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Saturn's auroral/polar H_3^+ infrared emission
II. A comparison with plasma flow models

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Abstract

We present a detailed analysis of the H_3^+ intensity and velocity profiles crossing Saturn's auroral/polar region, as described by Stallard et al. [Stallard, T., Miller, S., Melin, H., Lystrup, M., Dougherty, M., Achilleos, N., 2007. Icarus 189, 1–13], with a view to understanding the magnetospheric processes with which they are connected. The data are not consistent with the theory that Saturn's main auroral oval is associated with corotation enforcement currents in the middle magnetosphere. This implies that the main auroral oval can be associated with the open–closed field line boundary [Cowley, S.W.H., Bunce, E.J., O'Rourke, J.M., 2004. J. Geophys. Res. 109. A05212]; a third model, by Sittler et al. [Sittler, E.C., Blanc, M.F., Richardson, J.D., 2006. J. Geophys. Res. 111. A06208] associates the main oval with centrifugal instabilities in the outer magnetosphere, but does not make predictions about ionospheric plasma flows with which we can compare our data. We do, however, tentatively identify emission at latitudes lower than the main auroral oval which may be associated with the corotation enforcement currents in the middle magnetosphere. We also find that at latitudes higher than the main auroral oval there is often a region of the ionosphere that is in rigid corotation with the planet. We suggest that this region corresponds to field lines embedded in the centre of the magnetotail which are shielded from the solar wind such that their rotation is controlled only by the neutral atmosphere.

Keywords: Aurorae; Ionospheres; Infrared observations; Saturn, magnetosphere; Saturn, atmosphere

1. Introduction

The processes by which the saturnian aurorae are formed are an issue of intense current interest and debate. With the influx of new in situ data following Cassini's arrival at Saturn (Dougherty et al., 2005; Gurnett et al., 2005; Krimigis et al., 2005; Young et al., 2005) and the supporting UV images that show the morphology of the aurora in detail for the first time (Gérard et al., 2004; Clarke et al., 2005; Crary et al., 2005; Grodent et al., 2005; Kurth et al., 2005), it has been possible for detailed theories to be developed (Cowley et al., 2004; Hill, 2005; Sittler et al., 2006).

In the case of Jupiter, there is at present a reasonable consensus that the main auroral oval is associated with sub-corotation of plasma in the jovian middle magnetosphere (Hill, 2001; Cowley and Bunce, 2001). Polewards of the main oval there are more complicated structures (Pallier and Prangé, 2001; see Clarke et al., 2004, for a review) that have yet to be fully explained, but are likely to be associated with solar wind coupling (Cowley et al., 2003b). Infrared data (Rego et al., 1999; Stallard et al., 2001, 2002, 2003) has been important in our emerging understanding of these phenomena. The principal purpose of this paper is to use similar IR data acquired for Saturn (Stallard et al., 2007) to assess the existing models of the saturnian aurorae. We are also able to tentatively identify features in our data that correlate with structures in Saturn's magnetotail, and discuss

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the possible implications of these structures for the conditions within the thermosphere.

In Section 2 we briefly discuss our present understanding of the magnetosphere of Jupiter and its relation to that planet's aurorae. In this context we then discuss the extant models of Saturn's main auroral oval and describe the plasma flows that these models predict will exist in the polar regions of the planet's ionosphere. In Section 3 we review the observations presented in Stallard et al. (2007), and in Section 4 we assess their consistency with the predictions of Section 2. In Section 5 we discuss the velocity structure of the polar cap within our data, in Section 6 we calculate the energy the measured velocity structure deposits into the upper atmosphere, and in Section 7 we present our conclusions.

2. Models for the formation of giant planet aurorae

2.1. Jovian auroral models

The basis of our understanding of the saturnian aurorae is our more robust—but still developing—knowledge of the jovian aurorae. The jovian aurorae are dominated by a bright and stable 'main oval,' present in both the UV and IR emissions. The present consensus is that this main oval is associated with the system of currents that flow between the polar regions of the planet and the middle magnetosphere (Hill, 2001; Cowley and Bunce, 2001). This system of currents was first described by Hill (1979) as the mechanism by which planetary angular momentum is transferred to the magnetosphere. The currents in the upper atmosphere flow towards the equator, while those in the middle magnetosphere flow away from the planet. These two regions are linked by field-aligned currents that close the circuit.

The angular momentum transfer mediated by these currents is necessary because fresh plasma is continually supplied to the jovian inner magnetosphere by volcanism on the moon Io. In the inner magnetosphere the Hill currents spin up the plasma rapidly into rigid corotation with the planet, as collisions between ions and neutrals in the atmosphere provide sufficient torque to keep the plasma rigidly corotating. Close to the planet, the Hill currents required to maintain corotation are relatively weak. However, the plasma injected into the inner magnetosphere by Io gradually diffuses outwards, forming a vast plasma sheet in the equatorial plane of the middle magnetosphere. At a critical distance from the planet, the required angular momentum to maintain rigid corotation in the plasma sheet is greater than can be provided by collisions between ions and neutrals within the atmosphere, and so the plasma beyond this radius therefore substantially sub-corotates. In this region the Hill currents are considerably larger than in the inner magnetosphere as the differential rotation velocity of the planet and the plasma, which drives the currents, is much greater. Thus, at the inner edge of the sub-corotating region, the magnitude of the Hill currents increases greatly. Since in the middle magnetosphere the current is flowing away from the planet, there must be strong upwards currents on field lines mapping to the inner edge of this region. At the planet, these upwards currents are of too great an intensity to be carried by the ambient plasma; it is thus necessary for them to be carried by the downwards acceleration of magnetospheric electrons. It is these electrons—with energies of a few kiloelectron Volts (keV) to over 100 keV—that are believed to be responsible for exciting the main auroral oval emission seen in the UV, optical and IR.

The key point of this discussion is that the jovian main auroral oval lies at the inner edge of the sub-corotating region of the middle magnetosphere. The self-consistent theoretical treatment of the jovian middle magnetosphere presented by Nichols and Cowley (2004) further supports this insight. Nichols and Cowley took into account variations in the ionospheric conductivity induced by the auroral electrons. Since the impact of these electrons increases the density of the ionosphere in the region of upwards currents (the main oval), they also tend to increase the intensity of the upwards currents at the equatorwards edge of the main oval. The peak upwards currents is then at a lower latitude; thus the main oval itself has been pushed to lower latitudes (corresponding, in the magnetosphere, to regions closer to the planet). This process ensures that the field lines mapping to the main auroral oval are concentrated at the inner edge of the region of sub-corotation. Plasma on field lines at slightly lower latitudes (closer to the planet) than those corresponding to the main oval are very nearly in rigid corotation with the planet. Auroral emissions polewards of the jovian main oval are less well understood.

As well as a wealth of information derived from UV images of the jovian auroral polar regions (e.g., Clarke et al., 1998, 2004; Pallier and Prangé, 2001), the understanding of Jupiter's auroral features has greatly benefited from infrared imaging (e.g., Baron et al., 1991; Connerney et al., 1993, 1998) and spectroscopy (e.g., Drossart et al., 1989; Lam et al., 1997; Miller et al., 2000). For Jupiter, there is close correspondence between UV and IR images, indicating a related source for both UV and IR aurorae. But there are also differences: in particular, there is significant infrared emission across Jupiter's polar cap in regions where the UV emission is low, a situation that is still not fully explained. Measurements of ion velocities in the upper atmosphere have been used to identify the presence of a westward (in the planetary reference frame, i.e., counter to the rotation of the planet) wind associated with the main auroral oval (Rego et al., 1999), and to delineate distinct flow regions within the polar cap (Stallard et al., 2003). Modelling has shown that this ion drift engenders a strong neutral wind (Millward et al., 2005), with important consequences for energy inputs due to Joule heating and ion drag (Smith et al., 2005, 2007; Smith, 2006).

To demonstrate how IR data can be used to support theories of the formation of the jovian aurorae we show in Fig. 1 an example of jovian auroral structure first published in Stallard et al. (2003). The thin line shows H_3^+ emission intensity in the fundamental ν_2 $Q(1,0^-)$ line, at 3.953 microns, across the northern auroral/polar region. The bold line shows line-of-sight velocities in an inertial frame. In this figure, we have taken the reference frame as that which rigidly corotates with the planet's (North) magnetic pole, correcting for the small velocity change caused by it being tilted with respect to the rotational