The Use of Low-Earth-orbit satellites in the Study of Upstream Wave Related Geomagnetic Pulsations

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ABSTRACT

Recent studies have shown clearly that Pc3-Pc4 geomagnetic pulsations can be detected in the topside ionosphere using the unprecedented precision data of the CHAMP satellite. Based on the continuous observation of CHAMP and the MM100 magnetometer chain it was possible to carry out a comprehensive statistical survey of the upstream wave related pulsation events that discovered several new properties of the phenomenon and new features in its relation to upstream solar wind conditions. Moreover, the space-ground comparative studies helped us to identify the dominant propagation pathes of the wave energy and urged the developement of new wave propagation models. According to our current knowledge these waves are generated in the upstream solar wind, under appropriate conditions enter the magnetopause, propagate deep in magnetosphere down to the turning point, where they become evanescent. The energy of the evanescent wave penetrates the inner magnetosphere, reaches the ionosphere and can be detected on the ground as geomagnetic pulsations. This is the dominant source of Pc3-Pc4 pulsations in the equatorial and low latitude regions. Another significant part of the incoming energy copules to Alfvén mode and reaches the ionosphere as guided waves at mid latitudes. However, several questions remain still open. Although the latitudinal structure of the upstream wave related global mode is thought to be more or less understood, we have only a very limited knowledge on its longitudinal structure. Models need realistic parametrization, e.g. we need realistic azimuthal wave numbers. The constallation of the SWARM satellites will be suitable to address this and several other propagation related questions. With SWARM we will be able to study the ULF wave propagation above the ionospheric E-layer, where the 90 degrees rotation of the Alfvén mode, and consequently, the mixing of modes takes place.

Upstream source of ULF Pc3 geomagnetic pulsations

After decades of intensive study the question of the origin of dayside Pc3 (ULF waves in the 20-100 mHz band) activity still has not been fully answered. Upstream ULF waves (UWs) generated by backscattered ions in the foreshock (Fig 1), Kelvin-Helmholtz instability or pressure pulses at the magnetopause, cavity resonances in the outer or inner part of the magnetosphere have been all proposed as possible drivers of dayside field line resonances (FLRs) and dayside Pc3 activity in general.

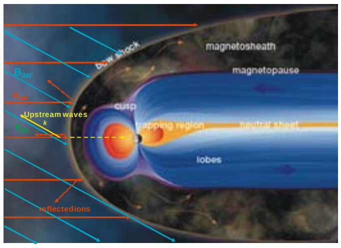

Figure 1 Upstream waves are generated in the upstream foreshock by the ion-cyclotron resonance of backscattered SW protons. UWs propagating upstream at the Alfvén speed are then convected back by the super-Alfvénic solar wind toward the dayside magnetosphere.

In a recent study (Heilig et al. 2007a) a clear correspondence was demonstrated between upstream wave-related Pc3 events observed at low-Earth orbit (LEO) by CHAMP and by the MM100 ground magnetometer array. The existence of this connection was confirmed by both statistical and case studies. It was found, in accordance with existing theories, that the **frequencies of these waves are determined by the IMF strength**, and that the **wave energy depends on both the solar wind speed and the IMF cone angle**.

Events of simultaneous occurrence of dayside Pc3s in the terrestrial foreshock (by CLUSTER), in the topside ionosphere (by CHAMP) and on the ground have been also studied.

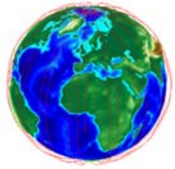

Figure 2 CHAMP orbits during a single day

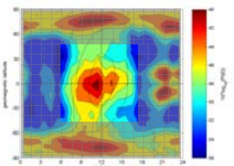

Figure 3 Magnetic latitude versus magnetic local time distribution of the normalized mean compressional signal power in the 16-100 mHz band. Power is normalized to a 400 km/s solar wind speed (1 Aug – 11 Dec, 2001). Dotted curves represent the average position of the 90°, 60°, 30° solar zenith angle isolines. Unshaded area is where upstream wave related ULF waves were observed

The LEO has several advantages and some disadvantages for the study of ULF waves

- **The orbit altitude is above the ionospheric E-layer. Hence ULF observations made at LEO are free from ionospheric screening effects.** There are basically two MHD modes in the (cold) magnetosphere: the isotropic magnetosonic (or compressional or fast) mode, and the shear Alfvén mode. Typical examples of the first type are the UW related ULF waves (Pc3s), while FLRs are the most prominent representatives for the second. The E-layer is the layer where FLR associated field aligned currents (FACs) are closed via Pedersen currents. The magnetic fields of the FACs and the Pedersen currents cancel each other below the ionosphere. What is observed on the ground is the magnetic effect of the associated Hall current. As a consequence a 90° degrees rotation of the FLR related magnetic perturbation takes place in the ionosphere. Since this rotation does not have influence on the compressional mode, although the magnetic perturbations associated with the two modes are perpendicular in the magnetosphere, they can be observed in the same (H) component on the ground. While on the ground special techniques are needed for the isolation of the two wave modes, they can be found separately in different components at LEO.

- Another important advantage of LEO of CHAMP is that using slighlty more than 4 months consecutive data **full local time and geographic coverage** (Fig 2) can be achieved. This yielded us the possibility to map the global distribution of compressional Pc3 activity, space-ground coherence and phase difference for the first time (Fig 3, Heilig et al., 2007).

- Because of the low orbit the fluctuations in the ULF band are „contaminated" by small scale **spatial structures, which when sampled by the fast moving satellite have periods in the ULF band**. The removal of the crustal field e.g. can be crucial when Pi2 or Pc4 pulsations are being investigated. This can be achieved by subtracting a crustal field model such as POMME.

Continued monitoring of dayside ULF waves at LEO

Since its launch in the July of 2000, CHAMP has been observing the ULF waves in the topside ionosphere for almost a whole solar cycle, including both the maximum and the minimum of cycle 23. The forthcoming SWARM mission will extend in time the global observation of ULF waves. The extended continuous monitoring will make it possible to study in detail the solar cycle and seasonal variations in the behaviour of the ULF waves.

Seasonal variation in the global distribution of compressional signal power

The seasonal variation in the global distribution of the compressional signal power was analysed using all data recorded between 1 Jan 2001 and 31 Dec 2006.

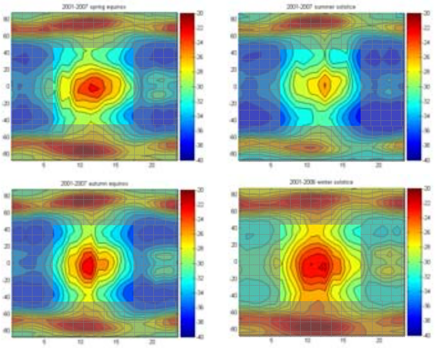

Figure 4 Magnetic latitude versus magnetic local time distribution of the mean compressional signal power in the 16-100 mHz band, 2001-2007, all data. Unshaded area is where upstream wave related ULF waves were observed **a)** sping equinox **b)** summer solstice, **c)** autumn equinox, **d)** winter solstice.

The global distribution of the compressional signal power was found to be very similar in the different seasons (Fig 4a,b,c,d). **Not any regular seasonal variation was found in the global activity level** of ULF compressional waves (unshaded area). The level of activity was first of all controlled by the solar wind speed.

The **maximum of the ULF activity** does not follow the subsolar point but **is fixed to the magnetic equator**. It supports our proposed explanation (Heilig et al. 2007) for the latitudinal distribution of ULF power. The maximum is not simply the ionospheric projection of the subsolar point, but the latitudinal distribution is formed by wave transmission and mode coupling in the magnetosphere. Near the equator the incoming UWs can penetrate deep into the magnetosphere without coupling to FLRs.

A **clear regular change could be identified, however, in the north-south asymmetry** of the ULF power distribution (Fig 5). Generally, there is somewhat more power in the summer hemisphere. The difference on the average is small, not more than 10-15% in amplitude.

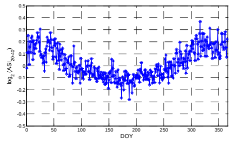

Figure 5 Seasonal variation of the asymmetry index ASI for the low latitude zone (20°-40° mag. lat.) in a log2 scale (06 h < MLT of CHAMP < 18 h), 2001-2006.

To characterize the asymmetry a set of of zonal indices were introduced. E.g. ASI(20-40) presented here (Fig 5) is defined as the south to north ratio of the square root of the mean compressional signal power in the 16-100 mHz band, observed in the 20°-40° (N and S) magnetic latitude zones, i.e. it can be interpreted as a south to north amplitude ratio.

The most prominent seasonal variation shows up in the low latitude zone (20°-40°), but it is still clearly observable in the equatorial (0°-20°) and mid-latitude (40°-60°) zones.

Solar cycle variations of the asymmetry indices (ASI)

The ASI also has a solar cycle variation. The **rate of annual changes of ASI follows the solar cycle** (Fig 6a) decreasing with decreasing sunspot number (Fig 6c). Moreover, the rate of change also depends even on the longitude. The largest changes was established in the 0°-90° magnetic latitude (Atlantic) sector (red line). The maximum interhemispheric amplitude ratio in this sector was more than 1.4 (ASI ~ 0.5) in the last quarter of 2002, while the smallest was observed during in 2005.

Similar, more prominent **interhemispheric asymmetry is also observable on the ground**. Fig 6b presents the amplitude ratio of the H-component recorded at HER (South Africa) and at THY (Hungary) at L=1.8. The general trends are the same here, both the seasonal and the solar cycle variation is obvious. However, here the amplitude ratio surpasses 2 (there is an offset maybe because of the different magnetic latitude).

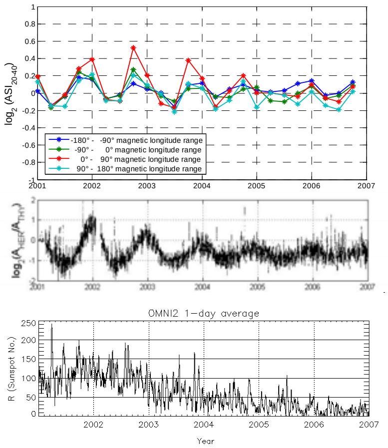

Figure 6a The variation of ASI(20-40) on logscale in four different magnetic longitude zones, 2001-2006. **6b** The variation of the HER to THY amplitude ratio on logscale (H-component), 2001-2006. **6c** The sunspot number, 2001-2006 (OMNI2 data, OMNIWeb)

We think that the same physical processes are responsible for the asymmetry both on ground and in the topside ionosphere. This asymmetry was first described in 1965 by Verő who termed the phenomenon the winter anomaly of geomagnetic pulsations. Verő observed that the pulsation amplitudes are smaller in winter in years around sunspot maximum. He also realized that this winter attennuation has a link to the topside ionospheric and plasmaspheric plasma density.

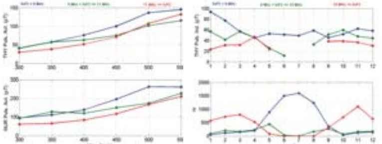

Figure 7a THY (top) and NUR (bottom) Pc3 amplitudes versus solar wind speed in different foF2 ranges, 2001-2003. **7**b THY Pc3 amplitude versus months (top) and the distribution of foF2 values for the considered cases (bottom)

The relation between the solar wind velocity and the ground geomagnetic pulsation activity is well known. The winter anomaly of pulsation activity can be demonstrated as a shift of this relation toward lower activities as F2 electron density increases (Fig 7a).
The attenuation cannot be observed during equinox months (7b) in accordance with CHAMP observations. This phenomenon requires further examination.

Coherence and phase reations

In Heilig et al. (2007a) it was also demonstrated that the coherence between ground and satellite wave signatures is high over wide latitude and longitude ranges.

In the case of mid latitude ground stations (such as THY) the space-ground coherence has a peak near the equator and the coherent region extends over 45° magnetic latitude (Fig 8). The coherence always significantly drops when the MLT difference between CHAMP and THY approaches zero. This feature may be attributed to the influence of local field line resonances (FLRs). However, the opposite sign of cross-phase (Fig 9) associated with the two coherence peaks cannot be explained by the existing MHD models. Based on the magnetic field measurements of CHAMP and the MM100 ground magnetometer array we could map the global distribution of space-ground phase difference in the Pc3 range for the first time.

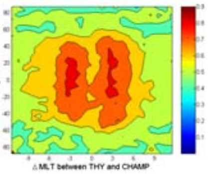

Figure 8 Magnetic latitude versus MLT difference distribution of the coherence at peak power between THY-H and CHAMP compressional waves on the dayside (09 h < MLT of CHAMP < 13 h), Jan-Dec 2003.

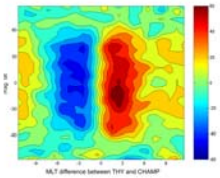

Figure 9 Magnetic latitude versus MLT difference distribution of the phase difference between THY-H and CHAMP compressional waves on the dayside (09 h < MLT of CHAMP < 13 h), Jan-Dec 2003.

Space-ground phase difference of magnetospheric (compressional) fast mode ULF waves and ground Pc3s (mainly H component) is considered to be as one of the key parameters from which the mode of magnetospheric waves can be determined. However, the observations and results published so far are rather controversial. Some authors established a constant 180 phase difference in the L= 2-3 range, independent of wave frequency, and interpreted this observation as a possible indicator of a plasmaspheric cavity resonance mode (e.g. Kim and Takahashi 1999). Others found that the phase delay observed between Ørsted at LEO and low latitude observatories (Kakioka) depends on both the wave frequency and the conductivity of the ionosphere (or LT). From the linear dependence of the phase delay on the wave frequency Jadhav et al. (2001) concluded that the delay is an effect introduced by the dayside ionosphere on a propagating mode. Theoretical approaches prompt that a proper interpretation of phase relations should take into account all the possible wave modes above and under the ionosphere, as well as the role of the ionosphere, including transmission and reflection (Pilipenko et al., 2008).

SWARM will help investigators to answer the still open questions. SWARM A+B and C satellites will have different orbital planes (Fig 10) drifting away from each other in local time (Fig 11).

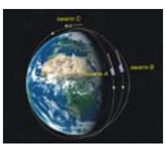

Figure 10 SWARM orbits at two diffrent altitudes in three different orbital planes

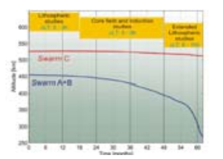

Figure 11 Orbit altitude and LT separation between SWARM A+B pair and SWARM C

In the first three years of the mission the LT separation of SWARM C and the A+B pair will be 0-6 h. During this period all satellites will be within the expected coherence length and we can observ several spatial features of the compressional ULF waves excluding the disturbing influence of the ionosphere. Coherence, phase difference, azimuthal wave number, apparent propagation speed can be measured directly. Combining then space and ground observations we can draw conclusions on ionospheric transmission. The A+B pair will solve the basis to distinguish between small scale temporal and spatial fluctuations.

References

Heilig B., H. Lühr, M. Rother (2007a), Comprehensive study of ULF upstream waves observed in the topside ionosphere by CHAMP and on the ground. Annales Geophys., 25, 737-754, 2007
Jadhav, G., Rajaram, M., Rajaram, R. 2001, Modification os daytime compressional waves by the ionosphere: first results from Oersted, GRL 28, 103.
Kim, K-H andTakahashi, K. 1999, Statistical analysis of compressional Pc 3-4 pulsations observed by AMPTE CCE at L=2-3 in the dayside magnetosphere. JGR 104, 4539.
Pilipenko, V., E. Fedorov, B. Heilig, M. J. Engebretson (2008) Structure of ULF Pc3 waves at low latitudes, J. Geophys. Res. 113 (2008), A11208, doi:10.1029/2008JA013243
Verő, J., Seasonal distribution of geomagnetic pulsations, J. Geophys. Res., 70, 2254, 1965

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