Final Progress Report
NASW-96007
Energy coupling between the ionosphere and inner magnetosphere related to substorm onset

Nelson C. Maynard, PI
Mission Research Corporation
Nashua, New Hampshire

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Accomplishments bullets:

- Determined perpendicular Poynting flux at CRRES in the inner magnetosphere at substorm onset
  - Primary direction is azimuthal, not radial, indicating a local source
  - No obvious signal from the magnetotail to trigger onset
  - Strongly supports substorm onset location near the inner edge of the plasma sheet
  - Process is local and a strong function of MI coupling
- Developed near geosynchronous onset (NGO) model for substorm onset and expansion
  - Onset at inner edge of plasma sheet
  - Drift Alfven Ballooning wave travels outward to activate X-line
  - Allows for internal or external triggering
  - Explains lack of substorms in driven convection bays

Our investigation of substorm effects in the inner magnetosphere with CRRES data looked in detail at over 50 substorms relative to signatures of onset and early expansion phases. 20 events were determined to be close enough to the region of onset to provide useful information about timing of effects.

Figure 1 schematized the typical observations associated with onset and expansion. Seven characteristic features are identified associated with substorm onsets and expansions observed by CRRES. (1) Quasi-electrostatic drift-wave oscillations with periods ranging from 60--90 seconds occur on the background westward electric field during the growth phase. (2) The first low-frequency power is detected several minutes before ground onset coincident with eastward excursions of the electric field (trigger waves) resulting from growth of these oscillation. At these times J dot E < 0, meaning that plasma kinetic energy is being converted into electromagnetic energy, and the drift wave couples to the Alfvén mode (ballooning). The power in these trigger waves is dominantly magnetic field aligned and flowing toward the ionosphere. (3) Dipolarization begins, and the SCW appears (local onset) following one or more of these trigger waves and before ground onset. The amplitude of magnetic field oscillations with 30-s period increases associated with this stage. The data suggests that magnetosphere-ionosphere coupling determines whether substorm expansion proceeds or dipolarization stops with a pseudobreakup. In two cases substorm expansion did not occur. In the other

17 events as the electric field turned eastward again (4) the power flowing toward the ionosphere began an explosive increase toward surge levels (local explosive onset). The ``explosive-growth-phase" (EGP) magnetic perturbation occurs at this time of tailward bulk flow and results from the current loop of the transient wave delivering that power toward the ionosphere. Expansions occur in two stages. (5) The first stage immediately follows local explosive onset as westward electric field is enhanced, dipolarization starts or resumes, and particle injection occurs. The first stage lasts less than 10 minutes; then a second stage begins. (6) The second stage of expansion commences with a new enhancement of westward electric field and earthward bulk flow, but without local explosive onset (#4 above) or EGP signatures. Finally, (7) the drift-wave oscillations of the electric field continue into the expansion and can turn the electric field eastward. If this occurs while reflected power is flowing away from the ionosphere, the electrojet wanes and can turn off completely (interference). Expansion can resume either as parallel power and the electric field oscillation return to phase, resulting in another local explosive onset, or as a stage-2 expansion.

We determined the perpendicular as well as parallel Poynting fluxes from wave activity. The parallel Poynting flux is initially toward the ionosphere as a result of dusk-dawn excursions of the electric field. If the reflection from the ionosphere is in phase, the dipolarization and the substorm are initiated. The perpendicular Poynting flux ($\delta E \times \delta B$) is an indication of wave activity and the source of that activity. In all events, the initial response was primarily azimuthal indicating that the source was local. There was no indication of significant wave energy coming in from the tail.

Figure 2 plots the perpendicular Poynting flux of the onset trigger waves. This figure dramatizes the fact that CRRES does not detect wave power arriving from the outside prior to the start of dipolarization (local onset). Figure 3 plots the perpendicular Poynting flux of the LEXO waves. Note that although the placement is done completely independent of the perpendicular vector power direction, vectors tend to point away from the wave centroids, providing an average pattern for this substorm onset feature. The three exceptions (M, O, and R) probably occur because an adjacent wavelength of the drift-ballooning wave is dominating. In all cases the primary perpendicular power is azimuthal with no significant earthward component. The pattern consistency with vectors emanating out from the centroids confirms a local source for wave power release.

If an X-line were to initiate the dipolarization seen at CRRES in the inner magnetosphere, as required by the renovated near-Earth neutral line model, it is not communicating to the inner magnetosphere by means of waves or by particle injections. Particle injections appear typically 5 minutes or greater after the beginning of dipolarization. We interpret this as further evidence of the source region of substorm onset being located at or near the inner edge of the plasma sheet. Magnetosphere-ionosphere coupling with parallel Poynting flux is critical to substorm onset. Dusk-dawn excursions of the electric field reverse the inward convective flow in the inner magnetosphere near the inner edge of the plasma sheet and provide a source of free energy. Alfvén waves couple the ionosphere with the magnetosphere and initiate the dipolarization and the substorm current wedge. We believe that this study constrains the onset process in general to the inner magnetosphere and greatly limits how effects in the near tail could influence the process. This places the near-Earth X-lines as a consequence, not an initiator, of the onset process. As a result we have put together a model for substorm onset.

Figure 4 depicts a meridional picture of how we view substorm onsets and expansions to occur, based on CRRES and correlated ground observations. Figure 1 schematized the typical observations associated with onset and expansion. This provides the framework event sequence for onsets and expansions depicted by Figure 4.

Prior to the start of activity, during the growth phase, quasi-electrostatic oscillations of the dawn-dusk electric field in the Pi-2 frequency band (periods from about 60 to 90 seconds) occur. We suggest that these oscillations are a drift wave, which results from inward, plasma-sheet convection into an earthward pressure gradient, i.e., an E x B-drift instability tapping the free energy available from the pressure gradient of ring-current ions. Trigger waves, small versions of the LEXO wave depicted in Figure 14(b), occur as the amplitude of the drift wave grows, causing reversals the total electric field to dusk-dawn. At these times J dot E < 0, and the drift wave couples to the Alfvén mode converting plasma kinetic energy into electromagnetic energy, which we observe flowing toward the ionosphere. We refer to this phenomenon as drift-Alfvén ballooning (DAB). This may occur in the absence of an external trigger; however, external triggering may couple with DAB as we discuss later.

Upon reflection of trigger waves from the ionosphere, the magnetic configuration is largely restored, except that some energy flux initially available has been dissipated as Joule heat in the ionosphere and some is still contained in the waves. When the energy is removed from the plasma by this process faster than plasma is energized by the background (growth-phase) electric field, cross-tail current is reduced, the magnetic field starts to dipolarize, and the SCW first appears. On the ground, there is a Pi-2 onset, a westward electrojet intensifies, and a magnetic bay begins. If this is not followed by LEXO, then a pseudobreakup results. However, in most of the onsets we observe LEXO does follow, and the trigger wave has caused onset of at least a small substorm. The power released by trigger waves increases explosively at LEXO (Figure 14(b)). The magnetic perturbation owing to the onset wave produces the EGP signature seen in the north-south component. Figure 14(b), which is based on CRRES observations, is basically the same as depicted in recent ballooning models as the meridional magnetic structure at "substorm detonation". During LEXO, energy is released from drifting plasma at a rate that far exceeds the rate of growth-phase energization, and the amplitude of the outward displacement of flux tubes is a significant fraction of the local equilibrium scalelength. (An eastward electric field of 10 mV/m lasting for 30 s in a 50 nT magnetic field near geosynchronous orbit produces a displacement of ~1 Re.) The configuration doesn't just relax to near its previous state as the electric field turns westward but significantly overshoots the prior quasi-equilibrium value, and a rarefaction wave is launched tailward (Figure 14(c)). Power flowing toward the ionosphere often continues to increase as the electric field turns westward. The source of the power flowing toward the ionosphere has switched from the J dot E < 0 conversion of plasma kinetic energy to stress reduction of the magnetic field as the rarefaction wave passes, leaving a more dipolar configuration in its wake (Figure 14(c)). During LEXO and the start of this stage-1 expansion, appreciable magnetic compression is observed.

DAB waves continue into the expansion phase. Roux et al. [1991] had correlated similar structures in the near-geosynchronous plasma sheet to WTSs. While power flows toward the ionosphere on average, parallel power can be observed locally as flowing in either direction. Whenever the electric field turns eastward as a ballooning wave passes by while net power is reflected power flowing away from the ionosphere, the substorm electrojet is observed to wane, or can turn off completely. Even in the absence of such interference, there is limited energy available from the near-Earth magnetosphere to power substorm expansion without invoking magnetic reconnection. However, the available energy is enough to account for a small substorm. Usually, however, a stage-2 expansion is subsequently observed.

While apogee of CRRES is too low to witness how expansion proceeds poleward in the auroral zone, the different signatures of stage-1 and stage-2 expansions permit us to speculate on the nature of that process. We assume that tailward propagating rarefaction waves activate NEXLs in the near-Earth to mid-tail plasma sheet as depicted in Figure 14(e). On the ground, poleward expansion can now continue into the polar cap. (Expansion might fall short of reaching the polar cap or require several NEXL activations in a substorm sequence [e.g., Maynard et al., 1997].) In the inner magnetosphere, a stage-2 expansion appears as an enhancement of westward electric field and dipolarization, but without the LEXO wave or EGP signature observed to initiate a stage-1 expansion. A stage-2 expansion may be nearly contiguous to stage-1, and thus, it might not be discerned as a separate stage-2 in the inner magnetosphere. For example, the expansion of event E (see M96) was sustained long enough, and the ground magnetic bay was large enough that a NEXL most likely activated. However, while the expansion started with a LEXO, two separate expansions are not obvious in either CRRES or ground data.

These results are explained in detail in the paper by Erickson et al. [1999] that has been submitted to Journal of Geophysical Research. A copy is attached. Copies of the two previous papers supported by this contract are also attached

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Fall AGU 1996

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Fall AGU 1999

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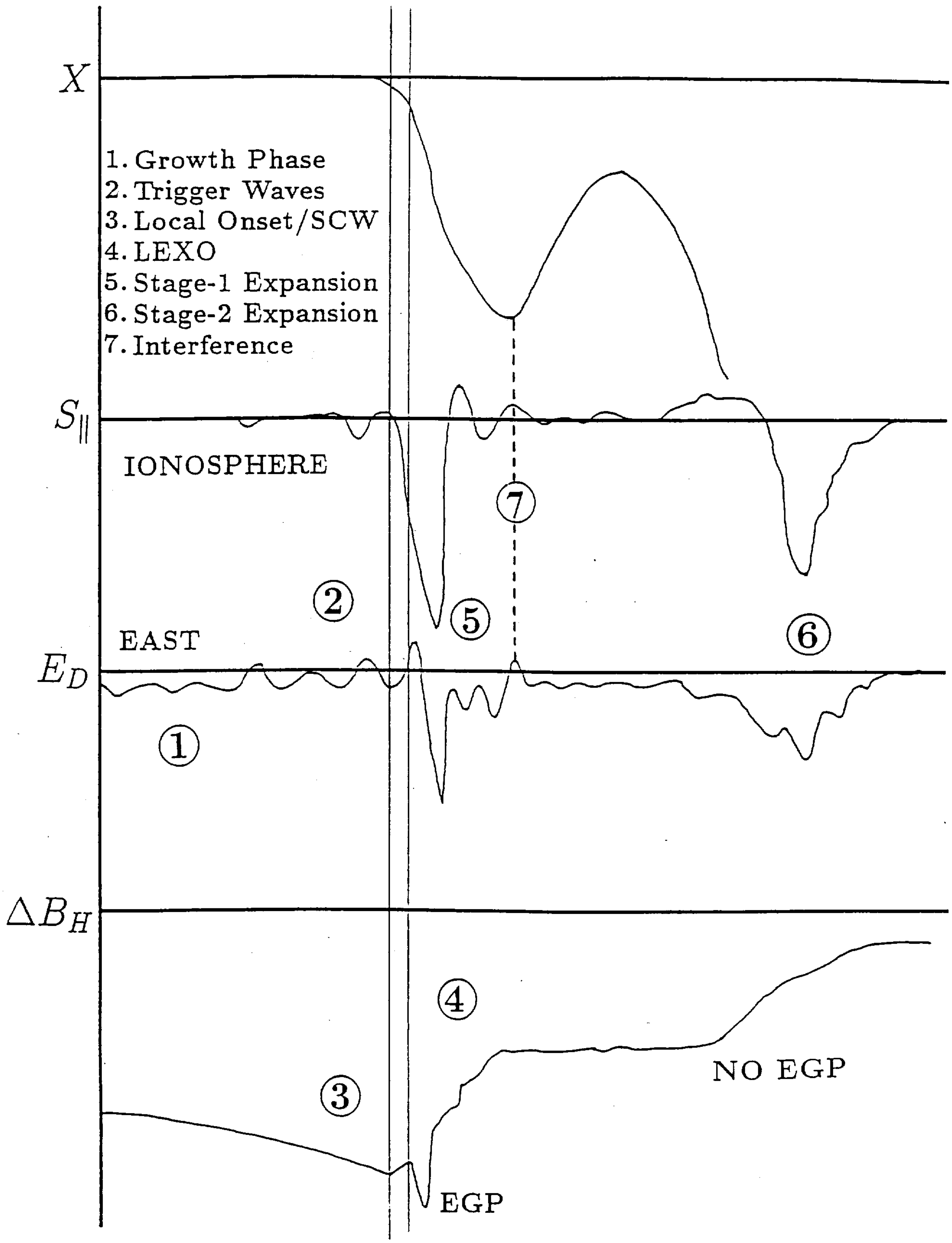


X
1. Growth Phase
2. Trigger Waves
3. Local Onset/SCW
4. LEXO
5. Stage-1 Expansion
6. Stage-2 Expansion
7. Interference
$S_{\|}$
IONOSPHERE
7
2
5
6
EAST
E_D
1
ΔB_H
4
NO EGP
3
EGP

Figure 1

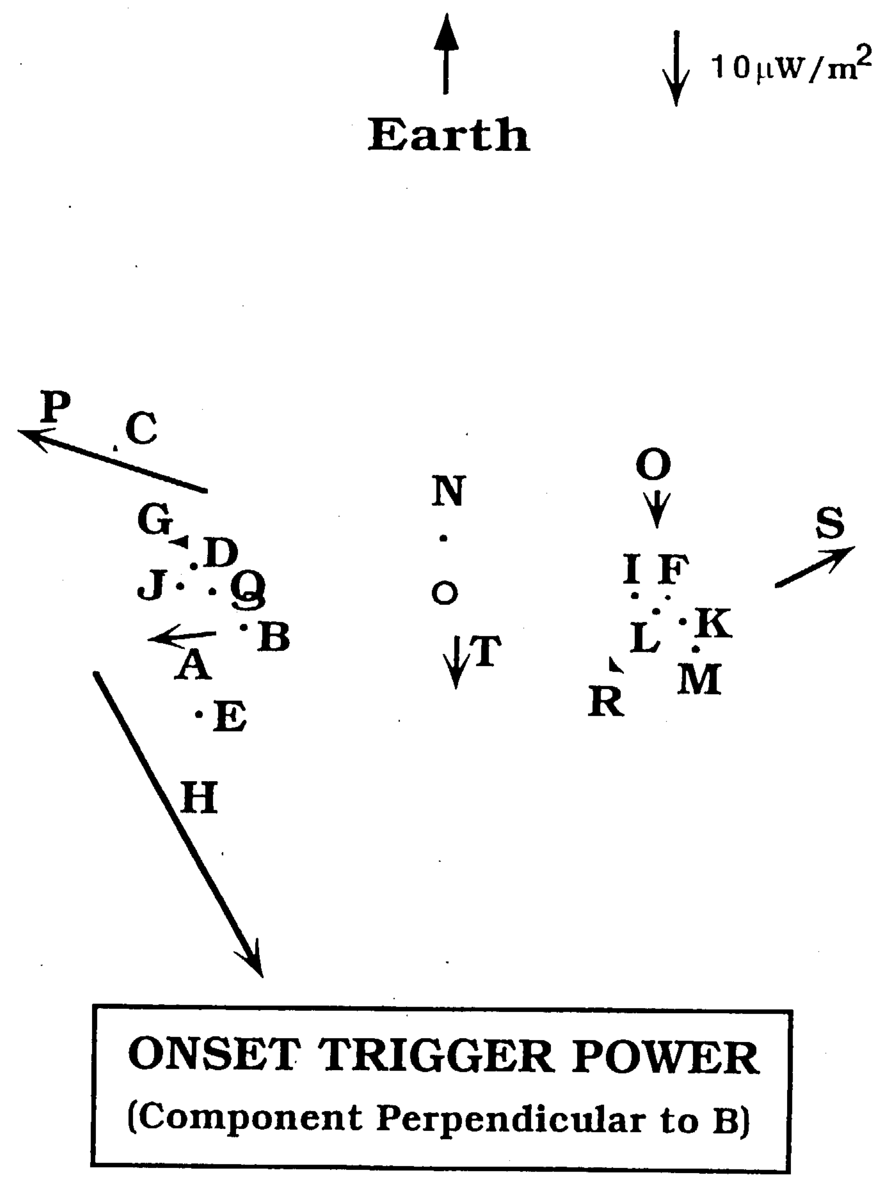
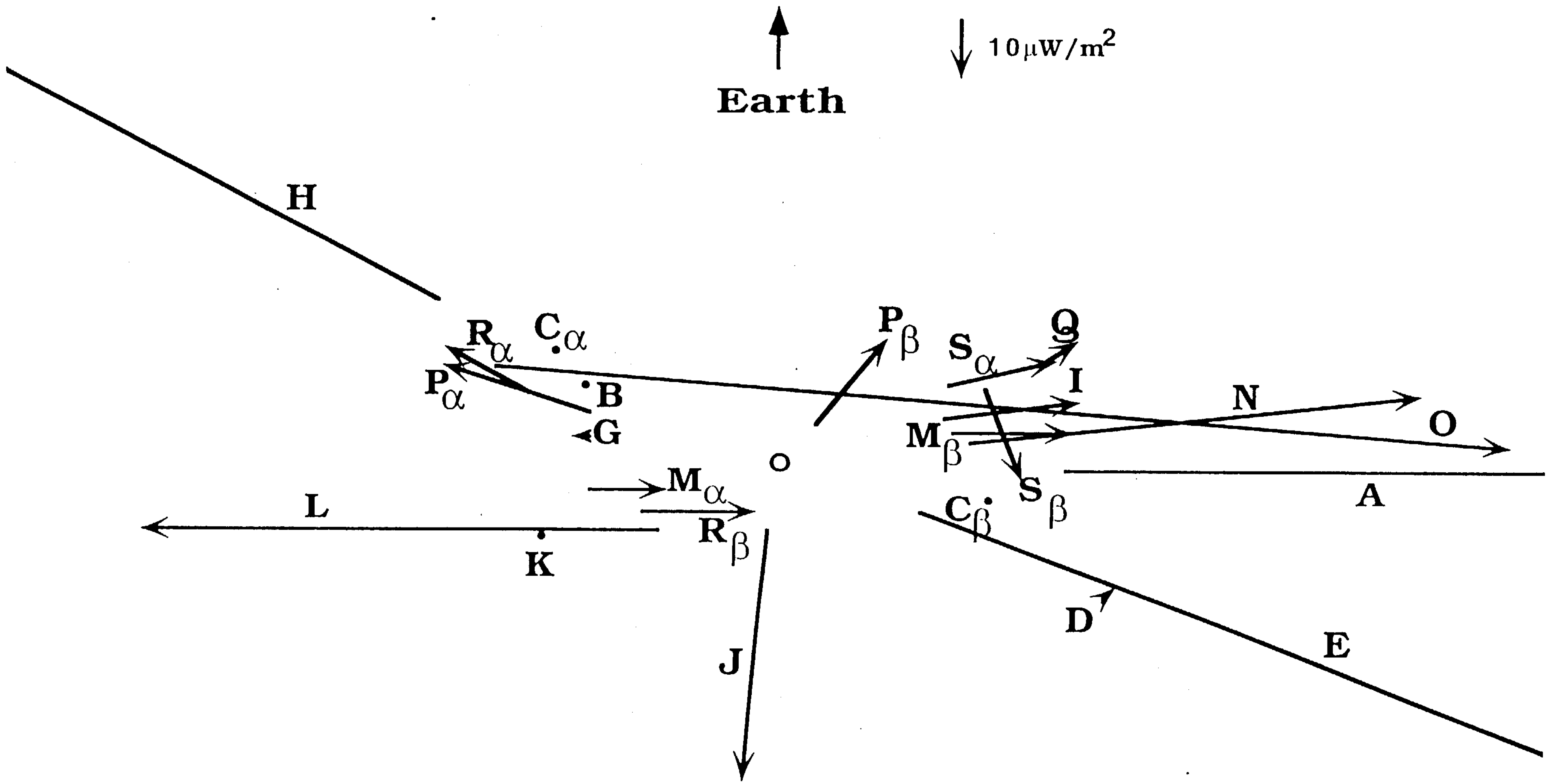

Earth
10μW/m2
P
C
G
D
J
Q
B
A
E
H
N
O
T
O
I
F
L
K
M
R
S
ONSET TRIGGER POWER
(Component Perpendicular to B)

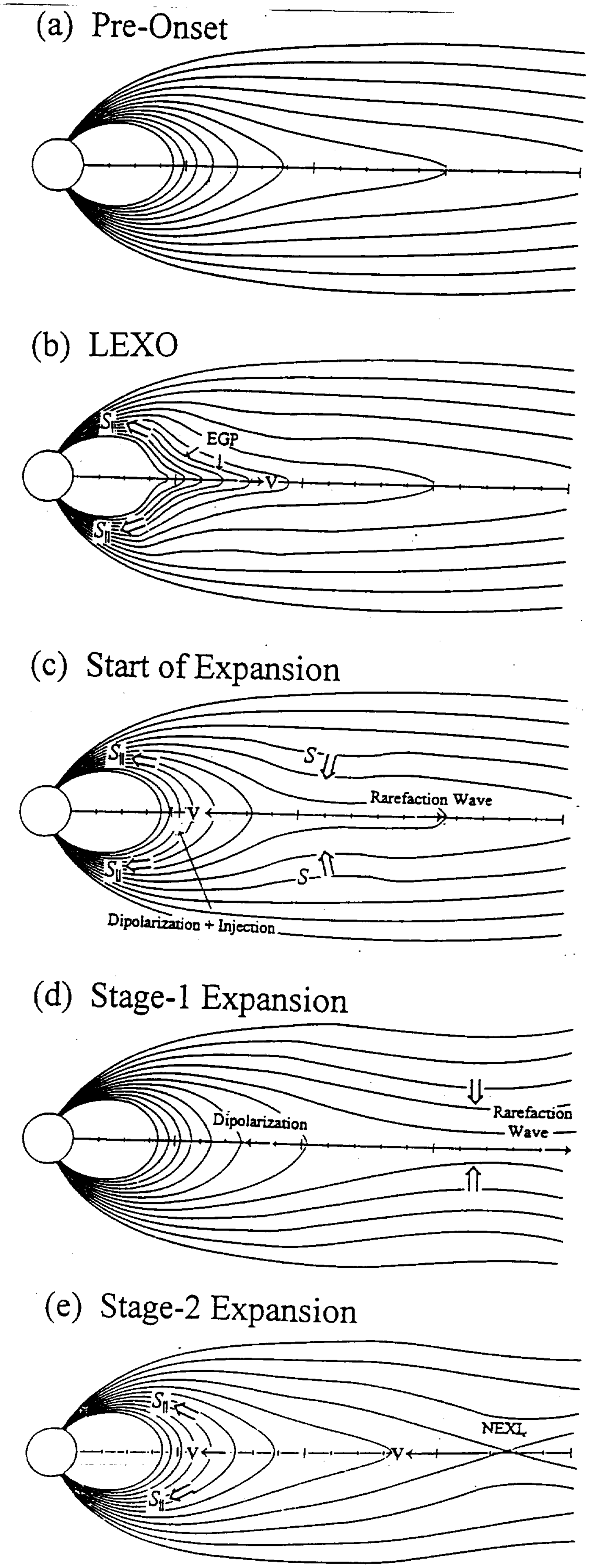
Figure 2



LEXO POWER

(Component Perpendicular To Magnetic Field)

Figure 3



(a) Pre-Onset
(b) LEXO
EGP
V
(c) Start of Expansion
V
Rarefaction Wave
Dipolarization + Injection
(d) Stage-1 Expansion
Dipolarization
Rarefaction
Wave
(e) Stage-2 Expansion
V
V
NEXL

Figure 4

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