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Pc5 modulation of high energy electron precipitation: particle interaction regions and scattering efficiency

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Abstract. Using the NORSTAR riometer and CANOPUS magnetometer arrays we have investigated the modulation of high energy electron precipitation by ULF waves in the Pc5 frequency band. We conducted two separate studies of Pc5 activity in the riometers. The first is an independent survey of three riometer stations in the Churchill line (one at each subauroral, auroral, and typical polar cap boundary latitudes) in which we identified all riometer Pc5-band pulsations over 11 years. All had a corresponding magnetometer pulsation implying that a magnetic pulsation, is a necessary condition for a riometer pulsation (in the Pc5 Band). We find seasonal and latitude dependencies in the occurrence of riometer pulsations. By a factor of two, there are more riometer pulsations occurring in the fall-winter than the spring-summer. At higher latitudes there is a tendency towards noon pulsations during the spring-summer, suggesting that the criteria for riometer pulsations is affected by the dipole tilt. Our second study was based on the previous magnetometer study of Baker et al. (2003). Using the database of Pc5 activity from that study we were able to select the riometer Pc5 pulsations which adhere to the strict Pc5 definition in the magnetometer. We find that roughly 95% of the riometer pulsations occurred in the morning sector compared to 70% in the magnetometer. Given a magnetometer pulsation at Gillam in the morning sector, there is a 70% chance of there being a corresponding riometer pulsation. The morning sector probabilities at Rankin (geomagnetic (PACE) latitude 74°) and Pinawa (61°) are 3% and 5%, respectively. These statistics suggest there is a localized region in the pre-noon magnetosphere where Pc5 band ULF activity can modulate high energy electron precipitation. We also find that riometer pulsations display a K_p selection towards mid (i.e. 3–4) activity levels which mimics the product of the K_p dependence of high-energy electron fluxes on the dawn side (from CRRES) and all magnetic Pc5 activity. A superposed epoch analysis revealed that the elevated electron flux needed to produce a riometer pulsation is most likely provided by substorm injections on the nightside. We also find that the amplitude of modulated precipitation correlates well with the product of the background absorption and the magnetic pulsation amplitude, again leading to the idea that a riometer pulsation needs both favorable magnetospheric electron flux conditions and large enough magnetic Pc5 wave activity. We further separate our pulsations into field line resonances (FLRs), and non-field line resonances (non-FLRs), as identified in the Baker et al. (2003) survey. We find that FLRs are more efficient at modulating particle precipitation, and non-FLRs display an amplitude cutoff below which they do not interact with the high energy electron population. We conclude that the high energy electron precipitation associated with Pc5 pulsations is caused by pitch angle scattering (diffusion) rather than parallel acceleration. We suggest two future studies that are natural extensions of this one.

Keywords. Energetic Particles/Precipitating; Wave-Particle Interactions; Auroral Phenomena

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1 Introduction

The spatio-temporal distribution of the aurora allows us to remotely sense magnetospheric processes. For example, soft electron precipitation gives rise to a well understood signature in the 630 nm nm "Oxygen Redline" aurora, which, in turn, is widely used to map out the ionospheric projection along magnetic field lines of the electron Central Plasma Sheet (CPS) (Blanchard et al., 1995). Such connections between specific types of aurora and magnetospheric regions have been made for essentially all diffuse types of precipitation. A second example is the proton aurora, which is a projection of that part of the ion CPS where pitch angle scattering is efficient enough to fill the loss cone every bounce period (Tsyganenko, 1982).

The above-mentioned use of the optical aurora to study the large-scale dynamics of the electron CPS and ion CPS is restricted to providing information about lower energy particles, typically in the 1–50 keV characteristic energy range. Further, although in principle rules of thumb concerning the ratios of the intensities of various emissions can be used to estimate characteristic energies (Judge, 1972), this has not proven to be entirely practical for a number of reasons. Hence, although the optical emissions give a fairly clear picture of what is going on in terms of the distribution of energy density through the CPS and its various boundaries, we cannot use such observations to track the higher energy inner CPS and ring current particle populations that are so very important during substorms and storms. Given the central importance of the inner magnetosphere in, for example, the NASA Living With a Star initiative, this is a significant limitation.

Early on it was recognized that Cosmic Noise Absorption (CNA), as measured by Relative Ionospheric Opacity Meters (riometers), provides information specifically about higher energy auroral electron precipitation. The underlying principle is straightforward: electrons with sufficient energy deposit their energy deep enough in the ionosphere so that the resulting ionization is subject to collisions with sufficient frequency to attenuate High Frequency (HF) radio waves. In general, it is understood that precipitating electrons with energies in excess of $\sim$25 keV will reach the D-region where the collision frequencies are large enough to cause this attenuation. The scientific use of riometers is based on the fact that the cosmic radio noise in the HF band is relatively unchanging. Deviations from the background are attributed to absorption, which, in turn, is attributed to precipitation. An excellent description of the principles of riometry is given by Hargreaves (1969).

The high energy electron population in the inner magnetosphere is produced by some combination of local energization and inward convection on the nightside. This duality complicates the interpretation of essentially all inner magnetospheric electron observations. One example is the substorm injection, which is now understood to be a consequence of either (or both) the convection surge (transport) or the current disruption (local) (Reeves, 1998). These high energy electrons undergo bounce and mostly azimuthal gradient-drift. Wave particle interactions are thought to be the primary mechanism for the precipitation of these electrons. Baker et al. (1981) showed that, provided that the K_p criterion for strong pitch angle diffusion was met, the integrated electron flux at a geostationary satellite was well correlated with the CNA, as observed by a magnetically conjugate riometer. Their result was tantalizing: provided that the high electrons are efficiently scattered into the loss cone, then riometers are able to provide quantitative information about the spatial distribution of the inner magnetospheric high energy electrons.

Ultra Low Frequency (ULF) magnetic pulsations are understood to play a role in the transport, energization, and loss of high energy electrons. While most of the focus on the ULF wave connection to the energetic electron population has been on particles with typical radiation belt energies, there is clearly a relationship between the fluxes of tens to hundreds of keV electrons and ULF waves.

Baker et al. (1980) used Los Alamos National Laboratory charged particle analyzers on board three spacecraft to explore the local time and magnetic latitude distribution of pulsations in high energy electron fluxes at geosynchronous orbit. They found three different distributions for three different magnetic latitudes (4.8°, 9.4°, and 11.4°). At lower magnetic latitudes the distribution was centred about noon and had the lowest absolute probability of observing an electron flux modulation. Higher probabilities were found at mid- and high- latitude geostationary positions where the distribution changes to a bimodal in spring-summer and centred about noon in the fall-winter. They suggested that the strong dependence of the distribution on latitude was a consequence of the mode structure of Field Line Resonances (FLRs) and an ionospheric conductivity pattern. Higbie et al. (1978), also using Los Alamos charged particle analyzer data, showed that flux oscillations occur most frequently in the 30–300 keV electron energy range, and occasionally in the higher energy electrons or lower energy protons. The pitch angle distribution of the modulated fluxes can either be "pancake" or "cigar" shaped. The oscillations are in phase across energy channels. Flux modulations are seen about 10% of the time. Local time distribution is symmetric about noon (peaks at 6 and 18 MLT), and has a small peak at noon. Flux modulations were seen most often during quiet times (K_p<4−), at higher K_p the distribution only changes on the dawn side.

Saka et al. (1992) suggested a causal relationship between high energy electrons and Pc5 magnetic pulsations. The suggested that at least some Pc5 waves are caused by the local injection of high energy electrons into the morning sector and that a ground-observed Pc5 pulsation is the signature of the resonating small Birkland current system being split off from east to west by injected electrons.

Paquette et al. (1994) surveyed the South Pole magnetometer and riometer data for pulsations occurring in the 100–1000 s range. They identified pulsations occurring in both instruments but restricted their survey to dayside activity. The resulting MLT distribution displayed a peak at 10:00 MLT with the vast majority of Pc5 activity on the dawnside. They also classified pulsations in terms of the relative timing of the onset of riometer and magnetometer pulsations and interpreted the delay or lack there of in terms of the source region. Nosé et al. (1998) used Dynamics Explorer and ground magnetometer and riometer data to argue that the riometer signature, accompanying Pc5 pulsations was due to parallel accelerated electrons in FLRs.

In a recent study, Baker et al. (2003) carried out an extensive survey of Pc5 waves in the CANOPUS magnetometer data set. Their study spanned more than a decade of data, and identified essentially every magnetic pulsation in over 1500 "complete" days of data. Their data set covered all seasons roughly evenly, spanned a solar cycle, covered all magnetic local times (MLTs), and covered invariant magnetic latitudes from $\sim$61° to $\sim$80°. As described below, there was a single beam riometer collocated with each magnetometer used in the Baker et al. (2003) study. This magnetic ULF data set, combined with the collocated riometers, provides us with an excellent chance to advance our understanding of the relationship between ULF waves and the precipitation of high energy electrons. The questions that we set out to answer relate to ULF pulsations in the riometer data which reflect ULF modulation of the precipitation. We restricted ourselves to the same 1.7 to 6.7 mHz frequency band that Baker et al. (2003) used. Further, we restrict ourselves to the ground-based data set only. Specifically, the questions we sought to address were the following:

1. Are riometer pulsations always accompanied by (ground observable) magnetic pulsations?

2. Are (ground observable) magnetic pulsations always accompanied by riometer pulsations?

3. Can we use this combined data set to explore how efficient various types and/or amplitudes of magnetic pulsations are at causing the precipitation of high energy electrons?

While we restrict our attention in this paper to just these questions, our longer term objective is to develop riometers as a quantitative tool for studying the spatio-temporal distribution of loss processes in the magnetosphere. This would be an important complement to the already developed capability of riometers mentioned above to track the evolution of the inner magnetospheric electron population.

2 Data

The riometer data used in this study is from the NORSTAR (formerly CANOPUS) array. These instruments are deployed across north-central Canada (see Fig. 1 and Table 1). These riometers utilize dual dipole broad-beam (∼60°) antennae, operate at 30 MHz, and collect data at 1 sample per second (although the final data product is processed down to a resolution of 1 sample every 5 s). Magnetometer data is from the co-located CANOPUS array which records the magnetic field strength in the X (geographic north-south), Y (geographic east-west), Z (vertical) coordinate system eight times per second (filtered and averaged to 0.2 Hz data) with a resolution of 0.025 nT.

In addition to ground-based data we use in-situ electron data from the Medium Electron B (MEB) instrument aboard the Combined Release and Radiation Effects Satellite (CRRES). The MEB instrument provides measurements of the mid-high energy electron populations in 14 energy channels (see Korth et al. (1992) for a more detailed description). In this study we use only one-minute data from the 40–50 keV energy channel.

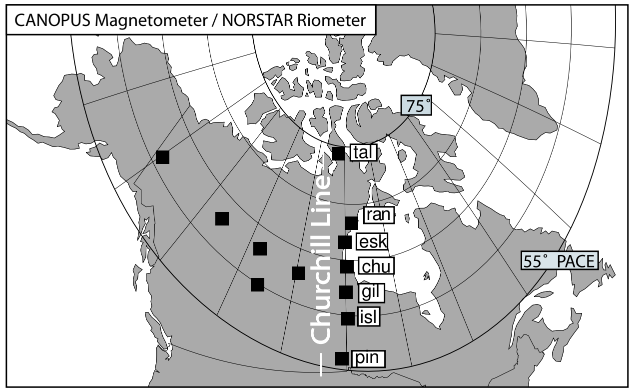

Fig. 1. Map of the CANOPUS (NORSTAR) magnetometer (riometer) array along with contours of constant geomagnetic (PACE) latitude and longitude.

Table 1. PACE geomagnetic and geodetic (in brackets) coordinates for the CANOPUS (NORSTAR) Churchill line magnetometer (riometer) stations.

Station Code	Station Name	Location (°) Latitude	Longitude
pin	Pinawa	61.2 (50.2)	328.4 (264.0)
isl	Island Lake	64.9 (53.9)	329.7 (265.3)
gil	Gillam	67.4 (56.4)	329.1 (265.4)
chu	Fort Churchill	69.7 (58.8)	329.2 (265.9)
esk	Eskimo Point	71.9 (61.1)	328.4 (266.0)
ran	Rankin Inlet	73.7 (62.8)	331.0 (267.9)
tal	Taloyoak	79.7 (69.5)	323.6 (266.5)

3 Observations

3.1 Riometer Pc5 Occurrence Statistics

We began with a manual survey of ten years of data (1989–1998) from three stations along the NORSTAR Churchill line. The stations were Pinawa, Gillam, and Rankin Inlet, which are typically at sub-auroral, auroral, and polar cap boundary latitudes, respective. We manually identified all pulsations in the Pc5 band (150–600 s periodicity). Our criteria demanded that pulsations complete at least three cycles and have an amplitude greater than twice the noise level in the raw data. This does not put a hard lower limit on the identified amplitudes in decibels, since the conversion from voltage (raw data) is both instrument and time dependent, but guarantees that we are identifying all visible pulsations. In total we identified over 750 h of riometer Pc5 activity in Pinawa, Gillam, or Rankin. Examples of Pc5 events in our database are shown in Fig. 2.

All riometer pulsations in this data set had a corresponding magnetic signature. In some cases the magnetometer pulsations were bursty and irregular, and would not strictly be classified as Pc5 pulsations; however, in all events the

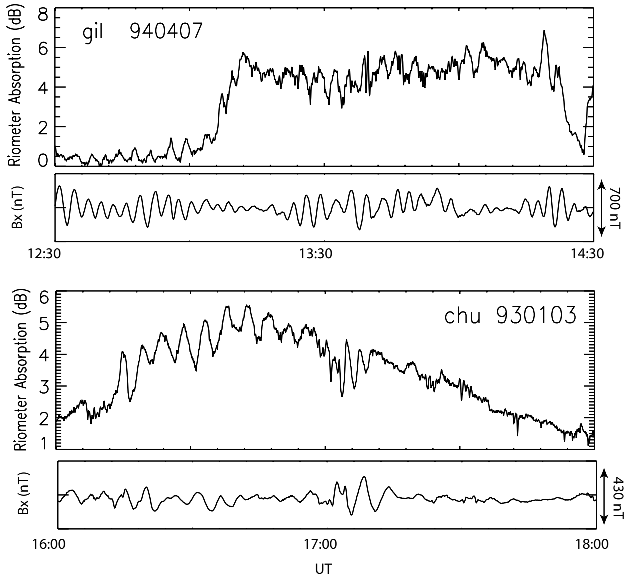

Fig. 2. Example Pc5 pulsations seen in both the magnetometer and riometer.

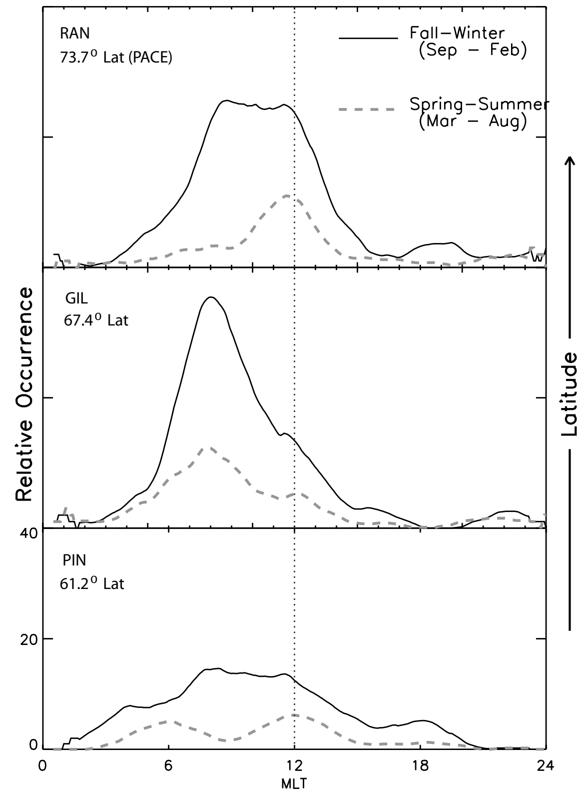

Fig. 3. Number of 5-min intervals containing Pc5 riometer activity.

corresponding magnetic perturbations were clearly visible in the raw magnetometer data. There did not appear to be any systematic qualitative difference between the riometer signature of a stable, quasi-monochromatic Pc5 magnetic pulsation and that of a bursty irregular one.

Figure 3 is the MLT occurrence of riometer pulsations identified in our survey. We have separated the statistics according to station (and hence geomagnetic latitude) and season. The peak occurrence of riometer pulsations is on the dawn-side at Gillam (67° or "auroral" latitudes), and in the fall-winter. This dawn-side maximum is consistent with the results of earlier similar studies of riometer Pc5 activity (see, e.g. Nosé et al., 1998 and Paquette et al., 1994) and appears to be half of the in-situ distribution of high-energy electron pulsations reported by (Baker et al. (1980) and Kremser et al. (1998). Our results indicate an increase of a factor of 2 in Pc5 activity during the fall-winter (September–February).

Two distinct populations of pulsations are also evident from Fig. 3. At higher latitudes there are a group of pulsations which occur on the dawn-side flank and a group of pulsations which occur at noon. During the spring-summer the flank pulsations disappear and only the noon pulsations remain. This trend is present to a much lesser extent at Gillam and not at all at low latitudes. Lower latitude pulsations are fewer (<20 puslations over 10 years were observed in the spring-summer) and display a much more uniform occurrence across dawn and noon.

In addition to the study of riometer Pc5 activity we conducted a separate survey of all of the Pc5 pulsations identified by Baker et al. (2003) in the collocated CANOPUS magnetometer array. In this survey, we considered only those magnetic signatures conforming to the strict Pc5 definition applied by Baker et al. (2003), and surveyed the corresponding riometer data. Having this database of magnetic Pc5 activity for the entire Churchill line gave us the unique opportunity to examine the effectiveness of magnetic pulsations in producing modulated precipitation under various conditions.

We first selected the subset of the Baker et al. (2003) survey which contained "good" riometer data (i.e. no data gaps, large scintillation events, etc.) and manually searched for corresponding riometer Pc5 pulsations. We show the results of this survey in Fig. 4. The MLT occurrence of magnetometer pulsations (as originally shown in Baker et al., 2003) is shown in dark grey and those which have simultaneous riometer pulsations are shown in light grey. The notch at 18:00 MLT (shown as the stripped region) is an artifact of the search technique used by Baker et al. (2003). Again, the peak occurrence for modulated precipitation is at Gillam, where ≈70% of magnetic pulsations produce riometer signatures. There is, in addition, dusk activity at lower latitudes and a tendency towards more pulsations at noon at higher latitudes. When mapped to the equatorial plane (see Fig. 5) the occurrence of riometer pulsations implies a restricted region of the dawn-side magnetosphere, where Pc5 waves are capable of interacting with the high-energy electron population (see discussion).

As a measure of magnetospheric activity during pulsation events, we added near simultaneous K_p and AE values to our database of Pc5 pulsation times. Figure 6 shows the K_p dependence of Pc5 pulsations in both the magnetometer and riometer. The subset of magnetic pulsations with concurrent riometer pulsations displays a selection towards mid to high

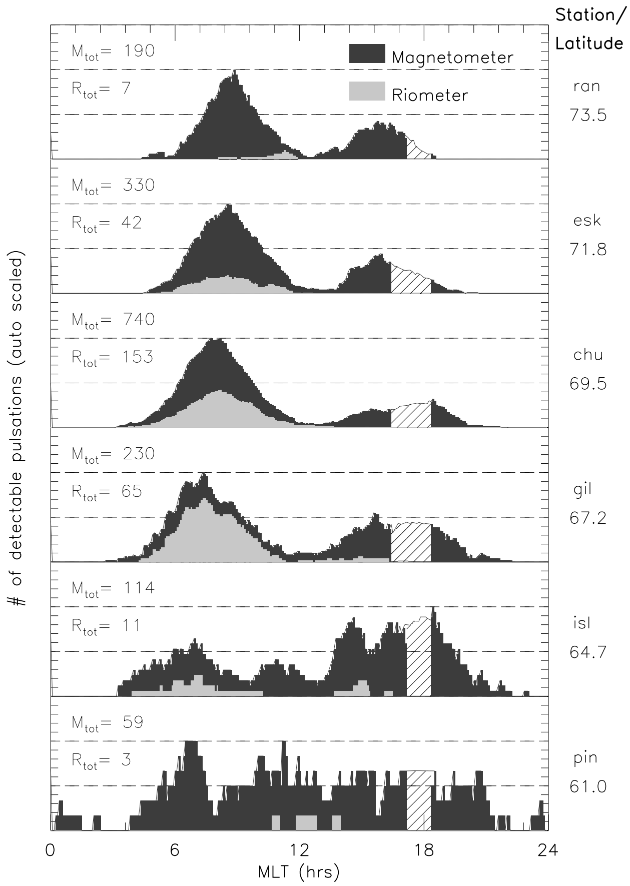

Fig. 4. Modified Pc5 Distribution from Baker et al. (2003) and the corresponding riometer pulsations (auto scaled). Magnetic pulsations are shown in dark grey and those which have a concurrent riometer pulsation are shown in light grey.

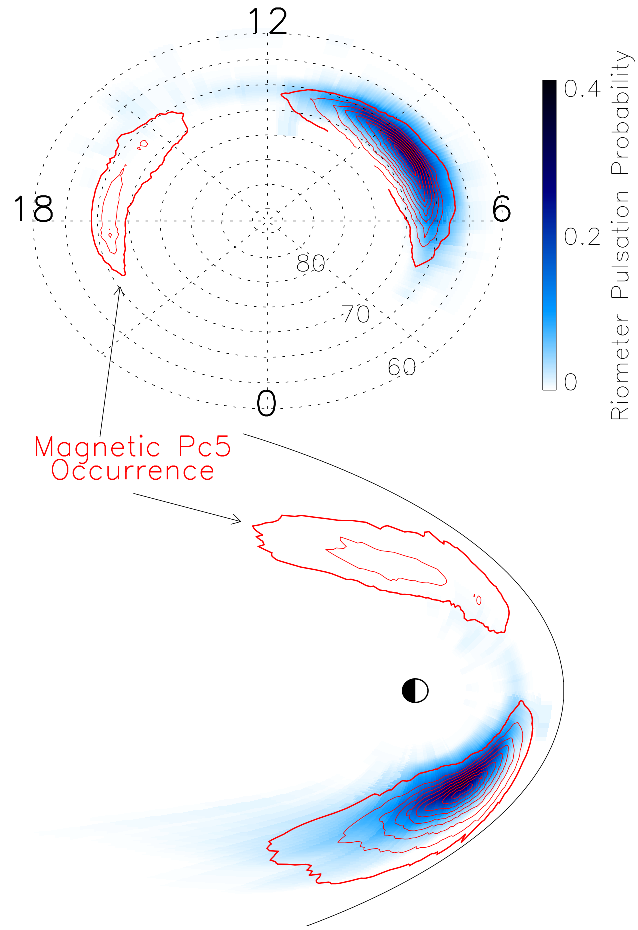

Fig. 5. Relative occurrence of magnetic and riometer Pc5 pulsations. The color level plot indicates the probability of observing a riometer pulsation given a magnetic pulsation. Contours of magnetic Pc5 occurrence (from Baker et al., 2003) are shown in red. We have filled in the notch in that survey to make the contours continuous (see Fig. 4)

activity levels. The upper K_p boundary of this population appears to be the K_p occurrence of Pc5 activity itself. Also plotted in Fig. 6 is the average dawn-side flux of 40–50 keV electrons seen from the CRRES satellite. This was obtained by taking all times when CRRES was between 5–13 MLT and was at an L-value greater than 5 (the orbit of CRRES puts an upper bound of L=9 on the measurements) and by taking the average flux, binned by K_p, over the lifetime of the observations. High-energy electron fluxes monotonically increase with K_p.

Figure 6 suggests that the elevated particle population during mid-high K_p contributes to the ability of the Pc5 waves to interact with the high-energy particles. A superposed epoch analysis (see Fig. 7) of all pulsation events before 1995 shows that at least, on average, the AE index is decreasing in the hours before a riometer pulsation. This implies that, in general, the elevated particle population present during riometer pulsations is provided by drifting electron clouds produced by substorm injections.

3.2 Amplitude effects

From our database of pulsation events we were able to extract amplitude information from both the riometer and magnetometer traces. The riometer pulsations amplitudes were found by first identifying an "absorption profile" for the selected data sample (i.e. the background absorption level). This was done by fitting a spline curve to the base of the Pc5 pulsation and the amplitude of the pulsation was taken to be the height of the modulated absorption. Magnetic pulsation amplitudes were calculated by removing a second order polynomial from the magnetic trace and for each interval the peak-to-peak amplitude was calculated by taking the difference between the values in the 5th and 95th percentile. To avoid complications with rapidly changing amplitudes and absorption profiles, all amplitudes from both techniques were checked by eye and only those which appeared "reasonable" were used in the final calculations.

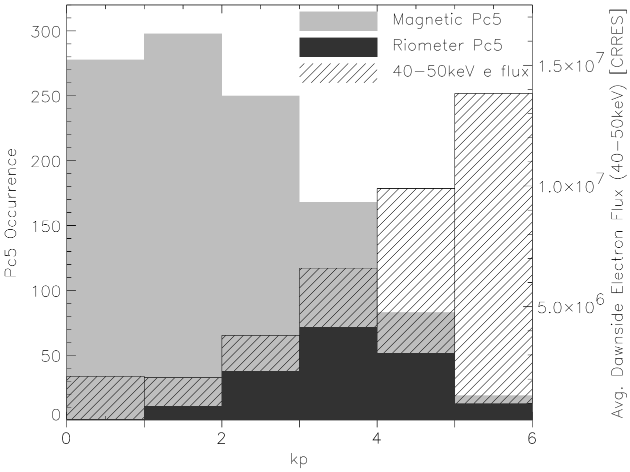

Fig. 6. Number of magnetometer (light grey) and riometer (dark grey) Pc5 pulsation events binned according to K_p. Also shown is the average dawnside (5–13 MLT) 40–50 keV electron flux at $5<L<9$ from the CRRES satellite.

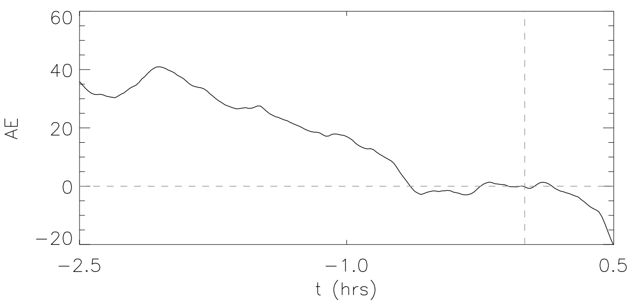

Fig. 7. Superposed epoch analysis for riometer Pc5 pulsation events for 1989–1995 (116 events). T=0 corresponds to the beginning of a pulsation event in the riometers.

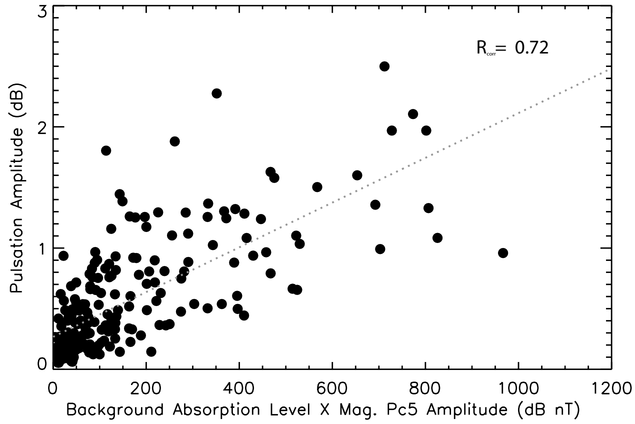

Fig. 8. Correlation between the amplitude of modulated precipitation and background absorption level multiplied by the amplitude of the magnetic pulsation (X-component).

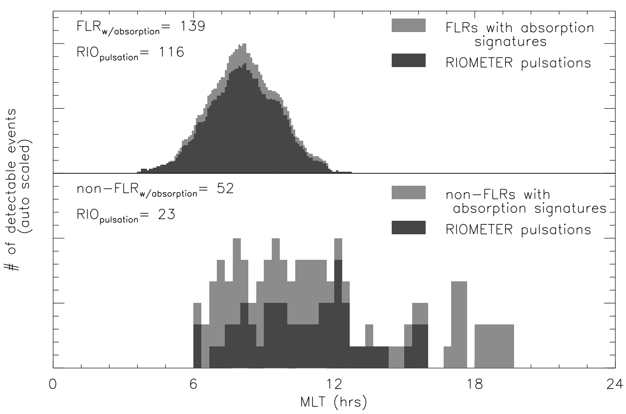

Fig. 9. MLT Occurrence of riometer pulsations corresponding to field line resonances from Baker et al. (2003) and non-field line resonances.

Previous studies (Olsen et al., 1980) have found a linear relationship between the background absorption and the amplitude of riometer pulsations. We find that while the correlation tests above the 95% significance level in our data set (we obtained a R value of 0.6), the correlation is greatly improved by multiplying the background absorption with the amplitude of the magnetic pulsations (see Fig. 8). In this scenario we obtained a correlation value of 0.72, again leading to the idea that riometer pulsations are a product of magnetic Pc5 activity and the availability of electrons to precipitate (presuming of course, a correlation between the number of high energy electrons on a flux tube and the background absorption).

3.3 Field line resonances

Baker et al. (2003) divided their data set into two categories, Field Line Resonances (FLRs) and non-FLRs. FLRs were identified by a latitude profile exhibiting a single amplitude maximum and corresponding 180° phase shift (for a more detailed explanation, see Sect. 3.5. of Baker et al., 2003). Since our riometer pulsation database was chosen from this survey, we were able to explore the response of precipitation to those Pc5 pulsations which correspond to FLRs and those which do not.

To investigate the efficiency of the two types of Pc5 pulsations in either modulating or driving precipitation we selected the Pc5 pulsation times which contained absorption (not necessarily modulated). This guaranteed that during the selected times, the particle conditions required for precipitation were met. We focussed out attention on Gillam, because Pc5 pulsations were most likely at that latitude. We then asked the question, Was the precipitation modulated at Gillam? Figure 9 shows the occurrence of modulated precipitation associated with FLRs and non-FLRs. We find that FLRs will produce a riometer pulsation >85% of the time, while non-FLRs only 45% of the time. The FLRs appear to also only interact with the high-energy electron population on the dawn side, while non-FLR riometer pulsations were observed across noon.

Once we classified whether or not the precipitation was modulated we further asked What was the amplitude of the pulsation which caused (or did not cause) the modulated precipitation? The distribution of amplitudes is shown in Fig. 10. The grey shaded regions correspond to those magnetic waves which produces riometer Pc5 signatures and the stripped area indicates the magnetic pulsations which did not. We remind the reader that background absorption was present in all cases, so the conditions sufficient to produce electron precipitation are met and cannot be a selection criterion for the trends in Fig. 10.

Pc5 waves in the two categories (FLR vs. non-FLR) appear to have different amplitude criteria for interacting with the high-energy electron population. The top panel of Fig. 10 is for the non-FLR pulsations and clearly shows an amplitude threshold (∼25−30 nT), above which the wave is likely to modulate eletron precipitation and below which the wave is not likely to modulate electron precipitation. Pulsations in the FLR category have a completely different distribution and there is no distinct cutoff amplitude below which the precipitation is not modulated.

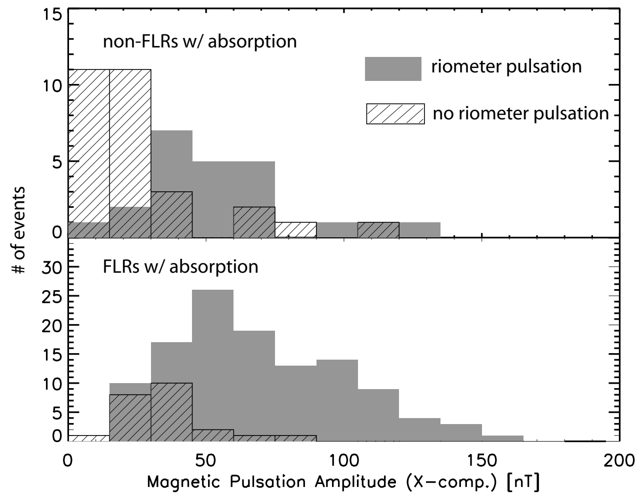

Fig. 10. Distributions of Pc5 wave amplitudes inducing (or not inducing) riometer Pc5 activity (top panel: non-FLRS , bottom panel: FLRs). Background absorption (sufficient particle population) is present for all events. The grey shaded region corresponds to those magnetic Pc5 waves which modulate electron precipitation, and the stripped region corresponds to those pulsations which do not.

4 Discussion

We have conducted two surveys of modulated high energy electron precipitation. In one, we examined data from three broad-beam riometers (one sub-auroral, one auroral, and one at typical open-closed boundary latitudes). In the other, we examined riometer data obtained contemporaneously with the CANOPUS magnetometer data upon which the Baker et al. (2003) study was based. Our primary results based on these two surveys (and on the results of Baker et al., 2003) are as follows:

1. Riometer pulsations are predominantly a dawn-side phenomenon, and display a seasonal dependence at higher latitudes with an increase in noon activity and decrease in flank activity occurring during the spring-summer.

2. Modulated precipitation occurs preferentially at moderate K_p (i.e. K_p∼3 to ∼4).

3. Superposed epoch analysis shows that riometer Pc5 pulsations occur predominantly during declining AE.

4. In general, one cannot distinguish a clear, continuous quasi-monochromatic Pc5 pulsation from a bursty, irregular Pc5 by the riometer signature.

5. All riometer pulsations have a corresponding ground observable magnetic pulsation signature, although the magnetic pulsation may not fit the strict Pc5 definition used by Baker et al. (2003).

6. A ground observable magnetic pulsation does not always have a corresponding riometer pulsation.

7. The amplitude of the modulated precipitation correlates with the product of the background absorption and the amplitude of the magnetic perturbation (R_{corr}=0.72).

8. Magnetic Pc5s that are FLRs are more effective at modulating high energy precipitation than are magnetic Pc5s that are not FLRs.

9. Non-FLR magnetic Pc5s with (ground-observed) amplitudes below ∼30 nT do not appear to cause significant high-energy electron precipitation.

10. There does not appear to be a lower amplitude cutoff in terms of magnetic Pc5s that are FLRs.

Results 1–4 pertain to the overall occurrence of pulsations in riometer absorption, and hence either the modulation or the driving of high energy electron precipitation by global magnetic pulsations in the Pc5 frequency band. The Baker et al. (2003) study, and references therein, indicate that the ground signature of magnetic pulsations is most predominant near dawn and dusk. This has been attributed to fast mode energy being driven into the magnetospheric cavity by surface waves on the magnetopause. These waves arise at local times where the magnetosheath plasma is accelerating back to near solar wind velocities. The fact that riometer pulsations occur primarily in the dawn sector, primarily at mid K_p levels, and during declining AE are all consistent with modulated precipitation of high energy inner magnetospheric electrons. The declining AE indicates that on average substorms have occurred in the preceding hours and that it is reasonable to expect, on a case-by-case basis, that there are enhanced equatorial high energy electron fluxes in the dawn sector (i.e. substorm injected electrons that have gradient curvature drifted into the morning sector). The K_p statistics of magnetic pulsations, equatorial fluxes (from CRRES), and riometer pulsations are consistent with this picture. The magnetic pulsations are more decreasingly likely with increasing K_p, while the electron fluxes are increasing with increasing K_p. A process that demands both a magnetic pulsation and enhanced magnetospheric electron fluxes will be predominantly a mid K_p phenomenon.

These results are also strongly supportive of the riometer pulsations being a result of pitch angle scattered rather than parallel accelerated precipitation. The dramatic dawn-dusk asymmetry in the riometer pulsation occurrence indicates that the riometer pulsations need high energy electrons to be present in the magnetosphere. This is further supported by the more azimuthally symmetric distribution of riometer pulsations at the lowest latitude station (see Pinawa in Fig. 4). If the riometer pulsations were the result of the precipitation of accelerated electrons, we would not expect preferential occurrence in regions where we also expect increased fluxes of high energy electrons. Our interpretation here is at odds with the conclusions of Nosé et al. (1998), who attributed CNA pulsations at the South Pole specifically to parallel acceleration in FLRs. The two views could be reconciled, however, if there is a causal link between injected particles in the magnetosphere and Pc5 pulsations, as has been suggested by Saka et al. (1992).

As stated above, our occurrence statistics for riometer Pc5 pulsations display a strong dawnside peak. In our survey we found that approximately 95% of riometer pulsations occur between 6 and 12 MLT. This is not comparable to the distribution seen with in-situ electron measurements. Both Baker et al. (1980) and Higbie et al. (1978) reported symmetric distributions (centered about noon) of Pc5 occurrence in the $>$30 keV electron population. Higbie et al. (1978) even noted that the majority of the flux pulsations at geosynchronous orbit occur during "quiet times" with K_p less than 4. We have surveyed essentially a solar cycle of ground magnetometer and riometer data. There is little chance that either our results or the previous in-situ results are in error. We point out that in a recent study, Glassmeier and Stellmacher (2000) used geosynchronous and ground-based magnetic field data to demonstrate that the longitudinal distributions of pulsations seen by the two platforms were markedly different. They found that the in-situ distribution was symmetric about noon and the ground-based distribution had a pronounced dawnside peak (see their Fig. 2). They attributed the difference to ionospheric shielding of narrow structures on the dusk side. While our results indicate a similar discrepancy between geosynchronous and ground-observed high energy electron pulsations, there is a difference. While the ionosphere can be expected to shield the magnetic effects of a narrow FLR structure, it cannot diminish the effect of high energy electron precipitation on radio-wave propagation (i.e. on CNA), even in narrow structures.

We could possibly reconcile the in-situ results (Baker et al., 1980) and our own ground-based results by considering a finite region where the strong pitch angle diffusion flux limit is met. Our overall occurrence statistics (Fig. 4) suggest that the interaction between high-energy electrons and Pc5 waves is restricted in latitude and MLT. This region has an average equatorial mapping indicated by the riometer pulsation occurrence in Fig. 5. In addition, it appears that the dipole tilt can force a high latitude station to map inside of or outside of this region. Specifically, Rankin Inlet during the summer has an equatorial mapping which reaches further out on the flanks and is pulled closer to the Earth at noon. If the scattering region were similar to that of Fig. 5, then Rankin Inlet would map to inside the scattering region at noon during both spring-summer and fall-winter, but could be pushed outside the dawn-side region in spring-summer. This is consistent with our lack of observed pulsations on the flanks. Not only does this define a boundary for modulated precipitation (at or around 73.7°), it implies that the interaction region likely lies in the equatorial plane. This also hints towards a possible reconciliation between in-situ and ground-based statistics. CNA pulsations will be limited by the availability of high-energy electrons to precipitate. The naturally higher electron fluxes on the dayside, be it from substorm injections or enhanced convection, are far more likely to be at or near the K_p limit where a Pc5 wave can significantly modulate existing precipitation (bottom panel of Fig. 2), or cause precipitation (top panel of Fig. 2). Thus, the filtering mechanism between ground-based and in-situ electron flux modulations is likely the K_p limit for strong pitch angle scattering.

As we stated in the Introduction, we set out to answer three questions. The first two were whether riometer pulsations were always accompanied by magnetic pulsations and vice versa. Our results indicate overwhelmingly that riometer pulsations are always accompanied by ground observable magnetic pulsations (result 5). Further, ground observable magnet pulsations are often not accompanied by a riometer pulsation (result 6). These results can be simply summarized as follows: ground observable magnetic pulsations are a necessary but not sufficient condition for riometer pulsations at the same location. This simple result is also consistent with the discussion in the previous two paragraphs. It is a natural consequence of the riometer pulsations being the modulation of either a pitch angle scattering condition or of a pre-existing (i.e. background) precipitation process. Further, the fact that not all magnetic pulsations cause high energy electron precipitation is supportive of the lack of involvement of parallel electric fields in pulsating high energy electron precipitation. If the precipitation of the high energy electrons were intimately related to the pulsation electrodynamics, then one would expect varying amplitudes of riometer pulsations which were otherwise always present during magnetic pulsations.

The third question we set out to answer was whether we can use the combined riometer and magnetometer Pc5 pulsation data set to investigate any possible dependencies of the efficiency of a global magnetic pulsation in terms of modulating or driving high energy electron precipitation on the type (i.e. FLR vs. non-FLR) and amplitude of the pulsation. Results 7–10 address this question, although more work clearly needs to be done along these lines (see discussion of future work, below).

As we reported in the Observations section, above the amplitude of riometer pulsation is well correlated with that of the ground observed magnetic pulsation (R_{corr}=0.6). We found a significantly higher correlation, however, between the riometer pulsation amplitude and the product of the background absorption and the ground observed magnitude of the magnetic pulsation (R_{corr}=0.72). Recalling the Baker et al. (1981) study which showed a strong correlation between the equatorial integrated high energy electron flux and the absorption as measured at a magnetically conjugate riometer, the correlation between the amplitude of the riometer pulsation and the product of the background absorption and the ground observed magnetic pulsation amplitude is sensible. The expectation is that the same magnetic pulsation will have a greater or lesser riometer signature depending on the amount of high energy electrons that can be dumped into the loss cone. Conversely, given the same background electron density, a larger ground observed magnetic pulsation will lead to a larger riometer signature. Note that in this part of our survey we demanded that "background absorption" be present. By doing so, we were attempting to separate out the effects of modulation of existing precipitation from the more complicated changing of a scattering condition. In other words, we are assuming that the strong pitch angle scattering criterion discussed in Baker et al. (1981) is met with or without the magnetic pulsation in those events.

Result 8 is derived from Figure 9. The Baker et al. (2003) study divided their Pc5 pulsations into FLRs and non-FLRs. The distinguishing feature was the presence (in FLRs) or absence (in non-FLRs) of a 180° degree phase shift across a latitudinally narrow amplitude maximum. The non-FLRs have, in general, more coherent behavior over much larger latitude ranges. Conversely, the FLRs represent a concentration of energy deposition in a narrow latitude range. The equatorial structure of an FLR would much more likely have strong radial gradients that are changing in time. Thus, FLRs are more likely have an effect on whether the scattering condition is met on a particular flux tube than non-FLRs, and, for the same magnetic signature on the ground, are more likely to have a larger magnetic fluctuation near the equator. In both cases, the FLR can be expected to have a greater effect on the high energy electron precipitation. Results 9 and 10 go along with Result 8. The occurrence of riometer Pc5s for even very small amplitude FLRs is consistent with their overall effectiveness at modulating or driving high energy electron precipitation.

Our results demonstrate that there is a strong causal relationship between global magnetic pulsations and riometer pulsations. We have shown that riometer (Pc5) pulsations are always accompanied by ground-observable magnetic pulsations, but that the converse is not true. Magnetic pulsations are a necessary but not sufficient criterion for CNA pulsations. Our statistical results are consistent with riometer pulsations, depending on sufficient fluxes of high energy electrons in the magnetosphere, and hence that the dominant process underlying the high energy electron precipitation in these events is scattering rather than acceleration. We have made some headway in elucidating the relationship (in as much as one exists) between the amplitudes of magnetic and riometer pulsations.

While there are a great many studies that one could carry out as follow ups to the present, two are particularly necessary for advancement. First, the longitudinal distributions of Pc5 occurrence in the riometers and in-situ electron fluxes have been carried out separately. There are now large data sets from riometers in Western Canada (particularly at Dawson) and in Finland. These riometers are typically longitudinally close to Los Alamos satellites. This provides us with the opportunity to study conditions at or near the equator while simultaneously measuring the CNA during Pc5 events. Such a study would allow us to better address why there are differences between the in-situ and ground-observed distributions. Second, we are asserting that our results indicate that the absorption in Pc5 riometer pulsations is a result of precipitation caused by pitch angle scattering and not parallel acceleration. Both observational and theoretical work is necessary to unravel what is undoubtedly a complicated relationship between the high energy magnetospheric (i.e. injected) electrons, FLRs, and high energy electron precipitation. Such work would be a natural follow up to our study, as well as those of Nosé et al. (1998) and Saka et al. (1992).

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