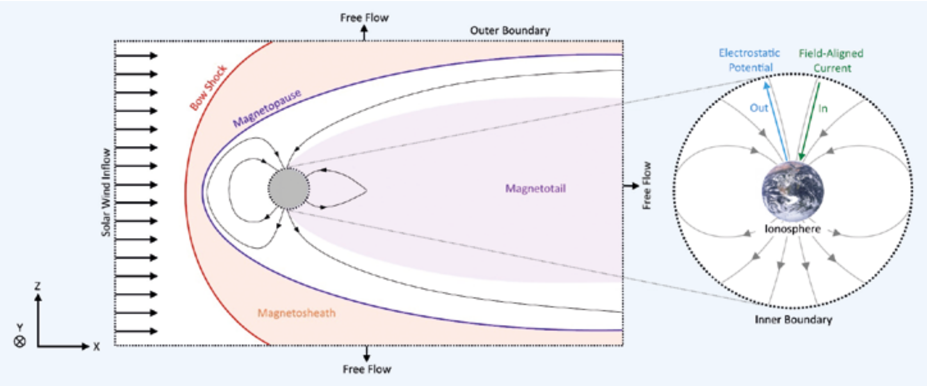
Forging links in Earth's plasma environment

Joseph W B Eggington and team describe the challenges and successes of modelling magnetosphere–ionosphere coupling in global MHD simulations, from a talk that won the Rishbeth Prize at the Spring MIST Meeting.



1 A schematic representation of the boundaries of a typical MHD simulation domain, key features of the magnetosphere, and the standard coupling with a model ionosphere obtained by mapping quantities along dipole magnetic field lines.

The magnetosphere is the region surrounding the Earth which is dominated by the planet's internal magnetic field, carving out a bubble in the solar wind that flows at supersonic speeds away from the Sun. However, the magnetosphere is not entirely closed to external plasma sources, as mass and energy are transported across its outer boundary (the magnetopause), driving what is in fact a highly dynamic, time-varying system. These transport processes can have significant societal impacts, such as degradation of spacecraft by energetic particles, disruption to satellite signals by changes in conditions in the ionosphere, and damage to ground-level infrastructure – all of which are described by the blanket term "space weather" (Eastwood 2008, Eastwood *et al.* 2017a).

Forecasting severe space weather events is crucial in mitigating any resulting damage, for example through sufficiently early warnings to satellite operators or power distributors. Doing so requires a robust detection and alert system, alongside a sound understanding of the underlying physical mechanisms driving space weather and thus the possible risk for any given solar wind conditions.

Spacecraft missions such as Cluster, THEMIS, and MMS (Magnetospheric Multiscale) seek to explore the interaction between the solar wind and magnetosphere, providing fundamental insights into the physics at work. However, *in situ* satellite observations are spatially sparse, and therefore can fall short as a basis for characterizing the behaviour of the magnetosphere on a global scale. To overcome this, computer simulations can be used to model the system in three dimensions, with the aim of replicating observed phenomena organically from first principles via an appropriate set of equations describing the plasma dynamics. This also provides a way to predict the resulting conditions around the Earth and on the ground (e.g. Eastwood *et al.* 2017b).

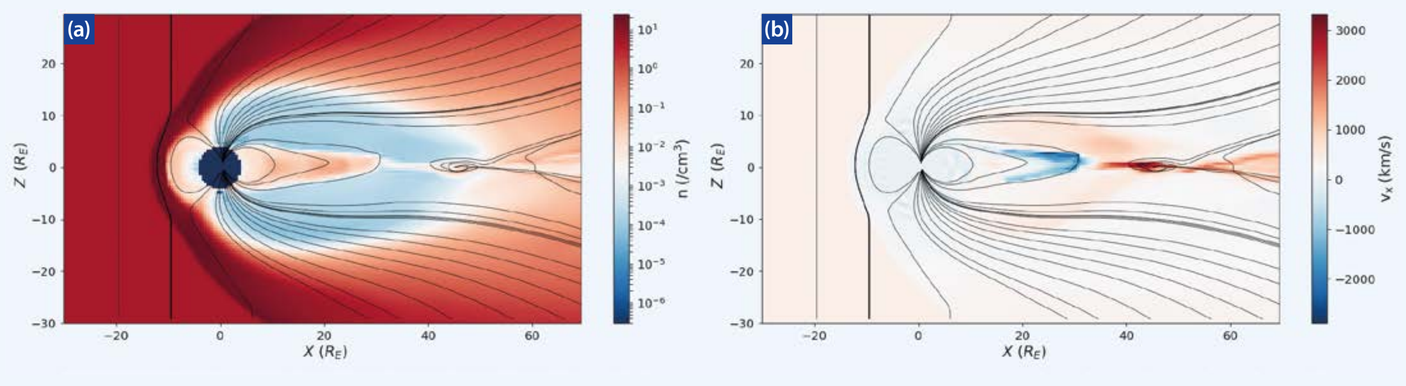
Global MHD simulations

Magnetohydrodynamics (MHD), combining the Navier–Stokes equations for fluids with Maxwell's equations of electromagnetism, is commonly used to model the magnetosphere. In the most basic form of MHD, the plasma is treated as a single conducting fluid. This is simplified further in the context of space plasmas, where collisions between particles are so rare that the conductivity of the plasma is effectively infinite – a regime termed "ideal MHD". While the use of ideal MHD for magnetospheric applications often falls under scrutiny – especially in regions close to the Earth where key assumptions do not apply – it has proven effective at reproducing phenomena on large spatial and temporal scales, and can do so faster than real time (Raeder 2003).

> **"MHD simulations are of great value for magnetospheric modelling efforts"**

MHD codes for magnetospheric applications were first developed in the 1980s; substantial advancements in computational power and improved knowledge of magnetospheric physics have allowed increasingly complex studies to be performed over time. Other treatments of the plasma, such as kinetic modelling (calculating the evolution of the distribution functions directly, rather than only their moments), or hybrid (treating only particular components of the plasma as kinetic), can capture certain aspects of the physics in much greater detail. However, these are far more computationally intensive and are generally limited to local or 2D global plasma modelling (e.g. Desai *et al.* 2017), although 3D global hybrid simulations have been performed for smaller scale magnetospheres (e.g. Parunakian *et al.* 2017). Within these constraints, MHD simulations are of great value for magnetospheric modelling efforts and their versatility means that they can be applied to effectively any planetary system.

Among the challenges of space weather forecasting is the coupling of models between different components of the



2 Plots in the *x*–*z* plane of (a) the plasma number density and (b) the *x*-component of the plasma flow in the magnetosphere after 4 h of southward IMF driving.

Sun–Earth system. In the case of magnetospheric models, the outer boundaries of the simulation domain connect to the solar wind (which can be defined using spacecraft data or synthetic conditions), while the inner boundary connects to the ionosphere. The ionosphere is known to regulate dynamics in the magnetosphere by acting like a resistor in an electrical circuit; magnetospheric field lines act as wires connected to the solar wind battery (Cowley 2013). Convection of the ionospheric plasma triggers collisions with neutral species causing Joule heating, while variations in ionospheric currents generate ground magnetic perturbations which drive geomagnetically induced currents (GICs).

Magnetospheric dynamics are largely driven by magnetic reconnection, which on the dayside magnetopause leads to the formation of "open" magnetic flux, in turn producing flows in the magnetosphere. Velocity shear at the open–closed boundary (OCB) of the magnetic field then sets up field-aligned currents (FACs) which close in the ionosphere with an associated electric field. Most simply, this effect can be modelled by treating the ionosphere as a thin, conducting shell, on which the generalized Ohm's law is solved for some given ionospheric conductance to obtain an electrostatic potential (Ridley *et al.* 2004). The corresponding electric field modifies plasma flow via the associated drift velocity, using the coupling technique demonstrated in figure 1. This approach is both computationally inexpensive and effective, and is used by the majority of MHD codes. Tunability of the conductance by including ionization effects, and extension of the electric field output to model Joule heating and GICs, makes it applicable for a range of forecasting purposes.

The Gorgon MHD code

The Gorgon MHD code was originally developed in Imperial College's Plasma Physics group for the purpose of simulating laboratory plasmas. As such, much of its original design is tailored towards collisional, resistive regimes capturing more complex MHD phenomena (Ciardi *et al.* 2007). As part of an initiative to develop new space plasma and space weather modelling capabilities, an optimized version of Gorgon has been developed to enable efficient, 3D global simulations of planetary magnetospheres with an approach similar to that of other magnetospheric MHD codes. However, unlike other codes, Gorgon solves for the magnetic vector potential rather than the magnetic field, ensuring that the field remains divergence-free to machine precision. Previous studies using the Gorgon code have included modelling Neptune's magnetosphere (Mejnertsen *et al.* 2016) and the motion of the outer boundaries of the Earth's magnetosphere in response to a varying solar wind (Mejnertsen *et al.* 2018).

"The Gorgon code was originally developed for simulating laboratory plasmas"

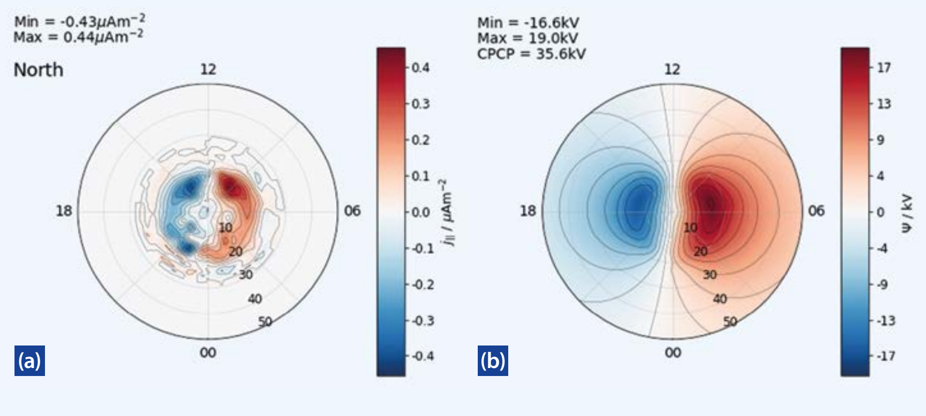
In these simulations, the inner boundary was treated as a resistive surface with a conductance comparable to those typically used in other global simulations (Mejnertsen 2018). This approach is sufficient to capture the global magnetospheric behaviour accurately and, in particular, the dynamics of the outer magnetosphere. To better capture the physics of magnetosphere–ionosphere coupling, a new ionosphere module has been developed in the same vein as those used in other codes. We apply the same thin-shell approximation as described above; FACs are calculated at the inner boundary of the simulation, and mapped onto a spherical grid along dipole field lines. A conductance is defined at each grid cell, which can be calculated using empirical relations for solar EUV ionization and auroral precipitation, or simply set to be constant. We solve for the potential and map this back out to the inner boundary, feeding it back into the MHD simulation as a boundary condition. The electrostatic approximation neglects any inductive effects by assuming magnetic field variations are negligible on timescales of order ~10 s and under (Lotko 2004), and as such we do not recalculate the potential more frequently than this.

Showcasing the model

Figure 2 shows an example simulation run. The simulation domain has the Earth at the origin, and employs a uniform Cartesian grid extending from 30 $R_{\rm E}$ (Earth radii) upstream of the solar wind (along the *x*-axis) to 70 $R_{\rm E}$ downstream. The *y* and *z*-axes extend from −30 $R_{\rm E}$ to 30 $R_{\rm E}$, with *z* pointing parallel to the rotational axis. The domain terminates at a spherical inner boundary near to the Earth at 4 $R_{\rm E}$, within which the MHD equations are no longer solved. This is designed to reduce computational cost because, this close to the planet, the Alfvén speed increases considerably as a result of the high magnetic field strength and the modelling would need to resolve increasingly small time steps. In this simulation we use a grid resolution of 0.5 $R_{\rm E}$. The code can be run with an arbitrary number of processors, thanks to efficient MPI parallelization with performance scaling linearly.

In figure 2, the solar wind propagates from the left onto the dayside magnetopause, with the magnetotail extending out on the right. The simulation was performed for steady-state southward interplanetary magnetic field (IMF) conditions. In this case the IMF points in the opposite direction to the planetary field at the dayside subsolar magnetopause, favouring reconnection, and the magnetosphere is maximally "open". This configuration should drive the strongest ionospheric currents. We use a solar wind with magnetic field strength of 5 nT, speed 400 km s^{-1}, density 5 cm^{-3} and temperature 5 eV. For simplicity the Earth's dipole axis is aligned perpendicular to the solar wind inflow, and the ionospheric Pedersen and Hall conductances are considered constant with values of 10 mho and 0 mho, respectively. This configuration is designed to ensure global north–south and dawn–dusk symmetry in the resulting magnetospheric and ionospheric parameters.

Figure 2a shows the plasma number density on a logarithmic scale. The discontinuity crossing the midplane at $X = -14\,R_{\rm E}$



3 Plots of the northern ionosphere showing (a) the field-aligned current and (b) the electrostatic potential after 4 h of southward IMF driving.

corresponds to the bow shock where the supersonic wind becomes subsonic. The enclosed region of increased density is the magnetosheath, bounded on the Earthward edge by the magnetopause, which crosses the midplane at $X = -11\,R_E$. The location of the inner boundary at a radius of $4\,R_E$ from the Earth is evident from the spherical region of low density (dark blue).

"The simulation has produced dynamics that agree with a basic Dungey cycle"

Magnetic field lines (shown in black) illustrate the boundary where the IMF in the solar wind meets closed magnetospheric field, opening flux at the dayside magnetopause via magnetic reconnection. This open flux can be seen extending out towards the magnetotail, where it closes again at a reconnection site at $\sim 30\,R_E$ from the planet. This reconnection is evident from the oppositely directed flows in figure 2b, where magnetic energy is being released as kinetic and thermal energy, accelerating the plasma to generate return flow back towards the Earth (blue) and ejecting some of the plasma downtail (red). The returning plasma and magnetic field will ultimately convect back towards the dayside via dawn and dusk, before reconnection occurs again at the magnetopause. This completes what is known as the "Dungey cycle" (Dungey 1961).

As described above, convection of the magnetic field in the magnetosphere generates FACs along the OCB, which manifests at the ionospheric footprints of the field lines as "region-1" or "Birkeland" currents. Figure 3a shows the field-aligned currents at the end of the simulation for the northern hemisphere. Distinct bands of FAC are found between 10° and 20° colatitude, where positive current points into the Earth and negative points out. As expected, these currents are oppositely directed on the dawn and dusk sides, indicating they are part of the region-1 current system. This is further evident when comparing the location of this current to that shown in AMPERE data (e.g. figure 2 of Coxon *et al.* 2014, where region-1 currents were detected at similar latitudes).

The resultant electrostatic potential (figure 3b) is consistent with the typical two-cell ionospheric convection pattern set up in response to the circulation of magnetospheric plasma. The overall dawn–dusk symmetry in the morphology of both the current and potential arises from the strong symmetry in the driving conditions of the simulation, although, as with other codes, the absolute value in the cross-polar cap potential (CPCP) is sensitive to the choice of grid resolution (Ridley *et al.* 2010) and thus requires further benchmarking. Nevertheless, the simulation has produced dynamics that agree with the basic description of the Dungey cycle, and the resulting ionospheric parameters appear to match expectations on a phenomenological level.

Ongoing and future work

One advantage of the generality of MHD codes is their ability to simulate arbitrary configurations of the Earth's magnetic field and the solar wind, enabling systematic studies into how different parameters, such as dipole tilt angle, affect the properties of field-aligned currents. This will reveal further details of the physics by which these currents arise and their role in magnetospheric dynamics.

Further work includes performing simulations with real solar wind data measured upstream of the Earth at the Sun–Earth L1 Lagrange point, for example for a severe event, and comparing the output to observations. Using results from other codes (e.g. Gordeev *et al.* 2015) to benchmark the CPCP for a variety of solar wind inputs will provide a further check on accuracy. Gorgon can now model radiation belt dynamics using embedded particle-tracing software running in parallel with the MHD simulation (developed as part of the NERC-funded Rad-Sat project). This allows the tracking of size and location of trapped particle populations during severe events, and thus the forecasting of satellite radiation environments – of importance to safeguarding communications networks. A point for future development of the code is the addition of a model ring current, which is responsible for a second ionospheric current system: region-2, situated at lower latitudes than region-1.

Finally, an important extension of Gorgon capabilities includes using the ionosphere model output to calculate GIC location and intensity, as part of the NERC-funded SWIGS (Space Weather Impacts on Ground-based Systems) project. This may ultimately provide a valuable component of a future space weather forecasting framework, allowing – for example – regional forecasting of GIC risk during a severe space weather event. ●

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RISHBETH PRIZE

This work was awarded a Rishbeth Prize for the best student talk at the Spring MIST Meeting in Southampton in 2018. The Rishbeth Prizes are awarded annually for the best talk by a research student and the best poster; they remember Henry Rishbeth, founder of MIST with Peter Kendall.

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