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Electrodynamic coupling of Jupiter's thermosphere and stratosphere: A new source of thermospheric heating?

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ABSTRACT

We investigate the vertical penetration of non-uniform electric fields in a planetary ionosphere. We develop a simple theoretical description of the vertical variation of electric fields with altitude in an ionosphere permeated with a vertical magnetic field. This framework is applied to the suggestion that winds in Jupiter's stratosphere could drive currents in the thermosphere. In particular, we propose that wind structures in the upper region of Jupiter's stratosphere (200–350 km above the 1 bar level) couple with the ionospheric plasma in this region to generate electric currents, some of which close by flowing vertically along magnetic field lines and then horizontally in the Pedersen conducting region of the thermosphere. These currents extract kinetic energy from the stratospheric winds and dissipate it, via Joule heating, as thermal energy in the thermosphere, thus providing a possible contribution to the observed high temperatures in this region. While the existence of significant wind structures in the upper stratosphere is speculative, the wind speeds that are required to generate significant heating ($\sim$100 m s^{-1}) are not unreasonable in comparison to the observed tropospheric, lower stratospheric and thermospheric wind speeds. The scale size of the wind structures is critical to the degree of penetration of the induced electric fields. Wind structures with scale sizes less than $\sim$10 km do not generate electric fields that penetrate significantly into the thermosphere, while those with scale sizes of greater than $\sim$100 km (which includes very large, planetary-scale wind structures) generate electric fields that penetrate almost unmodified across the whole of the thermosphere. Sharp ionospheric layers or holes can prevent penetration of the electric fields to the thermosphere, doing so more effectively if they are of greater magnitude, of greater vertical width, or located at lower altitude. The timescale for damping of the stratospheric winds by ion drag is found to be strongly altitude-dependent, ranging from $\sim$1 planetary rotation at 350 km altitude to >100 planetary rotations at 200 km altitude. The timescales also vary strongly with the nature and scale size of the wind structures. If the timescales of the processes driving stratospheric winds are longer than these timescales, then our mechanism will damp the winds almost to zero, and supply negligible energy to the thermosphere. We also discuss the possible relevance of our results to magnetosphere–ionosphere coupling in the auroral regions of Jupiter and other planets.

1. Introduction

The unexplained high temperatures of the thermospheres of the giant planets (Jupiter, Saturn, Uranus and Neptune) is a long standing problem in planetary science. Simple theoretical models of heating by absorption of solar extreme UV underestimate the observed thermospheric temperatures for all four planets (Strobel and Smith, 1973; Yelle and Miller, 2004). Processes that have been invoked to explain these high temperatures include dissipation of upward-propagating gravity waves (Young et al., 1997; Matcheva and Strobel, 1999; Hickey et al., 2000) or acoustic waves (Schubert et al., 2003), electron precipitation (Hunten and Dessler, 1977; Waite et al., 1983), Joule heating (Nishida and Watanabe, 1981) and kinetic energy changes due to ion drag (Miller et al., 2000; Smith et al., 2005; Stallard et al., 2007).

The effects of Joule heating and ion drag due to large scale magnetospheric electric fields have recently been examined for Jupiter and Saturn by the present author and co-authors (Smith et al., 2007; Smith and Aylward, 2008, 2009). In these studies we showed that at both planets ion drag from the sub-corotating middle and outer magnetospheres tends to confine thermal energy from associated Joule heating to high latitudes, and even marginally cools the equatorial regions. Separately, we also suggested (Smith et al., 2005), building on the terrestrial studies of Codrescu et al. (1995, 2000), that small-scale, fluctuating electric fields could

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increase the Joule heating without a corresponding increase in the confining effect of ion drag. In this paper, we suggest that such small-scale electric fields may originate in the upper part of the stratosphere (200–350 km above the 1 bar level) as winds couple to ionospheric plasma at these altitudes. These electric fields penetrate into the thermosphere and drive Pedersen and field-aligned currents, leading to Joule heating that contributes to the observed high temperatures.

It is common to assume in ionospheric electrodynamics studies that magnetic field lines behave as perfectly conducting wires, and are therefore equipotentials, so that the electric field penetrates the entire ionosphere unmodified. In the lower thermosphere and upper stratosphere this assumption breaks down because there are sufficient electron-neutral collisions to significantly increase the field-aligned resistance. The object of this study is thus to investigate the penetration of non-uniform electric field structures when the field lines cannot be treated as equipotentials. The motivation and context for these calculations is the investigation of thermospheric heating. However, the theoretical framework that we will develop is relevant to any context in which a non-uniform electric field penetrates a planetary ionosphere, for example the electric fields associated with magnetosphere–ionosphere coupling.

In this study we focus on Jupiter because we have available reasonably detailed profiles of temperature (Seiff et al., 1998) and ionospheric density (Hinson et al., 1997, 1998) in the region of interest. In Section 2 we summarise this information and discuss the evidence for upper stratospheric winds at Jupiter. Section 3 then outlines the general theory behind our mechanism, and applies it to some simple models of upper stratospheric winds. In Section 4 we investigate the effect of these wind models in a simplified model of the atmosphere, before applying them to a realistic model of the atmosphere in Section 5. In Sections 6 and 7 we discuss the applicability of our results, summarise, and conclude.

2. Structure of Jupiter's upper atmosphere

2.1. Thermal structure

The solid line in Fig. 1a shows the temperature structure of Jupiter's neutral atmosphere, from 200 km to 1200 km above the 1 bar level, as determined by the Galileo probe (Seiff et al., 1998). At the bottom of the range shown (200–300 km) is a region with temperatures in the range ~150–200 K. Above 300 km the temperature rises rapidly with altitude, reaching ~900 K at 800 km. At higher altitudes the atmosphere is approximately isothermal (and the profile has been extrapolated at constant temperature above ~1000 km).

The wavy structures in the temperature profile have been interpreted as evidence of upward propagating gravity waves (Young et al., 1997). We are not specifically interested in gravity waves in this study, so we wish to eliminate these wave structures from the temperature profile. To do so we use the functional fit of Hickey et al. (2000, henceforth HWS), which is described in their Appendix 2 and shown by the dotted line in Fig. 1. If we assume that the thermal structure is dominated by a balance between heating and thermal conduction, we can calculate the required net heating power per unit volume at each altitude (for details of this calculation, see Appendix A). The resulting profile of net heating or net cooling is shown in Fig. 1a, as a dashed line where net heating is required and a dot-dash line where net cooling is required. The region of net heating is the result that is of interest to this study. We do not expect to be able to reproduce the exact heating profile shown. Rather, we are interested in producing the correct order of magnitude of heating at approximately the correct altitude, in order to judge the plausibility of the proposed mechanism.

2.2. Ionosphere

Fig. 1b shows the corresponding structure of the ionosphere, in the form of electron density profiles determined by the Voyager and Galileo radio occultation experiments (Hinson et al., 1997, 1998).[1] Much of the ionosphere lies at altitudes above those at which the bulk of the heating is required, and these altitudes are not shown.

There is a great deal of variation in the electron density profiles, such that any heating associated with the ionosphere must vary significantly with location. The region above ~500 km is represented by data from all of the occultations shown, with electron densities in the range $\sim10^{9}$–10^{11} m^{-3}. There is considerable structure within this range, and in the case of the Voyager exit profile (V2X, thin solid line), there is a large electron density 'hole' between 500 and 800 km. Some of the Galileo profiles show similar holes where the calculated electron density falls to very small or negative values. The region below ~500 km is only represented by the Voyager profiles. Both profiles show electron densities in the range $\sim10^{10}$–10^{11} m^{-3}, although there is a narrow electron density hole in the exit profile close to 400 km, and there is no reported data for the entry profile below ~300 km.

Broadly speaking, there are two important features of these electron density profiles. Firstly, the evidence for the existence of electron density in the range 200–400 km, provided by the Voyager profiles, indicates that winds at these altitudes may be capable of generating electric fields and currents. Secondly, the complex structures, in particular the electron density holes, indicate that the penetration of electric fields from these low altitudes upwards is non-trivial, and must be calculated carefully. In Section 5 we will modify the Voyager profiles – in particular we will 'fill in' the electron density holes – to provide continuous electron density profiles that will allow us to investigate the penetration of electric fields. These modified profiles are shown in Fig. 1c and will be discussed in Section 5.

2.3. Wind structures

For this discussion we divide the atmosphere into three layers: the troposphere, below ~40 km, the thermosphere, above ~350 km, and the region between these levels, which is commonly referred to as the stratosphere. The mechanism proposed by this paper requires that there are wind structures in the upper stratosphere, which throughout this paper will be taken to refer to the altitude range 200–350 km, overlapping the lowest regions of the ionosphere. There are no direct measurements of winds in this region. However, we can find indirect evidence for two very different classes of wind structure: small-scale, rapidly varying structures which effectively represent turbulence, and large-scale slowly varying structures analogous to the persistent zonal jets observed in Jupiter's troposphere.

The evidence for small-scale turbulent structures in the upper stratosphere stems from the observation that Jupiter's homopause lies at ~350 km, approximately at the lower boundary of the thermosphere (Gladstone et al., 1996). Below the homopause, mixing of the atmosphere by bulk flow motions is more important than mixing by molecular diffusion. There must therefore be some winds in this region. The usual description of this bulk flow mixing as 'eddy mixing' implies that it is largely a consequence of

[1] The relevant datasets are archived in the NASA Planetary Data System and are also available from http://www-star.stanford.edu/projects/gll/gll-jup.html.