

# Compressional Perturbations of the Dayside Magnetosphere during High-Speed-Stream-Driven Geomagnetic Storms

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The quasi-DC compressions of the Earth's dayside magnetic field by ram-pressure fluctuations in the solar wind are characterized by using multiple GOES spacecraft in geosynchronous orbit, multiple Los Alamos spacecraft in geosynchronous orbit, global MHD simulations, and ACE and WIND solar-wind measurements. Owing to the inward-outward advection of plasma as the dayside magnetic field is compressed, magnetic field compressions experienced by the plasma in the dayside magnetosphere are greater than the magnetic-field compressions measured by a spacecraft. Theoretical calculations indicate that the plasma compression can be a factor of 2 higher than the observed magnetic-field compression. The solar-wind ram-pressure changes causing the quasi-DC magnetospheric compressions are mostly owed to rapid changes in the solar-wind number density associated with the crossing of plasma boundaries; an Earth crossing of a plasma boundary produces a sudden change in the dayside magnetic-field strength accompanied by a sudden inward or outward motion of the plasma in the dayside magnetosphere. Superposed epoch analysis of high-speed-stream-driven storms was used to explore solar-wind compressions and stormtime geosynchronous magnetic-field compressions, which are of particular interest for the possible contribution to the energization of the outer electron radiation belt. The occurrence distributions of dayside magnetic-field compressions, solar-wind ram-pressure changes, and dayside radial plasma-flow velocities were investigated: all three quantities approximately obey power-law statistics for large values. The approximate power-law indices for the distributions of magnetic compressions and ram-pressure changes were both -3.

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## 1. Introduction

Changes in the ram pressure of the solar wind result in changes in the amount of compression of the dayside magnetosphere: these are manifested in the magnetosphere as changes in the magnetic-field strength and as radial motions. In this report quasi-DC compressions of the magnetosphere at timescales longer than Pc5 ULF periods will be studied. These compressions may be important for the magnetic pumping of the outer electron radiation belt during high-speed-stream-driven storms.

It is well known that there is a connection between the time-integrated amplitude of magnetospheric ULF oscillations and the intensity of the flux of radiation-belt electrons in the outer magnetosphere [e.g. *Rostoker et al.*, 1998; *Mathie and Mann*, 2000; *Friedel et al.*, 2002; *Nakamura et al.*, 2002; *Kozyreva et al.*, 2007; *Romanova and Pilipenko*, 2009; *Borovsky and Denton*, 2014]. The amplitudes of ULF fluctuations in the magnetosphere are related to the solar-wind velocity [*Singer et al.*, 1977; *Mathie and Mann*, 2001; *Romanova et al.*, 2007; *Kozyreva et al.*, 2007], to the solar-wind density [*Menk et al.*, 2003; *Takahashi and Ukhorskiy*, 2008; *Viall et al.*, 2009], and to the IMF  $B_z$  [*Romanova et al.*, 2007] and magnetospheric ULF oscillations are observed to be anomalously intense during high-speed-stream-driven storms [*Takahashi and Ukhorskiy*, 2008; *Borovsky and Denton*, 2010a]. The ULF waves are interpreted as cavity modes of the Earth's magnetosphere [*Kivelson and Southwood*, 1985; *Walker*, 1998]. Much of the magnetospheric ULF wave power is believed to be driven by the solar wind (a) via variations in the ram pressure [*Kepko et al.*, 2002; *Eriksson et al.*, 2006; *Motoba et al.*, 2007; *Kessel*, 2008; *Viall et al.*, 2009; *Berube et al.*, 2014], (b) via Kelvin-Helmholtz instabilities [*Mann et al.*, 1999; *Claudepierre et al.*, 2008], or (c) via bow-shock or magnetosheath processes [*Eastwood et al.*, 2011; *Hartinger et al.*, 2013; *Regi et al.*, 2014]. Magnetospheric ULF waves can also arise from kinetic instabilities driven by magnetospheric particles [*Hughes et al.*, 1978; *Ozeke and Mann*, 2008].

Here we are interested in characterizing compressional magnetospheric perturbations at frequencies below the cavity modes of the magnetosphere for input to magnetic-pumping calculations for energetic particles traversing the dayside magnetosphere. Magnetic pumping is

an interplay between compression-decompression cycles and pitch-angle scattering [Alfven, 1950; Spitzer and Witten, 1953; Schluter, 1957; Alfven and Falthammar, 1963], wherein the pitch-angle scattering in a magnetosphere acts as a catalyst to enable the compression-decompression cycles to energize magnetospheric particles [Alfven, 1959; Goertz, 1978; Borovsky et al., 1981; Mu, 1993; Liu and Rostoker, 1995; Rostoker et al., 1998; Liu et al., 1999; Dmitriev et al., 2001]. Magnetic pumping is most effective when the pitch-angle scattering timescales and the compression-decompression timescales are similar [Berger et al., 1958; Murty and Varma, 1958; Borovsky et al., 1981; Borovsky, 1986]. For radiation-belt electrons in the dayside magnetosphere during high-speed-stream-driven geomagnetic storms, pitch-angle scattering is believed to be produced by whistler-mode chorus outside of the plasmasphere [Glauert and Horne, 2005; Thorne et al., 2005; Shprits et al., 2007] and by electromagnetic ion-cyclotron waves [Kovalevskiy, 1980,1981; Jordanova et al., 2006; Thorne et al., 2006; Spasojevic and Fuselier, 2009] and whistler-mode hiss [Chan and Holzer, 1976; Hayakawa et al., 1986; Summers et al., 2008] inside the plasmaspheric drainage plume and the plasmasphere. (In the high-mass-density warm plasma cloak [Chappell et al., 2008], which appears throughout the dayside magnetosphere commencing on day 2 of a high-speed-stream-driven storm [Borovsky et al., 2013], other plasma wavemodes might become important). Since pitch-angle-scattering timescales for the radiation belt in the dayside magnetosphere are longer than ULF periods [Borovsky et al., 2014], compression-decompression cycles that are longer than ULF periods are more effective at pumping. Transit timescales for radiation-belt electrons across the dayside magnetosphere limit the duration of the compressive timescales of interest for pumping. Here, 10-minute changes in the magnetic-field strength in the dayside magnetosphere will be studied; these 10-minute changes correspond to ~20-minute cycles of compression-decompression.

This report will relate observations of lower-than-ULF-frequency magnetic-field compressions in the dayside magnetosphere at geosynchronous orbit to observations of radial plasma motions in the dayside magnetosphere. The ram-pressure fluctuations will be caused dominantly by solar-wind density fluctuations rather than solar-wind speed fluctuations. It is argued that the observed magnetic-field-strength fluctuations in the dayside magnetosphere must

be related to radial motions of the magnetic flux surface: the magnitude of those motions are estimated theoretically and then those estimates are compared with observed cold-plasma radial flow velocities measured at geosynchronous orbit. The influence of the IMF clock angle on the reaction of the Earth's magnetosphere to solar-wind ram pressure changes [cf. *Wing and Sibeck, 1997; Wang et al., 2007; Li et al., 2013*] will not be considered. Superposed-epoch averaging during high-speed-stream-driven storms will be used.

This report is organized as follows. In Section 2 the mathematical relations between changes in the solar-wind ram pressure, changes in the dayside magnetic-field strength, and radial plasma motions in the dayside magnetosphere are explored; simulations of the reaction of the magnetosphere to the solar wind using the LFM global MHD code are utilized. In Section 3 stormtime observations of the dayside magnetic field, of dayside plasma flows, and of the solar wind are explored. Statistical values of the dayside magnetic-field compressions, the solar-wind ram-pressure changes, and the dayside-magnetosphere radial flow velocities are examined in Section 4. The results are summarized in Section 5. Section 6 contains a discussion about the difficulty of characterizing magnetic-field compressions and the associated plasma compressions in the nightside magnetosphere.

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## 2. Dayside-Magnetosphere Expectations for Solar-Wind Ram-Pressure Fluctuations

In general, the dayside magnetosphere is compressed by the solar wind into a state where the local magnetic-field strength is greater than the dipole field value  $M_E/r^3$ , where  $M_E$  is the dipole moment of the Earth. Note, however, that the dayside field strength in the magnetosphere can be below the dipole field strength (a) during intervals when the Mach number of the solar wind is low (cf. Fig. 19 of *Borovsky et al.* [2009]) or (b) when the cross-polar-cap current is strong while the ram pressure of the solar wind is weak (cf. Figs. 7 and 8 of *Borovsky et al.* [2013]).

A ballpark estimate of the magnetic-field strength along the Sun-Earth line in the dayside magnetosphere can be obtained with the use of an “image dipole” magnetic-field model [*Schild*, 1969]: an image dipole is placed at a distance of  $2r_m$  upstream of the Earth, where  $r_m$  is the magnetopause standoff distance along the Sun-Earth line. Thus, the field strength is approximated as

$$B(r) = M_E r^{-3} + M_E (2r_m - r)^{-3} \quad , \quad (1)$$

which is valid for  $r \leq r_m$ . In expression (1)  $M_E$  is the Earth’s dipole moment,  $M_E = 7.8 \times 10^{22} \text{ Am}^2 = 3.05 \times 10^4 \text{ nT } R_E^3$  [*Olson and Amit*, 2006]). At the magnetopause ( $r = r_m$ ) the field strength is

$$B_m = B(r_m) = 2M_E r_m^{-3} \quad , \quad (2)$$

which is twice the dipole field strength  $M_E r_m^{-3}$ . Pressure balance at the magnetopause with the ram pressure  $P_{\text{ram}}$  of the solar wind  $B^2/8\pi = P_{\text{ram}}$  yields, with the use of expression (2), the magnetopause standoff distance

$$r_m = (M_E^2/2\pi P_{\text{ram}})^{1/6} \quad . \quad (3)$$

Using expression (3), the magnetopause standoff distance in units of Earth radii ( $R_E$ ) is plotted as a function of  $P_{\text{ram}}$  as the green curve in Figure 1. Using expression (3) for  $r_m$  in expression (1) yields

$$B(r) = M_E r^{-3} + M_E [2(M_E^2/2\pi P_{\text{ram}})^{1/6} - r]^{-3} \quad (4)$$

for the magnetic-field strength at local noon in the magnetosphere. For geosynchronous orbit ( $r = 6.6 R_E$ ) expression (4) for the magnetic-field strength local noon  $B_{\text{geo}}$  is plotted as a function of

the solar-wind ram pressure  $P_{\text{ram}}$  as the blue solid curve in Figure 1. For comparison the fit to magnetic-field-strength measurements at geosynchronous orbit local noon during high-speed-stream-driven storms (eq. (2) of *Borovsky and Denton* [2010a])

$$B_{\text{geo}} = 106 + 6.3 P_{\text{ram}} \quad (5)$$

(where  $B_{\text{geo}}$  is in nT and  $P_{\text{ram}}$  is in nPa) is plotted as the purple dashed curve. As can be seen, the data fit of expression (5) (purple) is well described by the image-dipole expression (4) (blue).

The first derivative  $\partial B_{\text{geo}}/\partial P_{\text{ram}}$  of the image-dipole-model magnetic field (expression (4)) at geosynchronous orbit is plotted as a function of  $P_{\text{ram}}$  as the red curve in Figure 1. The red curve provides an estimate of how much change  $\Delta B_{\text{geo}}$  in the magnetic-field strength  $B_{\text{geo}}$  at geosynchronous orbit noon is expected for a change  $\Delta P_{\text{ram}}$  in the solar-wind ram pressure  $P_{\text{ram}}$ . For typical values of the solar-wind ram pressure ( $P_{\text{ram}} \sim 2$  nPa), the expected change in  $B_{\text{geo}}$  is about 6 nT for a 1 nPa change in  $P_{\text{ram}}$ . This is also about the value that would be given by taking the first derivative  $\partial B_{\text{geo}}/\partial P_{\text{ram}}$  of expression (5), which is

$$\partial B_{\text{geo}}/\partial P_{\text{ram}} = 6.3 \text{ nT/nPa} \quad , \quad (6)$$

or 6.3 nT for a 1 nPa change in ram pressure. Examples in the literature (e.g. Fig. 3a of *Kepko and Spence* [2003], Fig. 5a. of *Borodkova et al.* [2006], and Fig. 5 of *Borodkova et al.* [2008]) yield similar values for changes in the geosynchronous magnetic-field strength on the dayside for changes in the solar-wind ram pressure.

For the magnetic-field strength in the dayside magnetosphere to increase and decrease in response to changes in the solar-wind ram pressure, there must be a radial flow of flux inward and outward in the dayside magnetosphere. The image-dipole magnetic-field model will provide an estimate of the radial movement of flux, and hence an estimate of radial flow velocities in the dayside magnetosphere. This is depicted in Figure 2 for a case where the ram pressure changes from 1 nPa (blue) to 2 nPa (red) and, according to expression (3), the magnetopause moves inward from  $10.66 R_E$  (blue) to  $9.50 R_E$  (red). As the magnetic flux moves radially inward and outward, the integral  $\int B(r) 2\pi r dr$  must be conserved integrated from the surface of the Earth  $r = 1 R_E$  outward to the radius  $r_{\text{max}}$  that represents a radially moving flux surface. In Figure 2 the flux

surface at geosynchronous orbit when the ram pressure is 1 nPa is drawn as the vertical blue curve at  $r = 6.6 R_E$ . Integrating  $2\pi r$  times the blue curve in Figure 2 from  $r = 1 R_E$  to  $r = 6.6 R_E$  yields a value  $I_0$  for the integral. Integrating  $2\pi r$  times the red curve in Figure 2 from  $r = 1 R_E$  to a value  $r_{\max}$  where the integral equals  $I_0$  yields a value of  $r_{\max} = 6.50 R_E$ . Thus the flux surface at geosynchronous orbit moves from  $r = 6.6 R_E$  to  $r = 6.50 R_E$  when the ram pressure of the solar wind changes from 1 nPa to 2 nPa. Using expression (4) in the integral, the displacement of a flux surface at geosynchronous orbit ( $r = 6.6 R_E$ ) is calculated for changes in the solar-wind ram pressure by numerically integrating expression (4) before and after the change in  $P_{\text{ram}}$  and calculating the change in  $r_{\max}$ . In Figure 3 the change  $\Delta r$  in  $r_{\max}$  near geosynchronous orbit for a 1 nT change in the geosynchronous magnetic-field strength  $\Delta B_{\text{geo}}$  is plotted as a function of the magnetic-field strength  $B_{\text{geo}}$  at geosynchronous orbit. For  $B_{\text{geo}} = 110$  nT to  $B_{\text{geo}} = 200$  nT the curve in Figure 3 is well fit by the expression

$$\Delta r / \Delta B_{\text{geo}} = -115 B_{\text{geo}}^{-1.85}, \quad (7)$$

where  $\Delta r$  is in units of  $R_E$  and  $\Delta B_{\text{geo}}$  and  $B_{\text{geo}}$  are both in units of nT. For a  $\Delta B_{\text{geo}}$  that is positive,  $\Delta r$  is negative (Earthward). As can be seen, for a wide range in strengths of the dayside field at geosynchronous orbit (110 - 170 nT) the amount of radial displacement  $\Delta r$  for a change in the field strength  $\Delta B_{\text{geo}}$  is in the range of  $0.01 R_E$  to  $0.02 R_E$  for a 1 nT change in  $\Delta B_{\text{geo}}$ . Thus, the value

$$\Delta r \sim -(0.015 R_E / \text{nT}) \Delta B_{\text{geo}} \quad (8)$$

can be used as a rule of thumb, with the value being somewhat larger when the field is weaker and the value being somewhat less when the field is stronger.

In the dayside magnetosphere the magnetic flux (and the plasma) moves radially inward and outward as the field strength increases and decreases. The plasma moves radially inward or outward by an  $\underline{E} \times \underline{B}$  drift because there is an azimuthal induction electric field accompanying  $\partial B / \partial t$ ; it is the local curl (shear) of this induction electric field that also changes the energies of plasma particles to enforce the conservation of their first adiabatic invariants [Borovsky and Hansen, 1991]. The radial displacement for a given change in field strength is given by

expression (8). The radial velocity of the flow of flux (and plasma) can be obtained by dividing both sides of expression (8) by  $\Delta t$ , the timescale of the magnetic-field change in the magnetosphere. With  $v_r = \Delta r / \Delta t$  and  $\partial B_{\text{geo}} / \partial t = \Delta B_{\text{geo}} / \Delta t$ , this yields

$$v_r \sim -(0.015 R_E / \text{nT}) \partial B_{\text{geo}} / \partial t = -(95 \text{ km/nT}) \partial B_{\text{geo}} / \partial t \quad (9)$$

for the radial velocity at geosynchronous orbit. Expression (9) yields an expected radial velocity  $v_r \sim -95 \text{ km/s} \partial B_{\text{geo}} / \partial t$  when  $\partial B_{\text{geo}} / \partial t$  is measured in units of nT/s or  $v_r \sim -1.6 \text{ km/s} \partial B_{\text{geo}} / \partial t$  when  $\partial B_{\text{geo}} / \partial t$  is measured in units of nT/min. Tests of expression (9) using global MHD simulations (this section) and spacecraft measurements (Section 3.3) indicate that the image-dipole model underestimates the radial velocity  $v_r$  for displacement of the flux surface for a given observed change  $\partial B_{\text{geo}} / \partial t$  and hence may underestimate the radial displacement  $\Delta r$  of the flux surface for a given change  $\Delta B_{\text{geo}}$ .

Expression (9) can be used to obtain an expression for the geosynchronous-orbit radial velocity  $v_r$  as a function of the rate of change  $\partial P_{\text{ram}} / \partial t$  of the solar-wind ram pressure by writing  $\partial B_{\text{geo}} / \partial t$  as  $(\partial B_{\text{geo}} / \partial P_{\text{ram}})(\partial P_{\text{ram}} / \partial t)$  in expression (9), which yields

$$v_r = - (95 \text{ km/nT}) (\partial B_{\text{geo}} / \partial P_{\text{ram}})(\partial P_{\text{ram}} / \partial t) = - (599 \text{ km/nPa}) \partial P_{\text{ram}} / \partial t \quad , \quad (10)$$

where expression (6) was utilized to replace  $\partial B_{\text{geo}} / \partial P_{\text{ram}}$ . Here,  $\partial P_{\text{ram}} / \partial t$  is the time rate of change of  $P_{\text{ram}}$  at the magnetopause. Note that the temporal profiles of rapid changes in the solar wind will be altered by advection through the magnetosheath, which time delays all temporal features by a few minutes [Borovsky, 2012a] and has the feature hitting different parts of the magnetopause at different times, effectively broadening the temporal profile.

To demonstrate this radial flow in the dayside magnetosphere (Figure 4), a global MHD simulation of the solar-wind-driven magnetosphere is performed with the LFM (CMIT LFM-MIX) simulation code [Lyon *et al.*, 2004; Merkin and Lyon, 2010] at the Community Coordinated Modeling Center [Rastatter *et al.*, 2012]. Under purely northward IMF, an increase-then-decrease density step in the solar wind is run past the Earth without changing the solar-wind speed (400 km/s). After 55 minutes of density  $n_{\text{sw}} = 5 \text{ cm}^{-3}$ , the solar-wind density is suddenly switched to  $n_{\text{sw}} = 7.5 \text{ cm}^{-3}$ , and then 20 minutes later it is switched back to  $n_{\text{sw}} = 5 \text{ cm}^{-3}$ . The ram

pressure associated with this increase-decrease density step moving at 400 km/s goes from  $P_{\text{ram}} = 1.34$  nPa to  $P_{\text{ram}} = 2.00$  nPa and then back to  $P_{\text{ram}} = 1.34$  nPa. In the two panels of Figure 4 the magnetic-field strength  $B_{\text{geo}}$  in the LFM simulation at geosynchronous-orbit local noon (top panel) and at geosynchronous-orbit 15 LT (bottom panel) is plotted (blue, left axis) as a function of time; at the same locations in the LFM simulation the GSM X component of the plasma flow velocity  $v_{x \text{ geo}}$  (green, right axis) and the GSM Y component of the plasma flow velocity  $v_{y \text{ geo}}$  (red, right axis) are also plotted as functions of time. As can be seen in the top panel, at about  $t = 55$  min the magnetic-field strength at geosynchronous orbit local noon rises and this rise in field strength is accompanied by a negative  $v_{x \text{ geo}}$  (Earthward) flow; twenty minutes later the field strength  $B_{\text{geo}}$  drops and this drop is accompanied by a positive (sunward) flow. Note the temporal ringing in the flow velocities with a period of about 40 s; this ringing may be caused by Alfvén-wave transients in the very-low-density ( $n \sim 0.07 \text{ cm}^{-3}$ ) dayside magnetosphere of the simulation [John Lyon, private communication 2015]. In this simulation the flow velocities at geosynchronous orbit associated with the change in magnetic-field strength are about 20 km/s. In the bottom panel of Figure 4 the Earthward then sunward flows are still seen 3 hours away from local noon, although less intense. Note that the temporal behavior of the system is not fully resolved in the data output of the LFM simulation: but the radial flow velocities captured in the 1-min-resolution outputs were greater than 20 km/s at geosynchronous orbit.

Expression (9) can be applied to connect the change in the magnetic-field strength at geosynchronous orbit to the radial flow velocity in the top panel of Figure 4. During the negative velocity pulse at  $t \approx 55$  the magnetic-field rate of change is  $\partial B_{\text{geo}}/\partial t = 5.5 \text{ nT/min} = 8.7 \times 10^{-2} \text{ nT/s}$ ; using this value in expression (9) yields a prediction  $v_r = - 8.7 \text{ km/s}$ . This predicted velocity is a factor of 2 lower than the observed peak plasma flow velocity in the simulation. During the positive velocity pulse at  $t \approx 78$  in the top panel of Figure 4 the magnetic-field strength decreases at a rate  $\partial B_{\text{geo}}/\partial t = -4.1 \text{ nT/min} = - 6.8 \times 10^{-2} \text{ nT/s}$ ; using this value in expression (9) yields a prediction  $v_r = +6.5 \text{ km/s}$ . This predicted velocity is again about a factor of 2 lower than the observed peak flow velocity. This test may indicate that the image-dipole

model (expression (9)) underestimates the radial displacement of the flux surface for a given observed change  $\partial B_{\text{geo}}/\partial t$ .

As the magnetic-field strength at geosynchronous orbit increases and decreases, the flux surface at geosynchronous orbit moves radially inward and outward with a radial displacement given approximately by expression (8). This is shown in Figure 2 for a positive change  $\Delta B_{\text{geo}}$  in the magnetic-field strength at geosynchronous orbit. In Figure 2 when the magnetic-field strength at geosynchronous orbit increases the plasma that was at geosynchronous orbit moves inward to a new location with a new magnetic-field strength; the change in the field strength  $\Delta B_{\text{flux}}$  experienced by the plasma that moves with the flux surface will be larger than the change in the field strength  $\Delta B_{\text{geo}}$  measured by a spacecraft that remains at geosynchronous orbit. By computationally tracking the motion of the flux surface in the image-dipole model, the ratio of magnetic-field-strength change  $\Delta B_{\text{flux}}$  of plasma moving with the flux surface in the vicinity of geosynchronous orbit to the magnetic-field-strength change  $\Delta B_{\text{geo}}$  at geosynchronous orbit is calculated and plotted in black as a function of the geosynchronous field strength  $B_{\text{geo}}$  in Figure 5. For  $B_{\text{geo}} = 110$  nT to  $B_{\text{geo}} = 200$  nT the curve in Figure 5 is well fit by the stretched-exponential function

$$\Delta B_{\text{flux}}/\Delta B_{\text{geo}} = 0.96 + 20 \exp(-[B_{\text{geo}}/33.3]^{0.92}) \quad (11)$$

where  $B_{\text{geo}}$  is in units of nT. Expression (11) is plotted as the red dashed curve in Figure 5. As can be seen, for a mildly compressed dipole ( $B_{\text{geo}} \sim 110$  nT) the field-strength change of the plasma is about twice the field-strength change at geosynchronous orbit and for a more-strongly compressed dipole ( $B_{\text{geo}} \sim 135$  nT) the field-strength change of the plasma is about 1.5 times the field-strength change at geosynchronous orbit. Of course the magnetospheric plasma is compressed when the field is compressed [e.g. *Chen, 1974*]: wherever there is a  $\partial B/\partial t$ , there is a nonzero curl of the electric field which produces an  $E \times B$  drift with a nonzero divergence which compresses the plasma. Confirming the prediction of expression (11) by measuring the amount of compression of the plasma in the magnetosphere is in general not possible, since the parcels of plasma move radially as they are compressed. Analysis (not done here) of the evolution of

plasma and magnetic-field strength with a radial alignment of two or more spacecraft along the Sun-Earth line in the magnetosphere could provide an observed quantification of the amount of plasma compression.

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### 3. Storm-Time Observations of Magnetic Compressions, Radial Flow Velocities, and the Solar Wind

#### 3.1. Data Methods

To measure the magnetic-field strength at geosynchronous orbit in the dayside magnetosphere, vector magnetic-field measurements from the fluxgate magnetometers on the GOES spacecraft [Dunham *et al.*, 1996; Singer *et al.*, 1996] from the years 1995-2005 are used with 1-min time resolution. This data set involves 5 GOES satellites (GOES-8 - GOES-12). For the spacecraft GOES-8, the magnetic-field measurements are corrected by subtracting 7.22 nT from the z-component magnetic field following the recommendations of Tsyganenko *et al.* [2003]. The GOES magnetic-field data is cleaned to eliminate magnetosheath intervals using the methodology of Borovsky and Denton [2010a]; this methodology eliminates data when the measured magnetic field is southward, since magnetopause-crossing intervals at geosynchronous orbit are rare when the IMF is northward [Suvorova *et al.*, 2005].

To measure the ram pressure of the solar wind at Earth, proton measurements of the solar-wind plasma from the SWEPAM instrument [McComas *et al.*, 1998] on ACE are used with 64-s time resolution. For a higher-time-resolution look at the ram pressure of the solar wind, 3-s measurements from WIND 3DP [Lin *et al.*, 1995] will be used.

To measure radial flow velocities at geosynchronous orbit in the dayside magnetosphere, cold-ion moments from the multisatellite MPA data set [Bame *et al.*, 1993; Thomsen *et al.*, 1999] from Los Alamos National Laboratory spacecraft are used. The flow measurements from MPA are only utilized if the cold-plasma number density is above  $5 \text{ cm}^{-3}$ .

For the superposed-epoch averaging a collection of 70 high-speed-stream-driven storms is used. This list of 70 storms comes from a list of 93 high-speed-stream-driven storms that were used in previous studies [Denton and Borovsky, 2012; Borovsky and Denton, 2010a,b, 2011], with 23 storms eliminated from the list of 93. The majority of the 23 were eliminated owing to the presence of ejecta in the solar wind during the pre-storm and storm intervals, as determined using the new 4-plasma solar-wind-categorization scheme of Xu and Borovsky [2015] which



identifies ejecta plasma as having an anomalously low proton temperature and/or an anomalously high Alfvén speed. A substantial amount of ejecta during a storm interval will change the classification of a storm from a high-speed-stream-driven storm to a hybrid storm. A few of the 23 storms were eliminated owing to the storm being particularly weak or short lived. The zero epoch (trigger) for the superposed averaging is chosen to be the onset of storm levels of magnetospheric convection for each storm event, taken to be the time at which the MBI index crosses the value  $60.7^\circ$ , which is approximately equivalent to the value of the Kp index being 4+. MBI is an index created from measurements of the location of the low-latitude edge of the diffuse auroral precipitation as determined by DMSP-satellite overflights, mathematically shifted to local midnight [Gussenhoven *et al.*, 1983]. The storm onset times were determined to about 30-minute accuracy using MBI.

### 3.2. The Magnetic Field at Geosynchronous Orbit during Storms

In Figure 6 two examples of the global magnetic-field-strength perturbations of the dayside magnetosphere during high-speed-stream-driven storms are shown. In both panels of Figure 6 the dayside magnetic-field strength  $B_{\text{geo}}$  at geosynchronous orbit as measured by GOES 12 (blue) and GOES 10 (red) are plotted as functions of time when each spacecraft is between 6 LT and 18 LT. The ram pressure of the solar wind  $P_{\text{ram}} = m_p n_{\text{sw}} v_{\text{sw}}^2$  as measured by ACE upstream of the Earth is also plotted (green), delayed by a time  $230 R_E / v_{\text{sw}}$ . The top panel of Figure 6 is from a high-speed-stream-driven storm in 2004 and the bottom panel is from a high-speed-stream-driven storm in 2005. The local times of the two GOES spacecraft are indicated by the colored numbers next to the GOES curves in Figure 6. When the GOES spacecraft are in the vicinity of local noon the response of  $B_{\text{geo}}$  to  $P_{\text{ram}}$  can be clearly seen in Figure 6, with both spacecraft (which are separated by 4 hours of local time) responding. Near the dawn and dusk regions of geosynchronous orbit the magnetic-field strength is not responding as clearly to the solar-wind ram pressure, rather the field strength in these regions is determined to a large degree by magnetospheric plasma properties and by magnetospheric currents. Note in Figure 6 the temporal behaviors of  $B_{\text{geo}}$  that differ on the two spacecraft and that differ from the solar-wind

ram pressure: on the dayside there can be substantial magnetic-field-strength perturbations at geosynchronous orbit that are localized and that are not related to upstream solar-wind ram-pressure perturbations. Short-timescale localized perturbations could be owed to bow-shock kinetic processes such as hot flow anomalies [Sibeck *et al.*, 1999; Eastwood *et al.*, 2008; Fillingim *et al.*, 2011; Safrankova *et al.*, 2012], downstream pressure pulses [Lin *et al.*, 1996; Archer *et al.*, 2012], and foreshock bubbles [Sibeck *et al.*, 2008; Omid *et al.*, 2010; Hartinger *et al.*, 2013]. The origins of the longer-timescale perturbations that are not associated with the solar wind are not known: they could be caused by plasma diamagnetic effects or by temporally changing magnetospheric currents.

Note in Figure 6 that the ram-pressure changes in the solar wind tend to be sudden. This is because the changes in the ram pressure  $m_p n_{sw} v_{sw}^2$  tend to be caused by changes in the solar-wind density  $n_{sw}$  associated with different parcels of plasma and the plasma boundaries in the solar wind are fairly thin. Some examples of this are shown in Figure 7, where several plasma boundaries in the slow solar wind are shown for 90 minutes of 3-s-resolution solar-wind measurements by the WIND spacecraft. The plasma boundaries are marked with the red dashed vertical lines; these boundaries are clearly seen in the measurements of the plasma density  $n_{sw}$  (black points with purple curve, left axis) by the WIND 3DP instrument and in the measurements of the magnetic-field strength  $B_{sw}$  (blue curve, right axis) by the WIND MAG instrument [Lepping *et al.*, 1995]. Each of these boundaries has a thickness on the order of 10-s in the spacecraft frame; these plasma boundaries are typically about 4000-km thick, much larger than proton gyroradii ( $\sim 50$  km) and ion-inertial lengths ( $\sim 100$  km) in the solar wind. The green curve (left axis) in Figure 7 is the ram pressure of the solar wind  $P_{ram}$  measured at 3-s time resolution. As can be seen, sudden jumps in the ram pressure (green curve) are associated with the plasma boundaries and the jumps occur in about 10 s.

The duration of a ram-pressure perturbation is the duration of a plasma parcel (time between plasma boundaries). These plasma-parcel durations have been statistically studied: as can be seen in Fig. 3 of Borovsky [2012b] there is an abundance of parcels with durations on the order of 10 min.

To characterize the compressions of the magnetic field in the dayside magnetosphere at geosynchronous orbit, 10-minute changes in the 1-min resolution measurements of the magnetic-field strength are examined. This change  $\Delta B_{10}$  is defined as  $\Delta B_{10}(t) = |B_{\text{geo}}(t+5\text{min}) - B_{\text{geo}}(t-5\text{min})|$ , where  $B_{\text{geo}}$  is the magnetic-field strength  $B_{\text{geo}} = (B_x^2 + B_y^2 + B_z^2)^{1/2}$ .

In Figure 8 the superposed-epoch average of  $\Delta B_{10}$  is plotted for the dayside magnetosphere. In the top panel of Figure 8 the superposed average of the solar-wind speed  $v_{\text{sw}}$  is plotted for the 70 storms and in the middle panel the Kp index for the 70 storms is plotted. The bottom panel plots  $\Delta B_{10}$  at geosynchronous orbit. Measurements of  $\Delta B_{10}$  that are taken by a GOES spacecraft are only used in Figure 8 when the spacecraft is in the local-time 8 LT to 16 LT at geosynchronous orbit. Note that the GOES spacecraft are operated in pairs (GOES-East and GOES-West) and that coverage with two GOES spacecraft is sparse when there is a restriction on local time. Hence, superposed-epoch averages of the GOES dayside data will be noisy since only 54 of the 70 storms have GOES data coverage. As can be seen in Figure 8, the superposed average of  $\Delta B_{10}$  is increased substantially during the first day of a high-speed-stream-driven storm and relaxes back to normal values thereafter. Early in the storms the mean values of  $\Delta B_{10}$  are  $\sim 3$  nT, later in the storms the mean values of  $\Delta B_{10}$  are  $\sim 2$  nT.

The temporal profile of the superposed average of the amplitude  $\Delta B_{10}$  of the quasi-DC compressive perturbations differs from the temporal profile of the superposed average of the ULF indices, which are measures mainly of non-compressive magnetic fluctuations in the magnetosphere with Fourier periods of 143 s - 500 s [Kozyreva *et al.*, 2007; Romanova *et al.*, 2007]. For the 70 high-speed-stream-driven storms, the superposed-epoch average of the two ULF indices  $S_{\text{grd}}$  (blue, measured on the ground) and  $S_{\text{geod}}$  (red, measured in geosynchronous orbit) are plotted in Figure 9. The “detrended” (subscript “d”) ULF indices are used (using the detrending method of Borovsky and Denton [2014]); since the ULF indices  $S$  represent the logarithm of the spectral power the quantities  $10^S$  are plotted. As can be seen, both indices rise in magnitude at the onset of storms and both slowly decline in intensity through the several-day-long storms [see also Kozyreva and Kleimenova, 2008]. Note that the decline of the ground-

based ULF index  $S_{\text{grd}}$  is significantly slower than the decline of the geosynchronous-based ULF index  $S_{\text{geod}}$ : the two indices are different and respond differently to the solar wind [Borovsky and Denton, 2014]. The temporal profiles of the ULF indices (Figure 9) resemble the temporal profiles of the Kp index (Figure 8): indeed the correlation coefficients between each of the ULF indices and Kp are very high, higher than the correlation coefficients between each other (see Fig. 1 and Table 3 of Borovsky and Denton [2014]). These correlation coefficients can be written  $r_{\text{corr}}(S_{\text{grd}}, \text{Kp}) = +0.74$ ,  $r_{\text{corr}}(S_{\text{geod}}, \text{Kp}) = +0.76$ , and  $r_{\text{corr}}(S_{\text{grd}}, S_{\text{geod}}) = +0.66$ .

The temporal profile of the superposed average of the amplitude  $\Delta B_{10}$  of the lower-frequency compressive perturbations also differs from the temporal profile of the superposed average  $\Delta B_1$  of higher-frequency compressive perturbations. In Fig. 24 of Borovsky and Denton [2010a] the superposed-epoch average of the 1-min changes  $\Delta B_1$  in  $B_{\text{geo}}$  on the dayside at geosynchronous orbit is plotted. The amplitude of  $\Delta B_1$  rises early in the high-speed-stream-driven storms and then persists at elevated values throughout the several-day-long storm periods.

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### 3.3. Radial (Compressional) Flow Velocities at Geosynchronous Orbit

Radial flow velocities can be measured in the dayside magnetosphere at geosynchronous orbit in response to changes in the ram pressure of the solar wind: inward radial flow when the solar wind ram pressure increases and outward radial flow when the solar wind ram pressure decreases. These flow velocities are measured with the MPA instruments, but only when there are sufficient amounts of cold plasma present to calculate the flow velocity from the shift of the cold-ion distribution function. The flow measurements can only be made with MPA when a spacecraft is inside the plasmasphere. In the dayside magnetosphere that restricts the flow measurements to quiet geomagnetic conditions when the outer plasmasphere refills to beyond geosynchronous orbit, or to plasmaspheric drainage plumes during active times. However, the flow velocities within drainage plumes are temporally irregular [Borovsky and Denton, 2008] (owing perhaps to ULF waves during active times or to turbulence in the flow of the plumes) so matching measured flow velocities within plumes to changes in the ram pressure of the solar wind is very difficult.

In the top panel of Figure 10 an isolated ram-pressure change in the solar wind during very quiet geomagnetic conditions is examined at a time when two geosynchronous spacecraft are in the plasmasphere near local noon. The two green curves (right axis) are the number density  $n_{sw}$  and ram pressure  $P_{ram}$  of the solar wind as measured by the SWEPAM instrument on the ACE spacecraft upstream of the Earth. The dark red and purple curves (right axis) are the OMNI2 estimates of the solar wind density  $n_{sw}$  and ram pressure  $P_{ram}$  at Earth [King and Papitashvili, 2005], obtained by advecting the ACE solar-wind measurements to the nose of the bow shock. The timing of the pressure change  $P_{ram}$  reaching Earth is best obtained from the OMNI2 curves; the temporal profile of the pressure change is best obtained by examining the ACE curves. The red and blue curves (left axis) are measurements of the radial plasma flow velocity obtained by two geosynchronous spacecraft (1990-095 and LANL-01A) carrying the MPA plasma instruments. Both spacecraft are in the high-density plasmasphere this day as they traverse the dayside magnetosphere. When the ram-pressure change reaches Earth at 13:07 UT, the two spacecraft are straddling local noon. In the example of the top panel, inward radial

velocities of  $\sim 20$  km/s are obtained for a ram pressure increase of  $\sim 3.6$  nPa. Note that in the 64-s time-resolution ACE data of Figure 10 the thickness of the density change and ram-pressure change in the solar wind is not resolved. In Figure 10 the velocity measurements by MPA are also unresolved. The MPA instrument has a time resolution of 86 s and is measuring cold-ion flows during 10.15 s of that 86 s [cf. *Bame et al.*, 1993]: hence the MPA measurements are snapshots of the cold ions produced once every 86 s.

A second example of radial flows in the magnetosphere associated with ram-pressure changes in the solar wind is examined in the bottom panel of Figure 10. Again, two geosynchronous spacecraft are in the dayside plasmasphere straddling local noon when the ram-pressure perturbation hits Earth. The temporal profile, a decrease and then increase, of the ram pressure can be seen in the green ACE curves (right axis) at 23:28 UT on October 21, 2005 in the bottom panel. In the dark-red and purple curves (right axis) the perturbation is seen to hit the Earth at about 0:35 UT on October 22, 2005. The geosynchronous spacecraft 1994-084 (red curve, left axis) clearly sees an outward (positive) then inward (negative) radial flow associated with the solar-wind pressure decrease then increase. The spacecraft LANL-97A (blue curve, left axis) picks up only the inward radial flow. It could be that the outward flow persisted for less than 86 s and the timing of the 10.15-s measurement of cold ions within the 86-s window of MPA was off.

To a limited extent, expressions (9) can be applied to the radial velocities measured in the plasmasphere in comparison with  $\partial B_{\text{geo}}/\partial t$  values. Applying expression (9) is limited by the fact that the spacecraft that carry the MPA detectors do not carry magnetic-field instruments, and in general GOES geosynchronous spacecraft are not proximate to the MPA spacecraft. For the May 2005 event in the top panel of Figure 10 the GOES 12 spacecraft was at 8 LT while 1990-095 was at 10.6 LT. GOES 12 saw  $\partial B_{\text{geo}}/\partial t = +3.35$  nT/min =  $+5.6 \times 10^{-2}$  nT/s; using this in expression (9) yields  $v_r = -5.3$  km/s. This value of  $v_r$  is lower than the peak value -15 km/s seen at 10.6 LT, but the measured  $\partial B_{\text{geo}}/\partial t$  at 8 LT was probably weaker than the actual value of  $\partial B_{\text{geo}}/\partial t$  at 10.6 LT. For the October 2005 event in the bottom panel of Figure 10 the GOES 10

spacecraft was at 15.5 LT while 1994-084 was at 13.5 LT. GOES 10 saw  $\partial B_{\text{geo}}/\partial t = -5.9 \text{ nT/min} = -9.8 \times 10^{-2} \text{ nT/s}$ ; using this in expression (9) yields  $v_r = +9.3 \text{ km/s}$ . This value 9.3 km/s is smaller than the peak value of 24 km/s measured by MPA, but the measured  $\partial B_{\text{geo}}/\partial t$  at 15.5 LT was probably less than the actual value of  $\partial B_{\text{geo}}/\partial t$  at 13.5 LT. The underestimate of  $v_r$  by expression (9) may also indicate that the image-dipole model underestimates the displacement of flux surfaces for a given change the magnetic-field strength.

- Expression (10) can also be applied to the radial velocities measured in the plasmasphere in comparison with  $\partial P_{\text{ram}}/\partial t$  values in the solar wind. For the May 2005 event in the top panel of figure 10 the ACE spacecraft sees a ram-pressure increase of 4.05 nPa in 64 s: this pressure change probably occurred in a timescale less than the 64-s resolution of ACE, but spreading of the pressure profile as it is advected though the magnetosheath probably broadens the time derivative. A change of 4.05 nPa in 64 s is  $\partial P_{\text{ram}}/\partial t = + 6.3 \times 10^{-2} \text{ nPa/s}$ ; using this value in expression (10) yields  $v_r = - 38 \text{ km/s}$ . The measured peak velocity from the MPA measurements are -20 km/s at 13.6 LT and -15 km/s at 10.6 LT. For the October 2005 event in the bottom panel of Figure 10 the ACE spacecraft sees a decrease of the ram pressure by 9.4 nPa in 7 intervals of 64 s. That is  $\partial P_{\text{ram}}/\partial t = - 2.0 \times 10^{-2} \text{ nPa/s}$ ; using this value in expression (10) yields  $v_r = +12 \text{ km/s}$ . The measured peak value of the velocity measured by MPA is +24 km/s at 13.5 LT, with no flow picked up by MPA at 10.2 LT. The underestimate of  $v_r$  by expression (10) may also indicate that the image-dipole model underestimates the displacement of flux surfaces for a given change the solar-wind ram pressure.

In Figure 11 the radial and azimuthal velocities at geosynchronous orbit are examined for a forward interplanetary shock hitting the Earth when three geosynchronous spacecraft are in the plasmasphere in the dayside magnetosphere. In the top panel of Figure 11 the ram pressure  $P_{\text{ram}}$  of the solar wind is plotted as a function of time as measured by the 3DP plasma instrument on WIND (blue points) and as measured by the SWEPAM instrument on ACE (green curve); the upstream WIND measurements are time shifted by 51 minutes and the upstream ACE measurements are time shifted by 42 minutes.. The shock is represented here by the sudden

temporal increase in  $P_{\text{ram}}$ . The other three panels of Figure 11 are plots of the flow velocity measured with the MPA instrument onboard the three geosynchronous spacecraft within the dayside plasmasphere: 1990-095 was at 8.0 LT when the shock hit, LANL-02A was at 10.6 LT, and LANL-01A was at 15.2 LT. The red curves are the radial velocity (positive being a flow radially away from the Earth and negative being a flow radially toward the Earth) and the blue curves are the azimuthal velocity (positive being Eastward in the direction of corotation and negative being westward opposite to the corotation). On all three spacecraft the radial velocities commenced with an inward flow of on the order of 20 km/s. Note the ringing of both the radial and the azimuthal flows in Figure 11: ringing periods ranging from 340 s to 520 s are seen (considerably slower periods than in the low-density magnetosphere of the simulations in Figure 4).

In Figure 12, for five forward interplanetary shocks hitting the Earth when there are MPA instruments in geosynchronous orbit inside the dayside plasmasphere, the inward radial velocities  $-v_r$  measured by the MPA instruments are plotted as a function of the ram-pressure change  $\Delta P_{\text{ram}}$  across the interplanetary shocks. The Pearson linear correlation coefficient  $r_{\text{corr}}$  between  $-v_r$  and  $\Delta P_{\text{ram}}$  is  $r_{\text{corr}} = +0.76$  for the data of Figure 12. A major-axis linear-regression fit [Pearson, 1901; Smith, 2009] (also known as a ‘‘Gaussian fit’’ [Borovsky *et al.*, 1998] or a ‘‘total least squares fit’’ [Golub and Van Loan, 1980]), to the data is plotted as the green dashed line, which is

$$v_r = -4.3 \Delta P_{\text{ram}} - 5.4, \quad (12)$$

where  $v_r$  is in km/s and  $\Delta P_{\text{ram}}$  is in nPa. The value  $v_r \sim 20$  km/s for  $\Delta P_{\text{ram}} \sim 3.6$  nPa obtained in the top panel of Figure 10 approximately fits expression (12).

### 3.4. Ram-Pressure Fluctuations in the Solar Wind during Storms

To characterize the fluctuations of the ram pressure  $P_{\text{ram}}$  of the solar wind, 10-minute changes in the 64-s resolution measurements of the ram pressure from ACE are calculated. This change  $\Delta P_{\text{ram}10}$  is defined as  $\Delta P_{\text{ram}10}(t) = |P_{\text{ram}}(t+5\text{min}) - P_{\text{ram}}(t-5\text{min})|$ , where  $P_{\text{ram}} = m_p n_{\text{sw}} v_{\text{sw}}^2$ . The



70 storms utilized in this study are from the years 1993-2005; 29 of those storms are in the years 1998-2005. In Figure 13 the superposed-epoch average of  $\Delta P_{\text{ram}10}$  is plotted in green for the fraction (29 of 70) of the high-speed-stream-driven storms that overlap the years 1998-present of the ACE data set. The superposed average of  $\Delta P_{\text{ram}10}$  becomes very elevated at the onset of the high-speed-stream-driven storms and declines steadily during the first two days of the storms. Afterward,  $\Delta P_{\text{ram}10}$  is at typical levels (the mean value of  $\Delta P_{\text{ram}10}$  in the ACE data set is 0.28 nPa). In red and in blue the superposed average of  $\Delta P_{\text{ram}10}$  is plotted for a set of helmet-streamer high-speed-stream-driven storms and for a set of pseudostreamer high-speed-stream-driven storms: these two collections of storms are described in *Borovsky and Denton [2013]*. Note in Figure 13 that  $\Delta P_{\text{ram}10}$  tends to be greater in helmet-streamer storms (red) than in pseudostreamer storms (blue). Helmet-streamer storms are preceded by intervals of sector-reversal-region plasma [*Xu and Borovsky, 2015*], which is characterized by strong density fluctuations. The coronal-hole plasma of the high-speed stream later in the storms is also on average of lower speed for pseudostreamers than it is for helmet streamers and it has weaker values of  $\Delta P_{\text{ram}10}$ .

The quantity  $\Delta P_{\text{ram}10}$  is strongly correlated with the ram pressure of the solar wind  $P_{\text{ram}}$ , with a Pearson linear correlation coefficient  $r_{\text{corr}} = +0.551$  in the ACE data set. Hence,  $\Delta P_{\text{ram}10}$  tends to be large when  $P_{\text{ram}}$  is large. In Figure 13 the superposed average of  $P_{\text{ram}}$  is plotted in gray, multiplied by 0.13 to approximately match the amplitude of  $\Delta P_{\text{ram}10}$ . As can be seen by comparing the green and gray curves, the temporal profiles of  $\Delta P_{\text{ram}10}$  and  $P_{\text{ram}}$  are very similar in the stormtime superposed averages.

For the two years 2004 and 2005, Figure 14  $\Delta P_{\text{ram}10}$  is plotted as a function of  $\Delta n_{\text{sw}10} = |n_{\text{sw}}(t+5\text{min}) - n_{\text{sw}}(t-5\text{min})|$  in the top panel and as a function of  $\Delta v_{\text{sw}10} = |v_{\text{sw}}(t+5\text{min}) - v_{\text{sw}}(t-5\text{min})|$  in the bottom panel. Linear-regression fits are plotted in red in both panels and a major-axis linear-regression fit is plotted in blue in the top panel. The Pearson linear correlation coefficients are noted in each panel.  $\Delta P_{\text{ram}10}$  is highly correlated with  $\Delta n_{\text{sw}10}$  with a Pearson linear correlation coefficient  $r_{\text{corr}} = +0.848$  in the ACE data set. On the contrary,  $\Delta P_{\text{ram}10}$  is only weakly correlated with  $\Delta v_{\text{sw}10}$  with  $r_{\text{corr}} = +0.185$ . Hence, changes in the solar-wind ram pressure are dominantly

associated with changes in the solar-wind number density and much-more weakly associated with changes in the solar-wind speed.

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#### 4. Amplitude Statistics of the Magnetic-Field Compressions, the Ram-Pressure Changes, and the Radial Flow Velocities

In Figure 15 the magnitudes of the changes  $\Delta B$  in the magnetic-field strength  $B_{\text{geo}}$  of the dayside magnetosphere are explored for time intervals  $\delta t$  different from 10 minutes. Using the GOES magnetic-field data set for 1998-2005 restricted to local times from 11 LT to 13 LT, the mean value of  $\Delta B_{\delta t}$  taken at a time interval  $\delta t$  defined as  $\Delta B_{\delta t}(t) = |B_{\text{geo}}(t+\delta t) - B_{\text{geo}}(t-\delta t)|$  is plotted as a function of  $\delta t$ . In Figure 15 the  $\Delta B_{\delta t}$  values are normalized to  $\Delta B_{10}$ . As seen in the plot,  $\Delta B_{\delta t}$  increases for values of  $\delta t$  that are larger than 10 minutes, but not by much.  $\Delta B_{\delta t}$  decreases strongly as  $\delta t \rightarrow 1$  min. The ratio  $\Delta B_{\delta t}/\Delta B_{10}$  as a function of  $\delta t$  is well fit by the logarithmic function  $0.33 + 0.69[\log_{10}(\delta t)]^{3/2}$  that is plotted as the red dashed curve in Figure 15, which is valid for  $1 \text{ min} \leq \delta t \leq 30 \text{ min}$ . The curve  $0.33 + 0.69[\log_{10}(\delta t)]^{3/2}$  also fits the normalized change  $\Delta B_{\delta t}/B_{\text{mag}}$  in comparison with  $\Delta B_{10}/B_{\text{mag}}$ .

In Figure 16 the size distributions of  $\Delta B_{10}$  values,  $\Delta P_{\text{ram}10}$  values, and  $|v_r|$  values are examined. In the top panel the occurrence distribution of  $\Delta B_{10}$  values in the 1998-2005 GOES geosynchronous magnetic-field data set for local times between 11 LT and 13 LT is plotted in black. Variable-size binning was used for the various ranges of  $\Delta B_{10}$  values, so the units of the distribution function are arbitrary. The red dashed curve plotted in the top panel of Figure 16 is a  $\Delta B_{10}^{-3}$  power law. As can be seen by the approximate agreement between the plotted points and the red-dashed curve, larger values of  $\Delta B_{10}$  in the dayside magnetosphere approximately obey power-law statistics. The largest values of  $\Delta B_{10}$  in the top panel can be identified with interplanetary shocks reaching the Earth.

In the middle panel of Figure 16 the occurrence distribution of  $\Delta P_{\text{ram}10}$  in the solar wind is plotted. The  $\Delta P_{\text{ram}10}$  distribution was obtained from ACE SWEPAM 64-s measurements of the solar wind in the years 2003 and 2004. The red dashed curve in the second panel is a  $\Delta P_{\text{ram}10}^{-3}$  power law. As was the case for the  $\Delta B_{10}$  values in the dayside magnetosphere in the top panel, the occurrence distribution of  $\Delta P_{\text{ram}10}$  values in the solar wind approximately obeys power law

statistics for large values. Note that the two power laws that fit the large values of  $\Delta B_{10}$  and of  $\Delta P_{\text{ram}10}$  both have exponents -3. Most of the largest values of  $\Delta P_{\text{ram}10}$  in the middle panel are identified with interplanetary shocks; a few are identified with sudden density changes in the solar wind.

In the bottom panel of Figure 16 the occurrence distribution of radial velocities at geosynchronous orbit in the dayside magnetosphere is plotted. The  $|v_r|$  values were obtained from multi-satellite MPA measurements at geosynchronous orbit in the local time range between 11 LT and 13 LT in the years 1990 to 2007. The  $|v_r|$  values used to construct the distribution function in the bottom panel came from times when the MPA spacecraft were in the filled plasmasphere during intervals of low Kp. The red dashed curve in the bottom panel of Figure 16 is a  $|v_r|^{-6}$  power law. As were the cases for the distributions of  $\Delta B_{10}$  and  $\Delta P_{\text{ram}10}$  values in the top two panels of Figure 16, for large values the radial flow velocities  $|v_r|$  in the dayside magnetosphere approximately obey power law statistics. Note that the approximate power law indices of  $\Delta B_{10}$  and  $\Delta P_{\text{ram}10}$  are similar, but the index for  $|v_r|$  differs significantly. The reason why the distribution of velocities  $|v_r|$  has a different form from the distribution of pressure changes is not known. One possibility is that the flow velocity associated with  $\Delta P_{\text{ram}10}$  has a duration that is considerably less than 10 minutes. For example, if the velocity only lasted 1 min then a single large value of  $\Delta P_{\text{ram}10}$  would be associated with 9 small values of velocity and one large value of velocity. There would be fractionally less values of high velocity than of high  $\Delta P_{\text{ram}10}$ , hence the high-velocity tail of the distribution would be weaker than that of  $\Delta P_{\text{ram}10}$ .

## 5. Summary

For magnetic pumping calculations, the quasi-DC compressions of the Earth's dayside magnetic field by density fluctuations in the solar wind have been characterized. Magnetic field measurements at geosynchronous orbit, plasma flow measurements at geosynchronous orbit, and global MHD simulations were used in conjunction with solar-wind plasma measurements.

As the field strength in the dayside magnetosphere changes, there is a radial displacement of flux surfaces and a radial advection of plasma. Calculating the radial displacement of flux surfaces in an image-dipole model, it is predicted that the magnetic compression of parcels of plasma in the dayside magnetosphere is bigger than the change in magnetic-field strength observed onboard a spacecraft. The image-dipole model predicts that plasma compression can be a factor of 2 higher than the measured magnetic-field compression. This plasma-compression prediction is not confirmed with spacecraft measurements owing to the radial motion of the plasma parcels as they are compressed, however tests of the predicted radial velocity for the image-dipole model find that the model underpredicts the plasma radial velocities and hence probably underpredicts the amount of plasma compression

Examination of the solar wind demonstrated that the ram-pressure changes causing the quasi-DC magnetospheric compressions are mostly owed to changes in the solar-wind number density being advected past the Earth. Rapid changes in the solar-wind number density associated with the crossing of plasma boundaries produce rapid changes in the solar-wind ram pressure; an Earth crossing of a plasma boundary produces a sudden change in the dayside magnetic-field strength accompanied by a sudden inward or outward motion of the plasma in the dayside magnetosphere.

Superposed epoch analysis triggered on the temporal onsets of high-speed-stream-driven storms was used to explore solar-wind compressions and geosynchronous magnetic-field compressions during high-speed-stream-driven storms, which are of particular interest for the energization of the outer electron radiation belt. Mean values of the 10-minute changes  $\Delta B_{10}$  of the geosynchronous dayside field strength are  $\Delta B_{10} \sim 3$  nT early in storms and are  $\Delta B_{10} \sim 2$  nT later in storms.

The occurrence distributions of (a) 10-minute changes in the geosynchronous dayside magnetic-field strength  $\Delta B_{10}$ , (b) 10-minute changes in the solar-wind ram pressure  $\Delta P_{\text{ram}10}$ , and (c) instantaneous geosynchronous dayside radial flow velocities  $|v_r|$  were examined. All three distributions approximately obey power-law statistics for large values. In particular the approximate power-law indices for the distributions of  $\Delta B_{10}$  and  $\Delta P_{\text{ram}10}$  values are both -3. The power-law index for the  $|v_r|$  distribution is closer to -6.

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## 6. Discussion: Nightside Compressions

This report characterized the temporal compressions of the dayside magnetosphere at geosynchronous orbit. On the dayside of the relative magnitude of the compressions  $\Delta B_{\text{mag}10}/B_{\text{mag}}$  are a few per cent to 10's of percent and the plasma motions associated with the dayside compressions are discernible radial displacements inward or outward as the magnetic-field strength  $B_{\text{mag}}$  increases or decreases.

Temporal compressions of the nightside magnetosphere are not so easily characterized from the spacecraft data. In Figure 17 the magnetic-field strength  $B_{\text{mag}}$  measured by two GOES spacecraft in geosynchronous orbit is plotted for 7 days as a high-speed-stream-driven geomagnetic storm commences. The Kp index is plotted in the top panel. Day 284 is at the end of a “calm before the storm” with the storm commencing towards the end of Day 285. The storm is ongoing from Day 286 to beyond the end of the plot. The second panel of Figure 17 plots the measured magnetic-field strength  $B_{\text{mag}}$ , with GOES-10 plotted in red and GOES-12 plotted in blue. The local maximum of  $B_{\text{mag}}$  once a day occurs when each spacecraft is on the dayside and the local minimum of  $B_{\text{mag}}$  that occurs each day occurs when each spacecraft is on the nightside. In the third panel of Figure 17 the 10-minute change  $\Delta B_{\text{mag}10}$  in the magnetic field strength, normalized to the magnetic field strength  $B_{\text{mag}}$ , is plotted for GOES-10. The localized peaks in  $\Delta B_{\text{mag}10}/B_{\text{mag}}$  occur when GOES-10 is on the nightside. Note that these nightside values of  $\Delta B_{\text{mag}10}/B_{\text{mag}}$  approach unity. In the fourth panel of Figure 17 the solar-wind ram pressure  $P_{\text{ram}}$  is plotted as a function of time. Comparing the second and fourth panels one can see that the changes in the magnitude of the magnetic field are related to the solar-wind ram pressure when the GOES spacecraft is on the dayside, but such a relationship is not clear when the GOES spacecraft is on the night side.

The magnetic-field-strength changes at geosynchronous orbit in the nightside magnetosphere may be caused by temporally changing magnetospheric currents, or by moving magnetospheric currents, or by plasma diamagnetism, or by other causes. In the nightside magnetosphere at geosynchronous orbit the plasma motions associated with the temporal

changes in the magnetic-field strength, and hence the plasma compressions, would be difficult to characterize and quantify.

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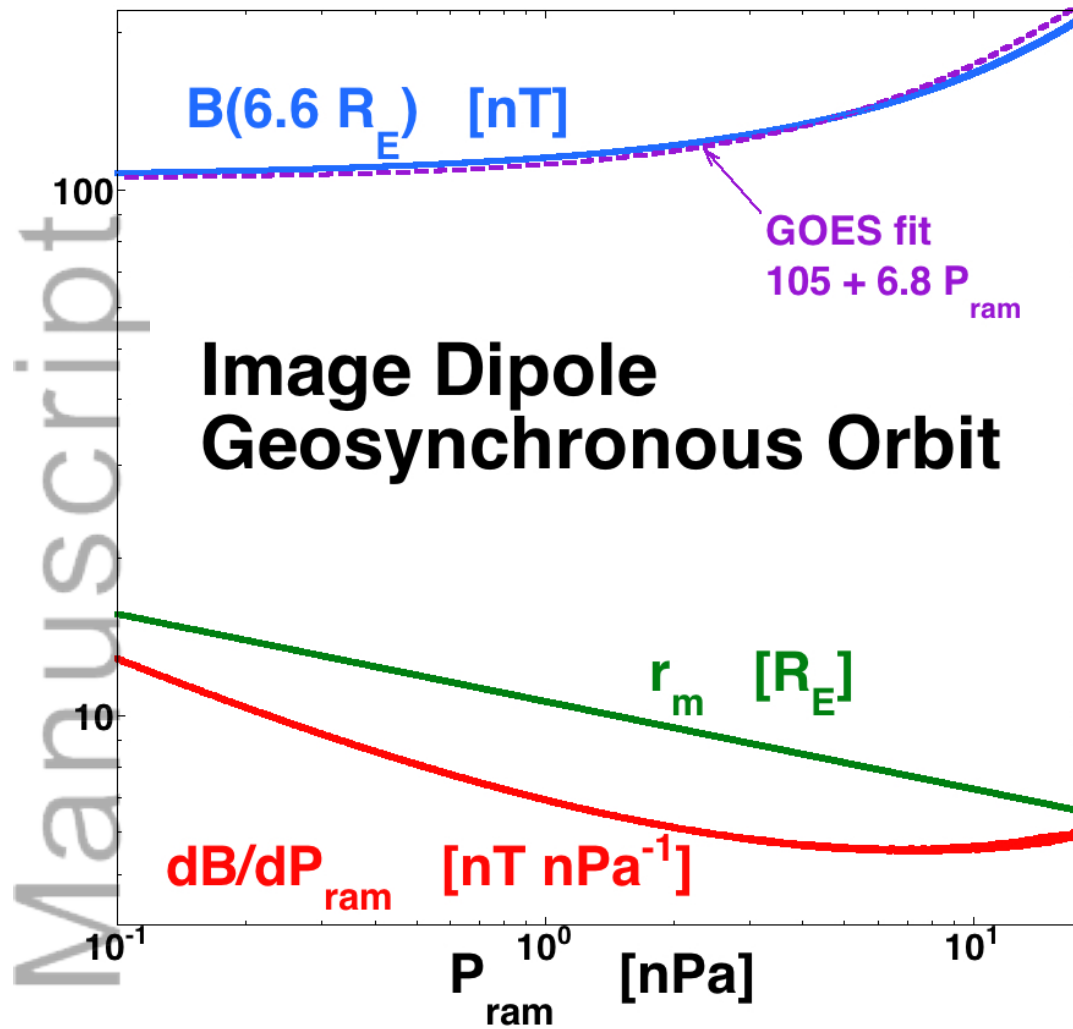


Figure 1. For an image dipole, a number of quantities along the Sun-Earth line are plotted as a function of the solar-wind ram pressure.



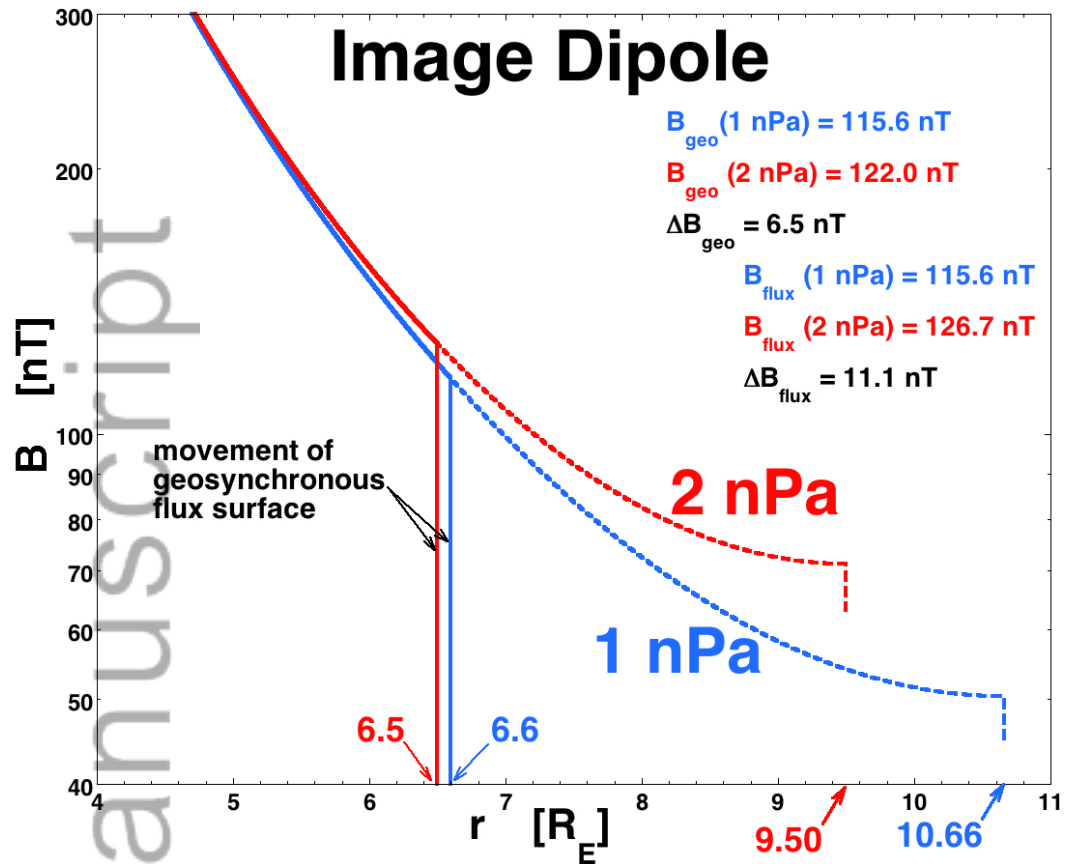


Figure 2. For an image dipole the magnetic-field strength along the Sun-Earth line is plotted for two values of the solar-wind ram pressure. The movement of the magnetopause is shown as well as the movement of a flux surface at geosynchronous orbit.

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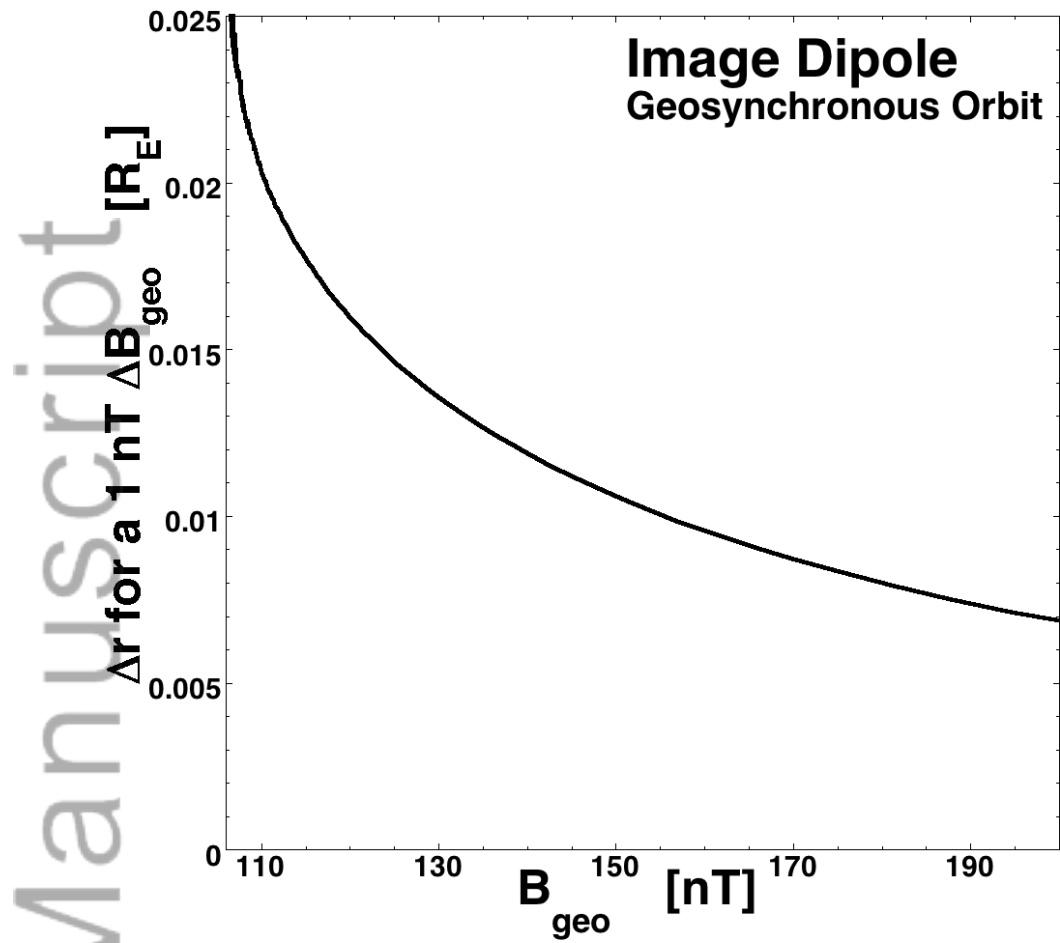


Figure 3. For an image dipole, the radial displacement of a geosynchronous flux surface (in  $R_E$ ) for a 1-nT change in the field strength at geosynchronous orbit is plotted as a function of the field strength at geosynchronous orbit.

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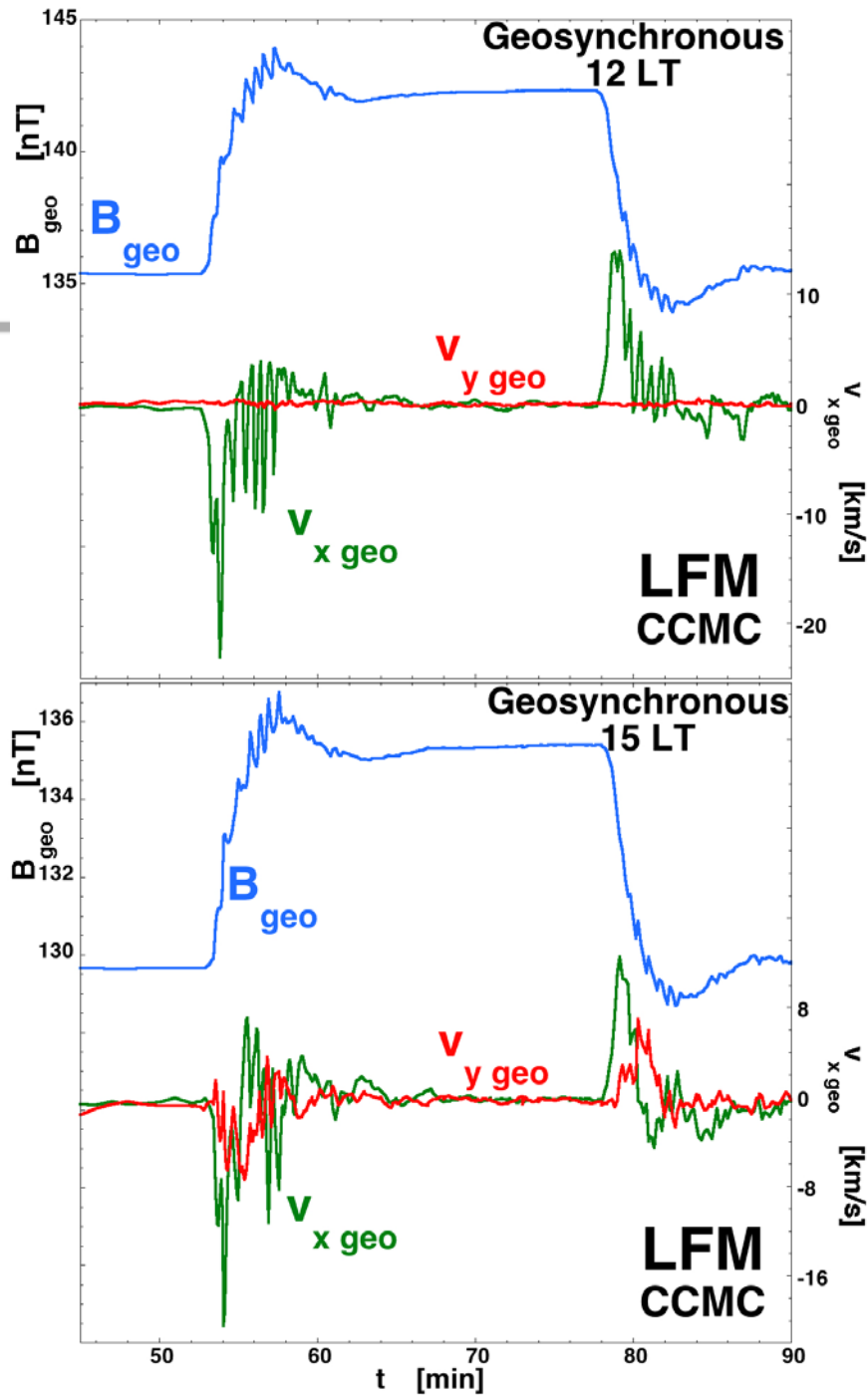


Figure 4. For a solar-wind-density increase then decrease, the magnetic-field strength at geosynchronous orbit is plotted in blue (left axis) and the  $v_x$  and  $v_y$  (GSM coordinates) plasma flow velocity components at geosynchronous are plotted in green and red (right axis). The top

panel is for local noon and the bottom panel is for 15 LT. (CCMC LFM simulation runs Joe\_Borovsky\_111014\_2b and Joe\_Borovsky\_111014\_2b)

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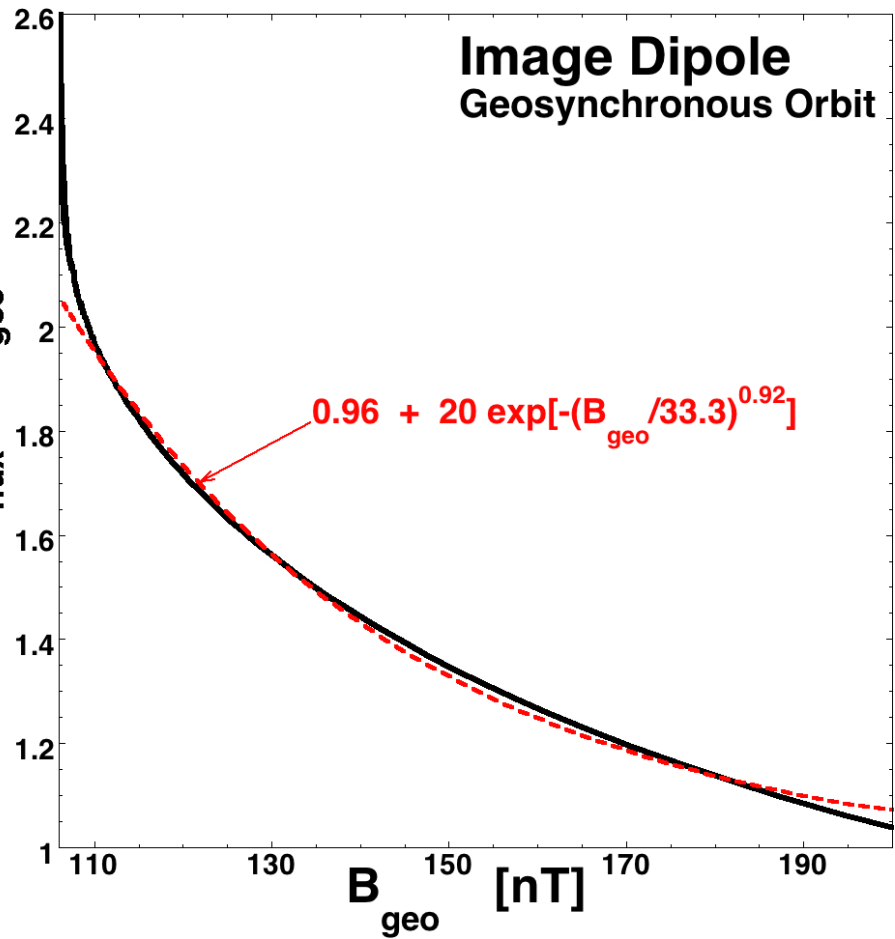


Figure 5. For an image dipole, the ratio of the change in magnetic-field strength at a flux surface moving from geosynchronous orbit to the change in magnetic-field strength at geosynchronous orbit is plotted as a function of the field strength at geosynchronous orbit.

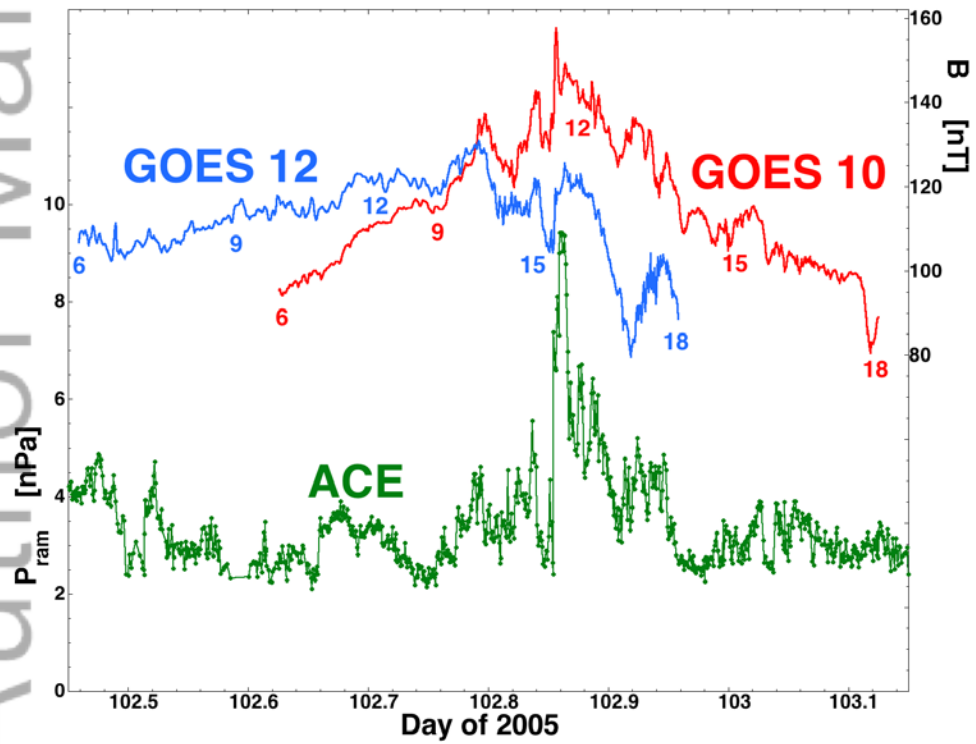
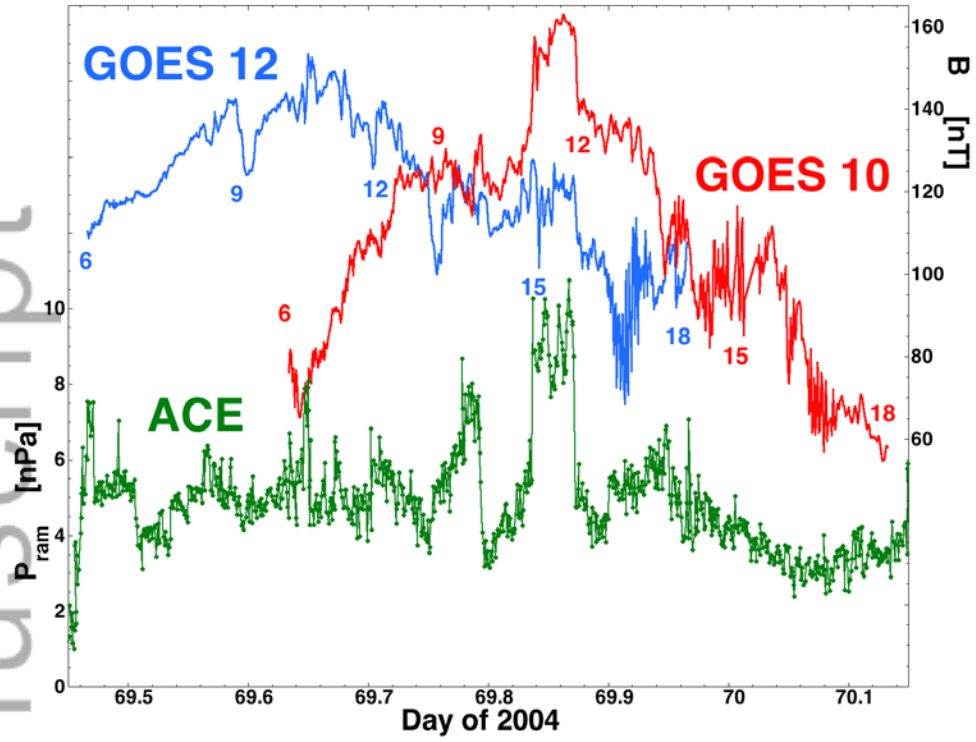


Figure 6. For single crossings of the dayside magnetosphere by GOES 10 (red) and GOES 12 (blue) the magnetic-field strength at geosynchronous orbit (right axis) is plotted as a function of time. The ram pressure of the solar wind as measured by ACE is plotted in green (left axis), time shifted to Earth by the solar-wind speed. The top panel is for March 9-10, 2004 and the bottom panel is for April 12-13, 2005.

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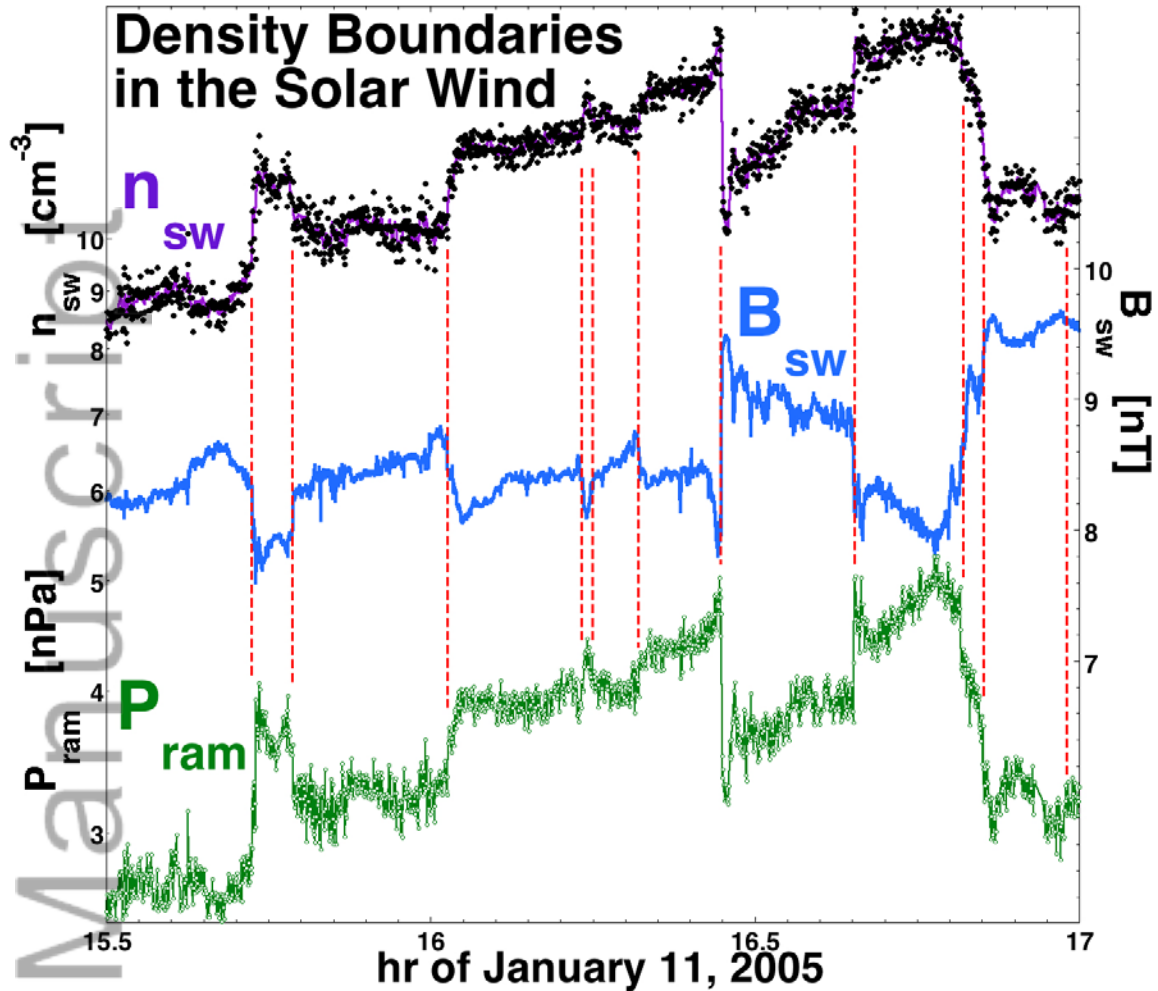


Figure 7. Using WIND 3DP measurements, several proton-density boundaries in the solar wind are denoted by vertical red dashed lines. The purple curve is a 30-s running average of the proton number density  $n_{sw}$  (left axis) with the black points being 3-s resolution measurements of  $n_{sw}$ . The green curve is the 3-s resolution measurement of the solar wind ram pressure  $P_{ram}$  (left axis). The blue curve is the 3-s resolution of the solar-wind magnetic-field strength  $B_{sw}$  (right axis) measured by WIND MAG.



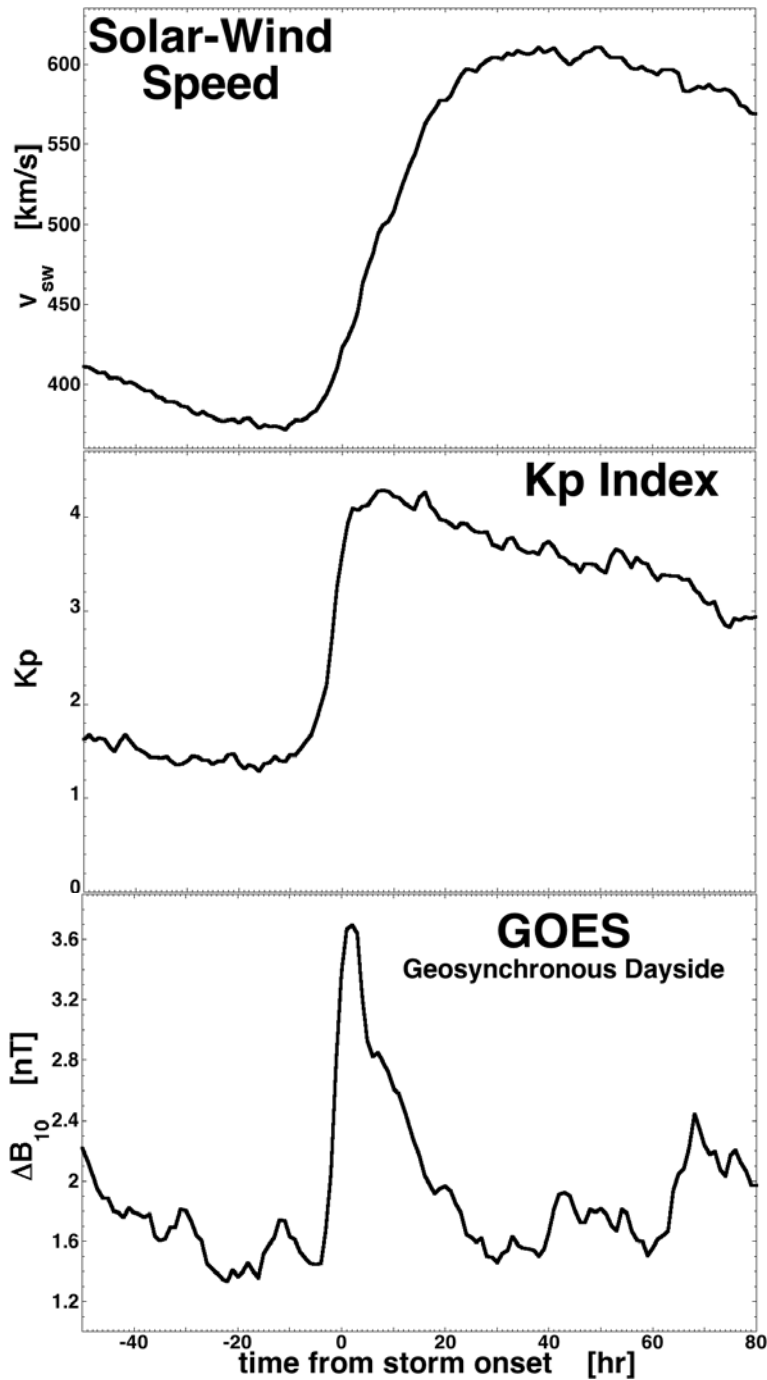


Figure 8. For 70 high-speed-stream-driven geomagnetic storms, superposed-epoch averages of the solar-wind speed (top panel), Kp index (middle panel), and 10-minute change in the geosynchronous magnetic-field strength  $\Delta B_{10}$  are plotted as a function of time with the zero

epoch being the onset of the storms. The  $\Delta B_{10}$  values averaged are from magnetic-field measurements by the GOES spacecraft between 9 LT and 16 LT.

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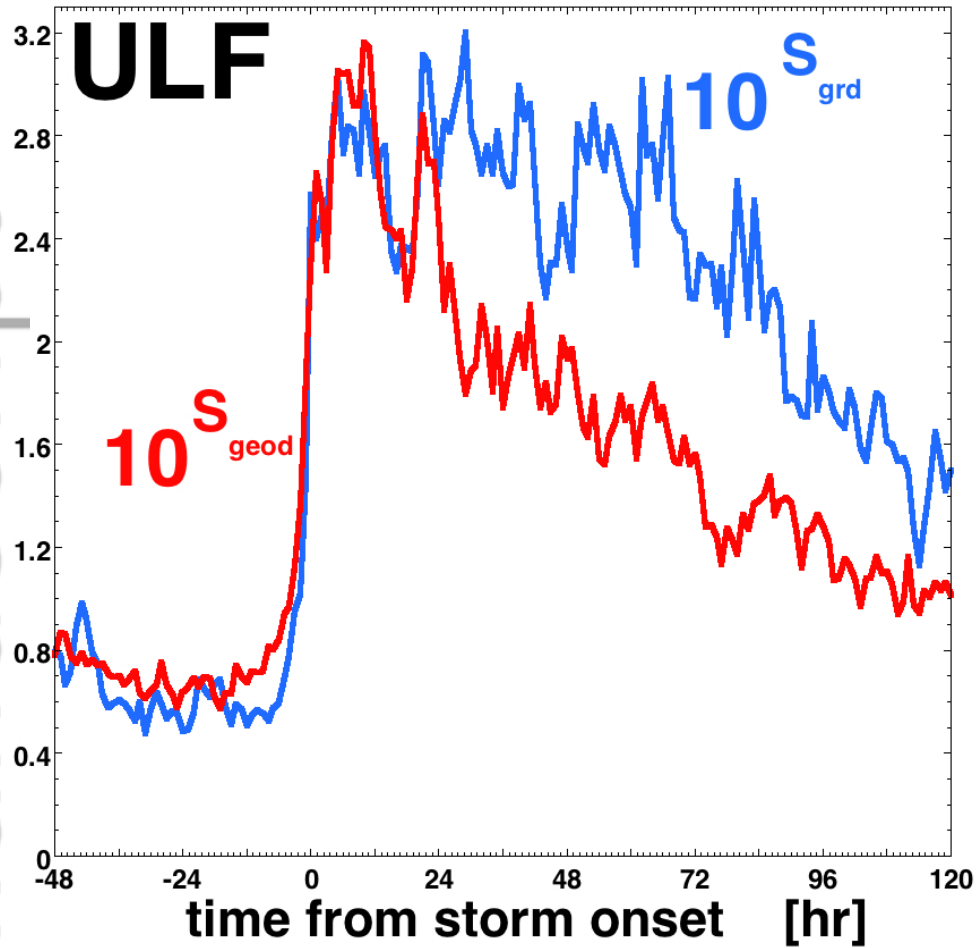


Figure 9. For 70 high-speed-stream-driven geomagnetic storms, superposed-epoch averages of the ground-based ULF index  $S_{\text{grd}}$  (blue) and the geosynchronous ULF index  $S_{\text{geod}}$  are plotted.

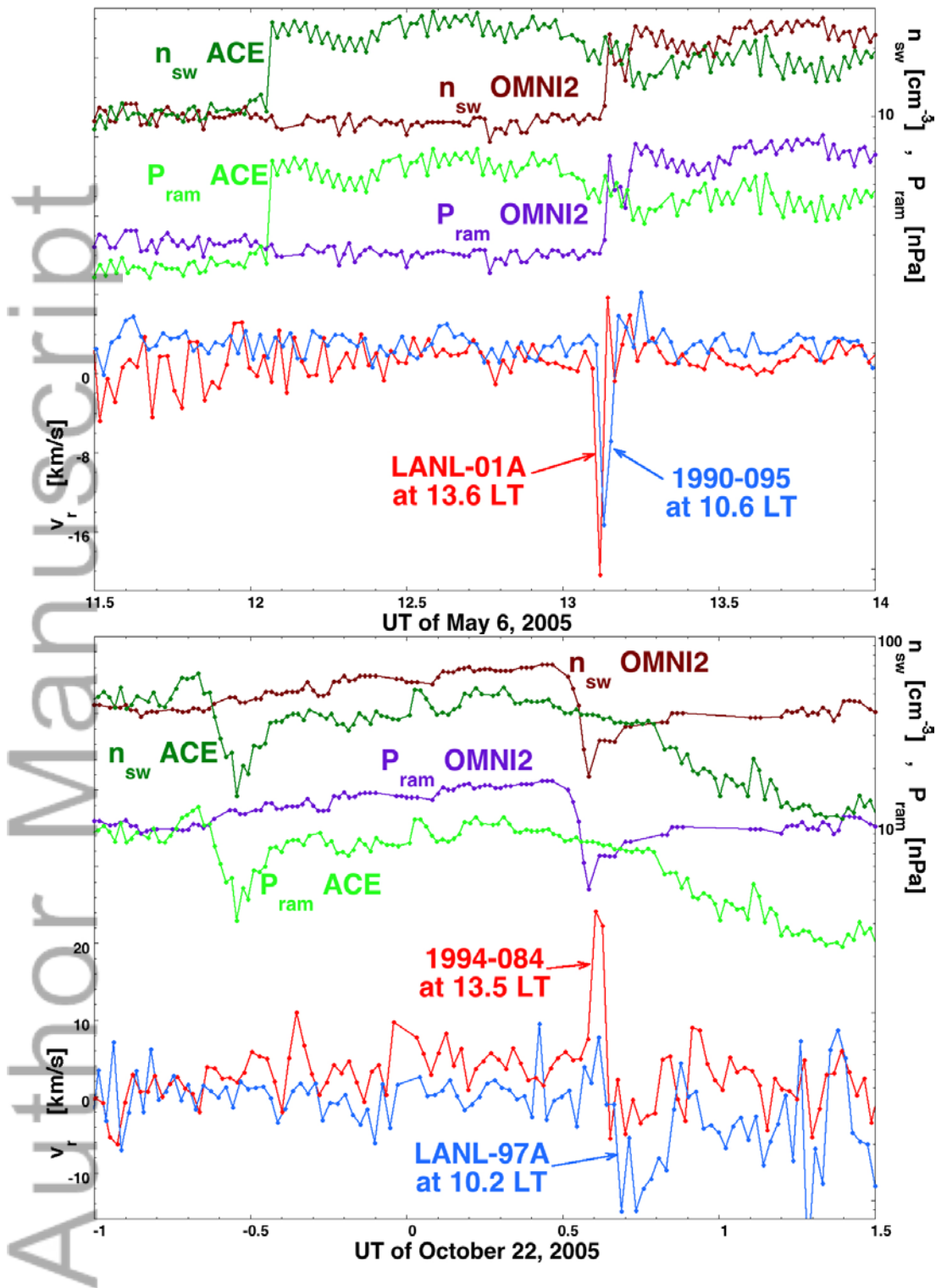


Figure 10. The radial plasma-flow velocities  $v_r$  as measured by MPA on two spacecraft in geosynchronous orbit are plotted (red and blue) as a function of time (left axis). The solar-wind density  $n_{sw}$  and ram pressure  $P_{ram}$  measured by ACE upstream and advected by OMNI2 are plotted (right axis). The top panel is for a solar-wind density increase and the bottom panel is for a solar-wind density decrease then increase.

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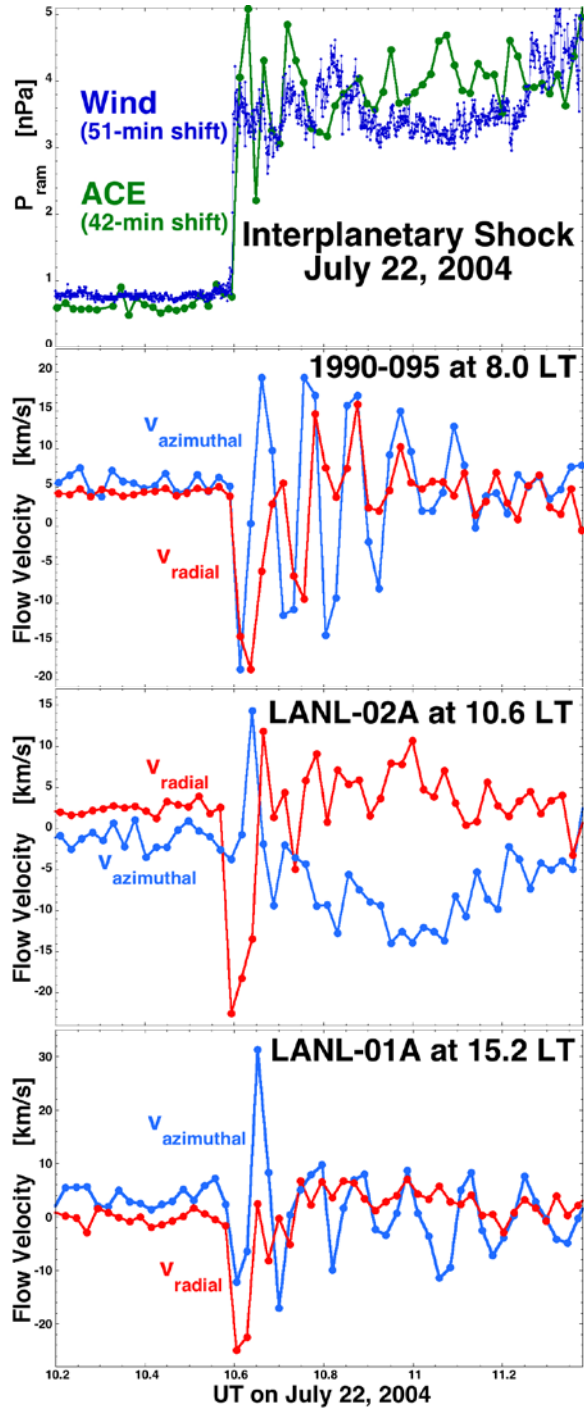


Figure 11. For a forward interplanetary shock hitting the Earth on July 22, 2004, the radial and azimuthal plasma flow velocities at geosynchronous orbit as measured by MPA on three spacecraft are plotted as a function of time. The top panel is the solar-wind ram pressure (time

shifted to Earth) as measured by ACE (green) and WIND (blue). The second, third, and fourth panels are the plasma flow velocities as measured on the satellites 1990-095, LANL-02A, and LANL-01A respectively. The second and third panels are pre-noon and the fourth panel is post-noon.

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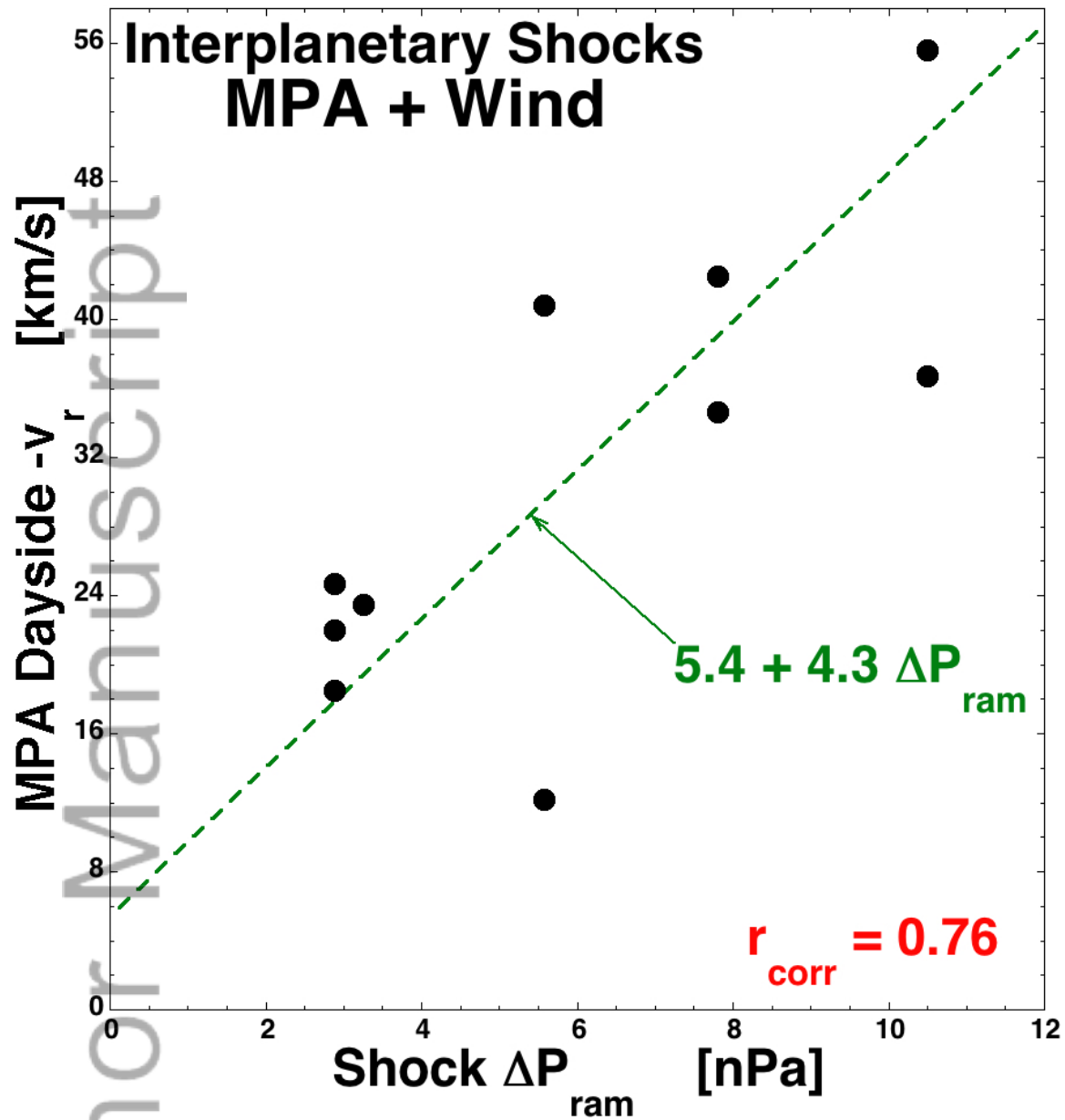


Figure 12. For 5 forward interplanetary shocks hitting the Earth, the measured radial flow velocities  $v_r$  at geosynchronous orbit in the dayside magnetosphere are plotted as a function of the increase in solar-wind ram pressure  $P_{ram}$  across the shocks.  $P_{ram}$  was measured by WIND 3DP and  $v_r$  was measured by MPA on multiple spacecraft.



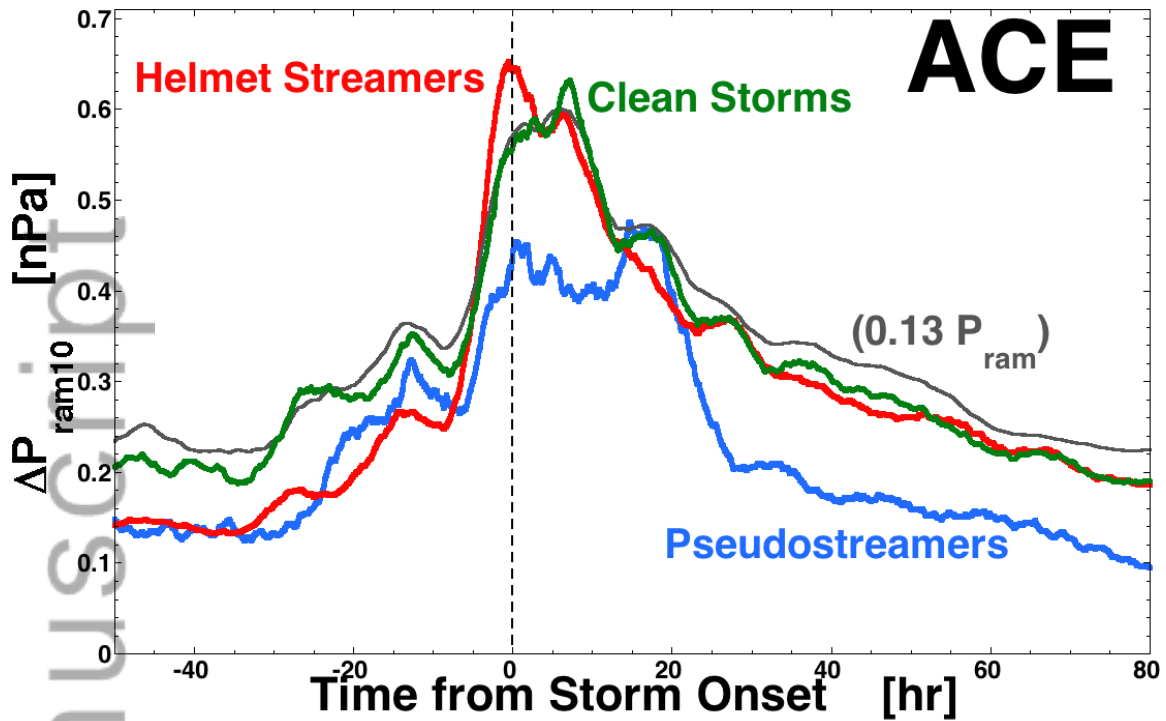


Figure 13. For 29 of the 70 high-speed-stream-driven storms in the collection, the superposed-epoch average of the 10-minute changes  $\Delta P_{\text{ram}10}$  in the solar-wind ram pressure  $P_{\text{ram}}$  is plotted in green. For the same storms 0.13 times the superposed average of  $P_{\text{ram}}$  is plotted in gray. For a collection of helmet-streamer high-speed-stream storms the superposed average of  $\Delta P_{\text{ram}10}$  is plotted in red and for a collection of pseudostreamer high-speed-stream storms the superposed average of  $\Delta P_{\text{ram}10}$  is plotted in blue.

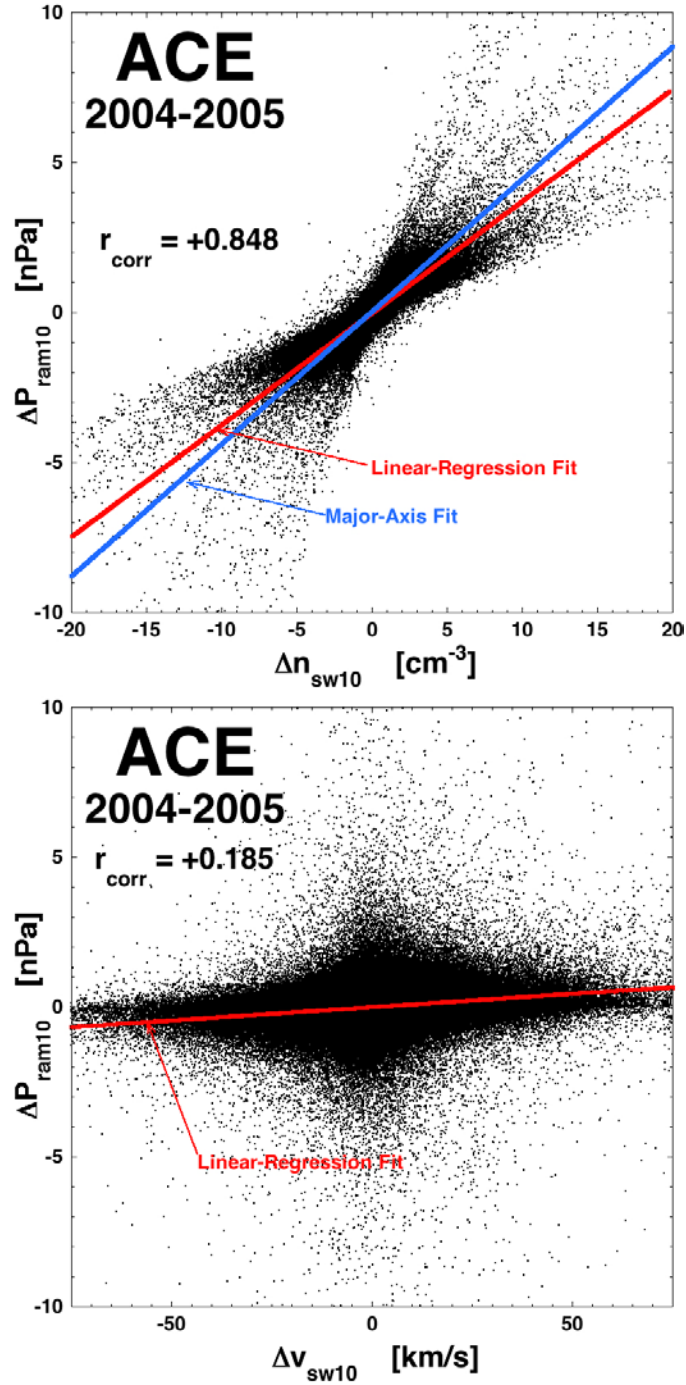


Figure 14. For the 64-s resolution ACE measurements in 2004 and 2005, the 10-min change  $\Delta P_{ram10}$  in the solar-wind ram pressure is plotted as a function of the 10-min change in the solar-

wind number density in the top panel and as a function of the 10-min change in the solar-wind speed in the bottom panel.

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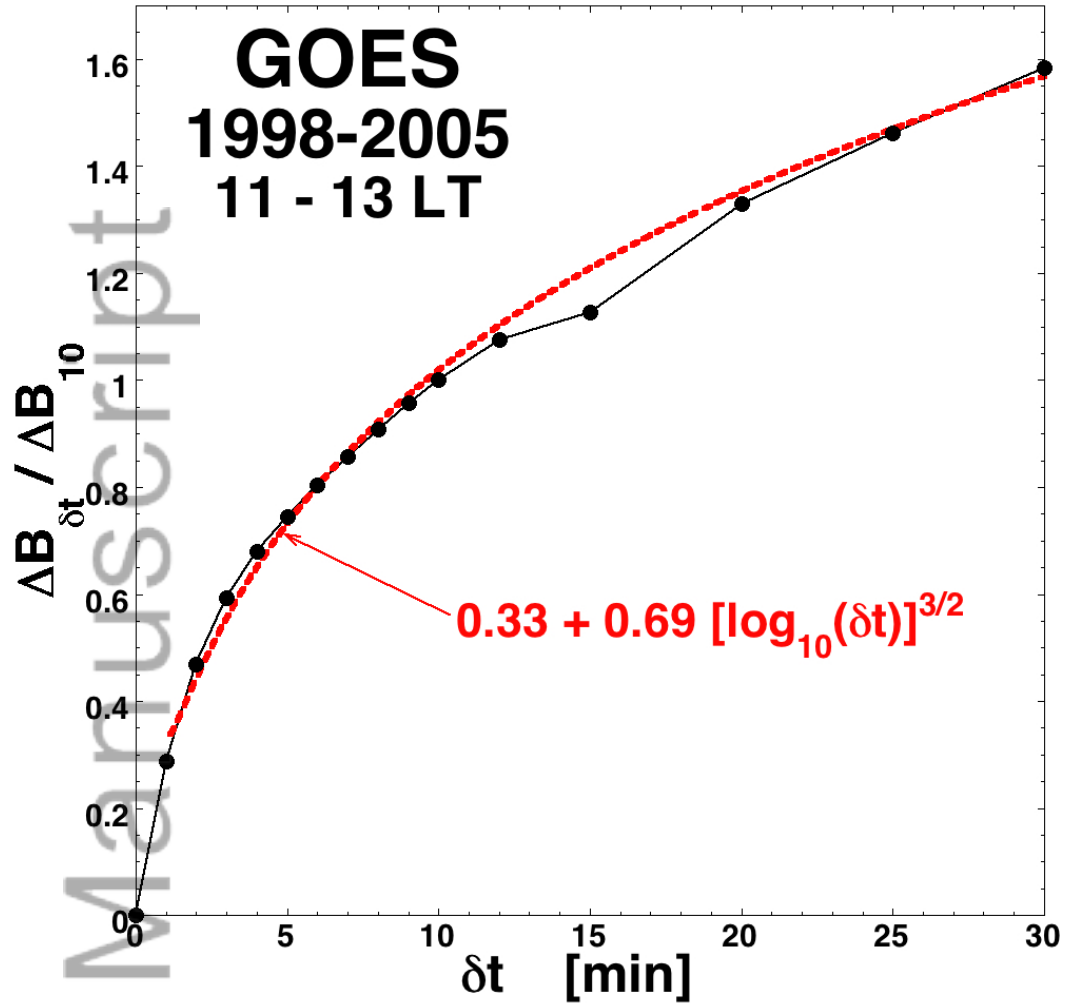


Figure 15. Calculating the change  $\Delta B_{\delta t}$  in the geosynchronous magnetic field strength near local noon over a timescale  $\delta t$ , the ratio of  $\Delta B_{\delta t}$  to the 10-minute change  $\Delta B_{10}$  is plotted as a function of  $\delta t$ . The values used are the mean values for the multisatellite GOES data set in the years 1998-2005.

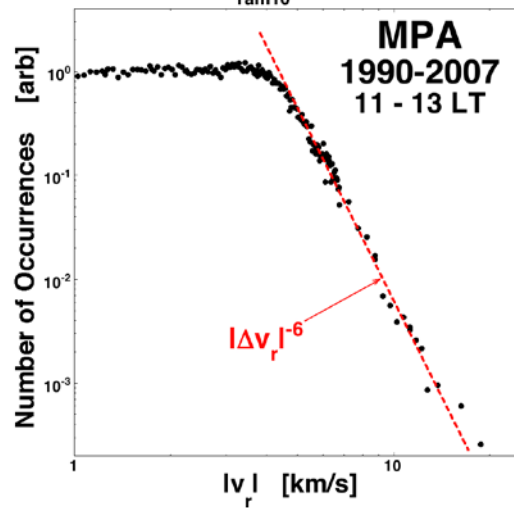
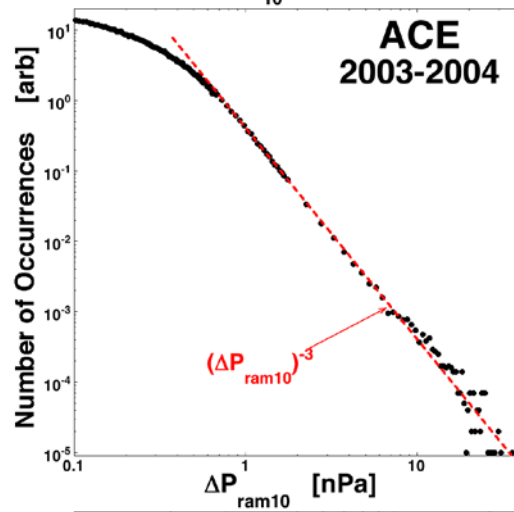
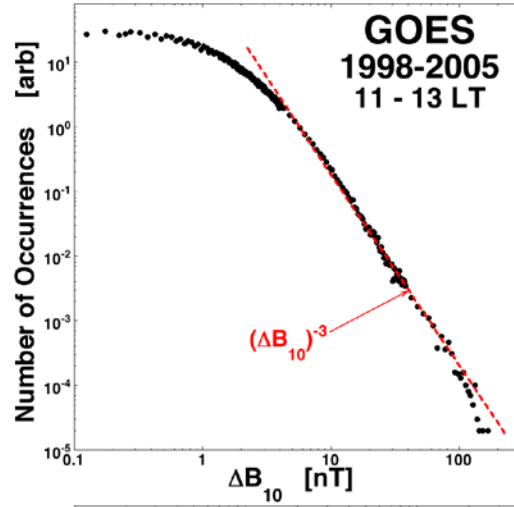


Figure 16. The occurrence distributions are plotted for the 10-minute change  $\Delta B_{10}$  in the dayside magnetic-field strength at geosynchronous orbit (top panel), the 10-minute change  $\Delta P_{\text{ram}10}$  of the solar wind ram pressure (middle panel), and the radial flow velocity  $v_r$  in the dayside magnetosphere at geosynchronous orbit. In all three panels the red dashed curve is a power law.

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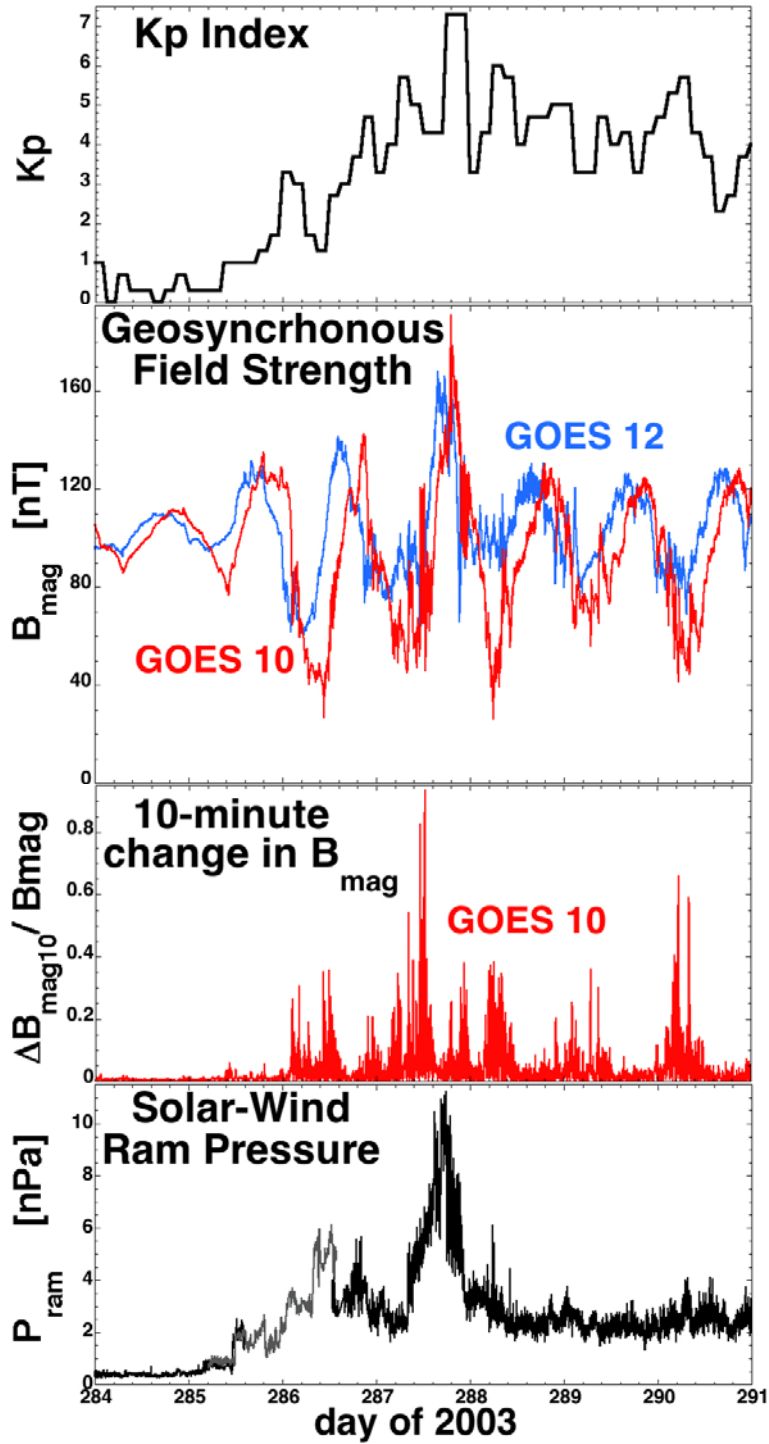


Figure 17. For 7 days in 2003 where geomagnetic activity goes from quiet to a high-speed-stream-driven storm, the magnetic-field strength at geosynchronous orbit is examined. In the top

panel the Kp index is plotted as a function of time, in the second panel the magnetic-field strength as measured by GOES 10 (red) and GOES 12 (blue) are plotted, in the third panel the 10-minute change in the geosynchronous field strength measured by GOES 10 is plotted, and in the bottom panel the solar-wind ram pressure as measured by ACE (black) and WIND (gray) is plotted.

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$B(6.6 R_E)$  [nT]

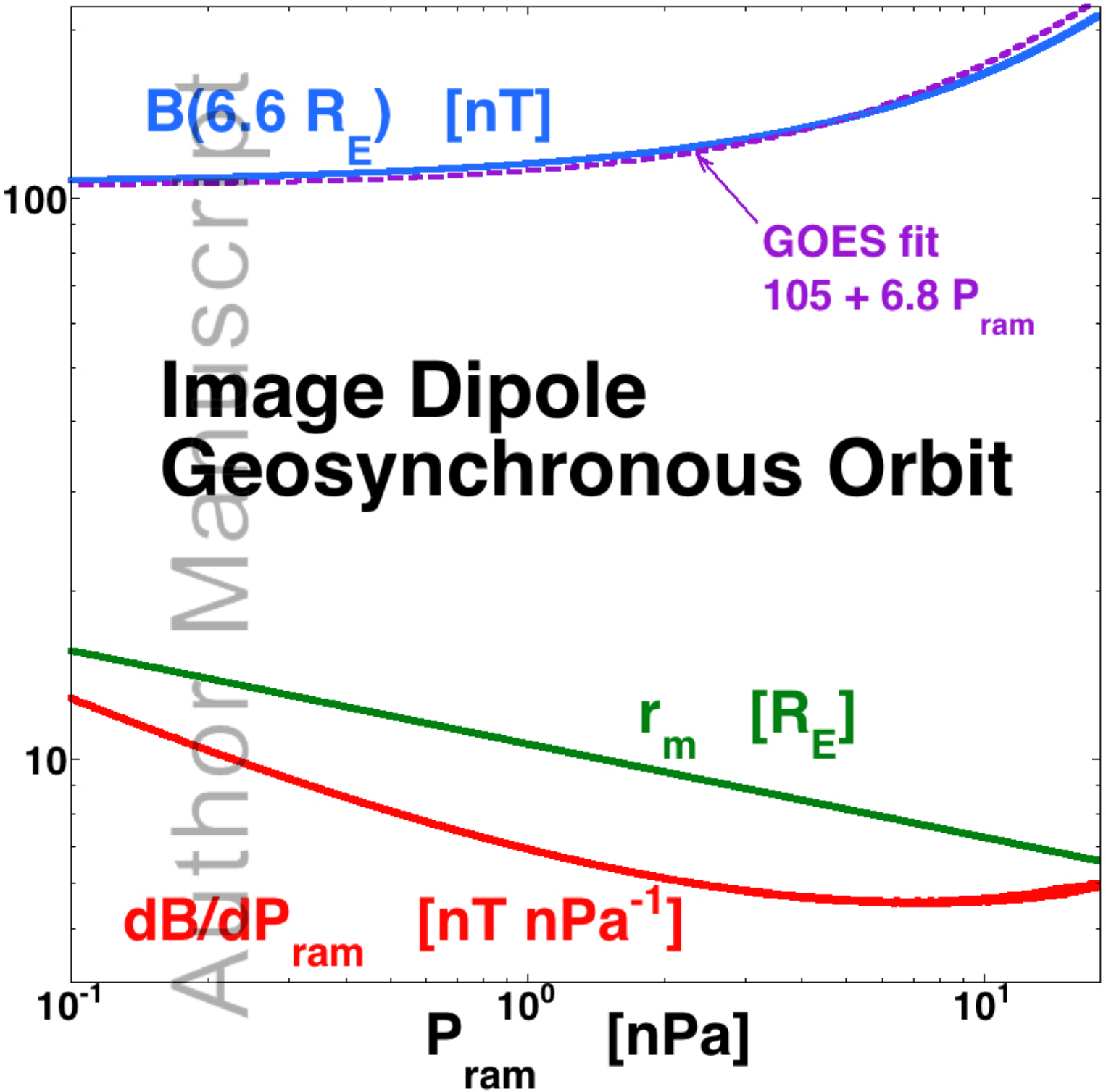
GOES fit  
 $105 + 6.8 P_{ram}$

# Image Dipole Geosynchronous Orbit

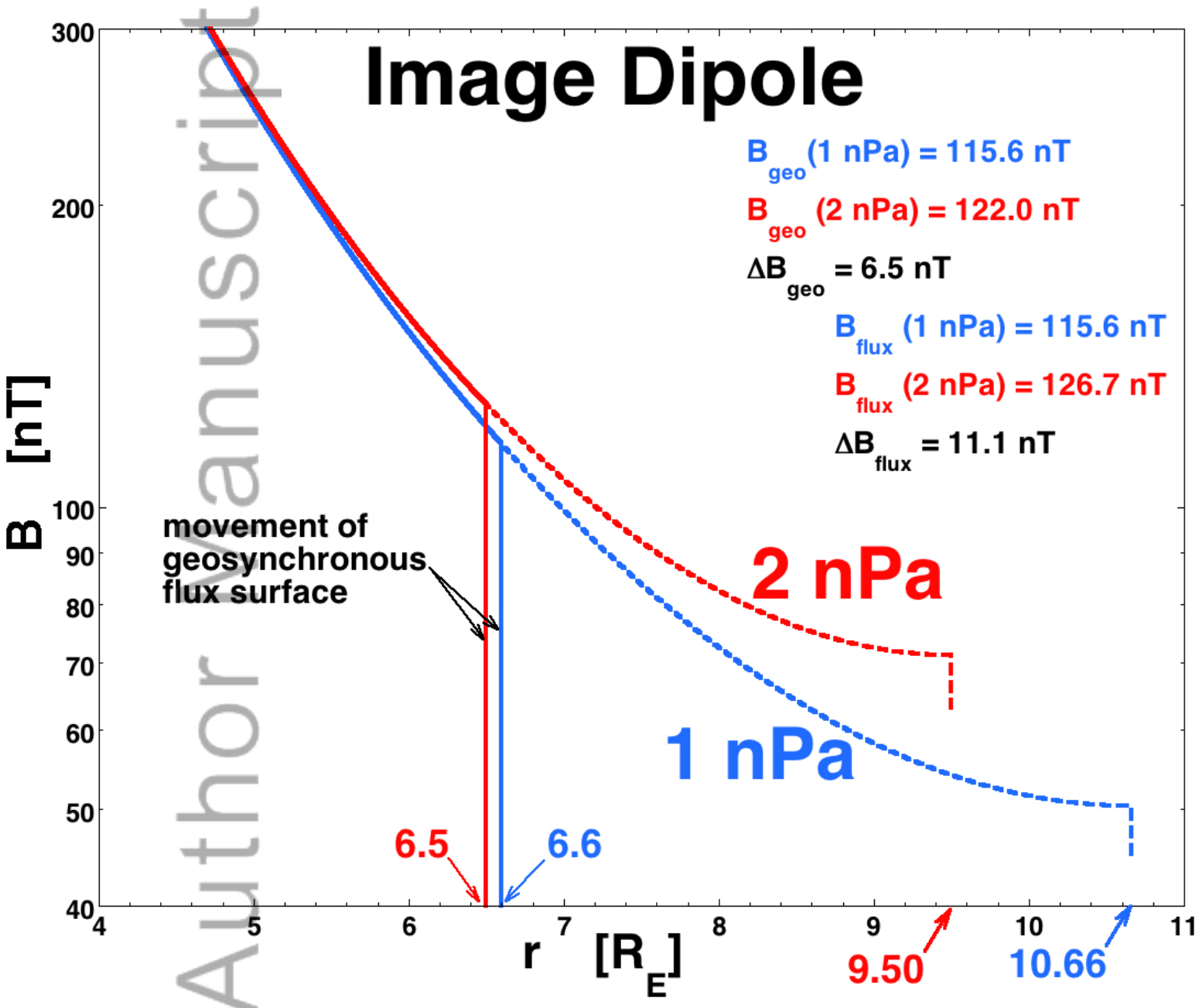
$r_m$  [ $R_E$ ]

$\frac{dB}{dP_{ram}}$  [ $nT nPa^{-1}$ ]

$P_{ram}$  [nPa]

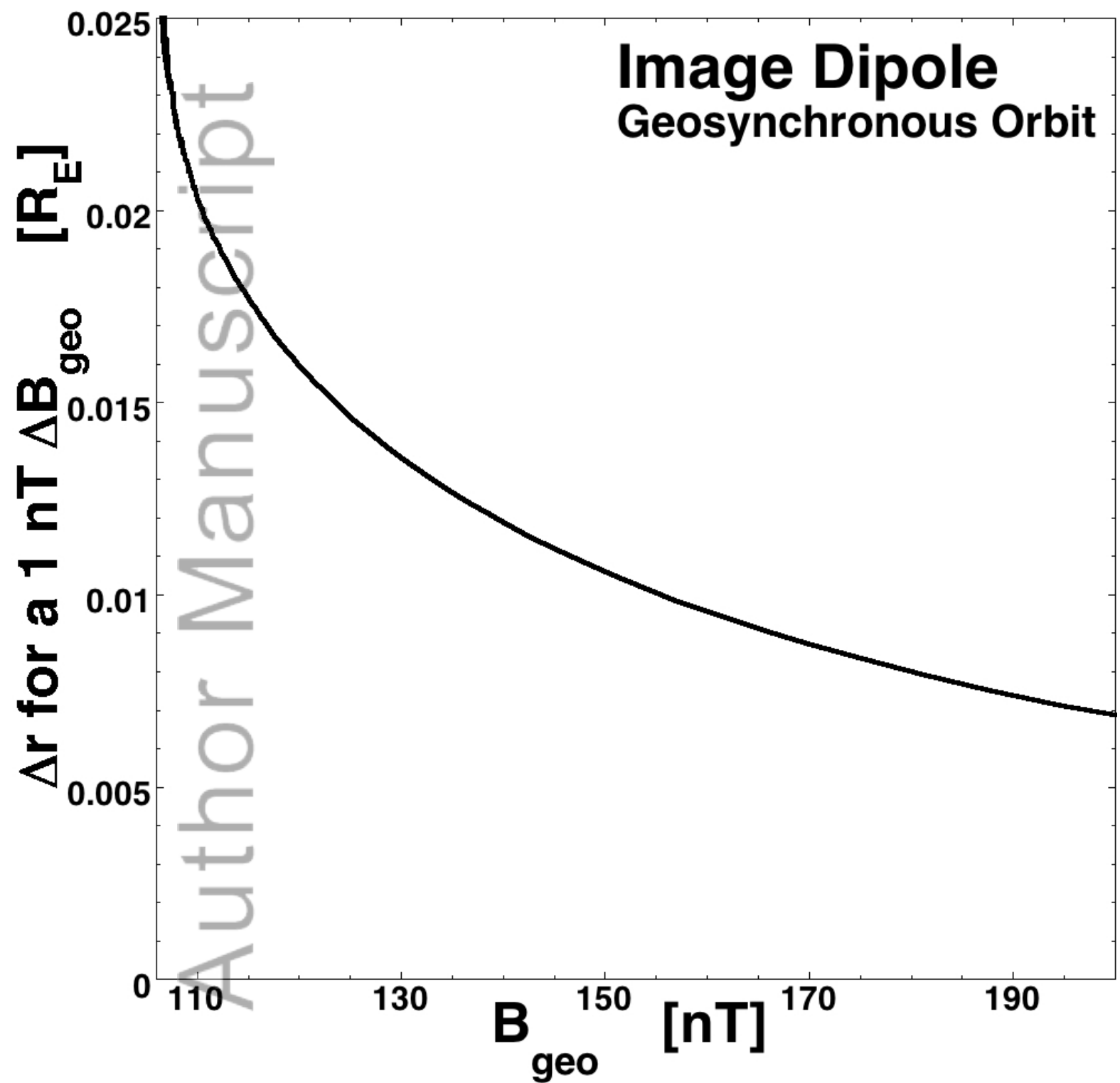


2015JA022136-f01-z-jpg

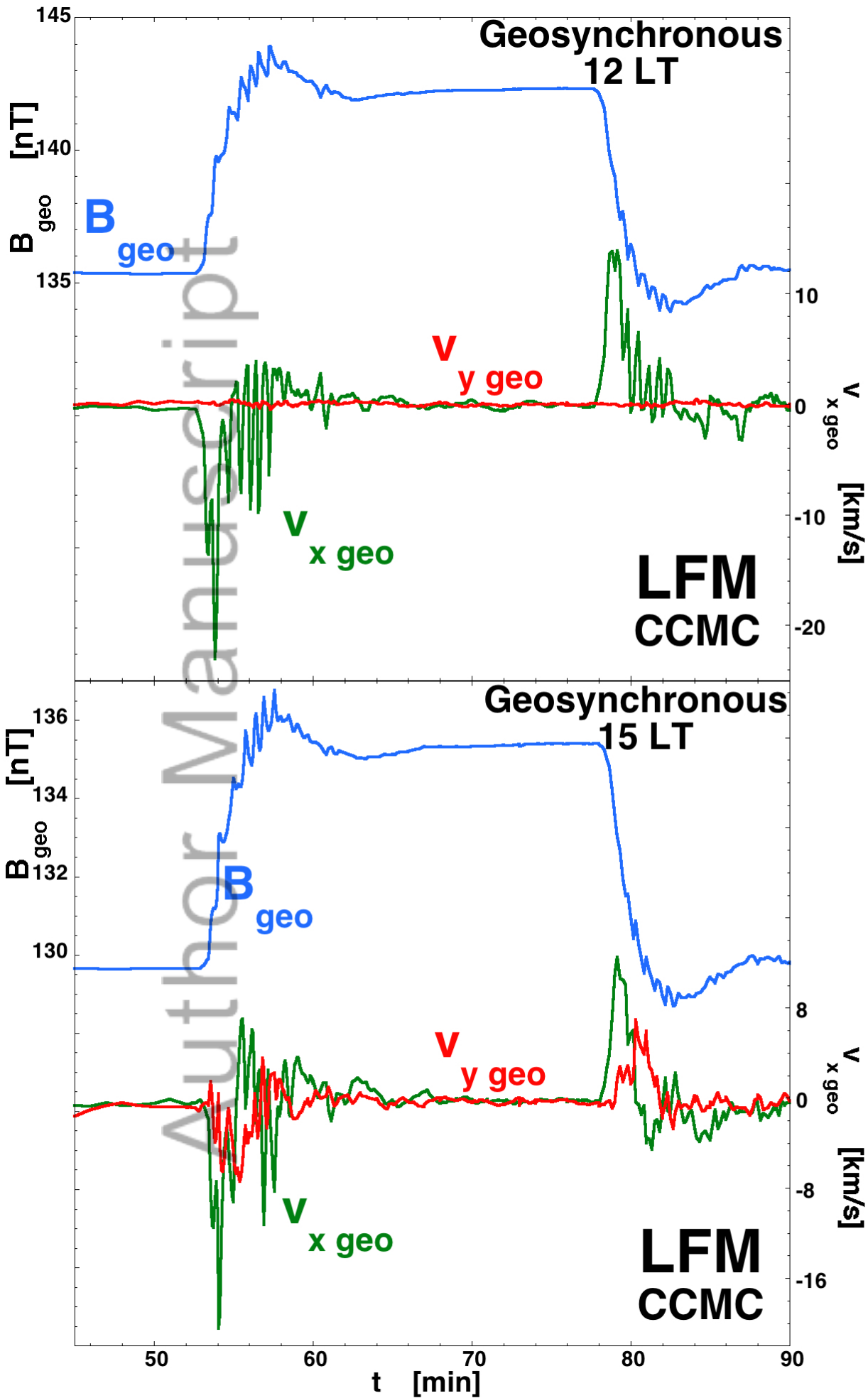


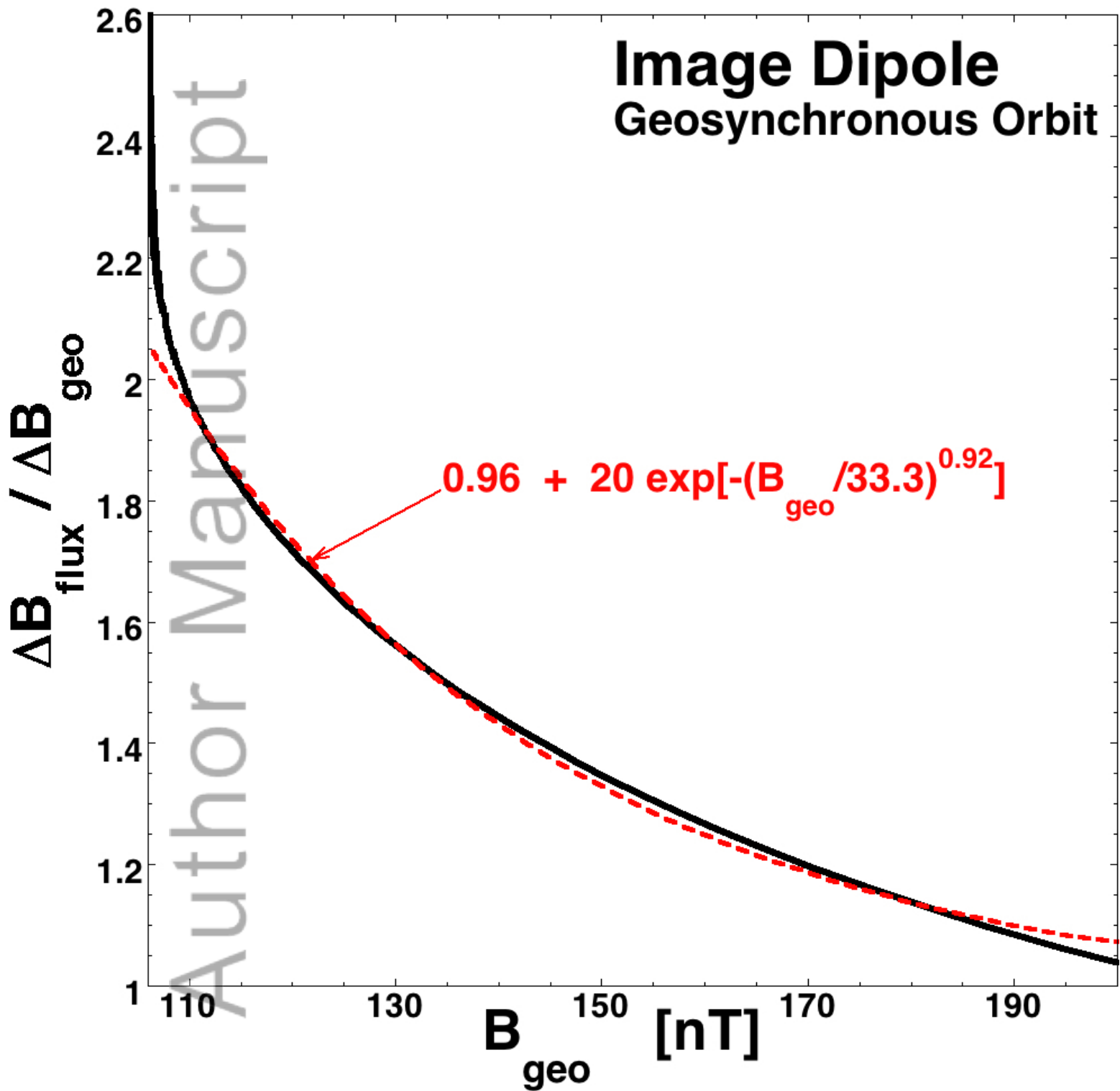
$B_{\text{geo}} (1 \text{ nPa}) = 115.6 \text{ nT}$   
 $B_{\text{geo}} (2 \text{ nPa}) = 122.0 \text{ nT}$   
 $\Delta B_{\text{geo}} = 6.5 \text{ nT}$   
 $B_{\text{flux}} (1 \text{ nPa}) = 115.6 \text{ nT}$   
 $B_{\text{flux}} (2 \text{ nPa}) = 126.7 \text{ nT}$   
 $\Delta B_{\text{flux}} = 11.1 \text{ nT}$

2015JA022136-f02-z-.jpg

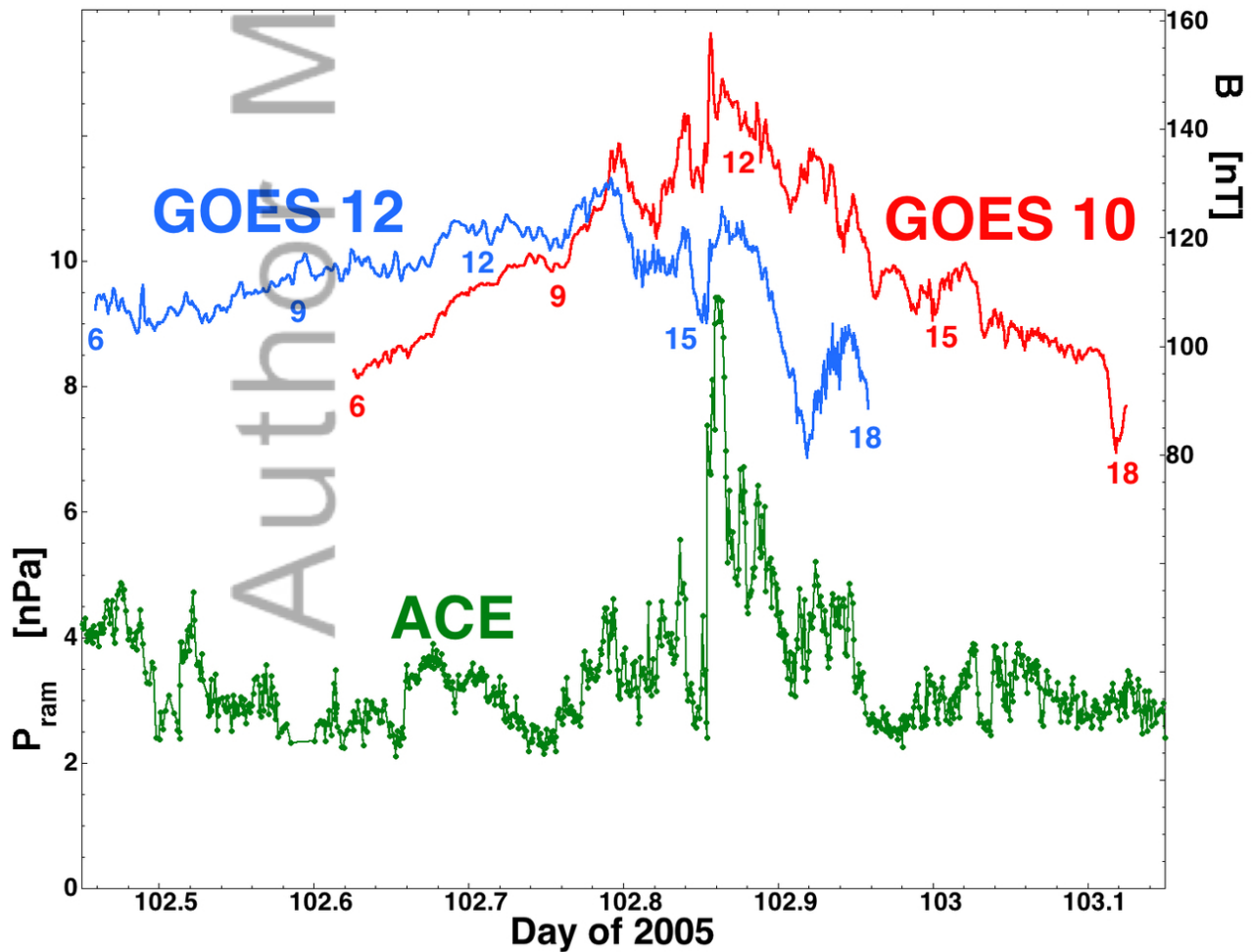
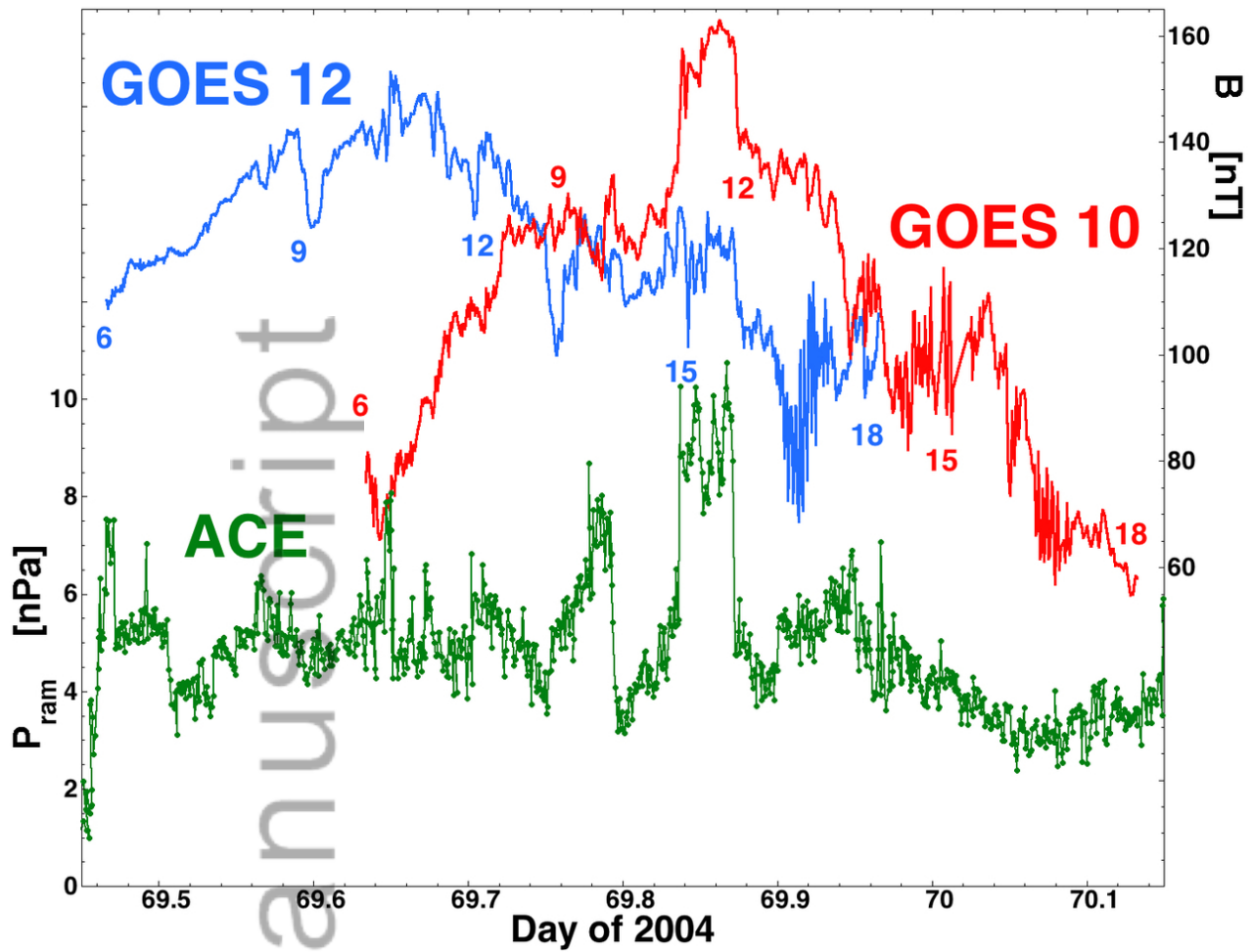


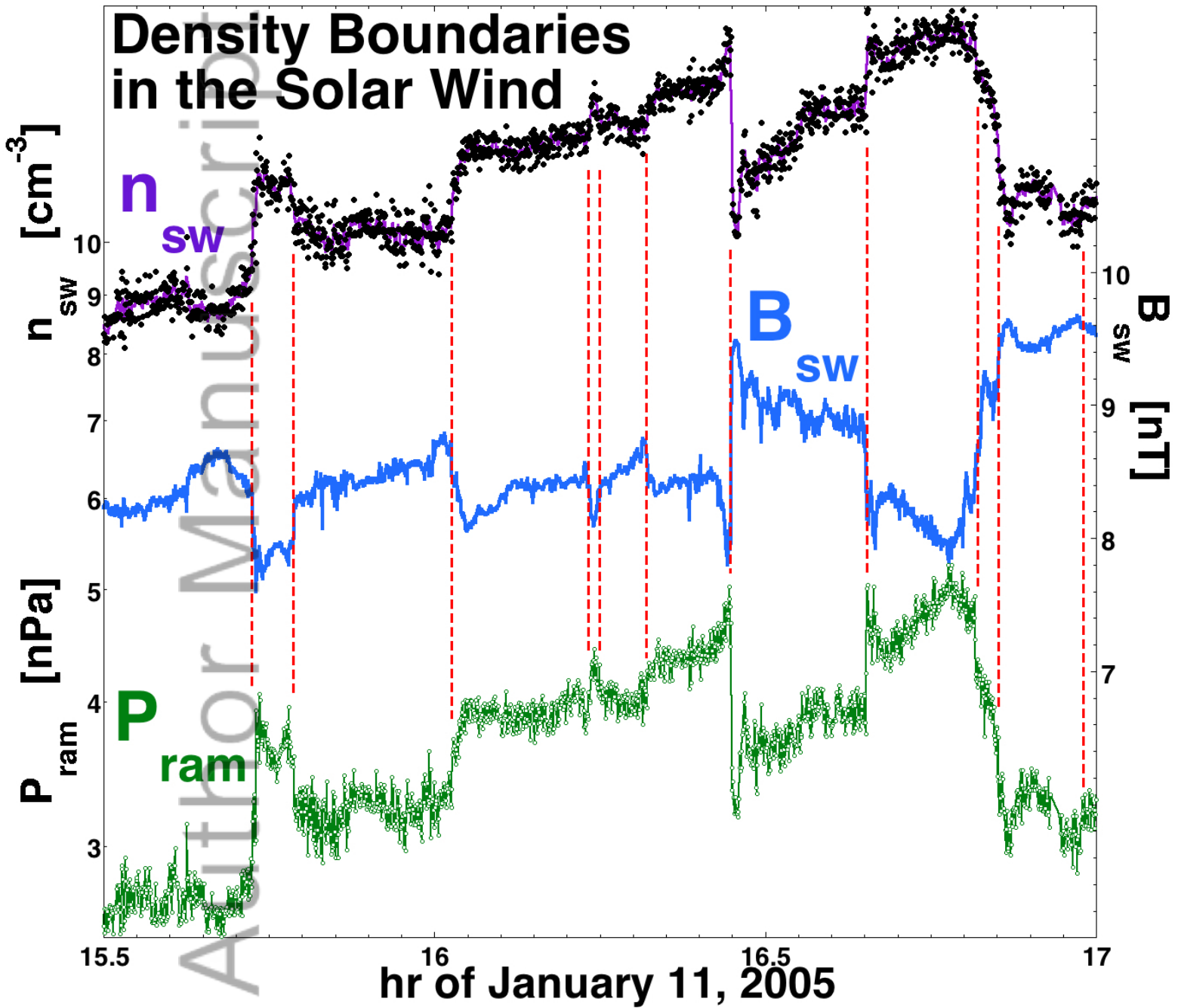
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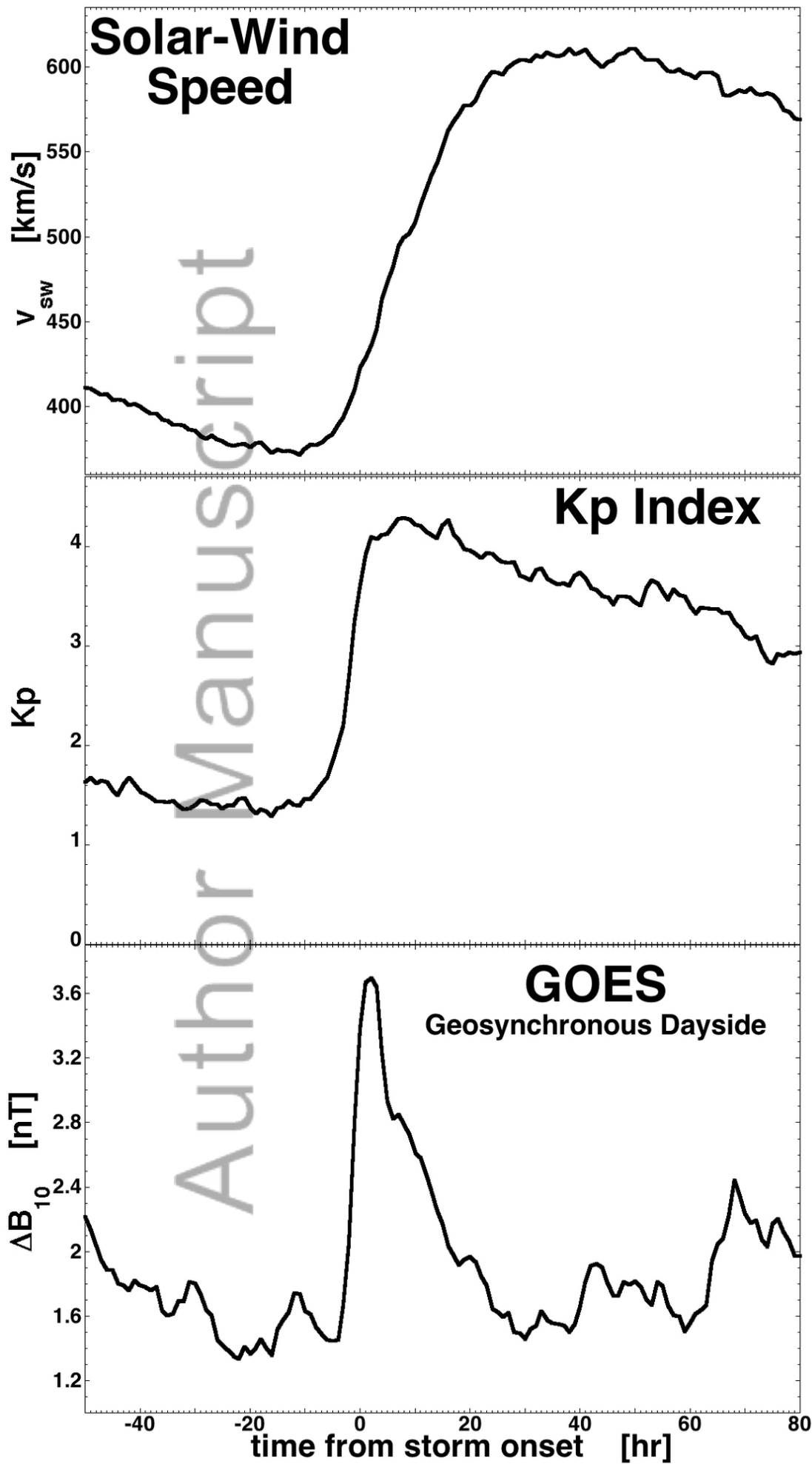


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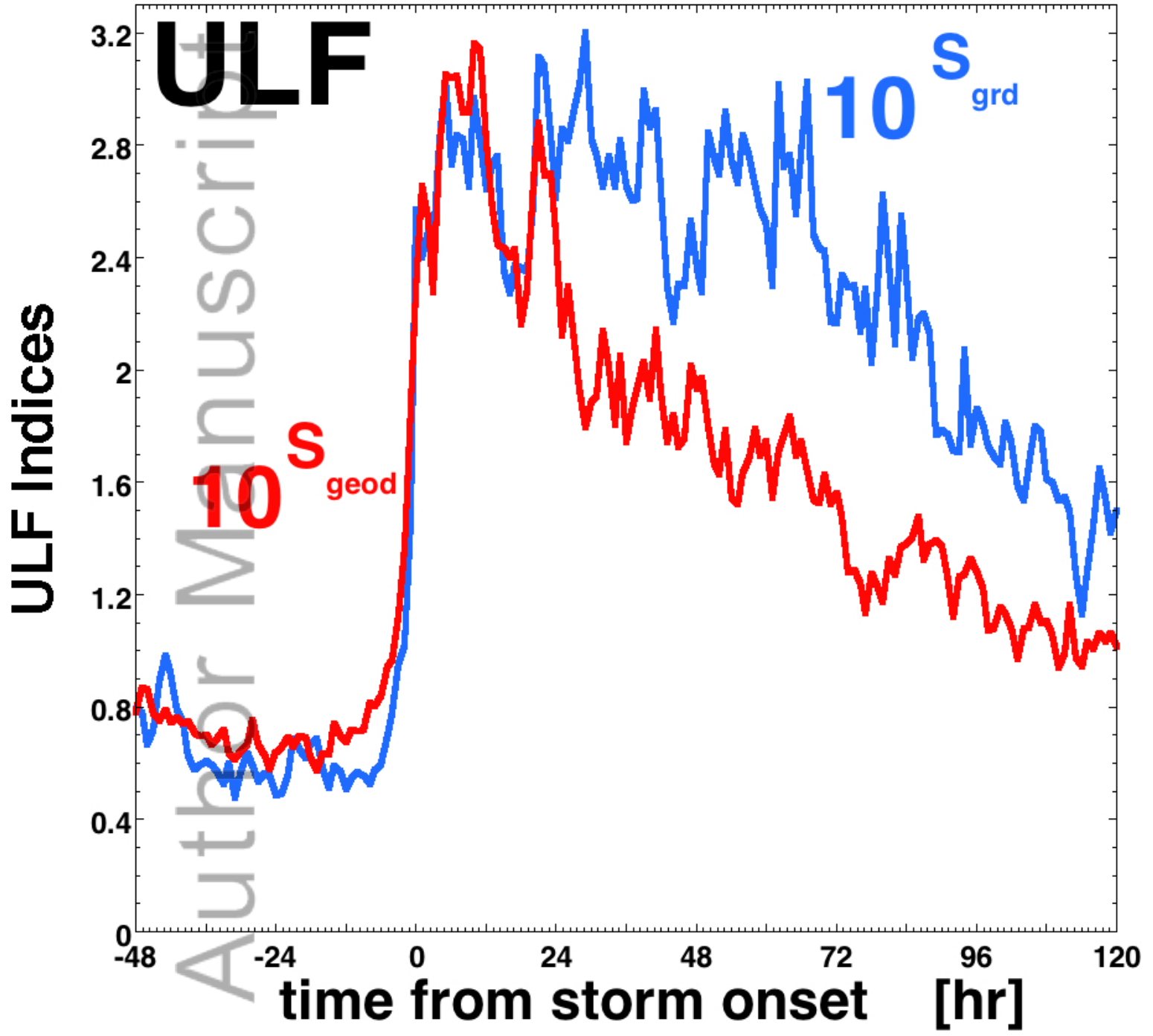




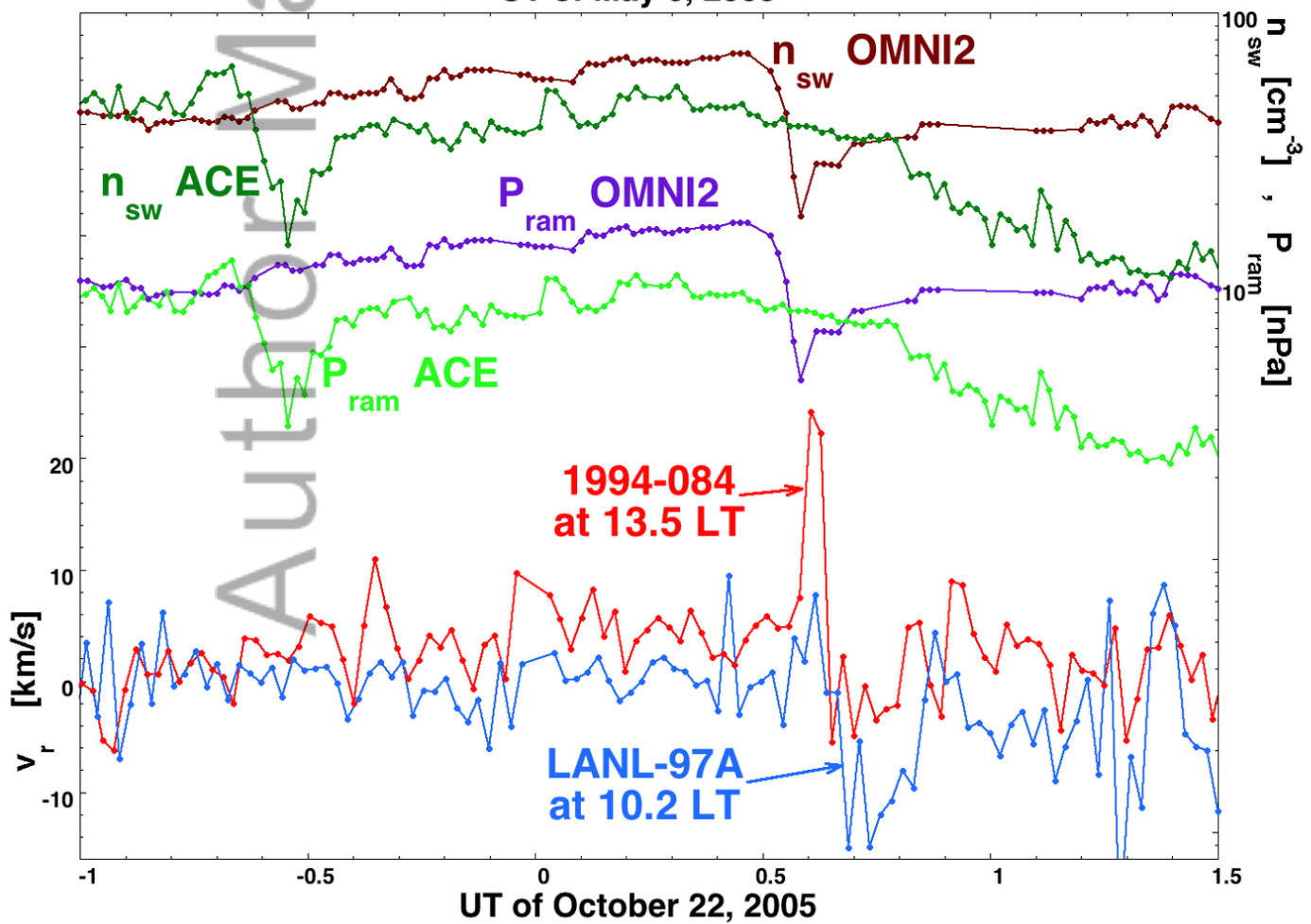
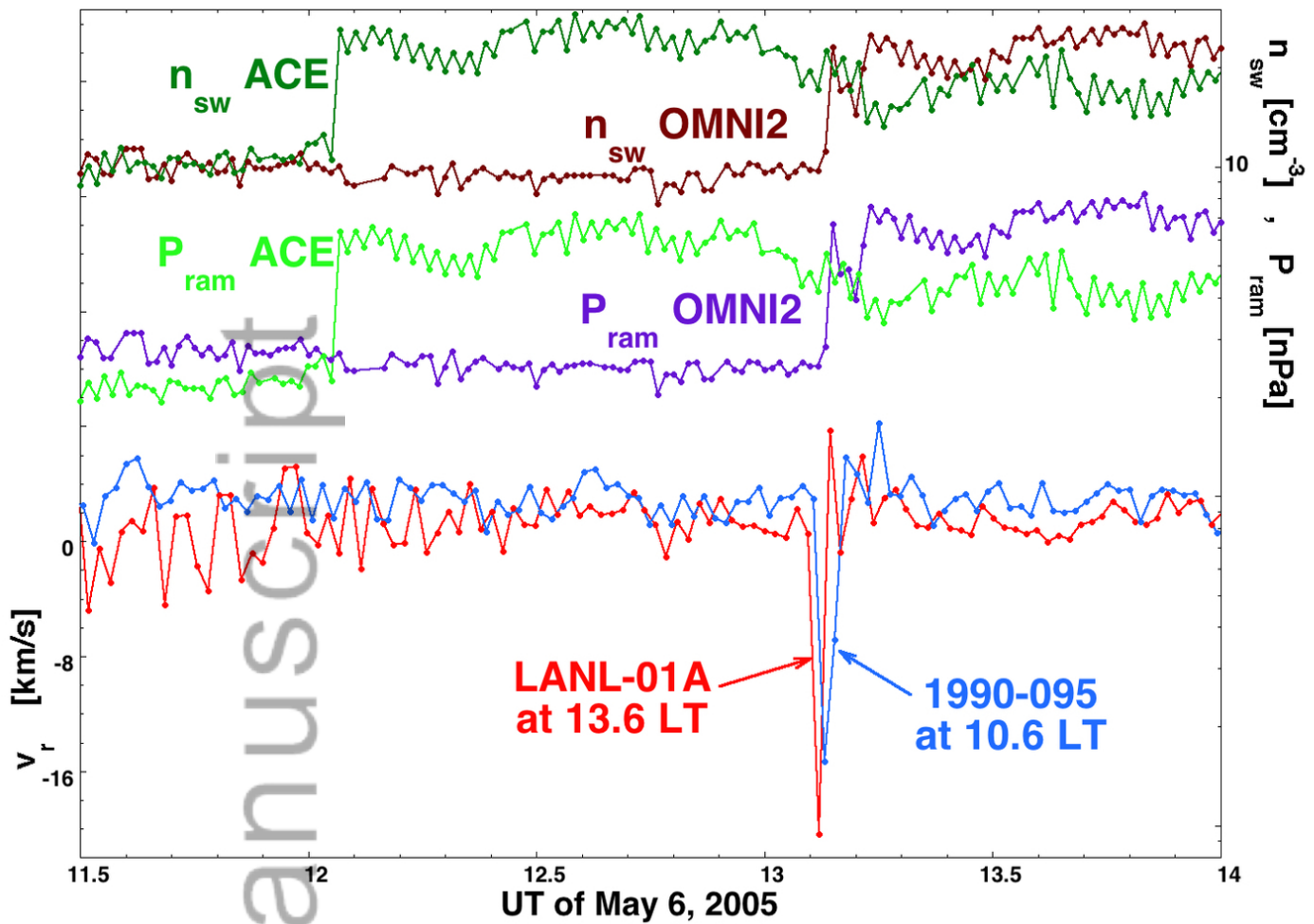
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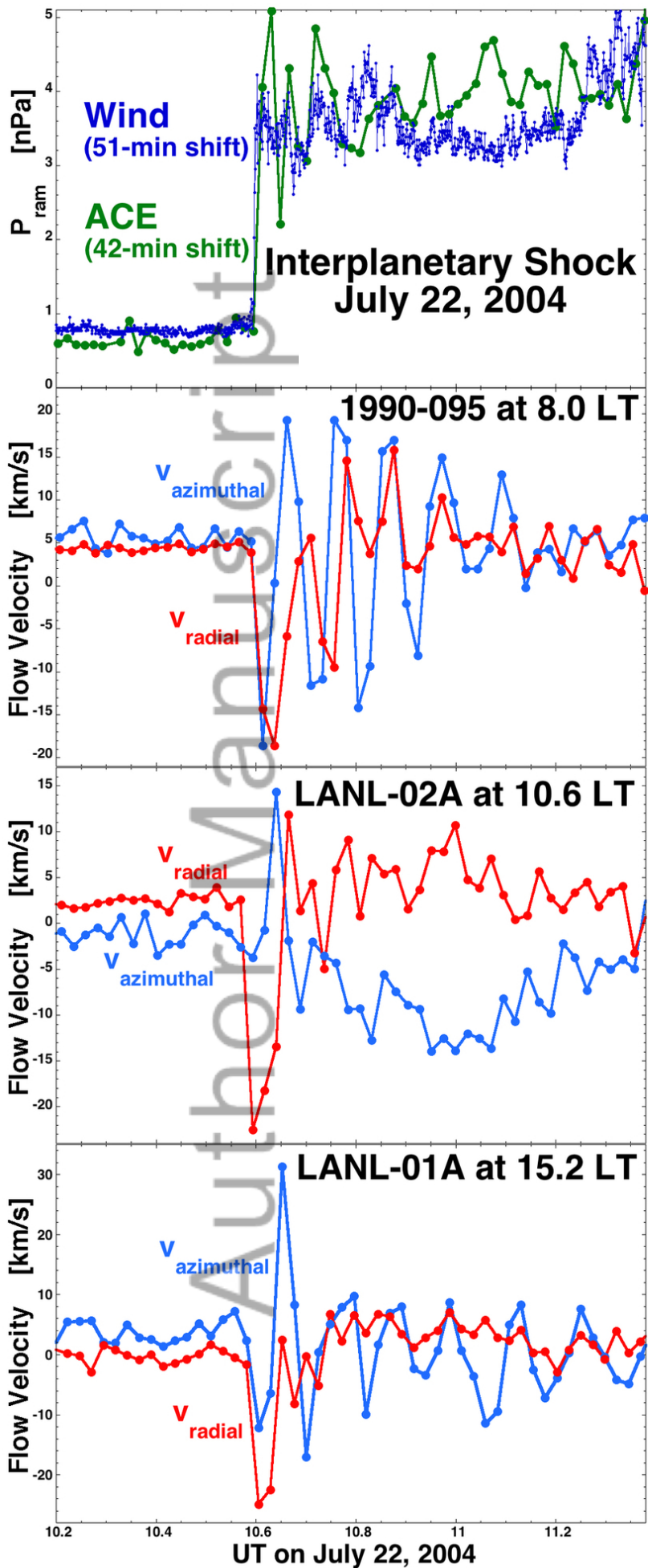






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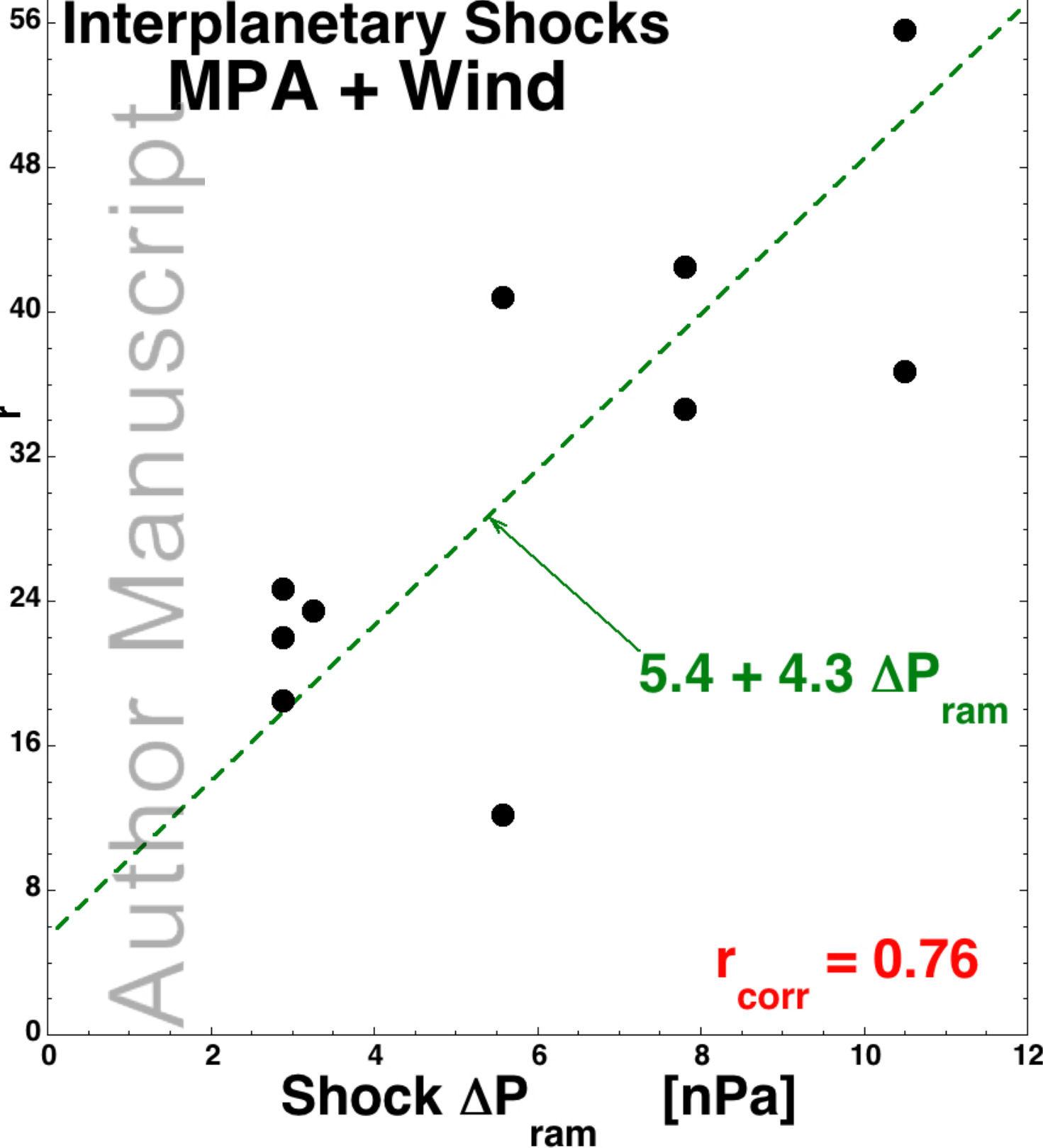




# Interplanetary Shocks MPA + Wind

MPA Dayside  $-v_r$  [km/s]

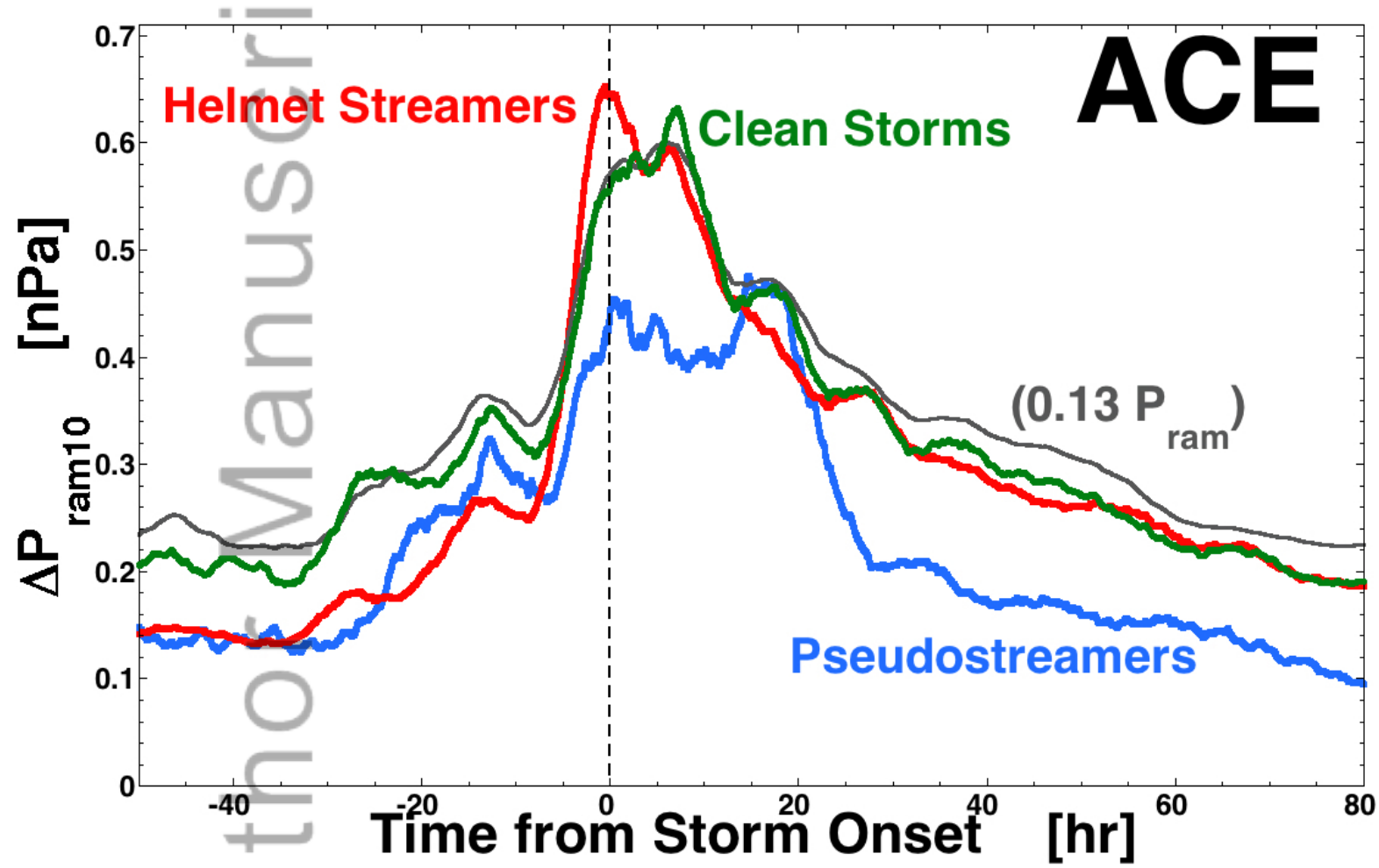
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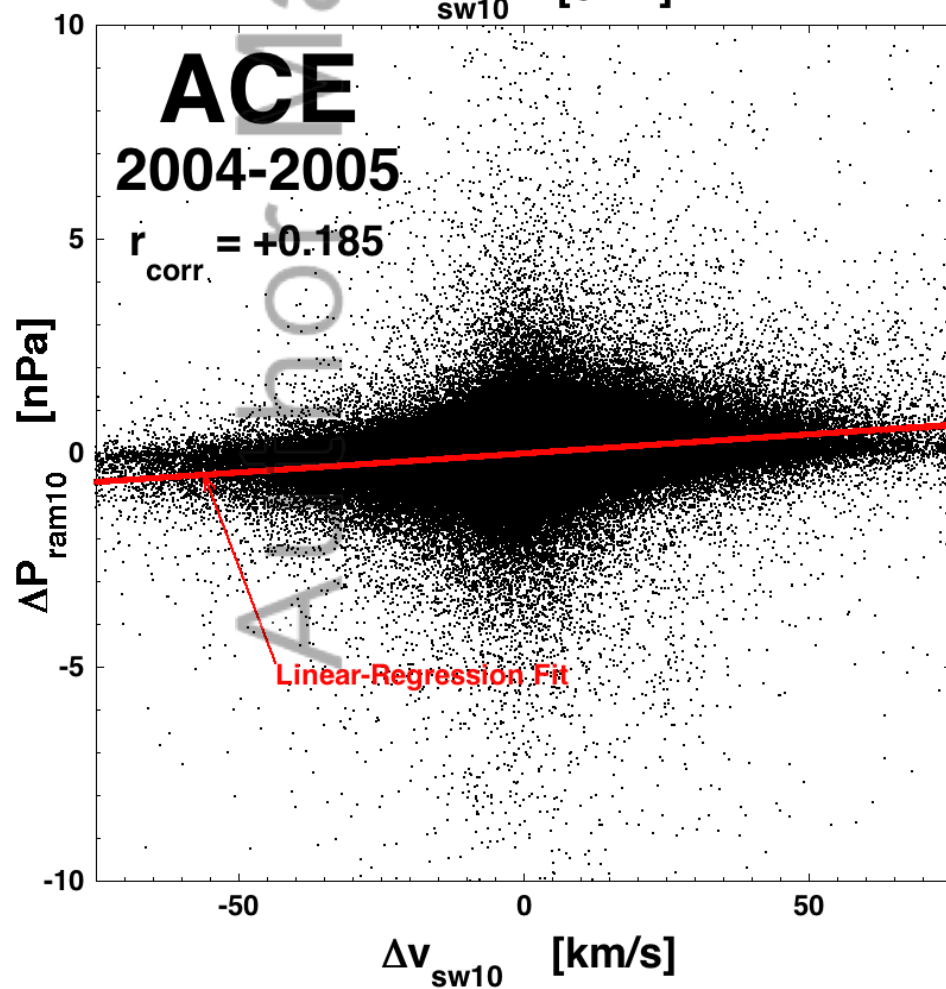
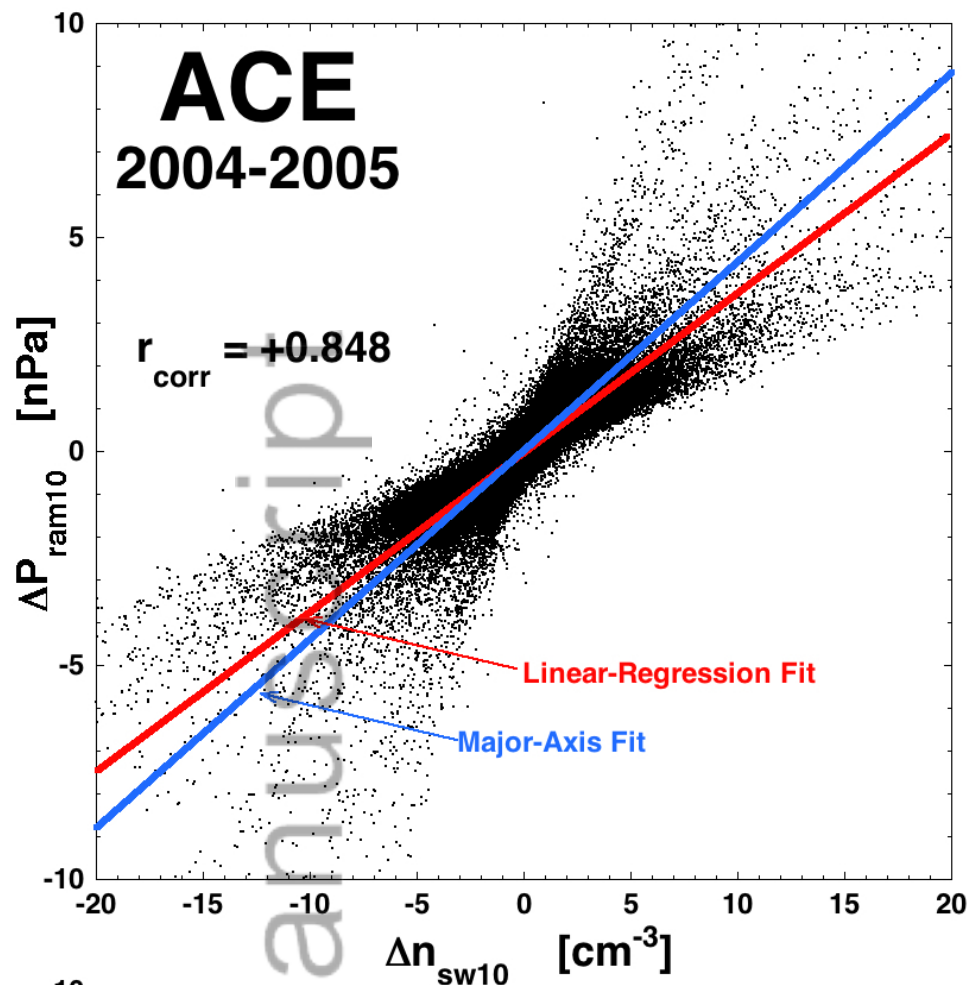
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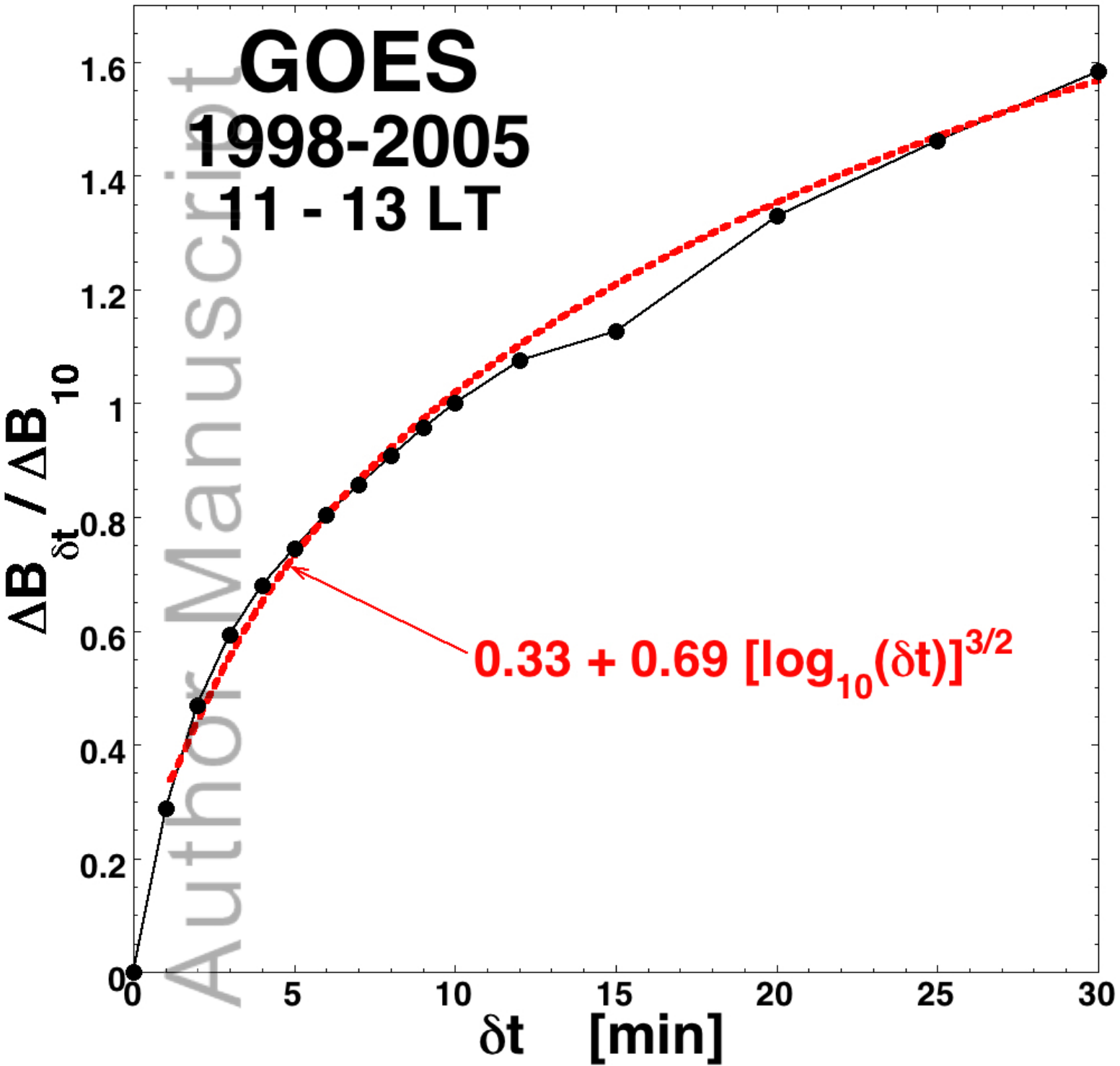
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**ACE**



2015JA022136-f13-z-.jpg





2015JA022136-f15-z-.jpg



