

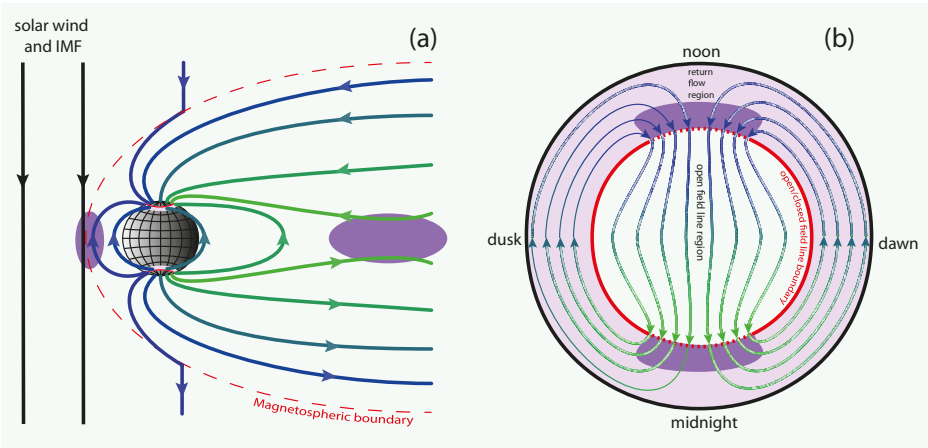
The irregular pulse of the magnetosphere

Maria-Theresia Walach, winner of the 2015 Rishbeth Prize, puts a physics-based mathematical model of the expanding and contracting polar cap paradigm to the test.

The Earth’s magnetosphere is a reservoir of energy, injected via interactions with the solar wind, a stream of plasma flowing from the Sun through space. With the solar wind flows the interplanetary magnetic field (IMF), which can wreak havoc all over the solar system. It regulates the energy that is unloaded into the inner parts of our magnetosphere and ionosphere, where it can have devastating effects on satellites, as well as power grids on the surface of the Earth. Even though this interaction can be dynamic and diverse, the focus here lies with understanding the most basic responses of the solar wind–magnetosphere–ionospheric coupling and quantifying it.

Our understanding of space-plasma physics suggests that the magnetosphere is, at least to some extent, a bubble enclosed by the solar wind. Through a process called reconnection, our magnetic bubble can open up and become leaky. Dungey (1961) proposed that on the dayside nose of the magnetosphere, reconnection between the Earth’s magnetic field and the IMF can take place, interconnecting the magnetic fields of the Earth and the solar wind (see box, “The Dungey cycle”). When this happens, the solar-wind plasma can funnel into the magnetosphere.

When Dungey first proposed this idea, the dayside and nightside reconnection



1 (a) Side-on view of the magnetosphere. Arrows on the magnetic field lines show the direction of the magnetic fields. The purple shaded areas indicate where reconnection takes place. (b) Top-down view of the pole. Here the arrows indicate the direction of flow of the magnetic flux traced out in (a), projected onto the Earth’s surface. The colours are analogous to the location of the flux in (a). The purple area shows where the reconnection regions shown in (a) map to on the surface. Not to scale.

rates were envisaged to be constant and continuous, as pictured in figure 1. We have since learnt that this does not have to be the case and the amount of open flux in the magnetospheric system varies. Not only does the open flux content of the magnetosphere vary, but the way the Earth’s magnetosphere responds is highly variable too (for example, Walach & Milan 2015a), making it a dynamic, diverse, but also at times unpredictable system.

The time-dependent Dungey cycle

The Earth’s magnetosphere contains approximately 8 GWb of magnetic flux and approximately 0.4 GWb of this is on average open flux; during extreme events, a total of almost 1 GWb of flux can be opened via dayside reconnection. We can observe this by looking at the auroral ovals, the bright

auroral bands that ring the polar caps. As the Earth’s magnetospheric system is being loaded and unloaded with open flux, we can see the auroral oval expanding and contracting by looking at pictures of the auroral oval taken from space. Depending on which reconnection rate, dayside or nightside, is dominant, an expansion or contraction, respectively, will take place.

To facilitate our understanding, we can think of this expanding or contracting polar cap as a time-dependent Dungey cycle (Cowley & Lockwood 1992). This pulsing of the magnetosphere is irregular, unlike the classic idea of the Dungey cycle, as a result of intermittent reconnection rates.

The dayside reconnection rate is dependent on the solar-wind speed and the direction and strength of the IMF, as parameterized by Milan *et al.* (2012). How

The Dungey cycle

In the scenario in figure 1a, where dayside reconnection takes place (the purple shaded area on the left), there is a proportion of magnetospheric flux near the magnetic poles that has one end rooted in the Earth’s surface and the other end connected into interplanetary space. Because this “open magnetic flux” is embedded in the solar wind, it is pushed by the solar wind towards the nightside of the Earth, past the magnetic poles, forming the magnetotail. The magnetospheric bubble is thus shaped rather like a bullet, compressed on the dayside with a long magnetic tail on the

nightside. The motion of the field from the dayside to the nightside is indicated in figure 1a by the colour of the magnetic flux changing from blue to green. Dungey postulated that there should also be a reconnection site on the nightside, where the open flux (green in figure 1a) from different hemispheres can reconnect with each other (the purple shaded area to the right). This newly closed flux then cycles back towards the dayside at lower latitudes than the open flux, indicated in the figure by the colour change from green to blue. This circulation of magnetospheric

flux has become known as the Dungey cycle and is considered the fundamental principle of our magnetospheric system. Looking down onto the magnetic pole of the northern hemisphere, the circulating magnetic flux cannot be measured or seen. However, its travelling companion, the plasma, can be tracked. The lines along which the magnetic flux travels past the poles in the Dungey cycle is shown by the arrows in figure 1b and is coloured using the same convention as in figure 1a. The open/closed field line boundary is indicated by the innermost circle, whereas the

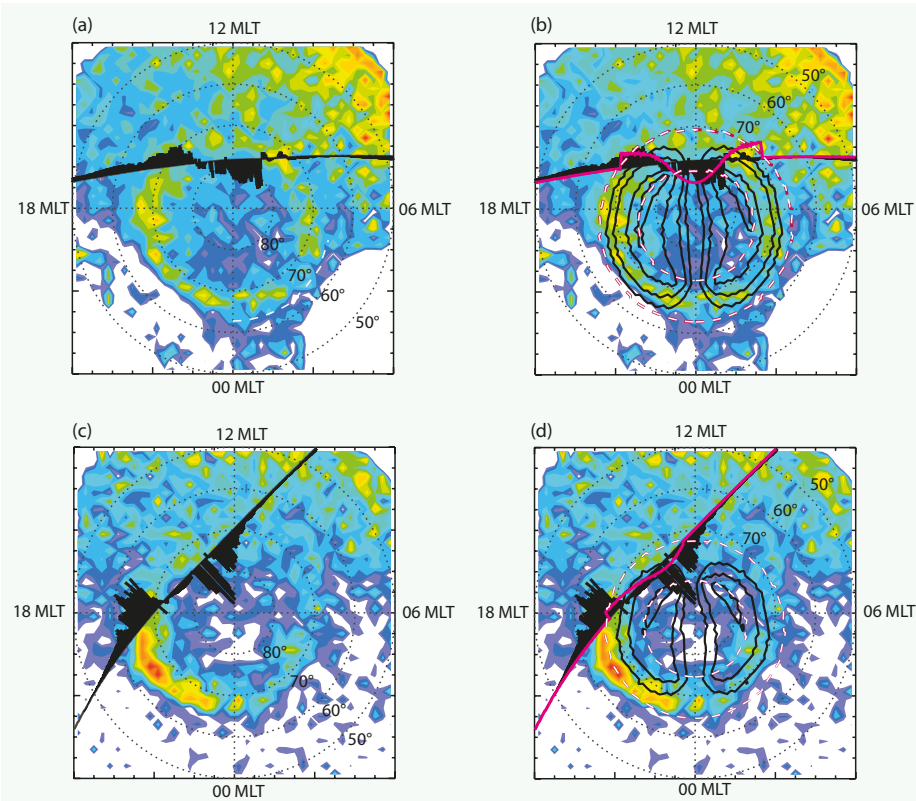
outer circle indicates the boundary where the reconnection-driven flows terminate. The area enclosed by the open/closed field line boundary is also known as the polar cap or the open field line region; this is where the open flux meets the Earth’s surface. The area on the Earth’s surface along which the closed flux travels when it returns to the dayside is wedged between the two circles in figure 1b and is known as the return flow region. It encompasses the latitudes where we see the aurora, the most visual manifestation of the solar wind–magnetospheric–ionospheric coupling.

exactly the nightside reconnection rate is modulated remains a mystery, but we can calculate it by measuring the rate of change of the amount of open flux in the system and the dayside reconnection rate.

Expanding and contracting polar cap

The notion of the expanding and contracting polar cap paradigm (ECPC) has existed for some time. It was conceptually developed by Cowley & Lockwood (1992), inspired by the work of Siscoe & Huang (1985) and many more. Over the years, the ECPC has become a powerful framework and been analysed qualitatively and quantitatively in many different ways. Some of the most prominent examples include observations matching the expansion and contractions of the auroral oval and more recently, the magnetospheric current systems (for example, Milan *et al.* 2003, Milan *et al.* 2009, Clausen *et al.* 2013, Coxon *et al.* 2014). Our understanding of the physics drawn from the observations, made over decades, match the Dungey cycle and the ECPC, but a rigorous test of the convection velocities has yet to be undertaken. If we could see the magnetic flux convecting as it is driven by day- and nightside reconnection, we would see this twin-cell convection pattern shown in figure 1b. In fact this is possible by looking at plasma convection in the ionosphere, because the plasma moves with the magnetic field and vice versa. A popular way of tracking the flow of plasma is by using radar networks such as the Super Dual Auroral Radar Network (SuperDARN). Indeed, studies using SuperDARN have confirmed the existence of convection patterns matching the dual lobe convection pattern in numerous studies (for example, Chisham *et al.* 2007).

Milan (2013) translated the physical



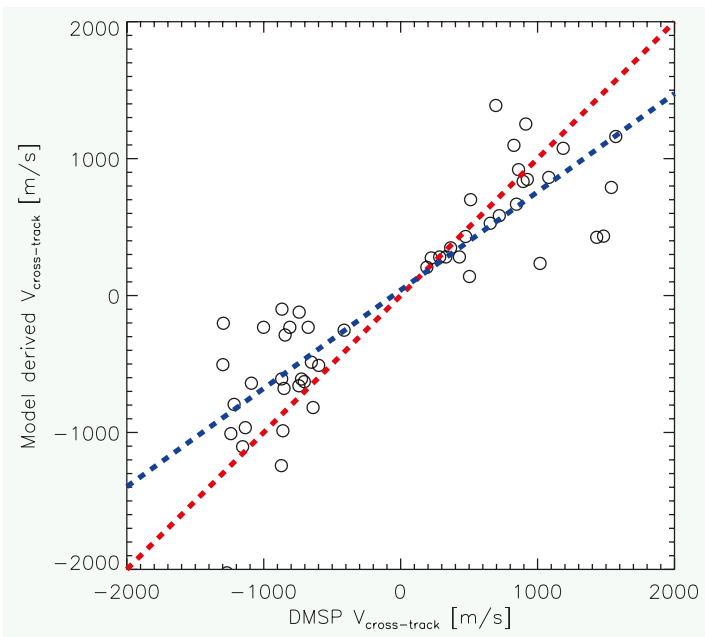
2 False-colour images of auroral brightness from the FUV SI12 instrument on-board IMAGE. Two DMSP passes are shown as examples: (a) and (b) show DMSP F13 polar pass at ~00:40 UT; (c) and (d) show DMSP F15 polar pass at ~06:07 UT, with cross-track plasma velocities plotted in black. Both the modelled flow velocities and boundaries are plotted in (b) and (d).

knowledge of the above described dynamics into a mathematical model. This model of the ECPC relies on spherical and circular symmetry. Drawing from observations of the aurora, the polar cap should perhaps be modelled as an oval, but for the model to remain simple, we have to make some basic assumptions. So, we approximate that the Earth’s magnetic field is dipolar near the poles and that the polar cap is circular.

As inputs into the model, knowing the

day- and nightside reconnection rates, as well as the polar cap flux are required. The polar cap flux is calculated from its area. To calculate the dayside reconnection rate, we use the solar-wind parameters from satellites at the Lagrangian L-1 point (King & Papitashvili 2005). Fitting ovals to ultra-violet auroral imagery from the IMAGE (Imager for Magnetopause-to-Aurora Global Exploration) mission (see false-colour images in figure 2), the polar cap

3 Scatter plot of the model-derived velocities versus the measured velocities, showing the maximum and minimum flow vectors for each of the 25 orbits. The dashed red line indicates where the two quantities would be equal and the dashed purple line indicates the line of best fit.



size can easily be calculated (Shukhtina & Milan 2014). Using cross-track plasma flow measurements from the DMSP (Defense Meteorological Satellite Programme) satellites in the ionosphere for a comparison, this model is put to the test.

Confronting the data with the model

Figure 2a shows a snapshot of a DMSP satellite crossing the northern hemisphere polar region. The colours indicate the brightness of the auroras observed by the IMAGE FUV SI12 instrument, which primarily images the proton aurora (red and blue show the brightest and least bright pixels, respectively). The camera was looking down at the Earth, with noon towards the top of the image and midnight towards the bottom. The dashed circles show a latitude grid of 10° difference between the concentric circles, such that the centre is aligned with the geomagnetic pole. This image was taken during the northern hemisphere summer (15 August 2001), where the aurora is hard to make out by eye, because the sky is almost always illuminated by sunlight. By using the far-ultraviolet waveband, the auroral oval is much easier to make out, even though there is a fair amount of dayglow contaminating the image. The black line which crosses the image shows the satellite track of the DMSP F13 satellite. This one almost reached a geomagnetic

co-latitude of 80° at 00:40 UT. The cross-track velocities as measured by the satellite are presented as lines (in black) that emanate orthogonally from the satellite track. Within the polar cap, i.e. inside the auroral boundary, the flows are directed towards the nightside and in the return flow region, i.e. in the auroral oval itself, the flows are directed towards the dayside. There is an asymmetry in the return flows: more plasma appears to return on the dusk-side. It is very likely that this is an effect of the consistent 5 nT IMF B_y (i.e. dusk–dawn) component that the solar wind was carrying throughout this day.

Figure 2b shows the same satellite pass and the same auroral image, with the model output overplotted. The black lines that have been added show the flow velocities as predicted by the model. The dashed magenta lines show the flow boundaries fitted to the auroral emission. The magenta line on the DMSP track shows the cross-track velocities, as predicted by the model, based on the track geometry. The magnitudes of the flows are predicted well, but the asymmetries cannot be predicted by a symmetrical model.

Figures 2c and 2d show another satellite pass with the same convention as figures 2a and 2b. These data were obtained a few hours later on the same day (~06:07 UT). The auroral oval is clearly visible, which

makes it obvious that the fitting of the polar cap circles is not ideal. The auroral oval appears shifted toward dusk, because the model is centred on the noon–midnight meridian. This is a problem, because the return flow region is in reality much larger than the model predicts. The magnitudes of the flows are also extremely underestimated here. This could be due to either the day- or nightside reconnection rates being underestimated.

For this whole day, there are 25 DMSP orbits where enough good quality data (DMSP and IMAGE) exist to draw conclusions. To summarize this day, the two most extreme data points (i.e. the points with the highest cross-track flow speeds) are extracted from each of the 25 orbits. These are plotted in figure 3. On the x-axis are the cross-track velocities measured by DMSP and on the y-axis are the model-derived cross-track velocities. The red dashed line indicates the line where both quantities would be equal, whereas the purple dashed line shows the line of best fit, derived from a linear regression analysis, where the square of the correlation coefficient is 0.779. This plot, and the plots of the individual orbits, lead to the conclusion that the magnitudes of the flows are predictable, using measurements of the open flux content from the auroral oval and solar-wind parameters as a proxy for dayside reconnection. This will be discussed in more detail in Walach & Milan (2015b).

Fitting the missing pieces

It is well known that the solar wind does not only have an effect on the dayside reconnection rate and thus on the strength of the convection flows, but the strength of the dawn–dusk component of the IMF also affects the relative sizes of the convection cells and can introduce asymmetries into polar cap flows. It remains a challenge to model these asymmetries and smaller scale dynamics accurately, while keeping this model physics-based.

Although the model may be considered overly simplistic, it models the strengths of the convection flows very well. This implies that the physical bases of our driven magnetospheric system are well understood, but as with any simple model, its main constraint is its own simplicity. ●

AUTHOR

Maria-Theresia Walach is a research student at the University of Leicester. She was awarded the RAS Rishbeth Prize for her talk (with co-author Steve Milan) entitled “A test of ionospheric convection predictions from the expanding/contracting polar cap paradigm” in the MIST open session at NAM 2015. **The Rishbeth Prizes** are named for Henry Rishbeth, a key figure in the

development of the magnetosphere, ionosphere and solar–terrestrial physics (MIST) community in the UK.

ACKNOWLEDGMENTS

I would like to thank STFC for sponsoring this work with their studentship. We would also like to thank the PI of the IMAGE FUV instrument, Stephen Mende of the University of California Berkeley, for the use of SI12 data. We acknowledge use of NASA/GSFC’s Space

Physics Data Facility’s CDAWeb service and OMNI data.

REFERENCES

Chisham G *et al.* 2007 *Surv. Geophys.* **28**(1) 33
Clausen LBN *et al.* 2013 *J. Geophys. Res. Space Physics* **118**(6) 3007
Cowley SWH & Lockwood M 1992 *Ann. Geophys.* **10** 103
Coxon JC *et al.* 2014 *J. Geophys. Res. Space Physics* **119** 1

Dungey JW 1961 *Phys. Rev. Lett.* **6**(2) 47
King JH & Papitashvili NE 2005 *J. Geophys. Res. Space Physics* **110** A02104
Milan SE 2013 *J. Geophys. Res. Space Physics* **118**(9) 5532
Milan SE *et al.* 2003 *Ann. Geophys.* **21** 1121
Milan SE *et al.* 2009 *Ann. Geophys.* **27**(2) 659
Milan SE *et al.* 2012 *J. Geophys. Res. Space Physics* **117** A03226
Shukhtina MA & Milan SE 2014

ECLAT System Level Data Product report (D430.1) <http://www2.le.ac.uk/departments/physics/research/rspp/missions/eclat/documents/d430-1-report>
Siscoe GL & Huang TS 1985 *J. Geophys. Res.* **90**(A1) 543
Walach M-T & Milan SE 2015a *J. Geophys. Res. Space Physics* **120** 1751
Walach M-T & Milan SE 2015b in prep.