Journal of Atmospheric and Solar-Terrestrial Physics ■ (■■■■) ■■■–■■■

Contents lists available at ScienceDirect

Journal of Atmospheric and Solar-Terrestrial Physics

journal homepage: www.elsevier.com/locate/jastp

The ionospheric outflow feedback loop

T.E. Moore*, M.-C. Fok, K. Garcia-Sage

NASA Goddard SFC, Greenbelt, MD 20771, USA

ARTICLE INFO

Article history:
Received 16 May 2013
Received in revised form
9 January 2014
Accepted 10 February 2014

Keywords:
Ionosphere
Feedback
Magnetosphere

ABSTRACT

Following a long period of observation and investigation beginning in the early 1970s, it has been firmly established that Earth's magnetosphere is defined as much by the geogenic plasma within it as by the geomagnetic field. This plasma is not confined to the ionosphere proper, defined as the region within a few density scale heights of the F-region plasma density peak. Rather, it fills the flux tubes on which it is created, and circulates throughout the magnetosphere in a pattern driven by solar wind plasma that becomes magnetically connected to the ionosphere by reconnection through the dayside magnetopause. Under certain solar wind conditions, plasma and field energy is stored in the magnetotail rather than being smoothly recirculated back to the dayside. Its release into the downstream solar wind is produced by magnetotail disconnection of stored plasma and fields both continuously and in the form of discrete plasmoids, with associated generation of energetic Earthward-moving bursty bulk flows and injection fronts. A new generation of global circulation models is showing us that outflowing ionospheric plasmas, especially O^+, load the system in a different way than the resistive F-region load of currents dissipating energy in the plasma and atmospheric neutral gas. The extended ionospheric load is reactive to the primary dissipation, forming a time-delayed feedback loop within the system. That sets up or intensifies bursty transient behaviors that would be weaker or absent if the ionosphere did not "strike back" when stimulated. Understanding this response appears to be a necessary, if not sufficient, condition for us to gain accurate predictive capability for space weather. However, full predictive understanding of outflow and incorporation into global simulations requires a clear observational and theoretical identification of the causal mechanisms of the outflows. This remains elusive and requires a dedicated mission effort.

1. Ionospheric plasma source

Earlier reviews of ionospheric outflows and their magnetospheric circulation have been given by Moore and Horwitz (2007), Lotko (2007), and Moore et al. (2008). A brief interpretive synopsis is given here as an introduction, supported by the schematic diagram of Fig. 1. The ionosphere was initially determined by sounding rocket measurements to have a steep topside density profile with a scale height of less than 100 km, at altitudes where the heavier species O^+ was dominant. Thus its densities were expected to be negligible at higher altitudes in space around Earth, and attention focused then on the entry of solar wind. However it was determined early on that the solar wind was deflected around a magnetopause, but that cold plasma had substantial densities out to several Earth radii. This was initially explained by the presence of light ions H^+ and He^+ with a larger scale height so they eventually dominated at high altitudes above the F layer occupied by O^+ and other heavy ions having smaller scale heights.

At higher invariant latitudes beyond the plasmasphere, ion outflows were initially thought to exist continuously as light ion-dominated polar winds that extend into the lobes, plasma sheet and trough regions. At these high invariant latitudes, typically above 55°, plasmaspheric conditions could not be established because of global circulation driven by reconnection of circulating flux tubes to the solar wind. This reconnection periodically opens the circulating flux tubes, allowing escape from the magnetosphere through the lobes and boundary layers. Moreover, hot plasma was produced by the magnetosphere with pressure sufficient to account for the stretching of the plasma sheet within the magnetotail.

The early view of ionospheric outflows described above was well supported by observations, with one glaring exception that demanded attention. The substantial presence of O^+ in magnetospheric hot plasma was noticed soon after the light ion polar wind was confirmed, a disruptive and somewhat disturbing observation that provoked a great deal of discussion and further investigation

* Corresponding author.

http://dx.doi.org/10.1016/j.jastp.2014.02.002
1364-6826

Please cite this article as: Moore, T.E., et al., The ionospheric outflow feedback loop. Journal of Atmospheric and Solar-Terrestrial Physics (2014), http://dx.doi.org/10.1016/j.jastp.2014.02.002

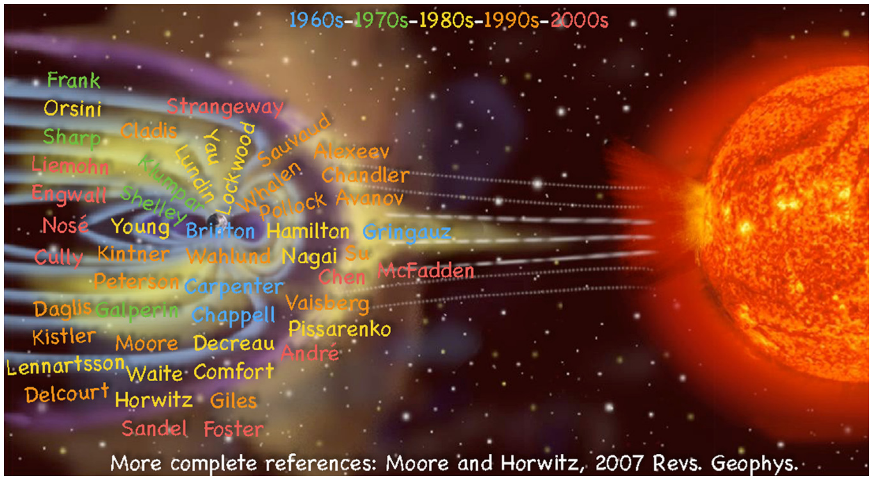

Fig. 1. A schematic depiction of the inter-decadal effort to observe and determine the importance of the ionospheric or geogenic source of magnetospheric plasma. The names of relevant researchers are placed in locations approximately reflecting their seminal contributions to this effort.

of plasma composition. Soon thereafter, O^+ was confirmed to be present in auroral accelerated ionospheric outflows, and later found to be accompanied by N^+, and in very active times by molecular ions $N2^+$, NO^+, and O_2^+. It became obvious in hindsight that solar wind energy being funneled into the upper atmosphere by auroras was raising the scale heights and causing escape of these heavy species with nominal thermal speeds well below escape velocity (Wilson and Craven, 1999). More active periods produced outflows of O^+ and at higher activity, molecular ions.

Attention then focused primarily on the auroral phenomena that produced heavy ion outflows. Beginning with the inferred lack of particle collisions in most of the magnetosphere, many clues contributed toward an eventual consensus paradigm that outflows result from a combination of ionospheric electron and ion heating by auroral processes.

Ion interactions with plasma waves must play an important role in heating the ion plasma transverse to the local magnetic field. The energy required to produce observed fluxes is quite small compared with the amount of energy transmitted from the magnetosphere to the atmosphere in active auroras, but the outflows nevertheless scaled directly with the available energy supply (Moore et al. (1999), Strangeway et al. (2005), Zheng et al. (2005)). Wave modes of different types were suggested, ranging from Alfvén (MHD) waves (Chaston et al., 2006) to ion cyclotron waves (André and Yau, 1997), to lower hybrid waves (Retterer et al., 1986). The energy to drive such waves has been suggested to come from sources such as the field aligned currents, the shear in the plasma convection pattern associated with such currents, or from more remote sources such as reconnection or turbulence associated with magnetospheric boundary layers or the plasma sheet. Hot plasma loss cone or other anisotropies may also contribute to the required wave growth. However, no theory or model of ionospheric heating has successfully derived a defensible physical parameterization from detailed bulk properties of the magnetosphere that are now calculated with considerable success by global simulation models.

Local in situ observations of outflow flux led to a power law scaling with Poynting flux, even at DC frequencies (Strangeway et al., 2005). Because this low-frequency electromagnetic energy reflects primarily convective motions, convective frictional heating of ions by collisions with neutrals appears to be causally important. However, it is not clear how the kinetic energy range of typical convective flow drifts, with velocities up to a few km/s, could impart escape energy to the ions. The heating and outflow was also responsive to the electromagnetic fluxes carried into the ionosphere from high altitudes by low frequency Alfvén waves, that is, in a frequency range extending up through the heavy ion cyclotron frequencies (Strangeway et al., 2005). Work continues to determine the effectiveness of waves at higher frequencies extending into the lower hybrid range.

Electron heating also occurs in the aurora, resulting from direct collisions with precipitating electrons or higher frequency plasma wave instabilities associated with auroral acceleration and precipitation. This was supported strongly by incoherent scatter radar observations of topside ionospheric upflow events that were at times associated with intense heating of the ionospheric electrons, or of the ionospheric ions, either or both of which appeared to produce strong upward bulk flows of plasma (Wahlund et al., 1992; Blelly et al., 1996). Modeling (Cannata and Gombosi, 1989; Khazanov et al., 1997) has shown that ionospheric electron heating is effective in producing outflows, by enhancing the ambipolar electric field that binds electrons to the ions from which they originated. No significant average flux of electrons can leave the ionosphere without also lifting a similar flux of ions out of the gravitational trap. The net result is that electron thermal energy or pressure is just as effective in lifting ions as electrons, regardless of the large difference in gravitational binding, because they are coupled together electrostatically.

Scaling relationships for ionospheric outflow can be put to work in specifying the outflow expected to result from energy and precipitation flows into the ionosphere, as generated by magnetospheric global circulation models. The scalings do not fully specify all relevant parameters, but with a few plausible assumptions, can be used to construct a reactive outflow response to conditions that develop at the inner boundary of a global magnetospheric simulation. Fig. 2 shows results from a scaling constructed for use within the original Lyon–Fedder–Mobary global circulation model (Lyon et al., 2004). It responds to Poynting Flux into the ionosphere, and also to the electron precipitation flux into the ionosphere, as estimated from the plasma density in the global simulation. The response to both the Poynting fux and the electron precipitation is determined from the scalings specified by Strangeway et al. (2005). Though the interaction of these two influences, acting in combination, was not specified by Strangeway et al., they have been taken here to have a multiplicative effect on total outflow. Thus, when precipitation flux is zero, no amount of Poynting flux can produce any significant outflow, and vice versa. The details are more fully specified by Moore et al. (2007). As described in the following sections, this type of scaling has been used to investigate the feedback effects of outflows on magnetospheric dynamics.

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