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Extreme ionospheric ion energization and electron heating in Alfvén waves in the storm-time inner magnetosphere.

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Abstract

We report measurements of energized outflowing/bouncing ionospheric ions and heated electrons in the inner magnetosphere during a geomagnetic storm. The ions arrive in the equatorial plane with pitch angles that increase with energy over a range from tens of eV to > 50 keV while the electrons are field-aligned up to ~1 keV. These particle distributions are observed during intervals of broadband low frequency electromagnetic field fluctuations consistent with a Doppler-shifted spectrum of kinetic Alfvén waves and kinetic field-line resonances. The fluctuations extend from $L\approx3$ out to the apogee of the Van Allen Probes spacecraft at $L\approx6.5$. They thereby span most of the L-shell range occupied by the ring current. These measurements suggest a model to account for large ionosphere derived contributions to magnetospheric energy density based on the ability of dispersive Alfvén waves to drive electron precipitation into the ionosphere and ion energization in the dipolar geomagnetic field.

Introduction

Large fractions of inner magnetospheric energy density are supplied by ions of ionospheric origin during large geomagnetic storms [e.g. review by Daglis et al.,, 1999]. The sources for these ions include outflows from the cusp/cleft [Delcourt, 1990a] and more generally the high latitude ionosphere [Cladis and Francis, 1985]. These ions have source temperatures less than 1 eV yet are observed in the equatorial plane of the inner magnetosphere at energies exceeding 100 keV. The challenge that these observations therefore present is how to account for ion extraction from the ionosphere, transport into the ring current and acceleration up to the very large energies observed. Various mechanisms are thought to facilitate this process starting with ionospheric heating leading to bulk ion upflows from the ionosphere [Wahlund et al., 1992; Strangeway et al., 2005] followed by a wide variety of wave particle interactions [e.g. review by Andre and Yau, 1997] to drive energization into the keV range in and above the topside ionosphere. It has been suggested that such processes are followed by acceleration to much higher energies in inductive electric fields during substorms for those ionospheric ions that are transported into the plasma sheet and then injected earthward [Delcourt et al, 1990b]. A review is provided by Keika et al. [2013].

An alternative mechanism that self-consistently drives ionospheric outflow and energization without requiring plasma sheet transport is suggested by the pervasive storm-time measurement along ring current field-lines of intense broadband low frequency electromagnetic waves which extend from the topside ionosphere [Nakajima et al., 2007; Yao et al., 2008] to the equatorial plane [Chaston et al., 2014a, 2015]. These waves have been identified as kinetic Alfvén waves and/or kinetic field line resonances [Chaston et al, 2014a] and can more generally be described as dispersive Alfvén waves. Waves of this kind are known to be accelerators of electrons parallel to the geomagnetic field [Chen and Hasegawa, 1974] and of ions in the perpendicular direction [Johnson and Cheng, 2001]. Indeed, just above the ionosphere the aforementioned studies indicate the broadband waves are accompanied by field-aligned down-going electrons and upflowing/outflowing transversely heated ionospheric ions.

In this paper we show that outflowing ionospheric ions observed in association with broadband electromagnetic waves arrive in the equatorial plane with energies that can be tens of keV, and after multiple bounces may reach energies in excess of 50 keV. Similar to observations at low altitudes these ions are observed coincident with field-aligned electron distributions. These observations suggest an Alfvén wave model for ionospheric ion extraction and energization along ring current field-lines due to wave driven precipitation of soft/supra-thermal electrons and the stochastic acceleration/trapping of outflowing/bouncing ionospheric ions in the large amplitude wave fields observed.

Measurements

Figure 1 presents a summary of field and particle observations from the Van Allen Probes recorded during the geomagnetic storm of 31 May-3 June 2013. Figure 1a indicates that during this interval the D_{st} index dipped below -120 nT coincident with large impulsive variations in the AE index. Figure 1b and c show spectral measurements of the electric field (E) variations from the EFW instrument [Wygant et al., 2013] provided from the onboard fast Fourier transform (FFT) of E in the spacecraft spin plane at frequencies above 20 Hz and from FFTs of the Z component of E in the $MGSE$ coordinate system performed on the ground. Here X_{MGSE} is directed along the nearly sun pointing spacecraft (s/c) spin axis and the Y_{MGSE} and Z_{MGSE} directions lie in the s/c spin-plane pointing close to the Y and Z GSE directions respectively. Throughout the main phase of the storm (indicated by the negative gradient in Dst) there exists a clear enhancement of broadband electric field variations over the range $0 \leq f_{sc} \lesssim 100\ Hz$ where f_{sc} is the frequency in the spacecraft frame.

Figures 1d-m show a zoomed-in view of the main phase. Over this sub-interval the spectral measurements shown in Figures 1d-e reveal the bursty, or intermittent, quality of the field variations which, with reference to the scaling on the x-axis, extend outward nearly continuously from $L \approx 3$. The electromagnetic nature of the lowest frequency portion of these field variations is apparent in Figure 1f which shows the FFT of the B_{X_MGSE} component from the EMFISIS instrument [Kletzing et al., 2013]. This spectrum is artificially truncated at the largest frequencies shown here by the digitization noise floor of the fluxgate magnetometer. However, magnetic field variations above a few Hz are often recorded from the search coil instrument during large amplitude events to allow a complete characterization of the magnetic field spectrum. This has facilitated mode identification of fluctuations of this type for the entire frequency range over which they are observed in E [Chaston et al., 2014a; 2015]. In these studies it has been shown that the observed temporal field variations are consistent with the motion of electromagnetic field structures identified as kinetic Alfvén waves embedded within the plasma flow over the spacecraft. The field variations therefore appear in the spacecraft frame with wave frequency $f_{sc} \approx (k \cdot v)/2\pi$ where k is the wavenumber and v is the relative velocity between the plasma and the spacecraft. On dipole-like field-lines these variations appear as kinetic field line resonances or Alfvén eigenmodes. The plasma frame wave frequency therefore satisfies $f \ll f_i$, where f_i is the ion gyro-frequency, and so f falls in the ULF range.

Figures 1g and h show the corresponding electron spectrograms in differential energy flux as measured from the HOPE [Funsten et al., 2013] and MAGEIS [Blake et al., 2013] instruments at energies below and above ~50 keV respectively. In general bursts in broadband wave activity are correlated with enhancements over the whole energy range observed consistent with the correlation between these waves and injections from the magnetotail [Chaston et al., 2014a]. Of particular interest, however, are the intermittent supra-thermal fluxes observed at energies below ~1 keV. Qualitatively the occurrence and intensity of these features is matched by that shown in the electric field spectrogram. Significantly, these low energy fluxes become nearly continuous in L-shell as the spacecraft penetrates deeper into the inner magnetosphere after 0600 UT.

Figures 1i-m present the coincident ion plasma measurements as provided by the HOPE and RBSPICE [Mitchell, et al., 2013] instruments at energies below and above ~50 keV respectively. Here the measurements from RBSPICE are taken from Van Allen Probe B as continuous coverage from the same instrument on s/c A is not available over this interval. However spacecraft A and B at this time are sufficiently close together that differences in the observations are not significant for our purposes. The proton spectrograms shown here in Figures 1i and 1j are similar to those observed in the electrons albeit show somewhat more energetic fluxes due to the higher temperature of plasma sheet ions. However the enhancements in proton differential energy flux are often time dispersed in nature especially at the lowest energies. For energies from 0.1-10 keV the dispersion time suggests a source separated from the s/c by a distance equivalent to that along the geomagnetic field to the ionosphere. This dispersive nature is more readily apparent in the O^+ spectrograms of Figures 1k-m. For this species the temporal dispersion for some bursts extends from > 50 keV down to a ~100 eV. Within this range there is a distinct component at energies below ~1 keV with a progressive decrease with L-shell to ~10 eV deep in the inner magnetosphere. The time dispersed bursts in O^+ persist over the entire interval shown (i.e. throughout the whole storm main phase). Similar features are observed in every storm recorded from the Van Allen Probes we have examined to date.

Figure 2 shows a further zoomed-in of the same interval of Figure 1as the spacecraft transitioned from stretched field-lines characteristic of the plasma sheet to more dipolar form consistent with the inner magnetosphere. Figures 1a and 1b show the spectrograms of E_{Z_MGSE} and B_{X_MGSE} as previously. Several wave bursts occur over this interval each corresponding to enhancements in the electron and ion energy flux shown in the subsequent panels. Here we present these particle data as functions of pitch angle at a number of energies spanning the range observed by the HOPE instrument. At this time Van Allen Probe A is located ~18^{o} above the magnetic equator and so the anti-parallel direction (θ=180^{o}) corresponds to motion upward out of the nearest ionosphere.

Figures 2c-e show that for energies below a few 100 eV the electrons are strongly field-aligned and generally appear to be counter-streaming along the magnetic field. These distributions become more isotropic at higher energies and lower L-shell. A similar pitch angle dependency is apparent in H^+ as shown in Figures 2f-i. These panels show that bursts of field aligned protons streaming outward from the nearest ionosphere at energies below 1 keV (Figure 2f) become counter-streaming with decreasing L-shell corresponding to ionospheric outflows from both ionospheres. Within $L \approx 3.5$ the distributions at this energy become isotropic with depletions in the field-aligned direction characteristic of ions trapped between mirror points and subject to heating/energization in the transverse direction. At higher energies (Figure 2f-h) the appearance of counter-streaming ions is nearly coincident with the onset of wave activity and enhancements of low energy electron flux. At energies above 50 keV, as shown Figure 2i, peaks in differential energy flux are observed at intermediate angles (45^o, 135^o) characteristic of what are commonly termed butterfly distributions [e.g. Ebihara et al, 2008].

Figures 2j-n show the corresponding measurements for O^+ ions. Here the field-aligned ion flux enhancements are observed to extend to energies larger than found for H^+ and during the wave burst at ~0500 UT reach even beyond 50 keV (0500 UT). As indicated on Figures 2k-m the alternate appearance of field-aligned O^+ fluxes at 0^o and 180^o on timescales similar to the expected bounce period suggests that these energized ionospheric ions are bouncing in packets between hemispheres. It is also apparent at energies above 10 keV (Figures 2l and m) that as the spacecraft penetrates deeper into the inner magnetosphere there is a progressive drift in pitch-angle from field-aligned toward θ=45^o and 135^o. This provides 'butterfly' distributions as already mentioned with regard to H^+. Subsequent to 0700 UT and within $L < 4.8$ these energetic O^+ ion distributions become more isotropic. However, as shown in Figure 2j and 2k the lower energy distributions remain field-aligned all the way into $L \approx 3$ and only terminate where the broadband wave activity ceases.

To provide evidence for the active role of the broadband waves in accounting for some of the features observed in the aforementioned particle spectra we show in Figure 3 time series fields observations for an individual wave burst 'event' together with the coincident particle distributions. This 'event' has been selected because of the full pitch-angle coverage from the HOPE instrument at this time, the quality of the electric measurement and the availability of high time resolution field 'burst' data over at least part of the interval. For the broadband waves of interest only the spacecraft spin plane electric field measurements are reliable and are presented here in Figure 3a in the de-spun $MGSE$ system described earlier. Figure 3b shows that the DC magnetic field observed at this time (allowing for the applied offsets) is largely in the X_{MGSE} direction so that the components of E shown in Figure 3a are mostly perpendicular to B_o. The largest electric fields over this interval exceed 200 mV/m and are correlated with the occurrence of current sheets manifest as impulsive steps and spike-like variations in B. The most prominent of these occurs at 05:50:55 UT marking the commencement of a weak 'dipolarisation' of the magnetic field with a subsequent progressive increase in B_{Z_MGSE}. Significantly the peak electric fields observed occur on the largest gradients in B (or at the peak in current) inconsistent with either a simple field-aligned current sheet model or travelling wave description but suggestive of standing electromagnetic waves or eigen-modes along B_o.

To confirm that the transverse field variations observed over this interval are consistent with a spectrum of multi-scale dispersive Alfvén waves we have performed a spectral analysis of the variation of the ratio of the perpendicular field components $E_{\perp}/B_{\perp}$ with f_{sc} over this interval. The analysis is identical to that performed for a similar interval previously reported by Chaston et al. [2014a] and from statistics [Chaston et al., 2015]. Since the results are in essence the same as found in these previous studies we do not repeat them here except to say the observed variation over the range $0.01 < f_{sc} < 20\ Hz$ is consistent with a dispersive Alfvén wave model for $f_{sc} \approx (k \cdot v)/2\pi$ and wavelengths across the geomagnetic field extending from multiple ion-gyro-radii down to ~1 km.

Figure 3c-k show snapshots of the e^-, H^+ and O^+ distributions observed just prior to the onset of broadband wave activity and at two times subsequent to the onset. From Figures 3c-e the origin of the counter-streaming electrons identified Figure 2 is readily apparent. With the onset of wave activity, and at low energies, the distribution is clearly heated in the direction parallel to B_o. Significantly the largest velocity at which this heating is observed corresponds approximately to twice the Alfvén speed ($v_A \approx 5 \times 10^6$ ms^{-1}) given by the observed $E_\perp/B_\perp$ ratio from the dispersion analysis mentioned above. This is expected for energization in dispersive Alfven waves [Kletzing et al., 1994].

For the H^+ distributions shown in Figures 3f-g, outflow from the ionosphere occurs subsequent to the onset of wave activity manifest as peaks in phase space density along $v_{||}$. These constitute field aligned (A) and anti-field aligned beams (B) emanating from the ionospheres at both ends of the field-line. Notably the outflow from the closest ionosphere ($A, -ve\ v_{||}$) is observed with larger phase space densities and is confined to a more field-aligned range of pitch angles than that arriving from the more distant ionosphere (B, $+ve\ v_{||}$). This is consistent with a source located at the ionospheric foot-point of the field-line rather than an injection from the plasma sheet. Furthermore, from Figures 3g to 3h the energy of the peak in phase space density associated with each of these populations increases. This energization occurs in a non-adiabatic manner as manifest in the extended from of the distributions in the perpendicular direction and peaks in phase space density at large pitch angle. The transverse energization of the counter-streaming beams in this manner leads to the butterfly pitch angle distributions identified earlier in Figure 2.

The O^+ distributions in Figures 3i-k reveal an evolution similar to that just described for H^+. However, for this species the operation of a heating/energization process is perhaps more obvious. In Figure 3j the peak in phase space density for locally outflowing ions at $v_{||} \approx$ -3x10^5 ms^{-1} (A) has a tail in $v_\perp$ extending out to 30 keV. Furthermore, there is a progressive increase in energy apparent with each bounce for the bouncing ion populations identified in Figure 2. For example, in Figure 3j the peak in phase space density for the component labelled ‘B’ occurs at $v_{||} \approx$ 5x10^5 ms^{-1} and then after mirroring below the s/c appears in Figure 3k at $v_{||} \approx$ -7x10^5 ms^{-1} – an increase of 20 keV. Finally, in a manner similar to that observed for H^+, it is apparent from these velocity space distributions that the transverse energization of the outflowing/bouncing O^+populations provides the butterfly pitch angle distributions at multi-keV energies identified in Figure 2.

Discussion

The measurements presented in Figures 1-3 suggest a model for ‘pumping-up’ ion energy density in the storm-time magnetosphere through the action of dispersive Alfvén waves on outflowing and trapped ionospheric ions. We present a schematic for this process in Figure 4. As shown in Figure 4a the process begins with the driving of dispersive Alfvén waves in the dipolar magnetosphere presumably as a consequence of the storm-time injection process and their precursors in the form of fast flows in the plasma sheet. These features are known to carry [Chaston et al. 2012; Ergun et al., 2015], and or generate [Wright and Allan, 2008; Lysak et al., 2009], very large Earthward directed energy fluxes of fast and shear Alfvén mode waves which couple to the dipolar field-lines of the inner magnetosphere [Lee and Lysak, 1991; Rankin et al., 1993a; Lee et al., 2001]]. With continual driving it may be expected that phase mixing, refractive focusing [Mann and Wright 1995; Rankin et al., 2005], and non-linear processes [Rankin et al., 1993b] will produce very large amplitude dispersive scale Alfvén waves. On dipolar like field-lines these will take the form of kinetic field-line resonances [Streltsov and Lotko, 1999]. As represented schematically in Figure 4a and demonstrated previously [Chaston et al., 2014a] this is what is observed.

Dispersive Alfvén waves carry a parallel electric field sufficient to drive field-aligned electron acceleration and heating of electron distributions [Chen and Hasegawa, 1974; Lysak and Lotko, 1996]. This process is manifest at low altitudes as precipitation into the auroral ionosphere and the formation of aurora [for a review see Chaston et al., 2006]. During storm times both low frequency electromagnetic field variations and precipitating electrons characteristic of this acceleration process occur along the low latitude edge of the auroral oval at invariant latitudes extending to below 60^{o} [Nakajima et al., 2008]. This latitude corresponds to $L \approx 4$ so that such events occur along field-lines comprising the heart of the storm-time ring current and cover a range of L-shells similar to those we examine here from the Van Allen Probes. It would therefore seem reasonable to conclude that the field-aligned electron distributions and electromagnetic field variations we observe from the Van Allen Probes are the equatorial counterpart of those previously reported at low altitudes.

Observations performed within the ionosphere by radars [Wahlund et al., 1992; Kagan et al., 1996] and rockets [Whalen et al., 1978; Lynch et al., 2007] have shown how electron precipitation at energies typical of those observed in dispersive Alfvén waves drive collisional heating and outward expansion of ionospheric electrons leading to ion upflows. These upflows may supply ionospheric ions to altitudes where they can experience electric fields in the Alfvén wave sufficient to drive trapping in the wave potential [Lysak, 1986] and/or the breakdown of gyro-motion [Cole et al., 1976; Johnson and Cheng, 2001; Chen et al., 2001]. The later has a well-known threshold condition for a single wave given as,

$$E_\perp/B_o \geq \Omega_i/k_\perp \quad 1$$

Where Ω_i is the ion gyro-frequency. Once this threshold is exceeded the ion motion becomes stochastic and the ions are free to gain energy directly from the transverse electric wave-field. These ions will be driven upward due to the mirror force to form ionospheric outflows. This process is schematically represented in Figure 4b. For a single Alfvén wave, the upper energy limit attainable via this process can be much larger than the wave potential [McChesney et al., 1991] and in multiple waves or non-planar field variations, which seem appropriate for our case, the stochastic threshold can be considerably lower than given by Equation 1 and the energy gain commensurately larger [Stasiewicz et al., 2013]. Simulations of this process based on observations from the FAST satellite of large amplitude dispersive Alfvén waves [Chaston et al., 2004] have demonstrated rapid gains in perpendicular ion energy as a consequence of trapping and multiple transitions through the wave potential to energies in excess of 10 keV over timescales of the order of a minute – much of this energy appears in the parallel direction due to the action of the mirror force. This process may therefore account for the observations of ionospherically sourced field-aligned energetic ions we report here from the Van Allen Probes.

Because these waves extend along the entire field-line it would seem plausible that this ion acceleration process is active along the entire field-line length. Consequently, as illustrated in Figure 4a, an ion may be continually accelerated over multiple bounces between hemispheres as wave activity persists throughout the storm's main phase. Inward transport of ions accelerated by the same process on higher L-shells and indeed from the plasma sheet [Chaston et al., 2014c] may also contribute. This process therefore can be expected to drive very large energy gains and to provide distributions which become progressively more anisotropic as the mirror points contract to the equatorial plane with increases in transverse ion energy. Given that these waves extend over several L-shells the net effect of such a process on inner magnetospheric ion energy density may be substantial.

Conclusion

We have presented field and particle measurements during a geomagnetic storm from the Van Allen Probes which reveal the coincident presence of bursty large amplitude broadband low frequency electromagnetic waves, field aligned heated electron distributions and energetic outflowing/bouncing or trapped ionospheric ions. These observations extend over a spatial range in the night-side inner magnetosphere from $L = 3$ out to the apogee of the Van Allen Probes at $L = 6.5$ during the main phase of the storm. The wave observations have the characteristics of a Doppler shifted spectrum of kinetic Alfvén waves and kinetic field-line resonances manifest as current sheets with impulsive large amplitude electric field variations. These observations suggest a model for 'pumping-up' ion energy density on dipolar field-lines based on the ability of dispersive Alfvén waves to drive field-aligned electron and transverse ion acceleration. The field-aligned electron acceleration in these waves serves to stimulate ion upflows while the transverse acceleration drives these uplifted ions into the equatorial plane where they can become trapped in the dipole field. Continual transverse acceleration of these trapped ions in the

Alfvén wave-field over multiple bounces between mirror points may provide large energies and significant enhancements of ion energy densities in the regions where these waves are observed.

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Figure Captions

Figure 1. 31st May-3 June Geomagnetic Storm Overview (all s/c data from Van Allen Probes A unless stated). a) D_{st} and AE index divided by 10. b) and c) Spectrograms of the spin-plane electric field variations. White trace is the H^+ cyclotron frequency. d) to m) 'Zoom-in' on main-phase field and particle spectrograms including: d,e) spin-plane electric field ; f) transverse magnetic field variations; g), h) Electron differential energy flux above and below 50 keV from MAGEIS and HOPE; i) H^+ differential energy flux above 50 keV from RBSPICE; j) H^+ differential energy below 50 keV from HOPE; k), l) O^+ differential energy flux from 200 keV-1 MeV and 50 keV-200 keV from the RBSPICE s/c B; m) O^+ differential energy flux below 50 keV from HOPE.

Figure 2. Transition to the inner magnetosphere. a) and b) Spectrograms of electric and magnetic field variations in MGSE coordinates. White trace on each is the H^+ cyclotron frequency. c)-n) Pitch-angle spectrograms in differential energy flux for the species and energies indicated.

Figure 3. Wave burst event. a) Electric field time series in MGSE coordinates. b) Magnetic field time series in MGSE coordinates. Offsets have been applied to each component to emphasis variations around the average value. c)-k) Velocity space distributions spanning the interval shown in panels a) and b). The species and time of measurement are indicated on each panel.

Figure 4. a) Schematic of the ionospheric ion extraction and energization process in Alfvén waves. b) A ‘zoom-in’ of the ionospheric interaction in the southern hemisphere.