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Giant pulsations: An explanation for their rarity and occurrence during geomagnetically quiet times

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Abstract. It is generally agreed that giant pulsations (Pgs) are the result of a particle instability that occurs inside the magnetosphere rather than the consequence of an external stimulus. Previous studies have suggested that protons with energies ~5-30 keV play a role in Pg excitation. It is shown that protons with energies ~5-30 keV, injected into the inner magnetosphere on the nightside, will only drift westward around the Earth on enclosed paths if the **E**×**B** drifts due to the magnetospheric convection and corotation electric fields are small. This is the case when the magnetosphere is quiet. If the **E**×**B** drifts are large, as is the case for more disturbed times, then their influence may overcome that of the gradient-curvature drift for these lower energy protons, detrapping them from their enclosed paths and allowing them to follow convective paths to the dayside magnetopause. At these times, the lower energy protons which may be an important factor in Pg generation will not reach the early morning sector where Pgs occur. This phenomena can explain the rarity and occurrence during quiet times of Pgs. It can also explain the quashing of Pg activity during substorms and the tendency for Pgs to occur on successive days, 24 hours apart. A similar reasoning can also explain why radially polarized waves with large azimuthal wave numbers, thought to be generated by the bounce resonance mechanism, are frequently observed in the afternoon/evening sector of the magnetosphere but occur infrequently in the morning sector.

Introduction

Giant pulsations (Pgs) are one of the most intriging of all the magnetospheric ULF wave types that have been observed by ground-based instrumentation. Their rarity and extremely sinusoidal appearance makes them unique among ULF pulsations. Pgs are waves in the Pc4 period range (45-150 s) which are characterized by their sinusoidal appearance and long duration of wavepacket. They occur in the early morning hours, with an occurrence peak around the equinoxes in years of solar minimum [*Brekke et al.*, 1987]. They are predominantly auroral zone phenomena, the center of the Pg disturbance being usually located just poleward of the equatorward edge of the auroral oval [*Chisham and Orr*, 1994]. They are characterized by a localization in latitude [*Glassmeier*, 1980; *Chisham et al.*, 1990] and moderately large azimuthal wave numbers [e.g., *Chisham et al.*, 1992]. Comprehensive studies of Pgs have been undertaken using data from magnetometer chains [*Green*, 1979, 1985; *Rostoker et al.*, 1979; *Chisham et al.*, 1990; *Chisham and Orr*, 1991], magnetometer arrays [*Glassmeier*, 1980; *Chisham et al.*, 1992; *Takahashi et al.*, 1992], spacecraft [*Hillebrand et al.*, 1982; *Kokubun et al.*, 1989; *Takahashi et al.*, 1992], and auroral radar [*Poulter et al.*, 1983; *Chisham et al.*, 1992]. They have also been observed in connection with pulsating auroral phenomena [*Taylor et al.*, 1989; *Chisham et al.*, 1990]. All these studies have provided no universally accepted generation mechanism, although it is generally agreed [e.g., *Takahashi et al.*, 1992; *Chisham et al.*, 1992; *Poulter et al.*, 1983] that Pgs are the result of a particle instability that occurs inside the magnetosphere rather than a consequence of solar wind fluctuations as is thought to be the case with some Pc4 pulsations [e.g., *Cao et al.*, 1994].

In the magnetosphere, numerous different particle distributions can occur as a result of the global convection driven by the solar wind. The bulk of this plasma population behaves reactively with any waves present in the plasma. However, particles with velocities which are close to the phase velocity of a wave (termed resonant particles) can exchange energy effectively with the wave and may be accelerated or decelerated by the wave field. Particles with a slightly lower velocity than the wave tend to be accelerated by the wave field, whereas those with slightly higher velocity tend to be decelerated. A Maxwellian distribution of particles which has more slower particles than faster particles about a given energy will damp wave motion. However, non-Maxwellian particle distributions, which can occur quite readily in the magnetosphere, give rise to the possibil-

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ity of wave growth [*Southwood et al.*, 1969; *Southwood*, 1980; *Southwood and Hughes*, 1983]. Whether a group of resonant particles makes a net contribution to wave growth or damping depends on whether the particle distribution function f is increasing or decreasing with energy W in the region where the particle velocity is close to the wave phase velocity. The important parameter is the sign of df/dW [*Southwood et al.*, 1969; *Southwood*, 1980], where

$$\frac{df}{dW} = \frac{\partial f}{\partial W} + \frac{dL}{dW}\frac{\partial f}{\partial L} \qquad (1)$$

where L represents the L shell position of the distribution. This equation shows that instability will only occur if there is a sufficient spatial gradient in some part of the resonant distribution (i.e., $\partial f/\partial L$ is large), or if the distribution is inverted at some point so that $\partial f/\partial W > 0$. Inverted distributions are often observed in the inner ring current [e.g., *Hughes et al.*, 1978; *Southwood*, 1980; *Baumjohann et al.*, 1987]. The quantity $dL/dW \propto m/\omega$, where m is the azimuthal wavenumber and ω is the frequency of the wave involved. It is obvious from (1) that large m and small ω will be effective in maximizing the gradient term and therefore are more favorable for instability.

Energetic protons in the magnetosphere can resonate with waves through the drift-bounce resonance condition [*Southwood et al.*, 1969; *Southwood*, 1976]

$$\omega - m\omega_d = N\omega_b \qquad (2)$$

where ω_d and ω_b are the drift and bounce frequencies of the resonant protons, and N is an integer which reflects the harmonic of the wave. The particles that satisfy this resonance condition see a constant wave electric field and so the wave will either grow or damp depending on the detailed structure of the particle distributions and the energy availability. *Southwood* [1976] showed that it is the N=0,±1 resonances that should be dominant in the magnetosphere. The N=0 drift resonance requires the wave to be an odd-mode standing wave, whereas the N=±1 bounce resonances require the wave to be an even-mode standing wave. Resonantly generated waves should have small east-west wavelengths (large m) and should be dominantly radially polarized [*Southwood*, 1976, 1980]. The N=±1 bounce resonance mechanism has been suggested as an excitation mechanism for Pgs [e.g., *Glassmeier*, 1980; *Poulter et al.*, 1983; *Chisham et al.*, 1992] and requires them to be even-mode standing wave oscillations.

The bounce resonance mechanism is almost alone in requiring even-mode waves, whereas there are many other instabilities that require an odd-mode standing wave. The drift mirror instability [*Hasegawa*, 1969] is the mechanism most often invoked to explain compressional Pc5 waves with an odd-mode standing wave nature. It has also been shown that drift mirror waves can couple to guided poloidal Alfvén waves [*Walker et al.*, 1982]. Another mechanism that requires odd-mode standing waves is the drift-wave instability of the compressional Alfvén mode [*Hasegawa*, 1971] which is excited in a plasma with mixed hot and cold components. These mechanisms have both been suggested as possible Pg excitation mechanisms [e.g., *Green*, 1979, 1985; *Takahashi et al.*, 1992] and require the waves to be odd-mode oscillations.

A major obstacle that restricts further progress in understanding the generation of Pgs is the uncertainty concerning the standing wave mode of the waves. Pgs are observed very rarely on the ground and due to their localization ground-satellite correlations are difficult to make. *Takahashi et al.* [1992] and *Hillebrand et al.* [1982], on the strength of spacecraft observations, have proposed that Pgs are odd-mode waves. Conversely, *Poulter et al.* [1983] and *Chisham and Orr* [1991], by comparing observed Pg periods with those calculated for a model magnetosphere, have suggested that Pgs are even-mode (second harmonic) waves. Two things would help to resolve these conflicting views: (1) in situ measurements of equatorial mass densities during Pg events to enable the calculation of the expected field line eigenperiods; (2) a statistically significant number of ground-satellite correlations with a spacecraft located in the equatorial plane and in the middle of the Pg disturbance. Until the standing wave mode of Pgs is known for certain, theories which rely on either harmonic mode should not be discarded.

Many features of Pg observations are unexplained by previous theories. These include their rarity and occurrence during quiet times, the quashing of Pg activity during substorms [*Rostoker et al.*, 1979] and the tendency of Pgs to occur on successive days, 24 hours apart [*Rostoker et al.*, 1979]. This paper addresses these features.

Some previous studies [e.g., *Chisham et al.*, 1992; *Poulter et al.*, 1983; *Glassmeier*, 1980] have suggested that protons with energies ~5-30 keV play a role in the Pg generation process, possibly through the bounce resonance instability. Therefore a knowledge of proton populations and dynamics in the magnetosphere could be important. *Takahashi* [1995] has pointed out the similarity between the equatorial ion drift orbits of particles with an initial energy of 10 keV [*Takahashi and Iyemori*, 1989] and the equatorial distribution of the occurrence of radially polarized and compressional waves in the magnetosphere [*Anderson et al.*, 1990] some of which are observed to have similar features to Pgs. The waves occur predominantly on the dusk and night sides of the magnetosphere which are the only regions of the inner magnetosphere that freshly injected 10 keV protons will usually travel through before exiting the magnetosphere. This example shows the potential importance of magnetospheric proton dynamics in explaining the occurrence patterns of ULF waves generated by particle instabilities inside the magnetosphere.

Proton Dynamics in the Magnetosphere

In the guiding center approximation, where a particle's cyclotron radius is much smaller than the scale length of the system, the motion of a charged particle in a dipole magnetic field can be broken down into three distinct components due to the large differences in their timescales. These three components of particle motion are the rapid gyration around a field line, the bouncing back and forth along a field line between the two mirror points and the slow drift in longitude around the Earth. In the quasi-dipolar magnetosphere where electric fields also influence particle motion the drift of particles can be described by two components; the drift due to the gradient and curvature of the magnetospheric magnetic field and the **E**×**B** drift due to the magnetospheric electric fields. The **E**×**B** drift induces radial motion of the particles within the field and also changes in the kinetic energy of the particles due to the changes in the magnetospheric electric potential. Particles generally lose energy as they drift to higher L shells, which accentuates the influence of the **E**×**B** drift and can lead to low energy particles leaving the magnetosphere through the dayside magnetopause. The total change in kinetic energy of a particle depends on the potential variation in the magnetosphere, which is related to geomagnetic activity.

Assuming the guiding center approximation and a time-stationary dipolar magnetospheric magnetic field, the change in azimuth ($\dot{\phi}$) and L shell ($\dot{L}$) of the equatorial drift path of a single proton with respect to time can be approximately described by the following:

$$\dot{\phi} = -\frac{6WLP(\alpha)}{B_S R_E^2} + \frac{2\psi_0 L^3 \sin\phi}{B_S R_E^2} + \Omega_E \qquad (3)$$

$$\dot{L} = -\frac{\psi_0 L^4 \cos\phi}{B_S R_E^2} \qquad (4)$$

(adapted from *Li et al.* [1993] and *Hamlin et al.* [1961]). These equations include the effects of gradient and curvature drift and **E**×**B** drifts due to the convection and corotation electric fields but take no account of any ULF wave fields that may be present. In the above equations, ϕ is the azimuthal angle (positive eastward with midnight at 0°), W is the proton energy in eV, L is the proton's L shell location, B_S is the equatorial magnetic field strength at the surface of the Earth, R_E is the radius of the Earth, Ω_E is the angular frequency of the Earth's rotation, and $P(\alpha)$ is a function of pitch angle given approximately by $P(\alpha) \approx 0.35 + 0.15 \sin\alpha$ [*Hamlin et al.*, 1961] where α is the proton's equatorial pitch angle. Also, ψ_0 is an electric potential that represents the dawn-dusk convection electric field and is calculated using the Volland-Stern empirical model [*Volland*, 1973; *Stern*, 1975]. This potential can be written as an empirically determined K_p-dependent expression [*Li et al.*, 1993; *Maynard and Chen*, 1975],

$$\psi_0 = 45\left(1 - 0.159K_p + 0.0093K_p^2\right)^{-3} \qquad (5)$$

Assuming a dipolar magnetic field means that the calculated particle drift paths are slightly different than they would be in the magnetosphere, especially at high L shells. However, away from the midnight meridian the dipole field is a very good approximation of the magnetospheric field out to $L{\sim}8$. Particle drift paths at greater L shells should be treated with caution. In this paper an attempt is made to avoid proton drift paths in the midnight sector due to its increasingly nondipolar nature at high L shells.

The kinetic energy W of a proton at any position in the field can be calculated by assuming the conservation of total energy. This assumes knowledge of the initial kinetic energy and position of the proton and also the difference in the electric potential between the initial position and the present position in the field. It also assumes that no energy has been lost through any wave-particle interactions. The electric potential at any position in the magnetospheric field can be estimated, including convection and corotation but excluding wave fields [e.g., *Fairfield and Viñas*, 1984] as

$$\Phi = \psi_0 L^2 \sin\phi - \frac{\Omega_E B_S R_E^2}{L} \qquad (6)$$

The change in the equatorial pitch angle of the proton also needs to be calculated, and this is done by assuming the conservation of the magnetic moment.

By using a small time step it is possible, using the above equations, to estimate proton equatorial drift paths through the magnetosphere. The motion of energetic protons ($\gtrsim$50 keV) is dominated by the gradient-curvature drift as its strength is energy dependent; that is, the first term in (3) is dominant. The **E**×**B** drifts become more important for the lower energy protons. Particles are lost through the magnetopause if the **E**×**B** drift due to the convection electric field starts to dominate. *Li et al.* [1993] report that during quiet to moderate times ($K_p{\sim}1.5$), ions near synchronous orbit need about 25 keV at dusk to be able to drift around the Earth and not be lost through the magnetopause.

Estimating Proton Drift Paths in the Magnetosphere

The above method has been used to trace the equatorial drift paths of protons with four different initial kinetic energies. The initial energies chosen range from 50 keV, for which the contribution of the gradient-curvature drift is much greater than that of the **E**×**B** drifts, to 10 keV, for which the **E**×**B** drifts are dominant. The start of the proton paths were chosen as a range of radial distances from L=5.0 to L=10.0 (every 0.5L), and at a local time of 2100 MLT. It is rare for substorm injected particles to be injected deeper into the magnetosphere than $L{\sim}5$. Therefore it seems likely that the majority of the protons injected into the magnetosphere during a substorm would pass through our initial positions. The time step for the simulation was chosen as 5 s, which is small enough to make the changes in L and ϕ a small fraction of their actual values (using a 20 s time step results in identical particle trajectories). The end of the proton paths was chosen to be either the magnetopause (as given empirically by *Fairfield* [1971]) or 0300 MLT, which is as early in magnetic local time as Pgs are usually observed. The initial pitch angle of the protons was chosen as 45° to show the behavior of average protons. Changing the initial proton pitch angle has a minimal effect on the particle drift paths. For larger pitch angles the lower energy particles have a slightly greater chance of reaching the morning sector of the magnetosphere due to the increasing influence of the gradient-curvature term in (3).

Figure 1 displays the drift paths of the four proton types in an average magnetosphere (K_p=2). The higher energy protons (50 keV), for which the gradient-curvature drift is dominant, drift round to the dawnside of the magnetosphere on almost circular paths. The **E**×**B** drifts have a small effect in slightly increasing the L shell of the protons on the dawnside of the magnetosphere and slightly decreasing their energy (e.g. the L=8.5 proton finishes at L=9.7, W=34.4 keV; the L=5.0 proton finishes at L=5.2, W=44.8 keV). For the midrange energy protons (30 keV), those protons that start at the higher L shells are lost through the magnetopause. Those that start at the lower L shells (L=5.0-6.5) manage to drift round to the morning sector with a consequent loss in energy and increase in L shell (e.g., the L=6.5 proton finishes at L=7.6, W=19.3 keV; the L=5.0 proton finishes at L=5.4, W=23.9 keV). For both the lower energy protons (20 keV, 10 keV) the **E**×**B** drifts have more influence and the protons are moved to higher L shells quicker than they drift in longitude. This accentuates the dominance of the **E**×**B** drifts to the extent that the protons exit the magnetosphere through the magnetopause.

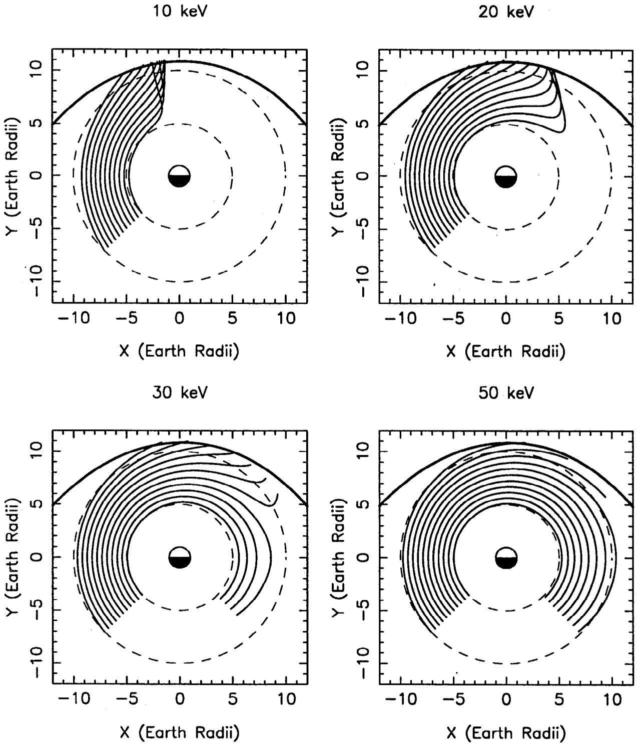

Figure 1. The drift paths of protons of four different energies through the magnetosphere for average geomagnetic conditions (K_p = 2). The initial pitch angle of the protons is 45°. The dashed circles are for reference and represent L=5 and L=10. The thick solid line represents an estimate of the magnetopause position.

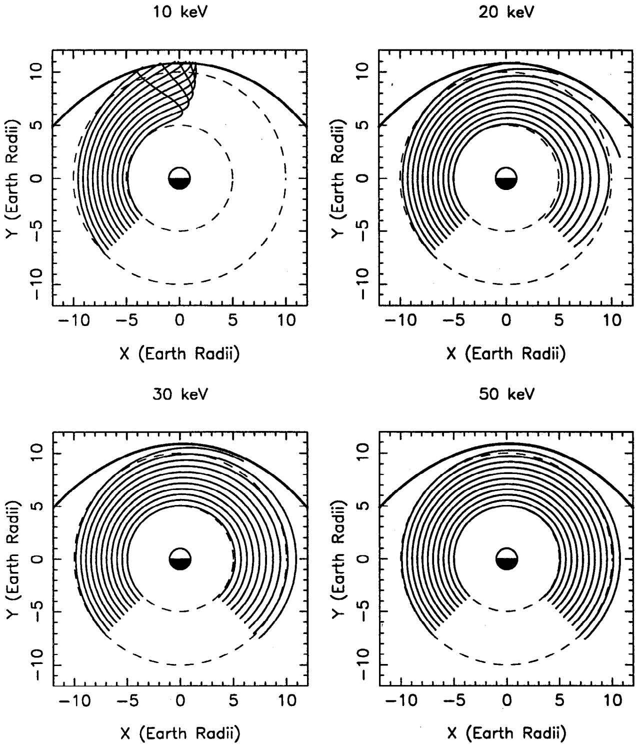

Figure 2. The drift paths of protons of four different energies through the magnetosphere for quiet geomagnetic conditions (K_p = 0). The initial pitch angle of the protons is 45°. The dashed circles are for reference and represent L=5 and L=10. The thick solid line represents an estimate of the magnetopause position.

Figure 2 displays the drift paths for the same four initial proton energies in a very quiet magnetosphere (K_p=0). When the magnetosphere is quiet the size of the convection electric field is reduced and hence the influence of **E**×**B** drifts is diminished. In this case the majority of the 20 keV protons can also make the journey round to the dawnside of the magnetosphere without being lost to the magnetopause. Once again the **E**×**B** drifts have the effect of increasing the L shell of the protons on the dawnside and decreasing their energy (e.g., the L=8.0 proton finishes at L=9.2, W=13.9 keV; the L=5.0 proton finishes at L=5.3, W=17.4 keV). The 10 keV protons, however, are still all lost from the magnetosphere. Generally, the lower the geomagnetic activity, the lower the energy of the protons which can drift to the morning sector of the magnetosphere.

A number of simulations have been carried out for a range of K_p~0-4. These show that protons injected at L~6 with energies $\lesssim$15-55 keV (depending on K_p) rarely reach the dawnside magnetosphere. However, the K_p index is a 3-hour averaged index and can only be used to give a crude estimate of the magnetospheric electric field. A lower electric field than that predicted by using K_p=0 could occur for short periods of time in very quiet conditions. It is therefore possible that lower energy protons than those predicted here could occasionally reach the dawnside of the magnetosphere.

The above simulations have not included any effect that large-scale ULF waves present in the magnetosphere may have on the drifting protons. The particle oscillations due to ULF wave electric fields involve much larger changes in L than those due to the convection electric fields. It has been shown [e.g., *Li et al.*, 1993] that the interaction with Pc5 waves can cause a particle's kinetic energy to drop below the amount required to overcome the convection potential, and hence the particle will be lost through the magnetopause. This means that at times when large-scale ULF waves are present in the magnetosphere, the lower energy protons which would otherwise have traveled to the morning sector could be lost through the magnetopause.

The fact that these lower energy protons have trouble reaching the early morning sector, where Pgs are observed, may be the reason for their rarity and occurrence during geomagnetically quiet times. Previous studies have suggested that protons with energies ~5-30 keV may play a role in the Pg generation process. *Glassmeier* [1980] suggested that Pgs may be the result of the bounce resonance instability with protons with energies ~13 keV. *Poulter et al.* [1983] similarly calculated that Pgs may be the result of the bounce resonance instability with protons with energies ~10 keV. *Chisham et al.* [1992] used three features of a Pg observation to suggest that low energy protons were associated with Pg generation. First, they showed that the movement of the Pg disturbance region in magnetic local time matched the drift velocity of protons with energies ~10-20 keV (depending on pitch angle). It is possible that this association explains the long duration and sinusoidal nature of Pgs, as the disturbance has time to build up [*Glassmeier*, 1980]. Second, they showed that the bounce resonance instability was satisfied for their event by protons with energies ~5-18 keV (depending on pitch angle). Third, they showed that protons with energies ~11-24 keV, injected into the inner magnetosphere during a substorm that occurred on the previous day, would have reached the Pg disturbance region at the time of the Pg observation. These observations show the possible link between Pgs and protons with energies ~5-30 keV. If this connection is crucial to Pg generation then the fact that these particles rarely reach the early morning sector of the magnetosphere could explain the rare occurrence of Pgs. The fact that this traverse is more easily made during quiet geomagnetic conditions can also explain the increased Pg occurrence at quiet times.

This theory can also explain the observation by *Rostoker et al.* [1979] of the quashing of a Pg event during a substorm. The occurrence of the substorm will temporarily increase the magnetospheric electric field meaning that the protons needed for the Pg generation are forced off their enclosed paths and out of the magnetosphere. When the magnetosphere returns to a quieter state these protons can then once again reach the morning sector and so the Pg event can recommence.

An Explanation for the 24-Hour Recurrence of Pgs

The occasional observations of Pgs recurring on consecutive days, approximately 24 hours apart, can also be explained if Pg generation is connected to these drifting proton populations. If, in the 24 hours following a Pg event, the magnetosphere remains in an approximately quiet state (i.e., very low K_p), then the particle populations which were responsible for exciting the original Pg will be able to make a full circuit of the magnetosphere. By coincidence, the drift period of protons with energies ~10-20 keV (at L~4-7) is approximately 24 hours. When an observation point on the Earth's surface reaches the same position where a Pg event has been observed 24 hours earlier, similar particle populations may be present in this region of the magnetosphere, resulting in a similar Pg disturbance. Obviously, any significant increase in magnetic activity during this time would stop this repetition from occurring as these particles would be lost from the magnetosphere.

This theory is backed up by the characteristics of Pgs observed on succesive days. In 34 Pg events observed by the EISCAT magnetometer cross [*Chisham and Orr*, 1991] an occurrence on successive days was observed twice. *Rostoker et al.* [1979] also observed a Pg event on three successive days. These events have been studied in order to compare the energy of protons with drift times which would link the successive events with the energy of protons whose bounce periods would satisfy the bounce resonance condition for that event. These comparisons are presented in Tables 1 and 2 for two different pitch angles, 20° and 80° respectively, to show the range of results possible.

Table 1 (α=20°) presents, for each Pg event, the start time in magnetic local time (MLT), the wave period at the start of the event and the resonant L shell at the start of the event. There are also two sets of proton energy calculations, one calculated from proton drift times (W_d) and the other from proton bounce times (W_b). W_d is the proton energy from two different calculations: (1) the energy of protons that would drift (in one orbit) from the start of the event on day 1, starting

Table 1. Proton Energy Calculations for Pgs Observed on Consecutive Days: 20° Pitch Angle Case

Date	Start Time, MLT	T, s[a]	L[b]	W_d, keV[c]	W_b, keV[d]
	EISCAT Magnetometer Cross Event 1				
Nov. 18, 1987	0520	135	6.3	12.0	8.2
Nov. 19, 1987	0400	128	6.1	12.7	8.6
	EISCAT Magnetometer Cross Event 2				
Oct. 10, 1985	0400	102	6.1	11.7	13.2
Oct. 11, 1985	0415	77	5.7	12.5	20.0
	Rostoker et al. [1979] Event 1				
Sept. 10, 1974	0450	80	5.4	16.2	17.0
Sept. 11, 1974	0100	85	5.4	17.2	15.2
	Rostoker et al. [1979] Event 2				
Sept. 11, 1974	0100	85	5.4	14.3	15.2
Sept. 12, 1974	0130	85	5.4	14.0	15.2

[a] The observed wave period at the start of the Pg event (±10 s).

[b] The estimated L shell of the resonant field line at the start of the Pg event (±0.1).

[c] The two proton energies calculated from proton drift times (±30%): (1) the energy of protons that would drift from the start of the event on day 1, starting at the resonant L shell measured for day 1, to the start of the event on day 2 in the time difference recorded; (2) the energy of protons that would drift from the start of the event on day 1 to the start of the event on day 2, finishing at the resonant L shell measured for day 2, in the time difference recorded.

[d] The two proton energies that satisfy the bounce resonance condition (±20%) for the wave characteristics observed at the start of days 1 and 2 (for m=−25).

at the resonant L shell measured for day 1, to the start of the event on day 2 in the time difference recorded; (2) the energy of protons that would drift (in one orbit) from the start of the event on day 1 to the start of the event on day 2, finishing at the resonant L shell measured for day 2, in the time difference recorded. W_b is the proton energy that satisfies the bounce resonance condition for the wave characteristics observed at the start of the event. What Table 1 shows is the similarity in the proton energies calculated from two different criteria. The majority of the energy estimates for an event match to within the error limits of the calculation.

Table 2 presents the same calculations but for α=80°. Once again the majority of the energy estimates for an event match to within the error limits. However, in this case $W_d > W_b$ on average. It appears that for some of the events an intermediate pitch angle would give an optimum match. The similarity between the estimates in both Tables 1 and 2 suggests that the bounce resonance instability may be playing a role in Pg generation, and this may also explain the occasional repetition of Pg events on successive days. It is a possibility that the Pg recurrence is occurring more often but on a different timescale, that is, with protons which have drift periods other than ~24 hours. These recurring waves would probably not be observed by the same magnetometer array and so the incidence of their recurrence could be missed.

Table 2. Proton Energy Calculations for Pgs Observed on Consecutive Days: 80° Pitch Angle Case

Date	Start Time, MLT	T, s	L	W_d, keV	W_b, keV
	EISCAT Magnetometer Cross Event 1				
Nov. 18, 1987	0520	135	6.3	9.4	3.9
Nov. 19, 1987	0400	128	6.1	10.0	4.1
	EISCAT Magnetometer Cross Event 2				
Oct. 10, 1985	0400	102	6.1	9.3	6.3
Oct. 11, 1985	0415	77	5.7	9.8	9.7
	Rostoker et al. [1979] Event 1				
Sept. 10, 1974	0450	80	5.4	12.8	8.1
Sept. 11, 1974	0100	85	5.4	13.9	7.2
	Rostoker et al. [1979] Event 2				
Sept. 11, 1974	0100	85	5.4	11.7	7.2
Sept. 12, 1974	0130	85	5.4	11.4	7.2

Notes as Table 1.

Bounce Resonance Generated Waves in the Magnetosphere

The question arises as to why the higher-energy protons which consistently make the traverse to the dawnside of the magnetosphere do not appear to be responsible for wave excitation through the bounce resonance mechanism. This can be explained simply by matching the wave periods that would satisfy the bounce resonance condition for different protons with typically observed periods in the magnetosphere which can be used as estimates of the field line eigenperiods. Figure 3 displays the variation with L shell of the wave period needed to satisfy the bounce resonance condition for four different proton energies and for an azimuthal wave number $m=-25$ (negative m represents westward phase propagation). For 34 Pg events observed by the EISCAT magnetometer cross, 70% of them had azimuthal wave numbers between $m=-20$ and $m=-30$, and so $m=-25$ represents a typical Pg. The dot-dashed lines in Figure 3 encompass the range of possible second harmonic eigenperiods based on satellite observations [*Hughes and Grard,* 1984; *Singer et al.,* 1982]. The dashed lines in Figure 3 encompass the range of possible fundamental eigenperiods based on ground-based observations [*Samson and Rostoker,* 1972; *Poulter et al.,* 1984]. Ground observations have been used as observations of fundamental waves are rarer in space due to the transverse magnetic perturbation being at a minimum in the equatorial plane. However, waves generated by the bounce resonance mechanism are likely to be second harmonic oscillations [*Southwood,* 1976].

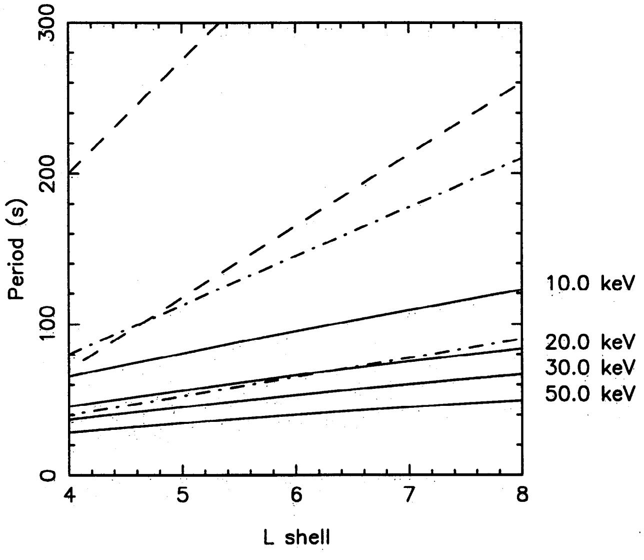

Figure 3. Comparison of periods which satisfy the bounce resonance condition (for $m=-25$ and $\alpha=45°$) for four different energies (solid lines) with typical ranges of second harmonic (dot-dashed lines) and fundamental (dashed lines) field line eigenperiods estimated from observations. The fundamental range is based on the observations of *Samson and Rostoker* [1972] and *Poulter et al.* [1984]. The second harmonic range is based on the observations of *Hughes and Grard* [1984] and *Singer et al.* [1982].

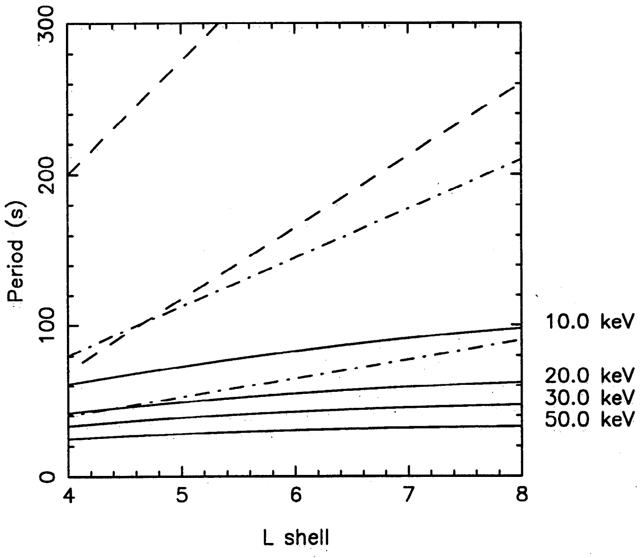

Figure 4. Comparison of periods which satisfy the bounce resonance condition (for $m=-100$ and $\alpha=45°$) for four different energies (solid lines) with typical ranges of second harmonic (dot-dashed lines) and fundamental (dashed lines) field line eigenperiods estimated from observations. See Figure 3 for details.

Figure 3 shows that only protons with energies $\lesssim 20$ keV (for the case $\alpha=45°$) can satisfy the bounce resonance condition for typically observed periods and for an azimuthal wave number of $m=-25$. The pitch angle (α) of the protons involved is of some importance. Reducing α to 20° (nearly field aligned protons) increases the periods that satisfy the resonance condition by ~20%. Similarly, increasing α to 80° (equatorially trapped protons) decreases the periods that satisfy the resonance condition by ~20%. Resonance will only occur if protons of the right energy and pitch angle to satisfy the resonance condition on a particular field line are present in sufficient numbers. In this case, protons with energies $\lesssim 20$ keV are needed to satisfy the bounce resonance condition and these protons rarely reach the morning sector of the magnetosphere. If these protons cannot make it to the morning sector then bounce resonance generated waves will not occur there. However, the resonance condition should be satisfied very easily in the afternoon/evening sector of the magnetosphere where the lower energy proton populations exist. Observations support this; radially polarized second harmonic waves which appear to be excited through the bounce resonance instability occur frequently in the afternoon/evening sector of the magnetosphere. However, the morning sector is dominated by azimuthally polarized fundamental waves thought to be generated by sources external to the magnetosphere [e.g., *Kokubun,* 1980].

The bounce resonance condition is also sensitive to the azimuthal wave number (m) of the waves being excited. Figure 4 presents the same parameters as in Figure 3 but for a larger azimuthal wave number $m=-100$. This has the effect of lowering the wave periods that satisfy the bounce resonance condition for a particular proton energy. This means that waves with these higher azimuthal wave numbers are even less likely to be observed on the morningside of the magnetosphere as the proton energies needed for resonance are even lower. This will not stop the higher wave number waves occurring on the afternoonside of the magnetosphere as the full range of particles are available. In fact, as already discussed in this paper, waves with higher azimuthal wave numbers are more likely to occur than those with lower azimuthal wave numbers as the chance of instability is increased if m is large.

The theories presented above fail to explain two important features of Pgs. Why they occur predominantly between L=5 and L=7 and why they appear to occur only in the early morning sector. It is easily explained why Pgs should occur rarely at low L shells, that is, within the plasmasphere ($L\lesssim 4$). Field line eigenperiods increase rapidly at the plasmapause and so there is little chance of these periods satisfying the bounce resonance mechanism for the proton populations present in the morning sector (i.e., there is little chance of an overlap in periods as in Figure 3). It is likely that the reasons for both the L shell and local time localization are related to factors which help to satisfy the instability criteria in (1), that is, inverted phase space distributions or spatial gradients. Indeed, *Chisham and Orr* [1994] suggested that Pgs may be triggered when the proton populations responsible for their generation interact with the inner edge of the plasma sheet. *Hughes and Grard* [1984] have also suggested that the inner edge of the plasma sheet is a region which is likely to be unstable to wave growth due to the strong plasma gradients observed there.

This does not explain, however, why Pgs do not occur in the afternoon sector. Radially polarized second harmonic waves thought to be generated by the bounce resonance mechanism are often observed in the afternoon/evening sector of the magnetosphere and so the conditions for instability must exist there. It may be that the particular instability conditions differ from the afternoon (where waves with $m\sim 100$ are observed) to the morning (where waves with $m\sim 25$ are observed), for example, inverted phase space distributions, which occur readily in the afternoon [*Hughes et al.*, 1978; *Southwood*, 1980; *Baumjohann et al.*, 1987] may provide the instability conditions for waves in the afternoon whereas a spatial gradient may provide the conditions for instability in the morning [*Chisham and Orr*, 1994; *Hughes and Grard*, 1984]. It is also possible that waves with $m\sim 100$ which are readily excited in the afternoon swamp any waves with smaller m that may be excited. The waves with larger m are not observed on the ground due to their localization. In the morning sector the very low energy particles needed to excite waves with $m\sim 100$ are rare, and so those waves with lower m can be excited when the particle populations are available.

Summary

For low energy protons ($\lesssim$50 keV) to reach the dawnside of the magnetosphere special conditions need to exist within the magnetosphere: (1) The magnetosphere must be in a state of geomagnetic quiet, that is, small convection electric fields; (2) There must be very little large amplitude wave activity. If protons with energies ~5-30 keV play a role in Pg generation, either through the bounce resonance mechanism or otherwise, the difficulty these protons have in reaching the morning sector can explain the rarity and occurrence during quiet times of Pgs. The idea that drifting proton populations play a role in Pg generation can also explain the observation of the quashing of a Pg during a substorm and also the occasional tendency of Pgs to occur on successive days, 24 hours apart. This theory can also explain why radially polarized second harmonic waves, thought to be generated by the bounce resonance mechanism are frequently observed in the afternoon/evening sector of the magnetosphere but not in the morning.

The major outstanding problem with regard to Pgs is still the determination of the harmonic mode. If Pgs are even mode waves, then it would seem extremely likely that they are generated by the bounce resonance instability with protons with energies ~5-30 keV. If Pgs are odd mode waves, it is still possible that protons with energies ~5-30 keV are playing a role in their generation and so the theory outlined in this paper could still explain their rare occurrence. However, in this case, the bounce resonance instability would be an unlikely generation mechanism.

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References

Anderson, B.J., M.J. Engebretson, S.P. Rounds, L.J. Zanetti, and T.A. Potemra, A statistical study of Pc3-5 pulsations observed by the AMPTE/CCE magnetic fields experiment, *J. Geophys. Res.*, *95*, 10,495, 1990.

Baumjohann, W., N. Sckopke, J. LaBelle, B. Klecker, H. Lühr, and K.-H. Glassmeier, Plasma and field observations of a compressional Pc5 wave event, *J. Geophys. Res.*, *92*, 12,203, 1987.

Brekke, A., T. Feder, and S. Berger, Pc4 giant pulsations recorded in Tromso, 1929-1985, *J. Atmos. Terr. Phys.*, *49*, 1027, 1987.

Cao, M., R.L. McPherron, and C.T. Russell, Statistical study of ULF wave occurrence in the dayside magnetosphere, *J. Geophys. Res.*, *99*, 8731, 1994.

Chisham, G., and D. Orr, Statistical studies of giant pulsations (Pgs): Harmonic mode, *Planet. Space Sci.*, *39*, 999, 1991.

Chisham, G., and D. Orr, The association between giant pulsations (Pgs) and the auroral oval, *Ann. Geophys.*, *12*, 649, 1994.

Chisham, G., D. Orr, M.J. Taylor, and H. Lühr, The magnetic and optical signature of a Pg pulsation, *Planet. Space Sci.*, *38*, 1443, 1990.

Chisham, G., D. Orr, and T.K. Yeoman, Observations of a giant pulsation (Pg) across an extended array of ground magnetometers and on auroral radar, *Planet. Space Sci.*, *40*, 953, 1992.

Fairfield, D.H., Average and unusual locations of the Earth's magnetopause and bow shock, *J. Geophys. Res.*, *76*, 6700, 1971.

Fairfield, D.H., and A.F. Viñas, The inner edge of the plasma sheet and the diffuse aurora, *J. Geophys. Res.*, *89*, 841, 1984.

Glassmeier, K.-H., Magnetometer array observations of a giant pulsation event, *J. Geophys.*, *48*, 127, 1980.

Green, C.A., Observations of Pg pulsations in the Northern auroral zone and at other lower latitude conjugate regions, *Planet. Space Sci.*, *27*, 63, 1979.

Green, C.A., Giant pulsations in the plasmasphere, *Planet. Space Sci.*, *33*, 1155, 1985.

Hamlin, D.A., R. Karplus, R.C. Vik, and K.M. Watson, Mirror and azimuthal drift frequencies for geomagnetically trapped particles, *J. Geophys. Res.*, *66*, 1, 1961.

Hasegawa, A., Drift mirror instability in the magnetosphere, *Phys. Fluids*, *12*, 2642, 1969.

Hasegawa, A., Drift-wave instabilities of a compressional mode in a high β plasma, *Phys. Rev. Lett.*, *27*, 11, 1971.

Hillebrand, O., J. Munch, and R.L. McPherron, Ground-satellite correlative study of a giant pulsation event, *J. Geophys.*, *51*, 129, 1982.

Hughes, W.J., and R.J.L. Grard, A second harmonic geomagnetic field line resonance at the inner edge of the plasma sheet: GEOS 1, ISEE 1, and ISEE 2 observations, *J. Geophys. Res.*, *89*, 2755, 1984.

Hughes, W.J., D.J. Southwood, B. Mauk, R.L. McPherron, and J.N. Barfield, Alfvén waves generated by an inverted plasma energy distribution, *Nature*, *275*, 43, 1978.

Kokubun, S., Observations of Pc pulsations in the magnetosphere: Satellite-ground correlation, *J. Geomagn. Geoelectr.*, *32*, SII 17, 1980.

Kokubun, S., K.N. Erickson, T.A. Fritz, and R.L. McPherron, Local time asymmetry of Pc4-5 pulsations and associated particle modulations at synchronous orbit, *J. Geophys. Res.*, *94*, 6607, 1989.

Li, X., M. Hudson, A. Chan, and I. Roth, Loss of ring current O^+ ions due to interaction with Pc5 waves, *J. Geophys. Res.*, *98*, 215, 1993.

Maynard, N.C., and J.J. Chen, Isolated cold plasma region: Observations and their relation to possible production mechanisms, *J. Geophys. Res.*, *80*, 1009, 1975.

Poulter, E.M., W. Allan, E. Nielsen, and K.-H. Glassmeier, STARE radar observations of a Pg pulsation, *J. Geophys. Res.*, *88*, 5668, 1983.

Poulter, E.M., W. Allan, J.G. Keys, and E. Nielsen, Plasmatrough ion mass densities determined from ULF pulsation eigenperiods, *Planet. Space Sci.*, *32*, 1069, 1984.

Rostoker, G, H.-L. Lam, and J.V. Olson, Pc4 giant pulsations in the morning sector, *J. Geophys. Res.*, *84*, 5153, 1979.

Samson, J.C., and G. Rostoker, Latitude-dependent characteristics of high latitude Pc4 and Pc5 micropulsations, *J. Geophys. Res.*, *77*, 6133, 1972.

Singer, H.J., W.J. Hughes and C.T. Russell, Standing hydromagnetic waves observed by ISEE 1 and 2: Radial extent and harmonic, *J. Geophys. Res.*, *87*, 3519, 1982.

Southwood, D.J., A general approach to low-frequency instability in the ring current plasma, *J. Geophys. Res.*, *81*, 3340, 1976.

Southwood, D.J., Low frequency pulsation generation by energetic particles, *J. Geomagn. Geoelectr.*, *32*, SII 75, 1980.

Southwood, D.J., and W.J. Hughes, Theory of hydromagnetic waves in the magnetosphere, *Space Sci. Rev.*, *35*, 301, 1983.

Southwood, D.J., J.W. Dungey, and R.J. Etherington, Bounce resonant interaction between pulsations and trapped particles, *Planet. Space Sci.*, *17*, 349, 1969.

Stern, D.P., The motion of a proton in the equatorial magnetosphere, *J. Geophys. Res.*, *80*, 595, 1975.

Takahashi, K., New observations, new theoretical results and controversies regarding Pc3-5 waves, *Adv. Space Res.*, *17*(10), 63, 1995.

Takahashi, K., N. Sato, J. Warnecke, H. Lühr, H.E. Spence, and Y. Tonegawa, On the standing wave mode of giant pulsations, *J. Geophys. Res.*, *97*, 10,717, 1992.

Takahashi, S., and T. Iyemori, Three-dimensional tracing of charged particle trajectories in a realistic magnetospheric model, *J. Geophys. Res.*, *94*, 5505, 1989.

Taylor, M.J., G. Chisham, and D. Orr, Pulsating auroral forms and their association with geomagnetic giant pulsations, *Planet. Space Sci.*, *37*, 1477, 1989.

Volland, H., A semi-empirical model of large-scale magnetospheric electric fields, *J. Geophys. Res.*, *78*, 171, 1973.

Walker, A.D.M., R.A. Greenwald, A. Korth, and G. Kremser, STARE and GEOS 2 observations of a storm-time Pc5 ULF pulsation, *J. Geophys. Res.*, *87*, 9135, 1982.

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