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# The Ionospheric Source of Magnetospheric Plasma is Not a Black-Box Input for Global Models

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**Abstract.** Including ionospheric outflow in global magnetohydrodynamic models of near-Earth outer space has become an important step towards understanding the role of this plasma source in the magnetosphere. Of the existing approaches, however, few tie the outflowing particle fluxes to magnetospheric conditions in a self-consistent manner. Doing so opens the magnetosphere-ionosphere system to non-linear mass-energy feedback loops, profoundly changing the behavior of the M-I system. Based on these new results, it is time for the community eschew treating ionospheric outflow as a simple black-box source of magnetospheric plasma.

## 1. Introduction

The ionosphere is not merely a black-box electrodynamic boundary condition on the magnetosphere-ionosphere system; rather, it is an integral part of the tightly-coupled, non-linear solar wind-magnetosphere-ionosphere system. The Birkeland currents flowing from the magnetosphere close through the ionosphere, creating a large scale electric field. This electric field controls magnetic convection and particle drifts in the magnetosphere, playing a profound role in global dynamics. The interplay between the two creates a system that is non-linear and tightly-coupled. This relationship is widely accepted as fact and the use of these adjectives should be neither controversial nor surprising.

This line of reasoning should apply to ionospheric outflow as well. It is now widely accepted that ionospheric outflow is an important, if not dominant, source of magnetospheric plasma [*Chappell et al.*, 1987]. Similar to the case of ionospheric electrodynamics, the characteristics of the outflowing plasma is tied to the energy input from both the magnetosphere and solar wind (in addition to the above reviews, see *Yau and André* [1997]). From these two statements alone, it would be expected that ionospheric outflow is a *tightly-coupled* and *non-linear* part of the solar-magnetosphere-ionosphere system and should be treated as such by the research community.

A review of global numerical modeling literature, however, shows that outflow is treated very differently than electrodynamics. Most global-level studies neglect outflow outright; only a fraction of those that include the ionospheric plasma source connect it to magnetospheric conditions in a causal, self-consistent manner. In contrast, it is exceedingly rare to find a simulation-based study of the global system that does not include a self-consistently calculated convection electric field.

Those studies that do include the ionospheric source of magnetospheric plasma are finding that it has a profound impact on global dynamics. The subset of this minority that includes outflow causally are discovering that previously unobserved mass-energy feedback loops can develop between the ionosphere and magnetosphere. Based on this small but growing body of work, it is time for the numerical modeling community to accept that ionospheric outflow is not merely a black-box input to the magnetosphere, but a critical part of the tightly-coupled, non-linear magnetosphere-ionosphere system.

## 2. Outflow and the Magnetosphere

The case for this argument begins with observations of heavy ions in the magnetosphere, a clear sign of plasma of ionospheric source. The report of plasma sheet oxygen by *Shelley et al.* [1974] marked the first of many observations of ionospheric plasma in the plasma sheet [*Lennartsson and Shelley*, 1986; *Nosé et al.*, 2003; *Denton et al.*, 2005; *Mouikis et al.*, 2010] and inner magnetosphere [*Sharp et al.*, 1985; *Daglis et al.*, 1999; *Nosé*, 2005; *Kronberg et al.*, 2012; *Nosé et al.*, 2015]. Multiple reviews now cover this topic in depth [*Hultqvist et al.*, 1999; *Yau and André*, 1997; *Yau et al.*, 2007; *Kronberg et al.*, 2014; *Welling et al.*, 2015]. Two themes emerge in these works: the strength of the ionospheric source varies with geomagnetic activity and this source plays a critical role in the storm time magnetosphere.

Many studies, both observational and numerical, have tied variability of outflow to different energy sources. Solar energy deposition is tied to increases in outflow, both in terms of increased photoionization of neutrals (via correlation with F10.7 solar radio flux [e.g., *Young et al.*, 1982; *Cully et al.*, 2003]) and production of photoelectrons on the day side [e.g., *Khazanov et al.*, 1997; *Tam et al.*, 1998; *Kitamura et al.*, 2011]. On the day side, especially the cusp region, Alfvenic Poynting flux and soft precipitating electron fluxes are associated with increases in outflow into the magnetosphere [e.g., *Barghouthi et al.*, 1998; *Barakat et al.*, 1998; *Barakat and Schunk*, 2001; *Strangeway et al.*, 2005]. Impulses in the solar wind dynamic pressure have also been tied to bursts of outflow [*Moore et al.*, 1999]. On the night side auroral zone, outflow is tied to various measures of magnetospheric activity [*Yau et al.*, 1985] and have been directly tied to magnetospheric substorms [e.g., *Ø ieroset et al.*, 1999; *Wilson et al.*, 2004]. *Gombosi and Nagy* [1989] showed that transient oxygen outflows can be tied to changes in field-aligned current strength. The reviews previously listed cover these topics in more depth.

Connecting these lines of research gives us the possibility of tight coupling between ionospheric outflow and magnetospheric activity. Clearly, outflow is important to magnetospheric dynamics. Conversely, many energy inputs to ionospheric ions, though ultimately of solar origin, are filtered through the magnetosphere. As one changes, we expect the other to evolve in response.

## 3. Outflow and Global Modeling

Though evidence concerning the importance of outflow in the magnetosphere was mounting, global magnetohydrodynamic (MHD) models of the magnetosphere were reluctant to include this source. The first model to purposely include this source was that of *Winglee* [1998], which relied on simple inner boundary conditions to provide an ionosphere population. Noting intent is necessary as other modelers had been including inner boundary sources via the same mechanism [*Siscoe et al.*, 2001; *Walker et al.*, 2003], but only recognized this after the work of *Winglee* [1998] and did not leverage this feature until some time later [*Zhang et al.*, 2007; *Welling and Ridley*, 2010; *Welling and Liemohn*, 2014]. The work of *Winglee* [1998] was an important step for the community because, though particle tracing models have previously explored ionospheric particles in the magnetosphere [e.g., *Delcourt et al.*, 1989; *Peroomian and Ashour-Abdalla*, 1996; *Huddleston et al.*, 2005; *Moore et al.*, 2007], global MHD provided the opportunity to do so in a self-consistent manner (i.e., where the ionospheric population can act on the fields through which it drifts). This breakthrough inclusion led to a series of successful follow up studies that included both ionospheric oxygen and hydrogen [*Winglee*, 2000; *Winglee et al.*, 2002; *Harnett et al.*, 2008], yet no other modeling group followed suit for a decade.

The slow pace to adopt outflow stands in stark contrast to the situation concerning ionospheric electrodynamics during the early MHD era [*Brecht*, 1985]. The first 3D MHD simulations of the Earth's magnetosphere [*Brecht et al.*, 1981; *LeBoeuf et al.*, 1981; *Wu et al.*, 1981] neglected any connection with the ionosphere (but frequently noted its abscence). Only three years later, rudimentary attempts to connect to the ionosphere were being made [*Fedder and Lyon*, 1984; *Ogino and Walker*, 1984]. Second generation MHD models, such as the Block Adaptive Tree Solar wind Roe type Upwind Scheme (BATS-R-US, *Gombosi et al.* [1994]), did not publish Earth simulation results until a full treatment of ionospheric electrodynamics was installed [e.g., *Gombosi et al.*, 1998].

Eventually, however, the rest of the MHD community began to realize the benefits of including both light and heavy ionospheric sources. The results were immediately enlightening. The importance of ionospheric plasma to the central plasma sheet and ring current, a result previously explored with observations and particle tracing methods, was confirmed in the global models, but the impacts of this outflow on magnetospheric dynamics could now be explored [*Glocer et al.*, 2009a, b; *Brambles et al.*, 2010; *Welling and Ridley*, 2010; *Welling et al.*, 2011]. Controlled, idealized experiments were constructed to test the impact of specific populations, including outflow from specific regions [*Garcia et al.*, 2010; *Yu and Ridley*, 2013a] and outflow with different characteristics [*Wiltberger et al.*, 2010; *Brambles et al.*, 2010; *Yu and Ridley*, 2013b] in isolation from other regions. The explosion of investigations into the role of outflow in the global system was just starting.

Intertwined within the flurry of new results were hints that non-linear feedback loops could manifest. The first hint came via the ubiquitous result that ionospheric outflow could strongly affect cross polar cap potential [*Winglee et al.*, 2002; *Glocer et al.*, 2009a; *Brambles et al.*, 2010; *Wiltberger et al.*, 2010; *Welling et al.*, 2011], indicating that mass loading of the magnetosphere is somehow capable of changing its electromagnetic coupling with the ionosphere. The exact nature of this effect remains unresolved [*Welling and Zaharia*, 2012]. Further, there were profound effects upon tail dynamics, including the potential for heavy ion outflow to trigger substorms [*Wiltberger et al.*, 2010], alter substorm intensity and onset timing [*Welling et al.*, 2016], and impact the development of Kelvin-Helmholtz stability criteria along the flanks of the magnetosphere. It was also found that as outflow from one region of the ionosphere changed the shape and dynamics of the magnetosphere, the role of outflow from other regions would be changed [*Welling et al.*, 2016], obfuscating results from previous studies. The complex role that ionospheric outflow plays in the global system was being realized.

## 4. Mass-Energy Feedback

In all of these studies, only a handful closed the ionosphere-magnetosphere-ionosphere loop by including a terrestrial plasma source that is *causal*, i.e., one that responds dynamically to solar and magnetospheric drivers. Two methods are currently employed. The first is an empirical method that leverages the work of *Strangeway et al.* [2005] to tie Poynting flux, as calculated by the MHD model, to $O^+$ outflow rates [*Gagne*, 2005; *Damiano et al.*, 2010; *Brambles et al.*, 2010]. The second is to use first-principles-based modeling via the Polar Wind Outflow Model (PWOM [*Glocer et al.*, 2007, 2012]), to simulate outflow dynamics using energy inputs from the magnetosphere [*Glocer et al.*, 2009a, b]. Both have been used in a number of studies, as listed above.

It was with the empirical approach that the first clear mass-energy feedback loop was discovered within the confines of global models. *Brambles et al.* [2011] found that, using constant solar wind drivers, heavy ion outflow as provided by the adapted *Strangeway et al.* [2005] formula could drive global sawtooth oscillations [e.g., *Huang*, 2003; *Henderson*, 2004] in the tail. The mechanism responsible was a chain of $O^+$ outflow that would mass-load and destabilize the tail, which in turn would drive a temporary increase in Poynting flux into the inner boundary, therefore releasing a new burst of $O^+$ [*Ouellette et al.*, 2013]. *Brambles et al.* [2013] further explored these dynamics for different categories of storms. These publications marked the first true identification of a possible ionosphere-magnetosphere feedback loop that relied entirely on the inclusion of outflow as a coupling mechanism.

The community was intensely interested in the ionosphere-magnetosphere connection illustrated in *Brambles et al.* [2011]. First, it was a potential solution to the mystery of sawteeth oscillations, which are yet to be fully understood. Statistical studies were immediately undertaken to test the veracity of this result, finding that $O^+$ in the plasma sheet appears to be a necessary but not sufficient condition for sawteeth events [*Liao et al.*, 2014]. Second, *Brambles et al.* [2011] was the first to demonstrate that ionospheric outflow can develop non-linear feedback loops with the magnetosphere if causality with the global system is considered. This idea was expanded upon by *Moore et al.* [2014], who chronicled the different ways that outflow may be interacting with the magnetosphere.

Following this new found excitement of outflow was the identification of another potential feedback loop [*Welling et al.*, 2015]. Using the first-principle-based PWOM model with global MHD and a dedicated ring current model, it was found that region 2 Birkeland currents could increase the amount of outflowing $O^+$ via a previously known mechanism [*Gombosi and Nagy*, 1989]. The increase in outflow mass loaded the ring current and increased energy density of the ring current significantly. This would, in turn, increase the magnitude of $O^+$ outflow associated with the region 2 currents. When compared to a similar simulation where the Birkeland currents from the ring current were not allowed to close to the ionosphere (a "one-way" coupled simulation), the "two-way coupled" simulation (i.e., the feedback loop is closed via the region 2 currents) yielded a six-fold increase in outflowing $O^+$, a ring current dominated by oxygen, and far more realistic behavior in terms of $D_{ST}$ index and Birkeland current distribution.

Figure 1 illustrates the dramatic change in outflow when the feedback loop is allowed to close. The solid lines show the total fluence, or outflowing flux integrated over the polar cap, over the duration of the storm when the feedback loop is broken (the simulation is only one-way coupled to the ring current). Colors indicate $O^+$ (green), $H^+$ (orange), or total fluence (black) values. When the feedback loop is closed (dashed lines), total outflow increases by about a factor of two owing almost completely to the increase in oxygen. This line plot clearly demonstrates the necessity of using a ionospheric source of plasma that is self-consistent with the state of the magnetosphere.

## 5. Forward to Outflow Self-Consistency

*Brambles et al.* [2011] and *Welling et al.* [2015], two illustrations of outflow-magnetosphere feedback loops, are not without faults. Both are, at best, a limited representation of the true system. Each of the outflow models include only a limited set of acceleration physics (*Strangeway et al.* [2005] representing wave-particle acceleration, PWOM representing ambipolar acceleration). Additionally, coupling from the magnetosphere into the ionosphere is limited. Assumptions must be made to obtain precipitating fluxes from the MHD models, and outflowing fluxes are very sensitive to these. Further, the extent to which different magnetospheric processes are being accurately captured, such as reconnection in the tail, is not well understood. It is reasonable to question if these feedback loops exist in the real system.

However, at a minimum, these studies have demonstrated the need to include two-way coupled outflow in global simulations. In each case, the inclusion of self-consistent outflow fundamentally changed the behavior of both the magnetosphere and of the spatial and temporal dynamics of the ionospheric plasma source. By continuing to ignore the possibility of such feedback loops and treating outflow as a black-box boundary condition, researchers risk severely limiting the capabilities of their models and misinterpreting the results. Now is the time for the community to embrace the challenge of advancing numerical models to include self-consistent ionospheric outflow.

Accepting this challenge will require redoubled effort to improve the physics capabilities in our models. Outflow model physics must be expanded to include as many acceleration mechanisms as possible. Currently, very few models have this capability and only one has been coupled to a global model [*Welling et al.*, 2016], albeit in a simple, one-way manner. Additionally, the coupling between outflow and magnetosphere models must be expanded so that all possible energy coupling paths can be included. Our current capabilities available for two-way coupling are, at present, singularly focused on either capturing wave-particle interactions or obtaining the ambipolar acceleration. This will likely require capabilities beyond multi-fluid MHD that provide additional information about the precipitating populations and parallel acceleration mechanisms at higher altitudes (e.g., *Glocer* [2016]). Finally, we need to start considering the problem from the bottom up by capturing densities and upflows from the thermosphere upwards. This will yield a more accurate and dynamic limit on the supply of ions from below. These efforts will require broad commitment from ionospheric and magnetospheric scientists as well as computational specialists. However, the scientific return on such an investment will be deeply beneficial to our understanding of the ionosphere-mangetosphere-heliosphere system.

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**Figure 1.** Hydrogen, oxygen, and total fluence (orange, green, and black lines, respectively) taken at the interface between the PWOM and BATS-R-US during the 1-way coupled simulation (solid lines) and the 2-way coupled simulation (dashed lines). Reproduced from *Welling et al.* [2015]

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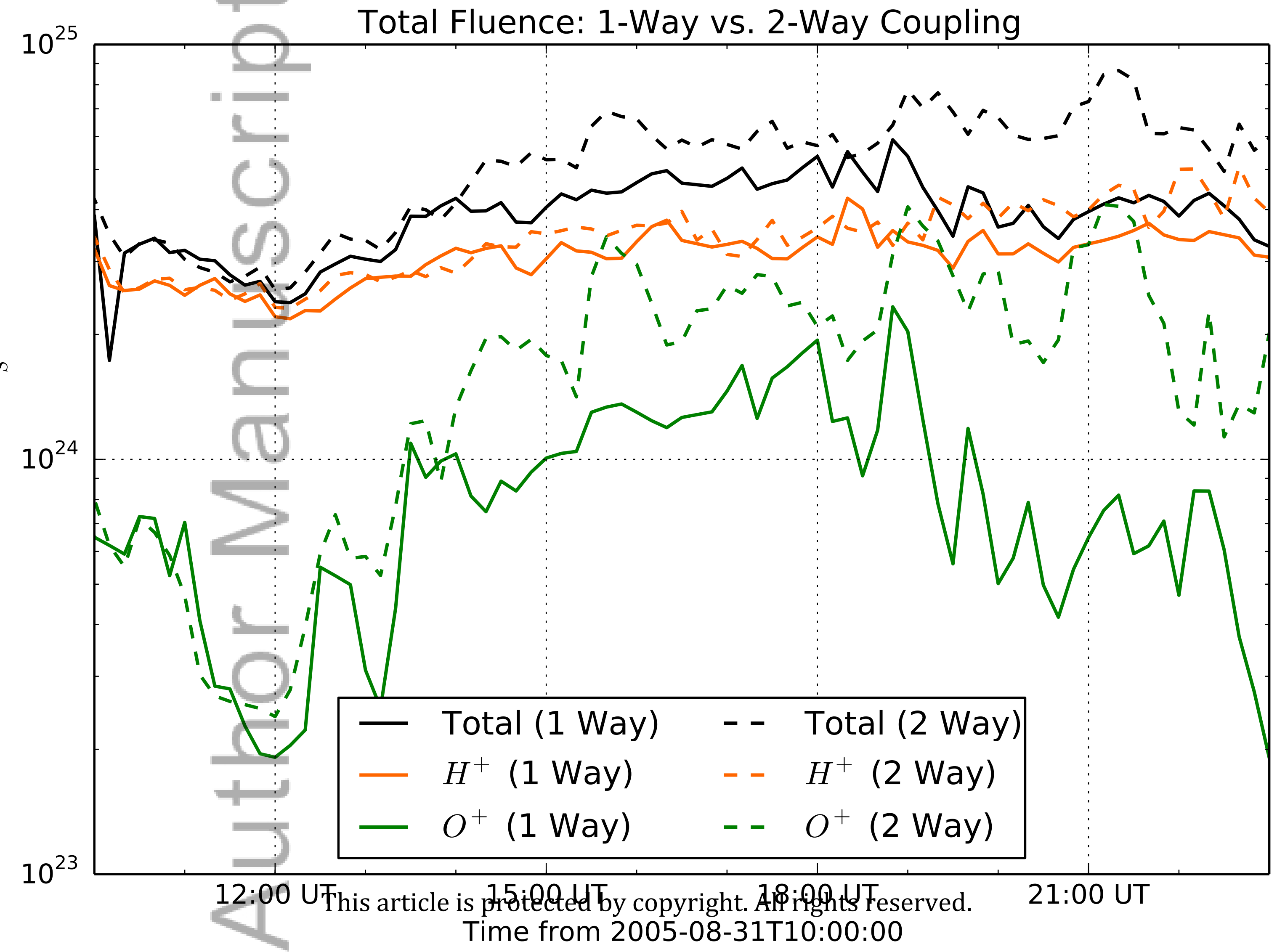
Total Fluence: 1-Way vs. 2-Way Coupling
$10^{25}$
$10^{24}$
$10^{23}$
12:00 UT
15:00 UT
18:00 UT
21:00 UT
Time from 2005-08-31T10:00:00
Total (1 Way)
Total (2 Way)
$H^+$ (1 Way)
$H^+$ (2 Way)
$O^+$ (1 Way)
$O^+$ (2 Way)