrestrial surface and the ionosphere, creating the so-called Schumann resonances

Ionospheric layers

Ionization appears at a number of atmospheric levels, producing layers or regions which may be identified by their interaction with radio waves. These layers are known as the D, E, and F layers, and their locations are shown in the figure for both night and day conditions at mid-latitudes.
The first ionospheric layer found was the so called E layer or region at about 110 km altitude. It is used by radio operators as a surface from which signals can be reflected to distant stations. It is interesting to note that this works also the other way round and, for example, the auroral kilometric radiation created by the precipitating particles high above the ionosphere does not reach the ground because of the ionospheric E layer. Above the E layer, a F layer consisting of two parts can be found: F1 is at about 170 km, and F2 at about 250 km altitude. Also F layer reflects radio waves. The lowermost region of the ionosphere below 80 km altitude, D layer, however, principally absorbs radio waves.

Density changes

Within the auroral oval the nighttime E layer plasma densities can be much higher than indicated by the figure. Densities are also very variable because of the spatial and temporal strucuture in the ionizing particle precipitation. The E layer plasma density profiles can also be drastically altered due to the occasional formation of so-called **sporadic E layers**.
In F layer altitudes one encounters such features as polar cap ionization patches and different types of troughs.
Note also that there is also a clear solar cycle effect seen: the average densities are higher during solar maximum years than during the minimum years.

Ionospheric conductivities

Ionospheric temperatures

The electron temperature responds readily to the auroral precipitation with a strong increase. Ion temperatures, on the other hand, are elevated mainly by frictional heating due to strong electric fields. The electric field can increase E layer electron temperature only indirectly via instabilities it creates (see radar aurora).

Ionospheric convection

Ionospheric electric fields are the main result of the coupling between the magnetosphere and ionosphere. While at low-latitudes the ionospheric plasma is co-rotating with the Earth, at higher latitudes it is convecting under the influence of the large scale magnetospheric electric field mapped to low altitudes. The Harang discontinuity is one of the ionospheric features related to the plasma convection pattern.

Ionospheric currents

The convection pattern leads to ionospheric Hall currents (see E x B drift), and along the auroral oval so-called convection electrojets are formed at about 100 km altitude: eastward electrojet on the duskside, westward on the dawnside. Historically a term DP-2 has also been used (disturbance polar of the second type).
The coupling between the ionosphere and magnetosphere results also into large and small scale field-aligned currents (FAC). As the down- and upward parts of the current systems are typically separated, horisontal current systems must be formed within the conducting ionosphere. The auroral (or substorm) electrojet, earlier known as the DP-1 current (disturbance polar of the first type), relates to the formation of substorm current wedge.

Ionospheric research

One of the best instruments to study ionosphere with is the incoherent scatter radar, of which EISCAT is a good example. Plasma instabilities are best studied with **coherent scatter radars**, and **ionosondes** are still used continuously to monitor ionospheric processes. Ionospheric currents are traditionally been studied by magnetometers.

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Pc 1-2 and IPDP pulsations

Introduction

Continuous geomagnetic ULF waves with period of **0.2 - 10 s** are called Pc 1-2 pulsations (a special subclass has been termed IPDP). Pulsations at these frequencies are generated by the electromagnetic ion cyclotron (EMIC) instability near the magnetic equator, and they are thus called **ion cyclotron waves**. There are three observational facts supporting the EMIC nature of the waves:

1. electromagnetic nature of the waves
2. predominance of left-hand polarization near the equator
3. existense of a gap in spectral power in the vicinity of the helium gyrofrequency, $F(He^+)$

Ground based observations of structured Pc 1 pulsations.

Pc 1-2 waves propagate towards the ionosphere along the field line, and can be observed also on the ground, as reported already by Sucksdorff (1936) and Harang (1936). Two main subgroups have been identified on basis of ground observations: structured pulsations (also known as periodic or pearl pulsations) and unstructured pulsations (Fukunishi et al., 1981).

Energy for the EMIC wave generation is provided by temperature anisotropies (Tperp > Tpar) of magnetospheric protons in the energy range 10 - 100 keV. For example, solar wind compressions of the magnetosphere favour Pc 1 generation, as the compressions increase the ion anisotropy which, in turn, increase the wave growth rate (Olson and Lee, 1983; Kangas et al., 1986). The necessary ions can be either of ring current (mid- and low-latitude events) or plasma sheet (high-latitude events) origin.

Occurrence distribution

The effective amplification of EMIC waves depends on the amount of time spent propagating through a finite growth region (Kozyra et al., 1984), and the convective growth rate is thus inversely related to the group velocity of the waves. Since the group velocity is related to the Alfvén velocity Va, enhanced cold plasma densities and low magnetic field strengths (= low Va) favour the wave growth. Since the magnetic field lines have minimums at the equator, the wave growth occurs there. A minimum in Va occurs typically just inside the plasmapause (maximum *at* the plasmapause; e.g., Fraser et al., 1992) and, accordingly, two types of Pc 1-2 pulsations are related to this region close to the ring current: the so-called structured or pearl Pc 1 pulsations (see, e.g., Erlandson et al., 1992) and the IPDP events. The ring current ion source depends strongly on geomagnetic activity, and the pearl events occur typically during a recovery phase of a geomagnetic storm, while the IPDPs occur during the active phase of a substorm. The structured pulsations are most often seen in the morning sector (Saito, 1969).

However, the plasmapause is not the most important region for EMIC wave growth. Observations from both magnetosphere (Anderson et al., 1992a) and ground (Plyasova-Bakounina et al., 1996) show maximum Pc 1-2 occurrence probability at L=7-9, ML=12-15, indicating that the **plasma sheet ions are the most important energy source** for the waves. A weaker maximum is found in the dawn sector (03-09 MLT). These high latitude pulsations are unstructured (e.g., hydromagnetic chorus type), and storm independent. However, the emissions may be modulated by Pc 4-5 pulsations (e.g., Plyasova-Bakounina et al., 1996).

Finally, some very high latitude (ground based) events observed in the dawn sector have been explained by ions injected in the cusp/cleft region, and drifting westward towards dawn (Hansen et al., 1992). However, it is possible that these are solar wind controlled pulsations leaking into the magnetosphere through the cusp (Plyasova-Bakounina et al., 1996), or waves related to plasma mantle (Dyrud et al., 1997).

Satellite observations have shown that the latitudinal extent of Pc 1 wave events are of the order of 100 km when projected into the ionosphere (Iyemori and Hayashi, 1989; Erlandson *et al.*, 1990; Erlandson and Anderson, 1996). Individual bursts have even smaller extent. The events are much more extended longitudinally, as the ions providing the energy drift around the Earth.

Structured (pearl) pulsations

The pearl pulsations appear as repetitive bursts of Pc 1 waves, formed by wave packets propagating along magnetic field lines between conjugate points and partially reflecting from the ionosphere. Accordingly, it has been shown that the bursts are in antiphase in the northern and southern hemispheres. The figure here shows a Pc 1 pearl (electric field component) as observed in the ionosphere by the Freja satellite (Mursula et al., 1994). For the wave growth to occur, the reflected wave's k-vector should be parallel to **B**, and this is possible only in the presence of a density gradient. Such a gradient occurs at the plasmapause and, indeed, all structured events have been found to occur just inside or near the plasmapause. Note, however, that the validity of the wave packet theory has lately been questioned (e.g., Mursula et al., 1997).

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Wave properties

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To investigate further the frequency properties, we introduce a normalized frequency $X = F/F(H^+)$, where F is the local, observed wave frequency, and $F(H^+)$ is the equatorial proton gyrofrequency along the same field line. This value is always < 1 and, for waves $F < F(He^+)$, $X < 0.25$. Waves with $X < 0.25$ and $0.25 < X < 0.45$ are typically seen at the early afternoon occurrence maxima, while waves with higher X are seen within the dawn sector (03-09 MLT) secondary peak. Even more striking difference concerns the **polarization** characteristics of these populations: the dawnside events seem to be generated with polarizations ranging from purely left-hand to linear, while the afternoon side events are of the typical left-hand type (Anderson et al., 1992b). It is not possible to explain this feature in terms of crossover from left- to right-hand polarization occurring typically during propagation from low to high magnetic field strengths (towards ionosphere).

Ionospheric effects

Comparison of the Pc 1 waves observed in space and on ground is not always straightforward, since the field line guidance of Pc 1 waves stops in the ionosphere, and ground-based observations are influenced by ducting of waves in the ionospheric waveguide (e.g., Fujita, 1987). The ducting has an interesting side-effect, called multiband Pc 1 events, where observed on the ground sees emissions at two or more frequency range simultaneously. They are formed as emissions from different source regions (L-shells) are ducted within the ionosphere to a point on the ground. Note that this is different than having band-like structure because of the splitting of the emission spectra by magnetospheric heavy ions (He^+ and O^+). Furthermore, there are some evidence of rare occurrence of multiband structured pulsations produced solely within one source (Feygin et al., 1994).

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IPDP (intervals of pulsations of diminishing periods) tend to occur during the active phase of geomagnetic substorms in the afternoon-evening sector (Hayakawa et al., 1992).

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Plasma

Matter in the known universe can be classified in terms of four states: **solid, liquid, gaseous, and plasma**. The basic distinction between solids, liquids and gases lies in the difference between the strength of the bonds that hold their constituent particles together. The equilibrium between particle thermal (=random kinetic) energy and the interparticle binding forces determines the state. Heating of a solid or liquid substance leads to phase transition to a liquid or gaseous state, respectively. This takes place at a constant temperature for a given pressure, and requires an amount of energy known as latent heat. On the other hand, the transition from a gas to an **ionized gas, i.e., plasma**, is not a phase transition, since it occurs gradually with increasing temperature. During the process, a molecular gas dissociates first into an atomic gas which, with increasing temperature, is ionized as the collisions between atoms are able to free the outermost orbital electrons. Resulting plasma consists of a mixture of neutral particles, positive ions (atoms or molecules that have lost one or more electrons), and negative electrons. In a weakly ionized plasma the charge-neutral interactions are still important, while in strongly ionized plasma the multiple Coulomb interactions are dominant.

Because some or all particles are electrically charged and capable of creating and interacting with electromagnetic fields, many phenomena not present in ordinary fluids and solids can be found in plasmas. A plasma is a conductor of electricity, but a volume with dimensions greater than the so-called Debye length exhibits electrically neutral behavior. At a microscopic level, corresponding to distances shorter than the Debye length, the particles of a plasma do not exhibit collective behavior but instead react individually to a disturbance, for example, an electric field. See Plasma theories for more information about kinetic theory and cold/warm/hot plasma models.

On the Earth , plasmas usually do not occur naturally except in the form of lightning bolts, which consist of narrow paths of air molecules of which approximately 20 percent are ionized, and in parts of flames. The free electrons in a metal can also be considered as a plasma. **Most of the universe, however, consists of matter in the plasma state**. The ionization is caused by high temperatures as described above (e.g., inside the Sun and other stars), or by radiation, as in interstellar gases (e.g., solar wind) or, closer to the Earth, in the ionosphere and magnetosphere.

Plasma instabilities

Introduction

A plasma instability involves plasma waves that grow exponentially or faster. For proper discription of a particular instability, one should be able to define

- the mode of the growing wave
- the nature of the growth
- source of the free energy

Because of all these points of view, the nomenclature for plasma instabilities is even more cumbersome than for the wave modes themselves. A solid understanding of plasma theories is needed in order to study the formation of different instabilities.

One important way to classify different instabilities is to devide them into **macroinstabilities and microinstabilities**.

A macroinstability is **driven by the structure of the medium in configuration space**. A familiar example of a macroinstability is for a convectively unstable system: when the temperature gradient is superadiabatic, internal gravity waves grow to large amplitude and cause a large-scale convection of the fluid, which tends to reduce the temperature gradient. Other familiar examples are the Rayleigh-Jeans instability, in which a denser fluid is supported by a less dense fluid, and the **Kelvin- Helmholtz instability**, in which one fluid flows over another fluid, e.g., wind over water, causing surface waves to grow. In plasmas the macroinstabilities occur in the low-frequency regime and usually involve the magnetic field. Examples include flute (or interchange) and ballooning instabilities. The latter ones are used, for example, in some substorm models.

Microinstabilities, on the other hand, are usually **driven by a velocity space anisotropy** in the plasma. A consequence of a microinstability is a greatly enhanced level of fluctuations in the plasma associated with the unstable mode. These fluctuations are called **microturbulence**. Microturbulence can lead to enhanced radiation from the plasma and to enhanced scattering of particles resulting in 'anomalous' transport coefficients, e.g., anomalous electric and thermal conductivities. The simplest example of a microinstability is a beam-driven instability in a unmagnetized plasma.