Self-sustaining Axial Asymmetries in the Thermosphere as a Driver of Rotational Periodicities in the Magnetosphere

C. G. A. Smith (1,2) & N. A. Achilleos (3)
1. The Brooksbank School, Elland, West Yorkshire, UK. email: cgasmith@gmail.com
2. Visiting Research Fellow, Dept. of Physics & Astronomy, UCL, London, UK
3. Dept. of Physics & Astronomy, UCL, London, UK

The rotational periodicities observed in various phenomena in Saturn's magnetosphere exhibit several puzzling aspects, in particular the different periodicities in the northern and southern hemispheres that appear to have a seasonal dependence.

We explore a possible mechanism for originating the periodicities in the thermosphere. Our model is based on a feedback effect between thermospheric winds and heating from particle precipitation. The feedback effect is shown to be able to permanently break the axisymmetry of the thermosphere, leading to independent rotating asymmetries in the wind-driven current systems in each hemisphere.

We show using a simple model that the period of these rotating asymmetries varies with the heating and conductance in each hemisphere, qualitatively explaining the observed seasonal dependence.

We also suggest that the delay of several months observed in the seasonal dependence could be explained by long chemical timescales in the upper and middle atmospheres introducing a corresponding delay in the response of the ionospheric conductance.

Introduction

It was originally suggested by Smith (2006) that the periodicities in Saturn's magnetosphere could be linked to thermospheric asymmetries. He also suggested that a similar mechanism could explain the System IV period at Jupiter.

Smith (2011) showed that an artificially generated axial asymmetry in the thermosphere could partially explain some of the observations.

The purpose of this study is to investigate a particular generation mechanism for a thermospheric asymmetry. Questions we wish to address include:

• Could an axially asymmetric distribution of winds persist permanently via feedback effects?

• Can different axial asymmetries exist in the northern and southern hemispheres that rotate with different periods?

• If so, do the northern and southern periods vary seasonally?

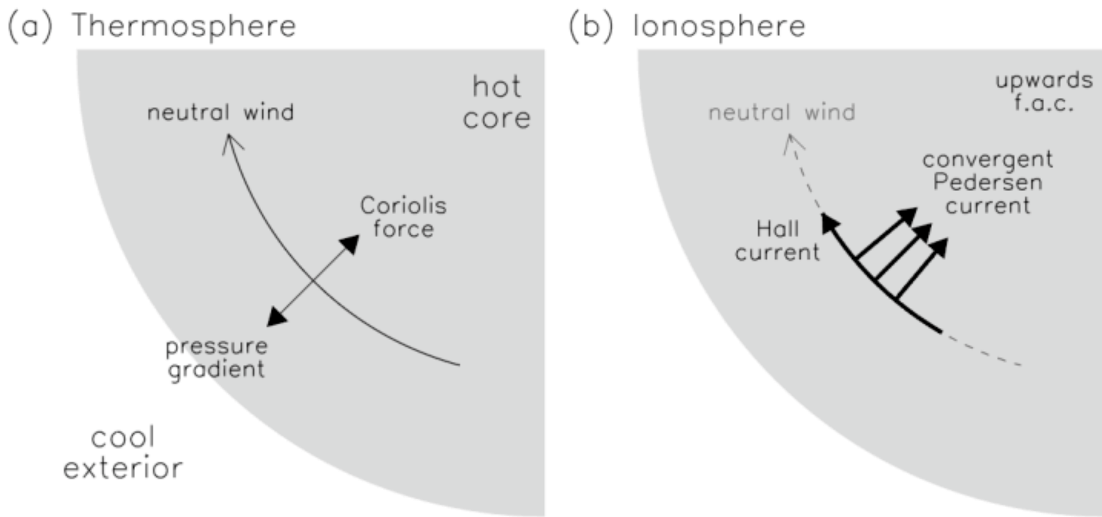
• If so, is there a time lag in the equinox crossing, as observed in SKR emissions (Gurnett et al. 2010)?

Thermospheric vortex model

The sketches show a model for a self-sustaining thermospheric vortex. The currents driven by the rotation of the vortex are convergent. The convergent current induces upwards currents and particle precipitation which sustain the temperature at the core of the vortex.

The vortex is essentially a ‘thermospheric hurricane’, which powers itself by extracting energy from the magnetosphere via particle precipitation.

If this mechanism works, then such a vortex could exist permanently in the thermosphere of Saturn.

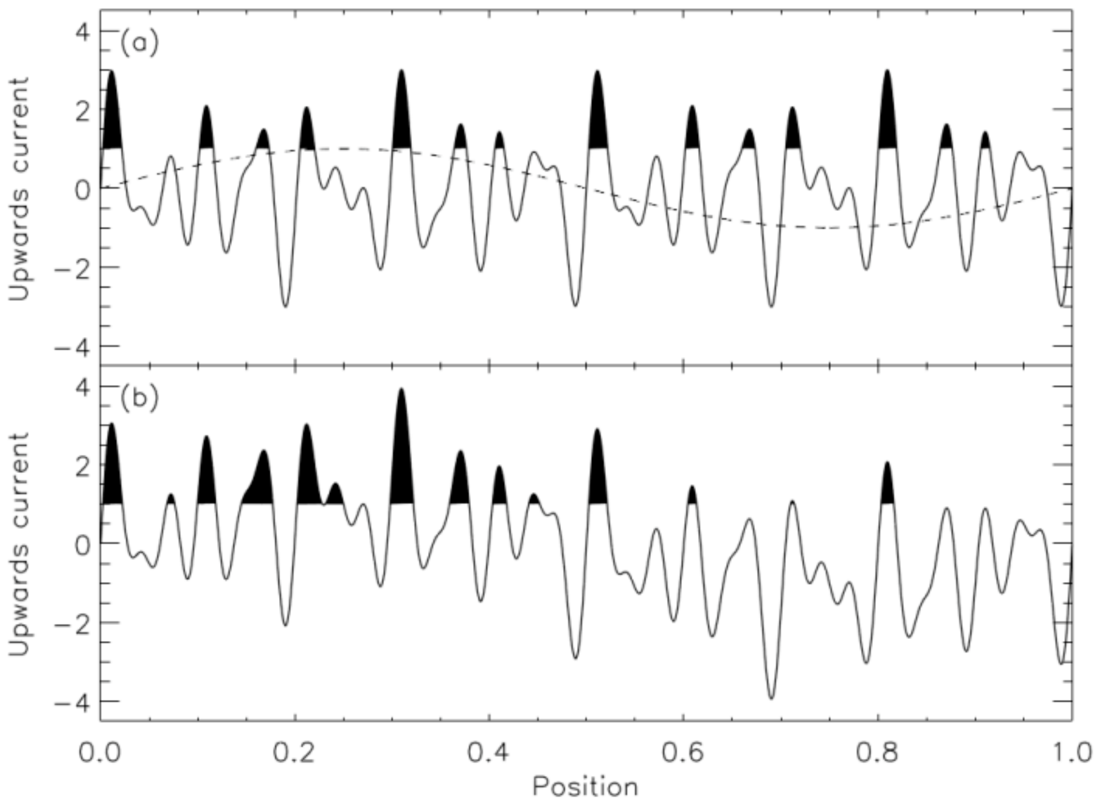


(a) A hot region of the thermosphere produces anticlockwise winds.
(b) The anticlockwise winds drive convergent currents. The resulting upward f.a.c. and particle precipitation maintains the high temperatures in the core.

The figures are for the northern hemisphere. In the south the direction of the Coriolis force and Pedersen current are reversed, so the same physics applies but in mirror image.

Feedback model

A problem with invoking feedback due to particle precipitation is that we do not see an obvious global scale asymmetry in the aurora. Is it possible to get increased/decreased particle precipitation without generating a global scale 'blob' of auroral emission?



Observed auroral emissions consist of small scale structures in parallel currents that shift location and intensity relatively rapidly. This is sketched in (a) as the solid line (arbitrary scale). Regions filled in black show currents exceeding the threshold for auroral acceleration.

Wind driven asymmetric parallel currents may be lower intensity but larger scale. Dashed line in (a) shows sketch of a large scale current system insufficient to produce auroral acceleration.

(b) shows these two current systems superposed. The weak large scale current system skews the small scale current distribution, increasing/ decreasing the amount of auroral acceleration in the left/right regions of the plot.

Thus large-scale asymmetric winds can produce an asymmetry in particle precipitation and heating without a corresponding large-scale 'blob' of auroral emission.

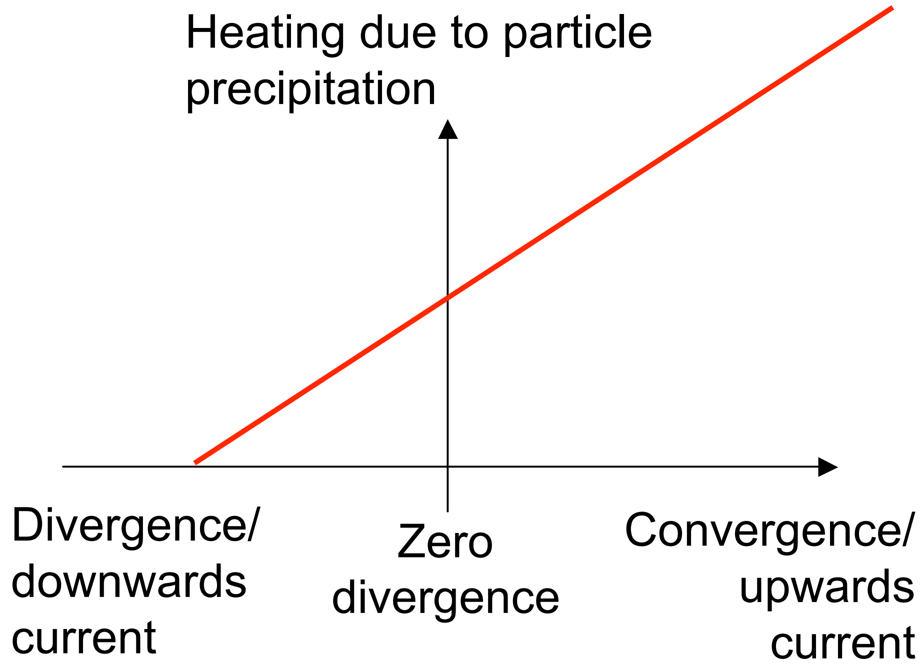
Numerical thermosphere model

We investigate the proposed feedback effect using a 3D general circulation model (Smith 2011).

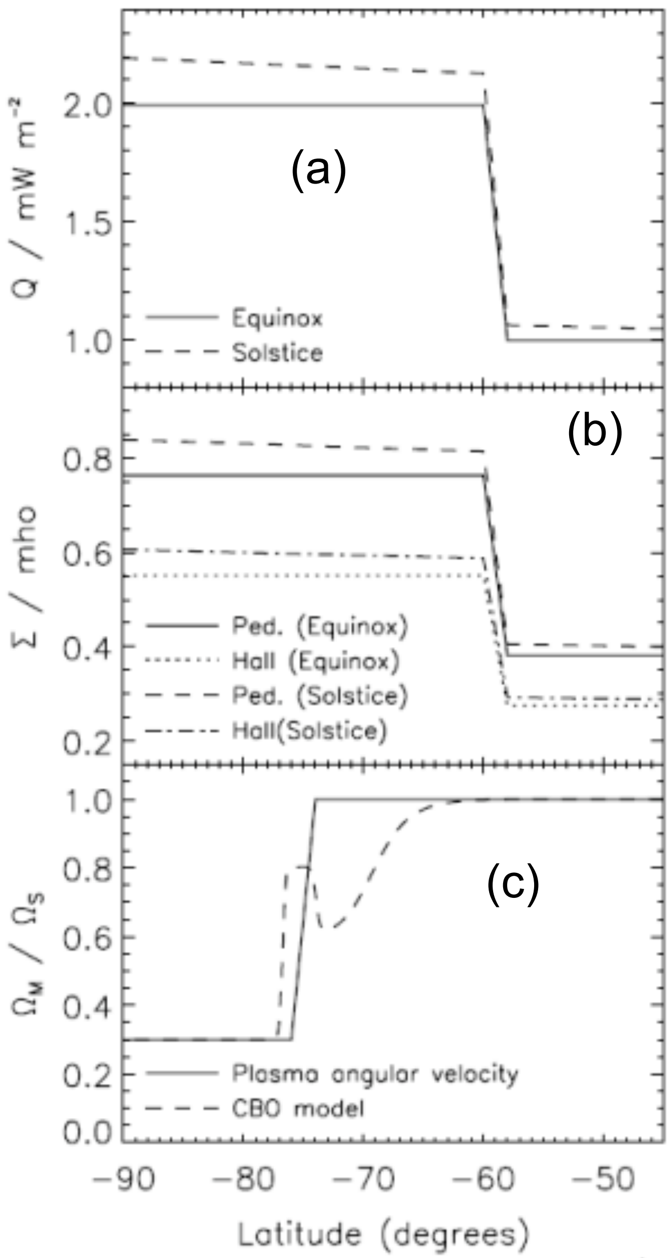
The model includes simplified heating, conductance and plasma flow distributions (see next slide). Joule heating and ion drag are fully implemented.

The feedback effect is implemented by scaling the high-latitude heating (which represents particle precipitation) with the convergence/divergence of the horizontal current (which should be correlated with large scale upwards/downwards currents).

We do not do any detailed calculations of particle precipitation. We simply scale our heating profiles linearly with the current convergence, as shown in the figure.



Heating, conductance and plasma flow models



(a) We use a simple heating distribution peaking at 4nb, very similar to that used by Smith (2011). This produces approximately the observed temperature profile at low latitudes. The figure shows the latitude distribution. We double the heating above 60° latitude to simulate particle precipitation.

The dashed line shows a solstice model in which we introduce a 10% bias into the heating in the northern and southern hemispheres.

(b) The conductance model is the same as Smith (2011), but we halve it at latitudes below 60° to simulate the effect of particle precipitation at high latitudes. The figure shows the latitude distributions of the Pedersen and Hall conductances in the equinox and solstice models.

(c) We use a simplified plasma flow model, identical to that used by Smith (2011). Polewards of 75° latitude the plasma lags corotation by 70%. Equatorwards of this latitude it corotates exactly. The dashed line shows the Cowley, Bunce & O'Rourke (2004) plasma flow model for comparison.

Description of Model Runs

We present the results of three model runs.

1. Equinox model

The model is run with completely axially symmetric heating inputs for 400 planetary rotations to establish approximate global equilibrium.

It is then run for 1 rotation with the asymmetric heating distribution of Smith (2011) also applied in the northern hemisphere only. This heating is then removed and it is run for a further 399 rotations to investigate whether the asymmetries are sustained by the feedback effect.

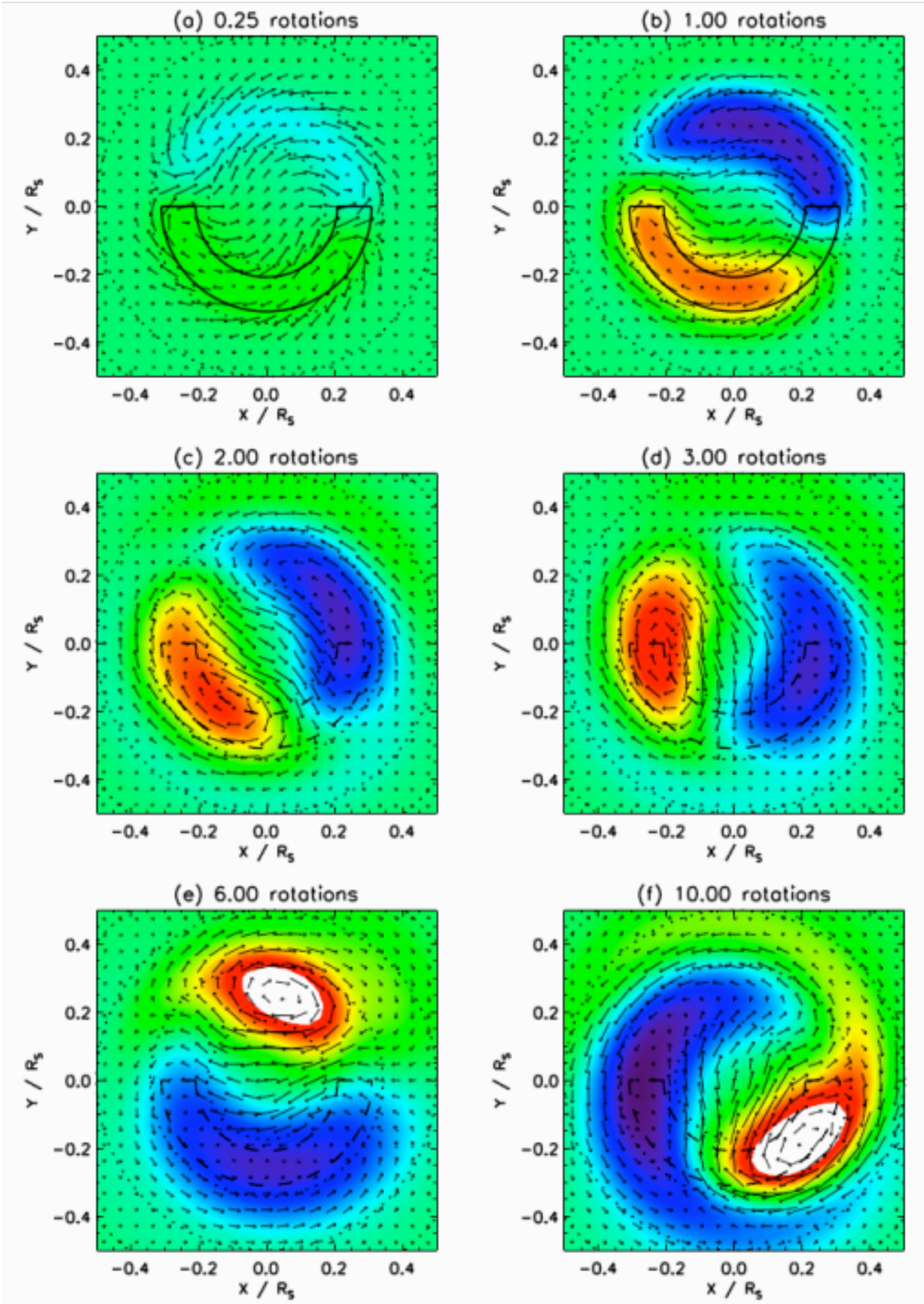
2. Solstice model

Identical to the above, but with a north-south bias in the heating and conductance distributions (see previous slide).

3. Seasonal variation model

Model run 2 is continued for a further 800 rotations, but with the north-south bias varied sinusoidally with a period of 800 rotations, to investigate seasonal variation.

(The true seasonal period is 29.5 years ~ 25,000 rotations. It is impractical to perform model runs of this length, so we investigate seasonal variation with a shorter period.)



Development of asymmetries

The plots show the progress of asymmetries in the winds and temperature at the 2nb level in the northern polar cap of the equinox model over the first 10 rotations after the asymmetric heating is first imposed.

Figs (a) and (b)
During the first rotation the thermosphere is strongly heated in the semicircular region marked with the solid line. This is the same heating distribution as used by Smith (2011). An asymmetry develops at this location but also begins to shift westwards.

Figs (c) to (f)
After the first rotation the fixed external heating is removed. The only asymmetric heating in the model is now a result of feedback between the existing asymmetry and particle precipitation. The asymmetry clearly intensifies and drifts steadily in longitude.

The colour scale is the same as the figure on next slide. The longest arrows show 80m/s in figures (b) to (f). The scaling of the arrows is three times greater in figure (a).

Asymmetric winds/temperatures

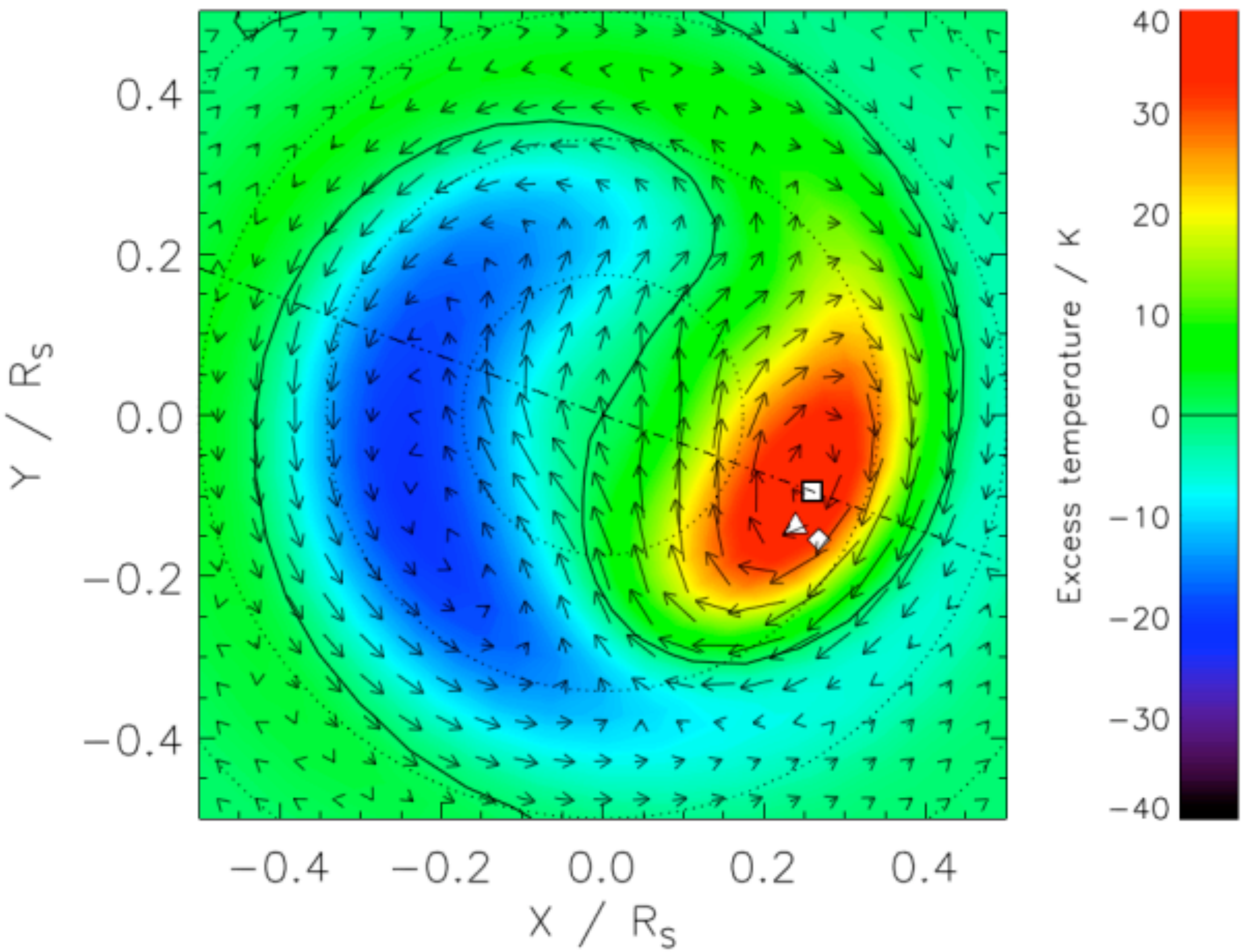
The arrows show the asymmetric components of the horizontal winds at the 2nb level in the northern polar cap at the end of the equinox run.

The colour scale shows the asymmetric component of the temperature.

Square: location of maximum temperature

Triangle: location of maximum current convergence

Diamond: location of maximum heating from particle precipitation



Solid contour: zero excess temperature compared to average at each latitude.
Dotted lines: constant latitude circles at 15° spacing

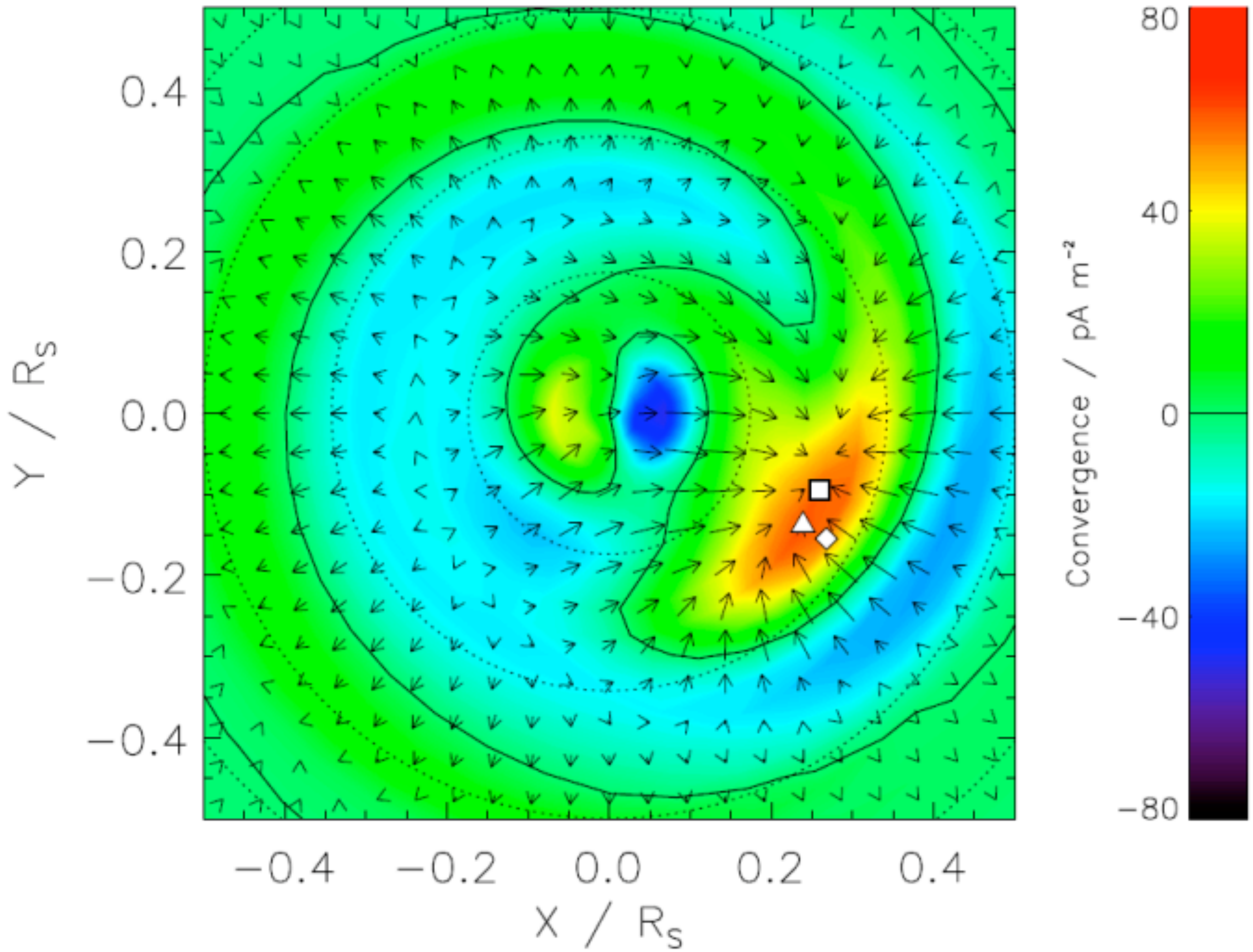
Asymmetric currents

The arrows show the asymmetric components of the horizontal currents at the 2nb level in the northern polar cap at the end of the equinox run.

The colour scale shows the convergence/ divergence of the currents, which we equate to the parallel current.

Positive regions (red) show upwards currents.

Negative regions (blue) show downwards currents.



Solid contour: zero current convergence.
Dotted lines: constant latitude circles at 15° spacing

Comments on equinox results in northern hemisphere

1. The feedback effect does sustain the asymmetry and it becomes a permanent asymmetric feature.

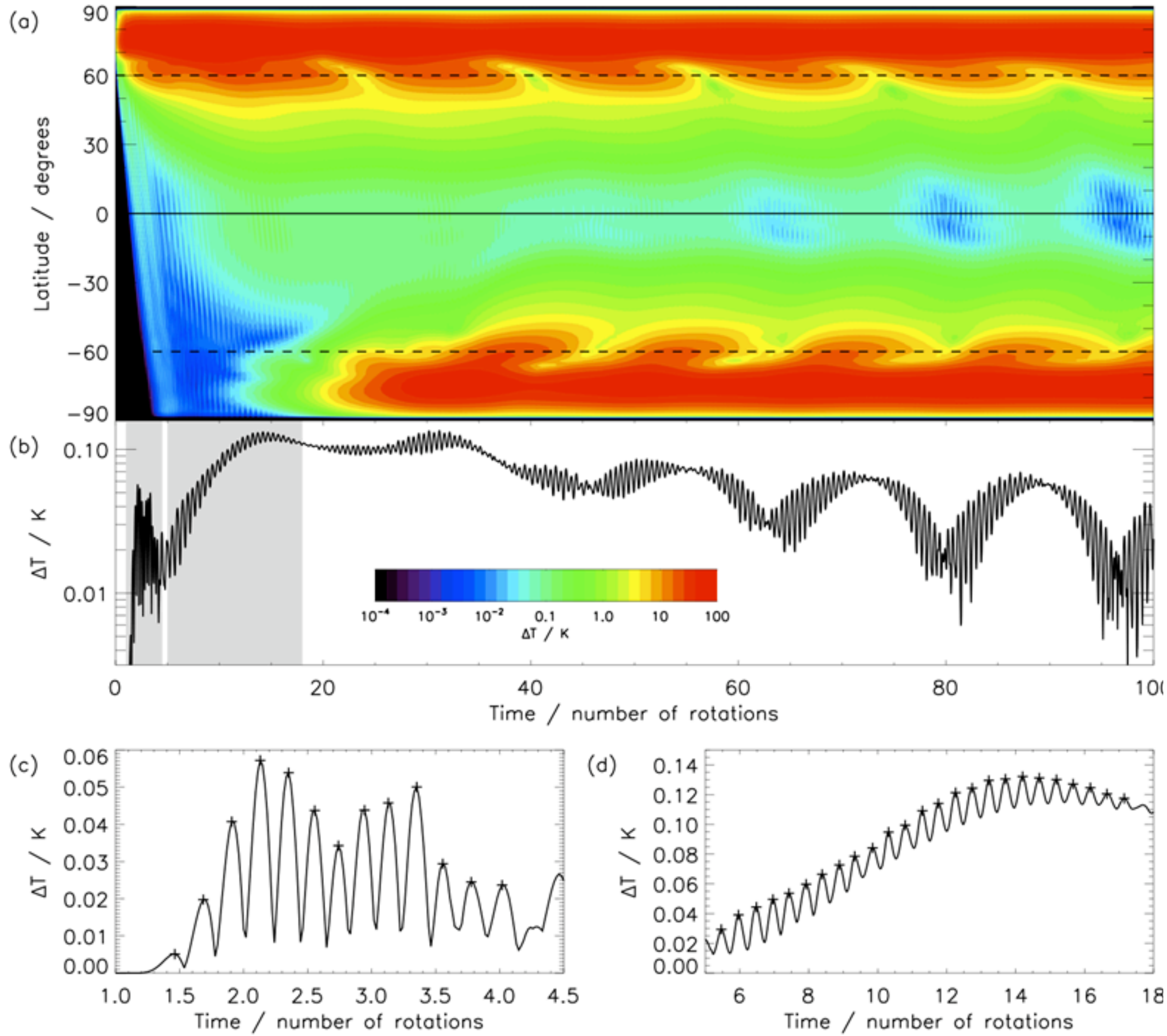
This is a ‘proof of concept’ – even though our particular model is imperfect, the basic physics of the thermosphere does allow a self-sustaining asymmetry.

2. The asymmetry is clearly not m=1. An asymmetry of exactly this form therefore does not explain the observations.

3. The ‘vortex’ drifts in longitude. This means it has a different period to the interior of the planet, providing a possible explanation for the varying periods observed.

4. The asymmetry is not a true vortex. The plots show asymmetric components of winds; the full wind field is generally strongly subcorotational. The ‘vortex’ is thus actually a small change to the meridional shear in a strong zonal wind.

Development of global asymmetries



The plots show the difference between the maximum and minimum temperatures at each latitude over the 100 rotations after the asymmetric heating is first imposed.

This is a proxy for the existence of asymmetry at each latitude.

(a) Colour scale shows this variable globally, using a log scale. Note that cyan/blue colours represent less than 0.1K temperature asymmetry.

(b) A cut through Figure (a) at the equator.

(c) and (d) Blow-ups of the sections shaded in grey in Figure (b), plotted on a linear scale. Crosses show peaks used to calculate wave frequencies.

Development of global asymmetries

Figures (a) to (d) on the previous slide illustrate how the asymmetries develop on a global scale under the influence of the feedback effect. Note that feedback only occurs polewards of the dashed lines in Figure (a). Important conclusions:

• After 40 days an asymmetry has developed in the southern hemisphere that is essentially identical to that in the north.

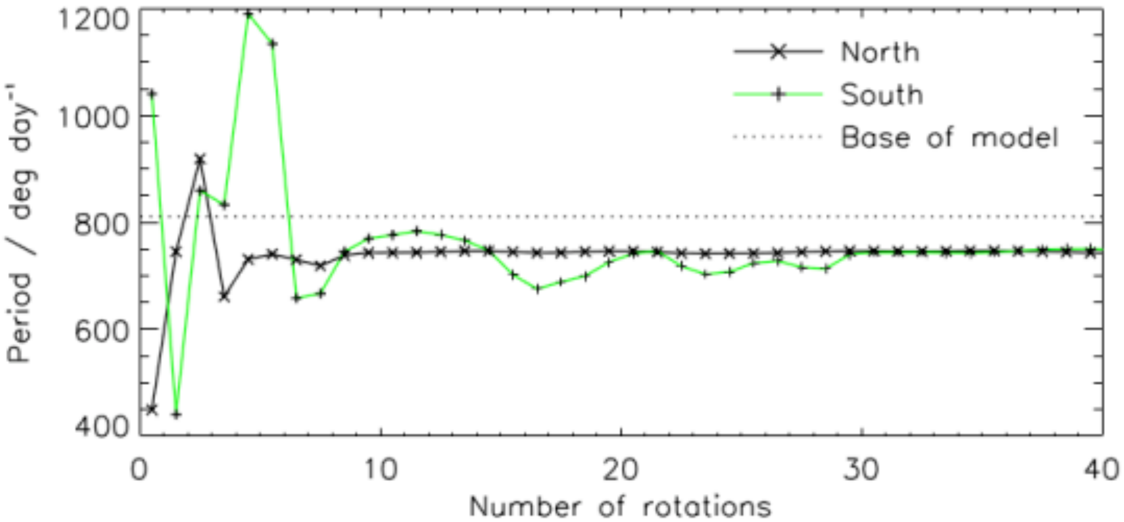
• Both the northern and southern hemisphere asymmetries show oscillations with a ~15 rotation period. The cause of these long period oscillations is unclear.

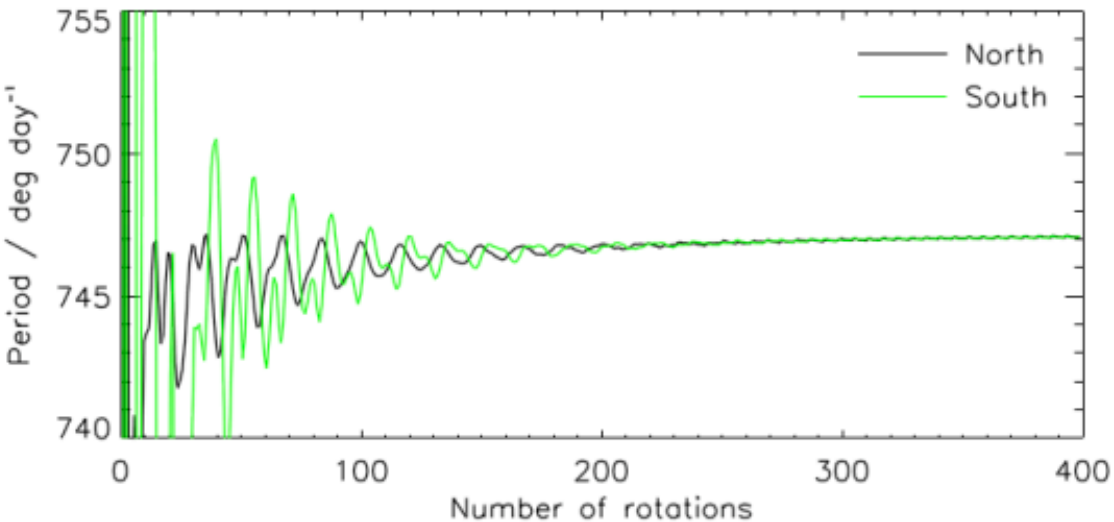
• The asymmetry has been communicated by wave structures across the equator (the diagonal features across the equatorial region). This means that even though there are essentially no large scale cross-equator winds, the two hemispheres can still ‘talk to each other’ to a certain extent.

• There are two distinct bunches of wave structures with different frequencies, as shown in Figures (c) and (d). The first appear to be transient oscillations related to the asymmetric heating imposed for the first rotation; the second may be related to oscillations of winds about geostrophic balance.

•These asymmetric wave structures have very small amplitudes (less than 0.1K), indicating that the thermosphere is unstable to symmetry breaking under the feedback effect.

Rotation period of asymmetry





We measure the rotation period of the asymmetry by measuring the change in longitude of the maximum current convergence at 74°N.

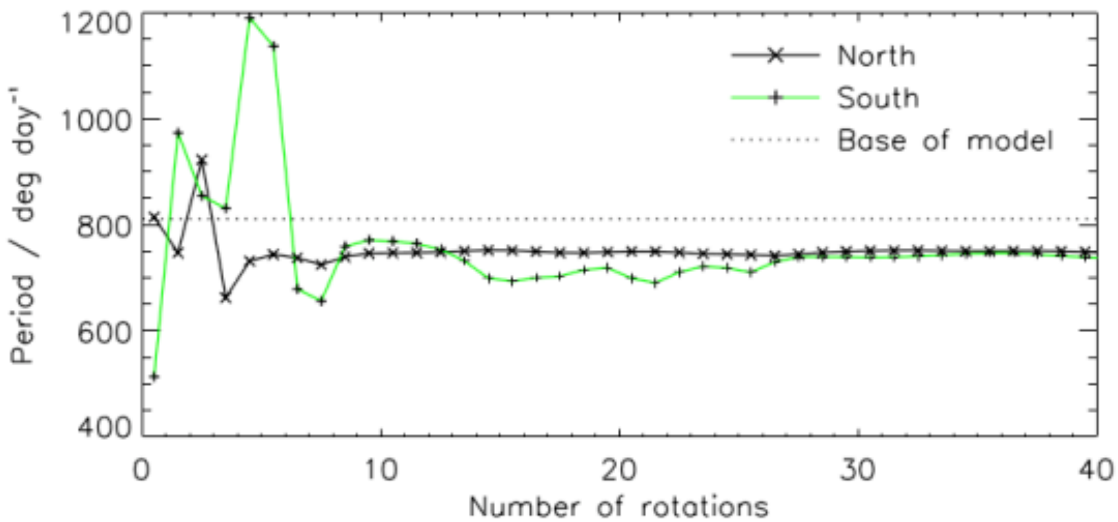
The plots show how the northern and southern rotation periods vary in the equinox model for the 400 rotations following the first imposition of asymmetric heating.

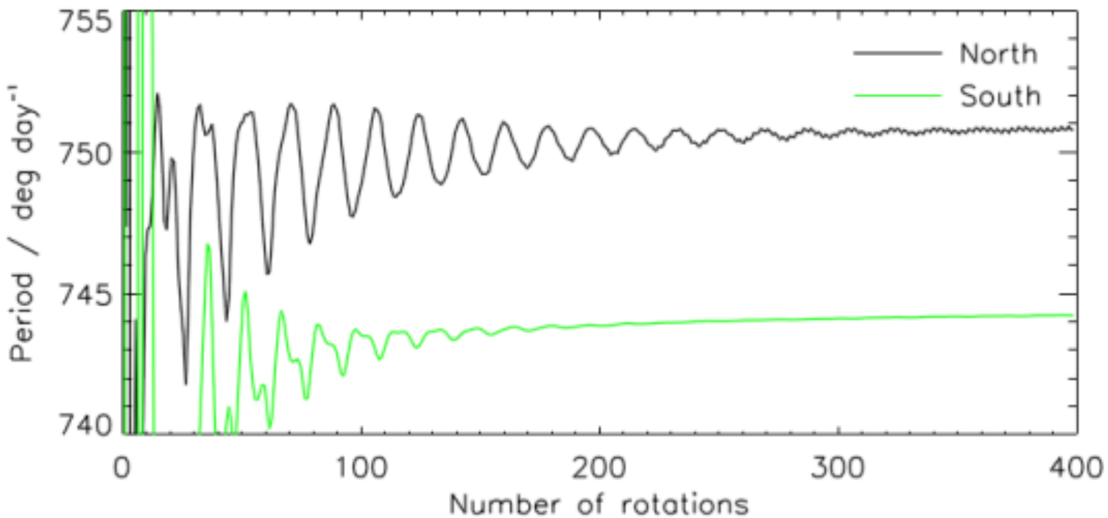
There is a large variation over the first few rotations as the asymmetry establishes itself.

15 rotation period oscillations persist with a decay timescale of ~50 rotations.

The northern and southern periods then settle down to the same period, about 60 deg/day slower than the base of the model.

Rotation period of asymmetry





This shows the same information but for the solstice model.

Again the period takes a while to settle down and there are ~15 rotation period oscillations that are presently unexplained.

However, the northern and southern periods settle down to different periods. The northern (winter) period is ~7 deg/day faster, which represents a smaller lag compared to the interior of the planet. This is the same order of magnitude as the ~20 deg/day difference observed in SKR periods close to solstice (Gurnett et al. 2010).

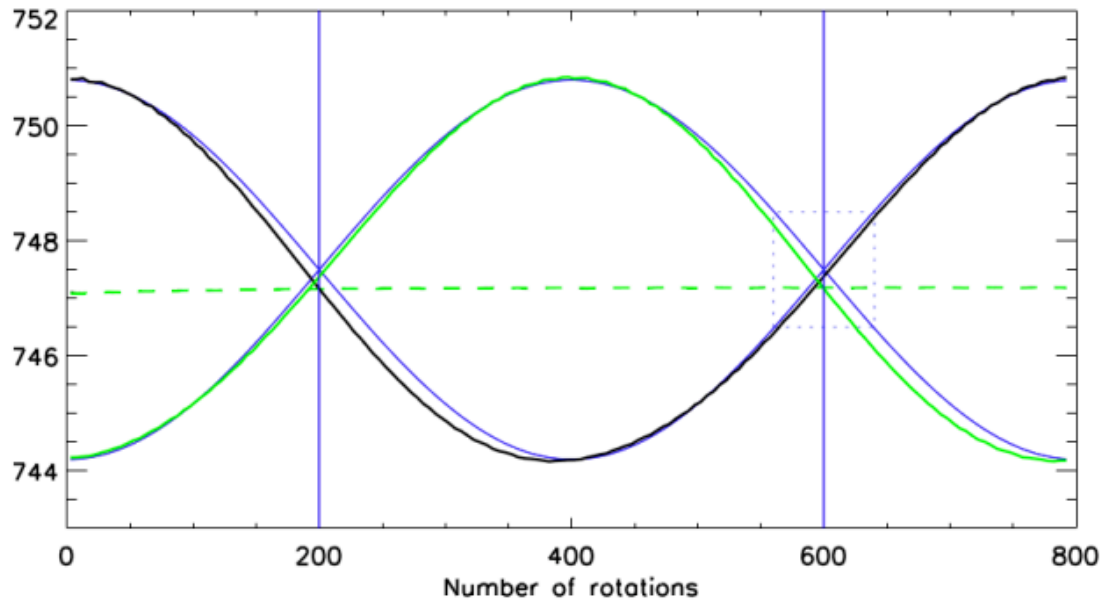
The lag of both periods compared to the internal rotation period (horizontal dotted line) also qualitatively matches the SKR observations.

Seasonal variation

The upper plot is a continuation of the plots on the last slide for a further 800 rotations as we vary the seasonal bias sinusoidally.

The sinusoidal variation is shown with the blue curves, which have been scaled to match the model output at the solstices. The vertical blue lines indicate the equinoxes. The dashed green and black lines show what happens if the equinox model is also run forward for a further 800 rotations.

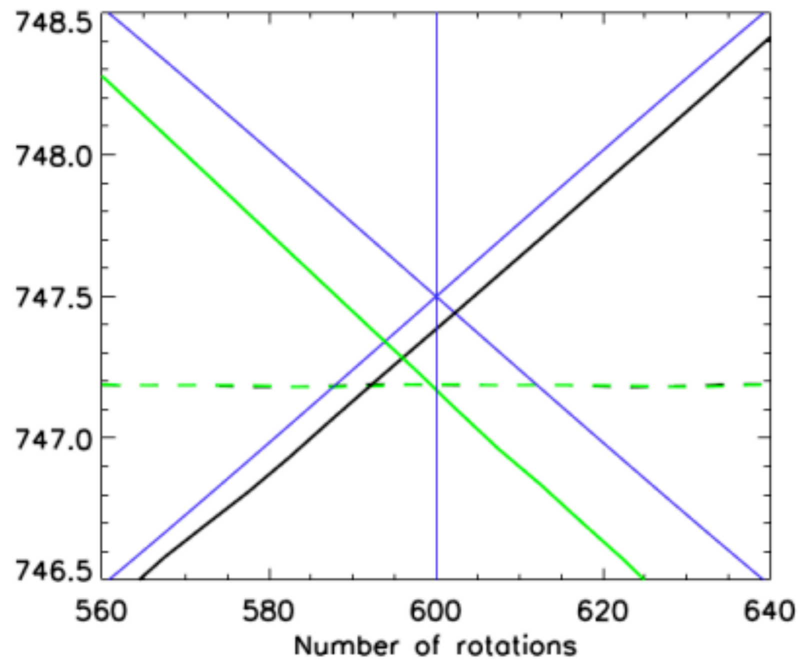
The lower plot is a blow up of the region marked with the dotted rectangle in the upper plot.



The rotation periods do vary almost exactly with the sinusoidal variation in the seasonal bias.

There is no time lag in the cross-over at equinox. Indeed the northern and southern periods cross slightly **before** equinox (see lower plot) and do not cross at the same period as the equinox model (dashed lines). One possible explanation for this early crossing is that the asymmetric feature changes shape, adding an extra sinusoidal component to the rotation period.

These results strongly imply that **thermospheric dynamics cannot provide a 7 month time lag** in the crossing of the periods at equinox. Changes to the period of the asymmetry are closely correlated to seasonal changes in conditions – to within just a few rotations.



Chemical model for time lag

We have shown that thermospheric dynamics do not provide a 7 month time lag. However, the seasonal variation in the rotation period of the asymmetries is mostly a response to the seasonal variation of the ionospheric conductance.

A 7 month time lag in the conductance should provide a 7 month time lag in the seasonal behaviour of the asymmetries. Chemistry may provide the long time-scales required. If the production of a neutral component varies seasonally, with period T, and its recombination has a timescale $t \ll T$, then this produces a time lag ~t in its seasonal variation, which may have a knock-on effect on electron densities and thus conductances.

We therefore require a chemical whose production varies seasonally, but whose recombination has a ~7 month timescale. Some speculations:

1. Meteoric material has a timescale of the order of months for recondensation (Moses & Bass 2000). It also has an influence on the electron densities in the lower layers of the ionosphere and thus may affect the conductance. Production may vary seasonally if (i) evaporation of condensed material is driven by absorption of solar photons, or (ii) the influx of meteoric material is asymmetric with respect to the Sun.

2. The influx of material from the rings may vary seasonally if there is greater transport of e.g. water ions from the sunlit side of the rings. The presence of water certainly affects electron densities. This may provide the required time lag if long timescales also apply for the removal of water from the thermosphere by transport or chemistry.

Problems with model

Our model is highly simplified. This is essential to make long model runs practical and to produce easily analysable results.

The main problem with the model is that the ‘gear ratio’ between parallel current and particle heating is implausibly large. We correlate a parallel current of 0.02 nA m^{-2} with heating of 1 mW m^{-2}. A rough calculation shows that this implies ~50MeV electrons, which is at least two orders of magnitude greater than observations imply.

If we reduce the magnitude of the feedback effect by a factor of two it is insufficient to drive self-sustaining asymmetries. The energy required to drive the feedback effect in the model as it stands is thus in conflict with the observations.

There are many additions/modifications that could be made that may make it possible for a feedback effect to operate with a more plausible energy input.

1. A higher resolution in latitude/longitude may allow larger gradients in currents – and thus larger parallel currents – without corresponding increases in total wind speeds.

2. Varying the vertical distribution of energy input at high latitudes or for different intensities of particle precipitation may change the energy required to sustain the asymmetry.

3. Including local time asymmetric solar heating may provide an additional forcing on a 1 rotation timescale, and thus provide an extra source of energy.

4. Including feedback between particle precipitation and ionospheric density/conductance may enhance the feedback effect with a lower energy input.

This last suggestion is particularly interesting, but is difficult to implement in the 3D model because feedback between winds and conductance tends to steepen gradients in the conductance into shock-like structures that are unresolved by our grid. Investigating this idea may thus require a different approach.

Conclusions

• A feedback effect between winds and particle precipitation is able to break the symmetry of the thermosphere on long timescales, providing a possible driver for the periodicities in the magnetosphere.

• The resulting asymmetries qualitatively match the observed behaviour of the SKR period: (i) they lag the internal rotation speed
(ii) they show seasonal differences in the north and south
(iii) the winter hemisphere asymmetry rotates faster

• The observed 7 month time lag can possibly be explained in terms of long timescales for chemical recombination of external material.

Summary of problems

• The energy required to drive the asymmetry is implausibly large.

• The mechanism implies an asymmetry in the brightness of auroral emissions. Such an asymmetry has not been reported.

• The asymmetry does not show m=1 symmetry in longitude.

Comments, questions and criticisms for the first author are most welcome, to cgasmith@gmail.com.

If sent during MOP I will endeavour to reply as soon as possible!

References

Cowley, S.H.C., Bunce, E.J. and O'Rourke, J.M., A simple quantitative model of plasma flows and currents in Saturn's polar ionosphere, JGR, 2004

Gurnett, D.A. et al., The reversal of the rotational modulation rates of the north and south components of Saturn kilometric radiation near equinox, GRL, 2010

Moses, J.I. & Bass, S.F., The effects of external material on the chemistry and structure of Saturn's ionosphere, JGR, 2000

Smith, C.G.A., A Saturnian cam current system driven by asymmetric thermospheric heating, MNRAS, 2011

Smith, C.G.A., Periodic modulation of gas giant magnetospheres by the neutral upper atmosphere, Annales Geophysicae, 2006