Multi-point Observation of Hiss Emerging from Lightning Whistlers

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Key Points:

- We use multi-point measurements of electromagnetic field fluctuations by the Cluster spacefleet to discuss the origin of plasmaspheric hiss.
- Our case study shows hiss which was triggered in the dayside outer plasmasphere by unducted whistlers emitted from strong lightning strokes.
- Spectral properties of magnetospherically reflecting whistlers and hiss strongly depend on geographical location of the source thunderstorm.

Abstract

We analyze continuous multi-point measurements of electromagnetic field waveforms onboard the Cluster spacecraft in order to contribute to the discussion on sources of plasmaspheric hiss, known as a shaping agent for the Earth radiation belts. In our case study we aim at finding sources of hiss observed close to the geomagnetic equator in the outer plasmasphere on the dayside. We find hiss to be triggered from whistlers of different spectral properties. Whistlers with the lowest observed dispersion arrive to different spacecraft with time delays indicating their origin in the northern hemisphere. Positions of source lightning discharges are then found using the time coincidences with the Word Wide Lightning Location Network data from three active thunderstorm regions in Europe. We find that subionospheric propagation of lightning atmospherics is necessary to explain the observations. Geographic locations of their ionospheric exit points then determine spectral properties of resulting unducted whistlers and triggered hiss. We conclude that magnetospherically reflecting whistlers are a good candidate for one of the embryonic sources of plasmaspheric hiss.

1 Introduction

Plasmaspheric hiss occurs in high plasma density regions surrounding the Earth as band-limited whistler mode waves (Russell et al., 1969; Dunckel and Helliwell, 1969; Thorne et al., 1973) with a well-defined intensity maximum at frequencies near a few hundred herz and on the dayside (Spasojevic et al., 2015; Li et al., 2015; Meredith et al., 2018).

These waves strongly influence the dynamics of the radiation belts (Van Allen, 1959), causing pitch angle diffusion and subsequent losses of electrons to the atmosphere (Kennel and Petschek, 1966), especially from the slot region between the inner and outer radiation belts (Lyons et al., 1972). These effects are highly variable (Watt et al., 2019, Zhu et al., 2021) and organized by the position of the plasmapause (Malaspina et al., 2020). Hiss acts together with other wave emissions also in the outer radiation belt (Drozdov et al., 2020), occurring at larger radial distances in plasmaspheric drainage plumes (Zhang et al., 2019).

The origin of plasmaspheric hiss is still under debate. Thorne et al. (1973, 1979), and Church and Thorne (1983) originally proposed a mechanism of the in situ growth and

amplification starting from background electromagnetic turbulence or from an embryonic source. This is, at least in some cases, supported by in situ observations of the amplification rate (Solomon et al., 1988) or by observations of hiss propagating to both hemispheres from the equatorial region close to the plasmapause (Parrot and Lefeuvre, 1986, Santolík et al., 2001) or in plasmaspheric plumes (Laakso et al., 2015). Other cases when hiss propagated close to the whistler mode resonance cone in the equatorial region are not easily reconcilable with this hypothesis (Storey et al., 1991).

Church and Thorne (1983) proposed three possibilities for the embryonic source of plasmaspheric hiss:

1. Chorus emissions (Storey, 1953) entering the plasmasphere at high latitude;
2. The low-frequency component of ducted whistlers that originate in lightning activity (Storey, 1953);
3. Auroral hiss (Gurnett and O'Brien, 1964) entering near the ionospheric foot of the plasmasphere and propagating into the plasmasphere via the magnetospherically reflected whistler mode.

The first suggestion has been verified by ray tracing studies of Chum and Santolík (2005), and Santolík et al. (2006), proving that chorus can enter the plasmasphere and provide an embryonic source of plasmaspheric hiss. Bortnik et al. (2007, 2008, 2009, 2011) confirmed this scenario and suggested that plasmaspheric hiss might be generally explained by accumulation of chorus which propagates into the plasmasphere and evolves into hiss without local amplification. However, Hartley et al. (2019) found that chorus wave vectors are rarely favorable for accessing the plasmasphere and evolving into hiss and that chorus most probably doesn't directly contribute to a significant fraction of plasmaspheric hiss.

Concerning the second suggestion of Church and Thorne (1983) for the embryonic source of plasmaspheric hiss, Sonwalker and Inan (1989) reported that magnetospherically reflected whistlers (Kimura, 1966; Smith and Angerami, 1968; Edgar, 1976) often trigger hiss emissions and therefore serve as an embryonic source. Draganov et al. (1993) put forward a hypothesis that simple accumulation of many nonducted whistlers can explain the presence of hiss in the plasmasphere. Green et al. (2005) showed that longitudinal, seasonal, and local time distribution

of the hiss intensity is similar to the distribution of lightning, with a conclusion that lightning is the dominant source for plasmaspheric hiss. In the follow-up discussion, Meredith et al. (2006) concluded that there is no relation between whistlers and hiss under 2 kHz on the global scale. However, results of Green et al. (2005) have been recently supported by Záhlava et al. (2019). Furthermore, importance of whistlers for the precipitation of energetic electrons in the radiation belts has been stressed by Bortnik et al. (2003) and Rodger et al. (2003). Green et al. (2020) also showed a significant contribution of whistlers at frequencies below 2 kHz.

Santolík and Chum (2009), commenting on conclusions of Bortnik et al. (2009), suggested that at different times plasmaspheric hiss may arise by different mechanisms, while none of them can explain all the obtained observations. To contribute to this discussion, we have reexamined the mechanism of Sonwalker and Inan (1989), using the multi-point data recorded by the WBD instruments on Cluster 1, 3 and 4 spacecraft during the close separation campaign on 4th July 2013, when all three Cluster spacecraft recorded the same sequence of lightning generated whistlers which induced hiss bands. Section 2 is devoted to the description of our data set, Section 3 shows results of a detailed analysis of the observed whistlers, and Section 4 describes their source lightning discharges. The results are discussed in Section 5, and Section 6 contains brief conclusions of our study.

2 Data

The present study is based on the Wide Band Data (WBD) instruments onboard the Cluster spacefleet (Gurnett et al., 1997, 2001), which primarily provide us with multi-point measurements of fluctuations of the electric field detected by one of the 88 m long double probe electric field antennas (Gustafsson et al., 1997) with effective lengths of 52-53 m (Béghin et al., 2005). The input of the WBD instruments can be alternatively switched to the signals from one of the search coil sensors (Cornilleau-Wehrlin et al., 1997).

Direct telemetry transmissions of real time data from the WBD instruments were received by the NASA Deep Space Network (DSN) stations before October 2007, when two 10m dishes of the Panska Ves telemetry station (operated by the Institute of Atmospheric Physics of the Czech Academy of Sciences) have been added to the telemetry receiving network. Starting

January 2015, only Panska Ves station receives the real time WBD telemetry. Another downlink possibility is to record data at a decreased rate into the onboard memory during the burst mode operations, and channel them eventually to the ESA ground stations together with the telemetry of other Cluster instruments.

During the analyzed interval on the 4th of July 2013 between 12:00 and 12:10 UT, Cluster 3 and 4 were approximately 40 km apart and the separation of this pair from Cluster 1 was approximately 500 km. The WBD instruments on Cluster 3 and 4 were switched to a mode, in which the measurements are continuously recorded with a sampling frequency of 27.4 kHz and 8 bits per sample, in a pass band between 25 Hz and 9.5 kHz. Electric field antennas Ey and Ez, which are located in the spin plane, were respectively used on Cluster 3 and 4 as sensors, replaced on each spacecraft by the magnetic search coil antenna Bx during the transmission intervals of the active sounder (Décréau et al., 1997). In these cases, the search coil characteristics limit the bandwidth below 4 kHz.

As Cluster 3 and Cluster 4 were at close separations, the real time telemetry streams from both spacecraft were received by a single dish Y (PAN80) of the Panska Ves station. The telemetry of Cluster 1 was acquired through the burst mode operations with the onboard storage, resulting in a data rate reduced to one third of the original value. The records are thus not continuous but form a cycle of ~40 milliseconds long data intervals followed always by ~80 ms long gaps. The data structure is otherwise the same as on Cluster 4, with alternating Ez and Bx components.

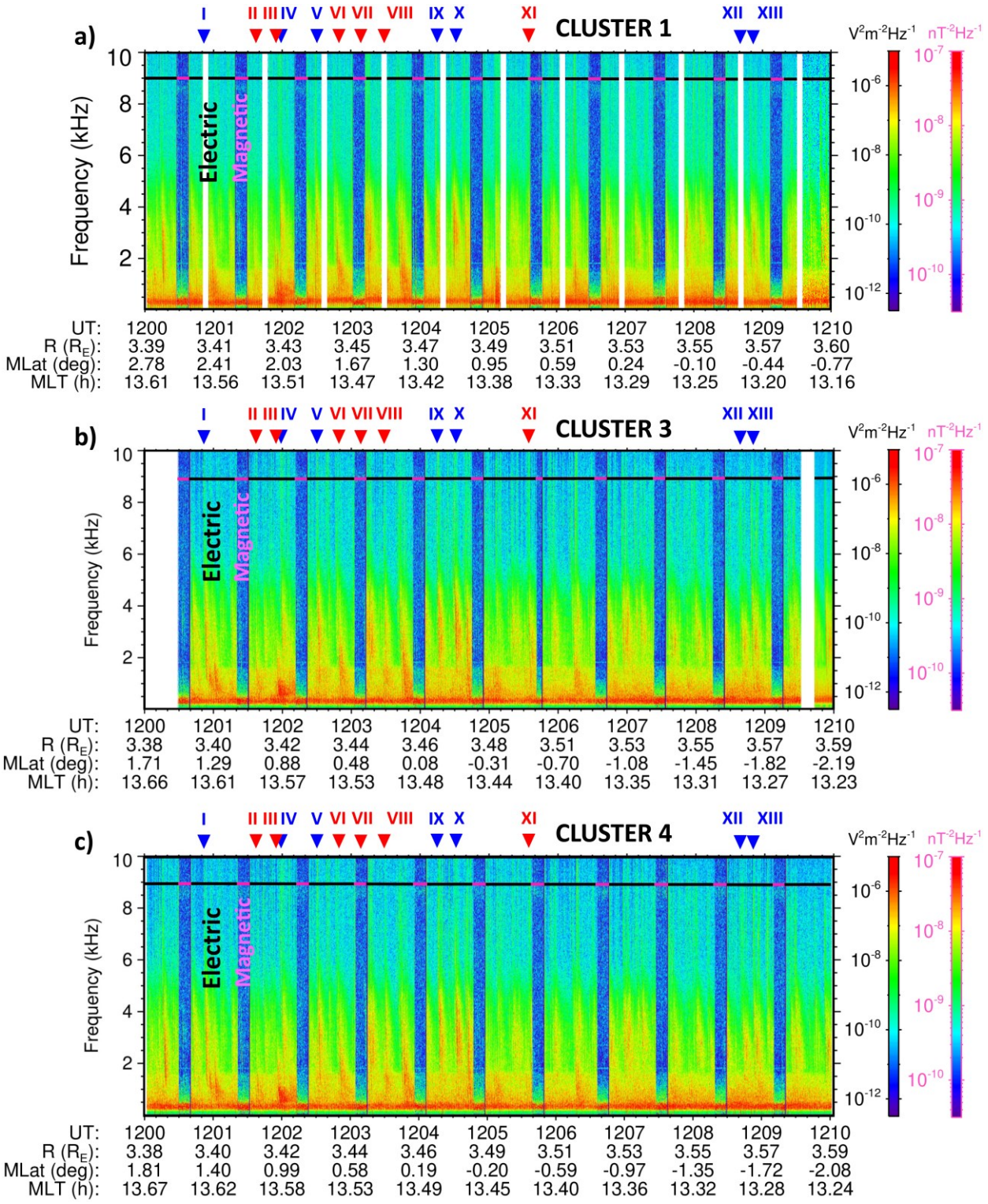

Figure 1. *Frequency-time spectrograms obtained from waveform measurements of (a) Cluster 1, (b) Cluster 3, and (c) Cluster 4 on the 4th of July 2013 between 12:00 and 12:10 UT. Electric and magnetic field measurements are interleaved, as shown by the color coded black-magenta*

horizontal line on the top of each spectrogram. Representative alternating blocks of electric and magnetic data are indicated near the start of the spectrogram with bold black and magenta colored text, respectively. Magnetic field power spectral densities are given in nT^2 Hz^{-1}, with the corresponding color scales on the right hand side of each spectrogram, while electric field power spectral densities in V^2 m^{-2} Hz^{-1} are coded according to the second color scale from the right. Thirteen selected intervals of 10 seconds (according to Table 1) are marked by roman numerals I - XIII on the top of each panel. Blue and red numerals respectively denote the type 1 and type 2 whistlers, examples of which are given in Fig. 2. Positions of each spacecraft are given on the bottom of the corresponding panels: radial distance R in the Earth radii, magnetic latitude MLat in degrees, and magnetic local time MLT in hours.

An overview of the data set is shown in Fig. 1. Cluster 3, 4, and 1 move one after the other along roughly the same orbit, crossing successively the magnetic equator from the northern to the southern hemisphere. The measurements were recorded on the dayside, at a radial distance of 3.5 Earth radii. All three spacecraft are still in the plasmasphere with high plasma densities above 80 cm^{-3}, exceeding the upper limit of the active sounder and consistent with a very small potential difference of the probes at the tips of electric antennas relative to the spacecraft body (not shown). The WBD observations are very similar on the three closely separated spacecraft. The measurement cycle with a duration of 52 s repeats approximately synchronously on the three spacecraft, alternating ~10s long magnetic field measurements with the electric field measurements in the remaining part of the cycle. On the time scale of 10 minutes, shown in Fig.1, we can identify several distinct features. (i) A steady hiss band at few hundreds of Hz is detected by electric and magnetic antennas. (ii) Electric antennas detect a weaker and also relatively stable hiss band with an upper frequency cutoff around 1.5 kHz, with a weak counterpart in the magnetic field measurements. (iii) Frequent bursts of broadband hiss detected at the same time by the different spacecraft at frequencies up to 4-5 kHz are also found mainly in the electric field measurements.

3 Whistlers

A closer look at the data on the time scales of several seconds reveals that hiss is accompanied by whistlers which originate from return strokes of lightning discharges in the Earth's atmosphere (Storey, 1953). Whistlers occur throughout the entire analyzed interval. Many of them are overlapping and from those which occur separately we have selected thirteen intervals of 10 s which are marked by roman numerals I - XIII in Fig. 1.

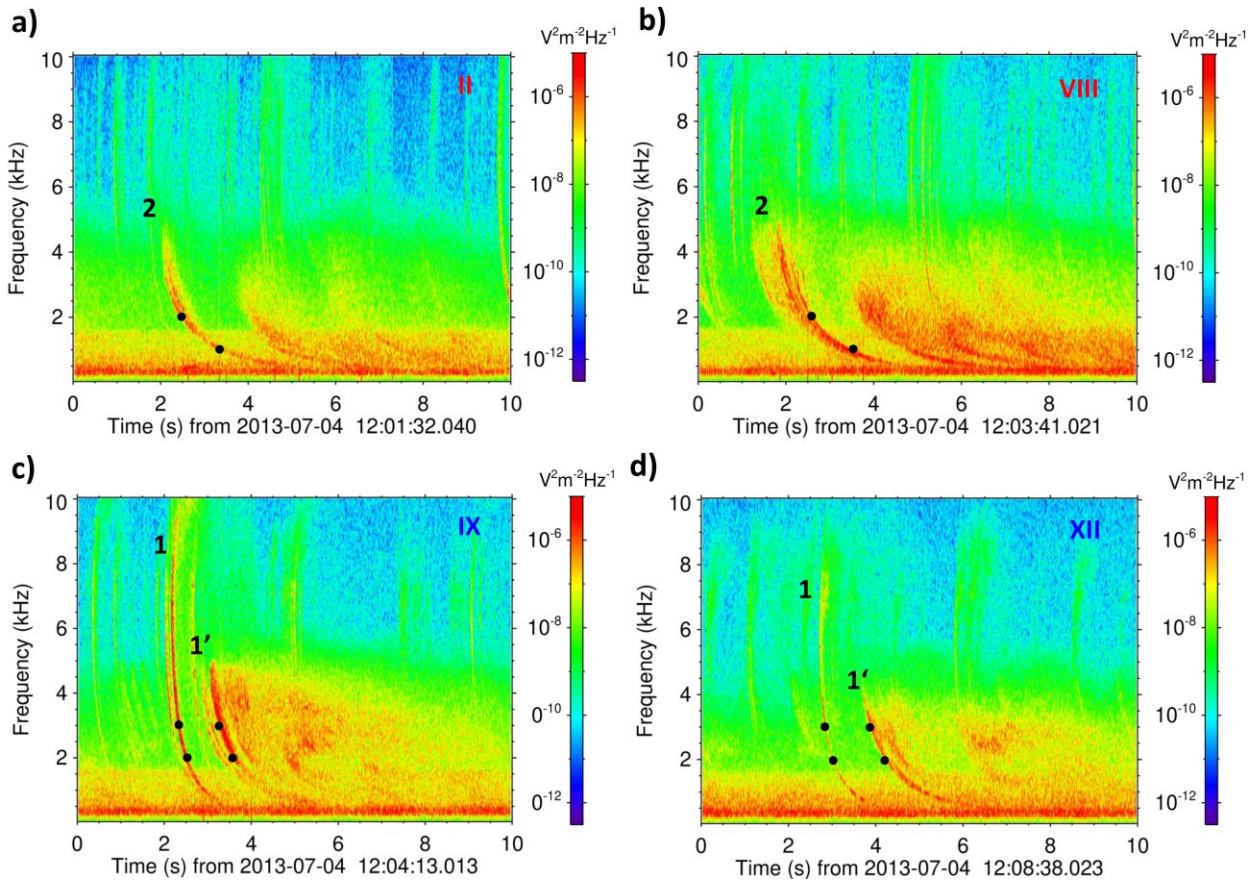

Figure 2. *Examples of four selected 10 s intervals, which are respectively marked by II, VIII, IX and XII in the overview Figure 1. (a,b) Type 2 whistlers from intervals II and VIII; (c,d) type 1 whistlers from intervals IX and XII. In all cases, electric field power spectral density is obtained from spectral analysis of waveform data recorded by Cluster 3 by using a 512 point FFT with 50% overlapping and averages over 5 neighboring spectra. Black dots show time delays and frequencies that we use to calculate whistler dispersions for three types of traces: 1, 1' and 2.*

171

172 We have found two distinct patterns in the recorded whistlers which we denote as type 1
173 and type 2 whistlers. Examples are given in Fig. 2, where we show power spectral densities
174 obtained from electric field waveforms recorded by Cluster 3 during intervals II, VIII, IX, and
175 XII. Other spacecraft provide us with very similar spectrograms from these intervals. We can see
176 that the latter two intervals in Fig. 2c and 2d contain a distinct whistler trace 1 with a lower
177 dispersion and with a nose frequency (Helliwell et al., 1956; Helliwell, 1965) around 6 kHz,
178 which is, as expected, slightly higher than one quarter of the local electron cyclotron frequency
179 (f_{ce} = 18.8 kHz) obtained from magnetic field measurements onboard the Cluster 3 spacecraft.

180 Trace 1 is followed by a blurred higher dispersion trace 1', which is accompanied by
181 weaker hiss at frequencies above 2 kHz, sometimes showing also signs of subsequent whistler
182 traces, especially for strong whistlers. These patterns often repeat in our data set as "type 1"
183 whistlers, occurring 7 times in our selected set of 13 intervals. Intervals in figures 2a and 2b
184 show blurred whistler traces triggering intense bursts of hiss below 2-3 kHz and followed, for
185 strong whistlers, by one or more traces with higher dispersion. These "type 2" intervals repeat 6
186 times in the selected set occasionally preceded with a very weak trace with a low dispersion,
187 similar to type 1 trace.

Interval no.	Whistler trace type	start time UT (hour: min)	start time UT (s)	t_1 from start time (s)	f_1 (kHz)	t_2 from start time (s)	f_2 (kHz)	D (s√Hz)	t_0 from start time (s)	Estimated UT of the causative lightning		WWLLN World Wide Lightning Location Network Corresponding strokes			
										(hours : min)	(s)	Universal Time	Lat (°N)	Lon (°E)	Peak current (kA)
I	1	12:00	48.019	2.231	3.5	2.365	2.5	43.27	1.500	12:00	49.519	12:00:49.326314	59.22	38.29	147
	1'	12:00	48.019	3.867	2	4.200	1.5	96.26							
II	2	12:01	32.040	2.437	2	3.268	1	89.72	0.431	12:01	32.471	12:01:32.150764	47.55	28.33	96
III	2	12:01	50.019	2.762	2	3.663	1	97.28	0.587	12:01	50.606	12:01:50.441402	45.63	32.36	163
IV	1	12:01	50.019	7.794	4	8.046	2	38.48	7.186	12:01	57.205	12:01:56.891150	57.57	38.59	180
	1'	12:01	50.019	8.983	3	9.355	2	90.66							
V	1	12:02	29.037	0.259	4	0.399	3	57.24	-0.646	12:02	28.391	12:02:28.607433	59.45	38.86	135
	1'	12:02	29.037	1.468	3	1.860	2	95.53							
VI	2	12:02	46.020	1.719	2	2.560	1	90.80	-0.311	12:02	45.709	12:02:45.418684	45.13	32.57	213
VII	2	12:03	03.000	2.073	2	2.919	1	91.32	0.031	12:03	3.031	none			
VIII	2	12:03	41.021	3.630	2	4.525	1	96.63	2.469	12:03	41.490	12:03:41.125780	48.25	26.16	293
IX	1	12:04	13.013	2.310	3	2.511	2	48.99	2.416	12:04	14.429	none			
	1'	12:04	13.013	3.324	3	3.680	2	86.76							
X	1	12:04	27.008	3.009	3	3.184	2	42.65	3.230	12:04	29.240	12:04:28.979911	59.23	38.34	236
	1'	12:04	27.008	4.089	3	4.466	2	91.88							
XI	2	12:05	34.000	1.136	2	1.987	1	91.85	-0.918	12:05	34.082	12:05:34.062749	44.54	33.67	60
XII	1	12:08	38.023	2.861	3	3.036	2	42.65	2.082	12:08	40.105	none			
	1'	12:08	38.023	3.890	3	4.227	2	82.13							
XIII	1	12:08	49.025	1.210	3.5	1.267	3	42.09	0.499	12:08	49.524	12:08:49.138110	57.45	38.52	247
	1'	12:08	49.025	2.253	3	2.610	2	87.00							

Table 1. *Results of analysis of 13 selected whistler intervals, see text for details*

190 We estimated the dispersion coefficients D for all these whistler traces using the classical
191 method based on the cold plasma approach (Stix, 1992) in a quasi-parallel approximation for a
192 dense plasma at frequencies well below the nose frequency,

201 $$t = t_0 + \frac{D}{\sqrt{f}}, \qquad (1)$$

193 where t is the time of arrival of the whistler trace at a selected frequency f from an originally
194 broadband source emitting at time t_0. We chose frequencies f_1 and f_2 so that the whistler trace
195 can be accurately scanned from the frequency-time spectrograms, and we determined the
196 corresponding times t_1 and t_2. A typical uncertainty of the estimated frequency is around 5 Hz
197 and a typical uncertainty of time estimation ranges from 50 ms (for trace 1) to 100 ms (for traces
198 1' or 2). This analysis allows us to estimate the dispersion coefficients D and source times t_0 for
199 all the analyzed whistler traces 1, 1', and 2. The results, based on Cluster 3 data from the 13
200 selected intervals, are summarized in Table 1.

202 The average dispersion coefficient from all trace 1 results is $D_1 = 45 \pm 7$ s√Hz, while the
203 average dispersion coefficient from the trace 1' analysis was $D_{1'} = 90 \pm 5$ s√Hz. Analysis of type
204 2 whistler traces yields a very similar average dispersion coefficient, $D_2 = 93 \pm 3$ s√Hz. This
205 strongly suggests a similar mechanism for the 1' and 2 traces. The simplest possible explanation
206 therefore is that the whistler trace 1 corresponds to a half-hop whistler propagating to the equator
207 from the source lightning directly to the spacecraft, without any reflections. Whistler traces 1'
208 and 2 would then correspond to whistlers after the first magnetospheric reflection, where for
209 type 2 events the rays of the original half-hop whistlers miss the spacecraft position.

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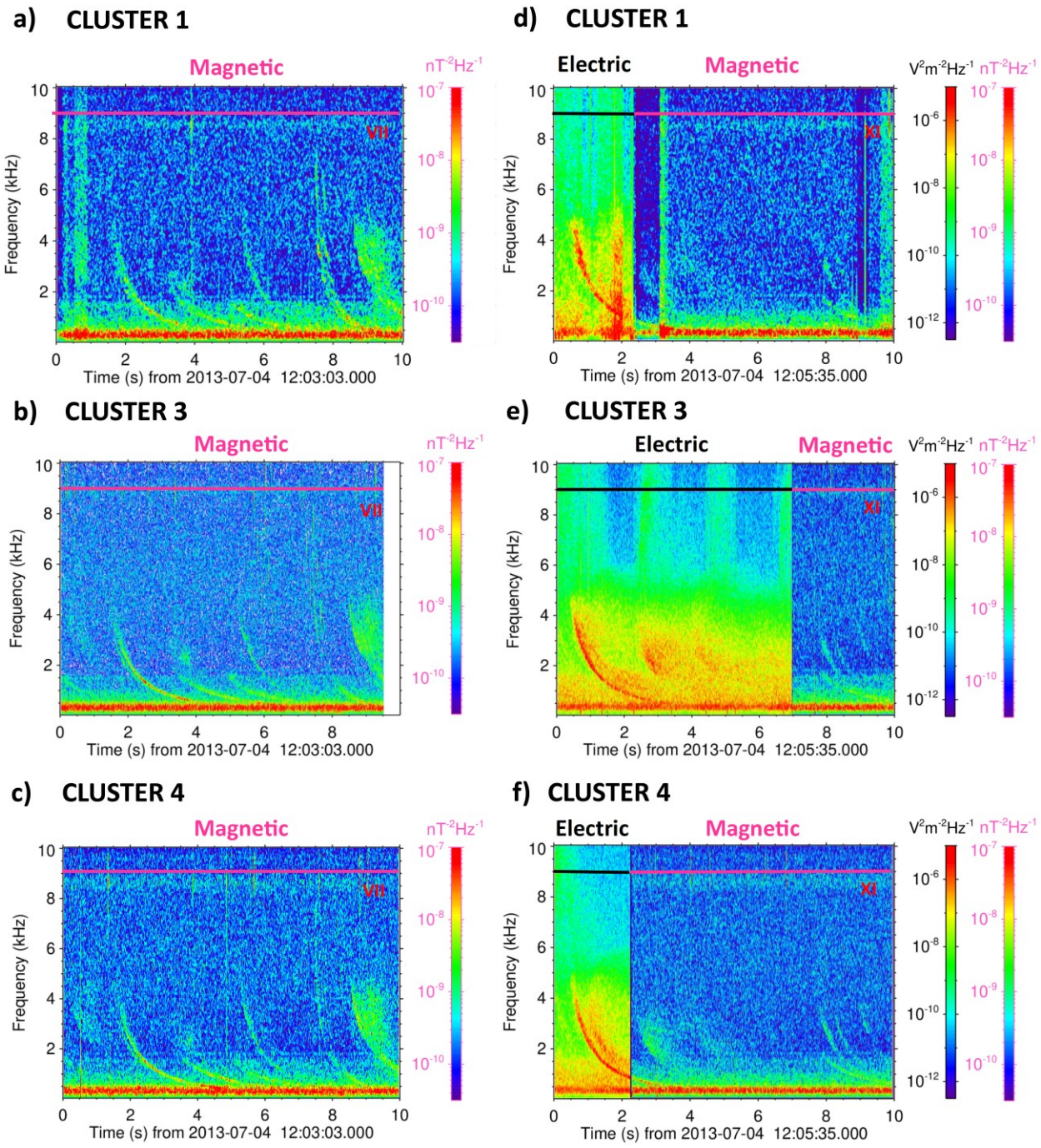

Figure 3. *Frequency-time spectrograms obtained from the magnetic field waveforms recorded during interval VII by (a) Cluster 1, (b) Cluster 3, and (c) Cluster 4. Spectrograms from the same three spacecraft for interval XI when the electric field measurements have been switched to the magnetic field at a different time on (e) Cluster 3 than on (d) Cluster 1 and (f) Cluster 4.*

To verify this hypothesis on propagation of whistlers and to estimate possible effects of associated hiss it is important to know if the waves are electromagnetic or if some of the observed features correspond to quasi-electrostatic waves. Fig. 3 shows data for the intervals where signals of the magnetic search coil antennas were used as the WBD input on the three spacecraft. Frequency-time spectrograms from interval VII in Fig 3a-c clearly show the magnetic field components of type 2 whistler traces (with a corresponding dispersion coefficient of 91 s√Hz, see Table 1) converging into an intense hiss band at hundreds of hertz, and accompanied by faint signatures of the hiss band with the upper cutoff around 1.5 kHz. Hiss bursts following the whistler traces at frequencies above 2 kHz are also observed.

Spectrograms from interval XI shown in Fig. 3d-f provide us with the opportunity to compare the electric and magnetic components of the measured waves, as the WBD input on Cluster 3 was switched to the magnetic antenna later than on the two other spacecraft. Comparison of power spectral densities of the electric field and magnetic field for hiss at a frequency f ~300 Hz results in a ratio of magnetic to electric field amplitudes $cB\ /\ E \sim 50$, where c is the speed of light. This is roughly consistent with the expected value, obtained as

$$cB\ /\ E = \frac{f_{pe}}{\sqrt{f(f_{ce}-f)}} \qquad (2)$$

assuming quasiparallel propagating whistler mode waves in a cold plasma (Stix, 1992) with a density of ~200 cm^{-3} and the corresponding plasma frequency f_{pe}, yielding $cB\ /\ E \sim 54$ with the measured electron cyclotron frequency f_{ce} = 18.8 kHz. Onboard analysis of measurements by the triaxial search coil sensors (Cornilleau-Wehrlin et al., 1997), averaged over 4 s measurement intervals, indeed indicates a right handed polarization of hiss at 300 Hz. This confirms the presence of whistler mode waves and excludes the presence of the X-mode equatorial noise below the lower hybrid frequency (f_{lh}~ 470 Hz). However, the measured magnetic field fluctuations are not well confined to a single plane so any further propagation analysis in not possible using this data set (not shown).

The observed type 2 whistler trace, with a dispersion coefficient of 92 s√Hz (see Table 1) is partly seen in both the electric and magnetic field data but the ratio of magnetic to electric field amplitudes is substantially lower than for the 300 Hz hiss, with $cB\ /\ E \sim$ 20-30, indicating propagation at large angles between the wave vector and the background magnetic field line. The

247 same holds true for the following reflection and induced hiss at above 2 kHz. Hiss below 1.5 kHz
248 shows even lower values of $cB\,/\,E \sim 15$, which indicates propagation closer to the whistler mode
249 resonance angle.

250 Unfortunately, this comparison is not available for the type 1 whistlers in our data set.
251 Therefore, a question still remains: why do we observe two separate types of lightning whistlers,
252 some of which are clearly able to contribute to hiss both below and above 2 kHz? We start
253 answering this question by analyzing multi-spacecraft measurements. We can benefit from the
254 close separation of Cluster spacecraft and analyze the time of arrival of the nose of the sharp
255 whistler trace 1. A rough calculation of the group velocity based on the cold plasma
256 approximation (Stix, 1992) for quasi-parallel propagation in a dense plasma,

257 $$v_g = \frac{2c}{f_{pe} f_{ce}} (f_{ce} - f)^{3/2} f^{1/2} \qquad (3)$$

258 yields an expected minimum time delay of one millisecond between Cluster 3 and Cluster 4 at
259 the nose frequency f = 6 kHz, for plasma densities above 100 cm^{-3}. Realistically higher plasma
260 densities and oblique propagation only increase this time delay, and it therefore can be detected
261 using the WBD waveform measurements.
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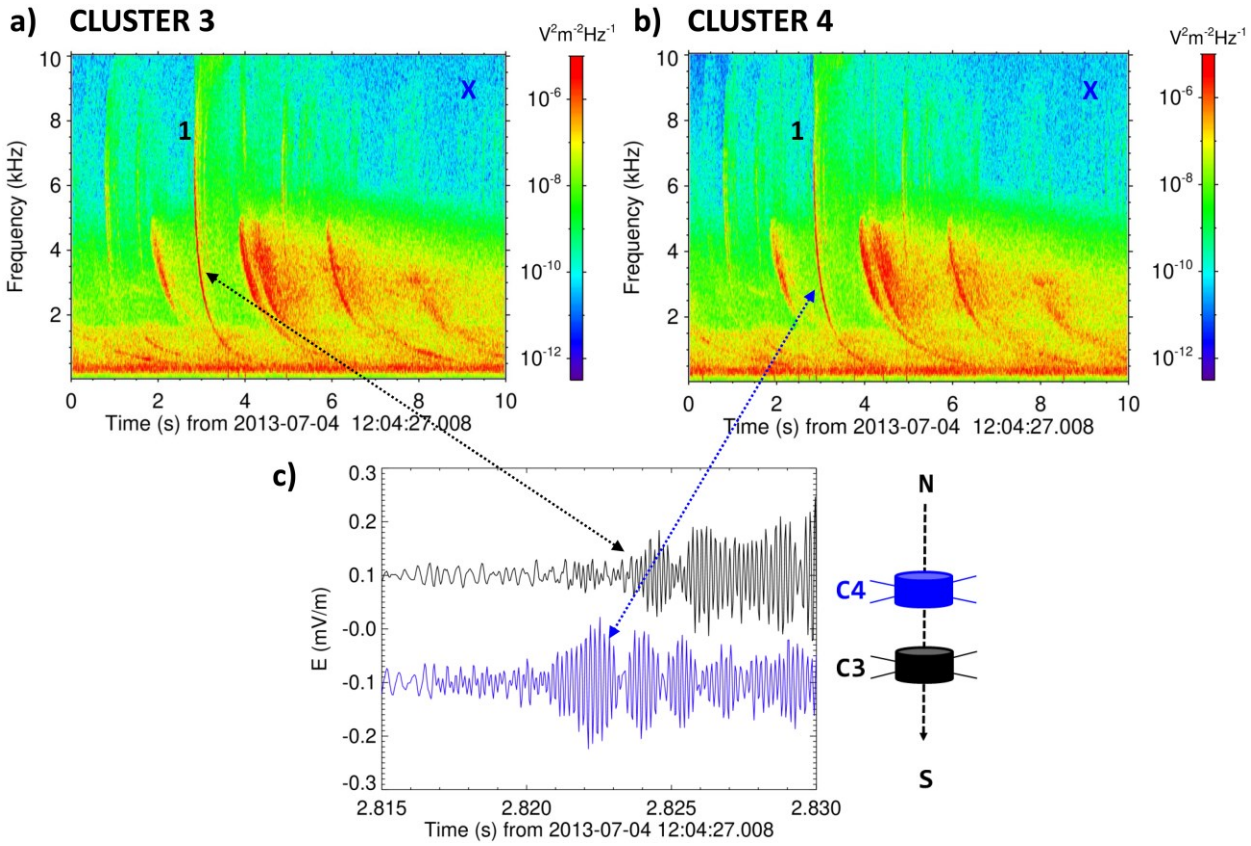

Figure 4. *(a,b) Electric field power spectral density, which were respectively obtained from spectral analysis of waveform data recorded by Cluster 3 and Cluster 4 during interval X. (c) Initial part of the electric field waveforms of the type 1 whistler trace, shown by a black line for Cluster 3 and by a blue line for Cluster 4.*

Figure 4 shows a type 1 whistler from interval X. Power spectrograms from Cluster 3 and Cluster 4 in Figs 4a and 4b give nearly identical pictures with a sharp first whistler trace, but detailed electric field waveform recordings from both spacecraft in Fig. 4c clearly show differences in the initial part of the whistler signature. Both spacecraft detect arrival of strongly modulated sinusoidal signals of the first intensification, with approximately 6 wave periods per millisecond, corresponding well to the estimated nose frequency of 6 kHz. The subsequent amplitude modulation can be explained by beating of coherent monochromatic waves above and below the nose frequency, which arrive later. The time of arrival of the first signal is, as expected, different by a few ms on the two spacecraft, Cluster 4 detecting it first. As Cluster 4 is to the North from Cluster 3, it is clear that the whistlers arrive from the northern hemisphere.

279 This propagation pattern is observed for all first traces in the analyzed intervals of type 1
280 whistlers.

281

282 **4 Source lightning**

283 Assuming that type 1 whistler traces arrive directly from their sources as half-hop whistlers we
284 can identify their source lightning return strokes using the data of one of the ground based
285 lightning location networks. We used the data of the World Wide Lightning Location Network
286 (WWLLNN), which are obtained using time of arrival analysis of signals from very low
287 frequency sensors distributed at 70 different locations around the globe. Their detection
288 efficiency depends on location, time of the day, and strength of the stroke (Hutchins et al.,
289 2012a) but for strong lightning with peak currents larger than 50 kA the absolute efficiency was
290 evaluated to be around 75% over New Zealand (Holzworth et al., 2019).

291 Over Europe, where the Cluster 3 and Cluster 4 spacecraft have their magnetic footprints
292 during the analyzed parts of their orbits (see the purple line in Fig. 5, linked to the real time
293 reception in Panska Ves), the density of the WWLLN detectors is high and we can therefore
294 expect that we would be able to find sources for the majority of whistlers originating in strong
295 discharges. The strength of the discharges was measured by the WWLLN stroke energy, which
296 we converted to the more usual peak current estimator using relations derived by Hutchins et al.
297 (2012b).

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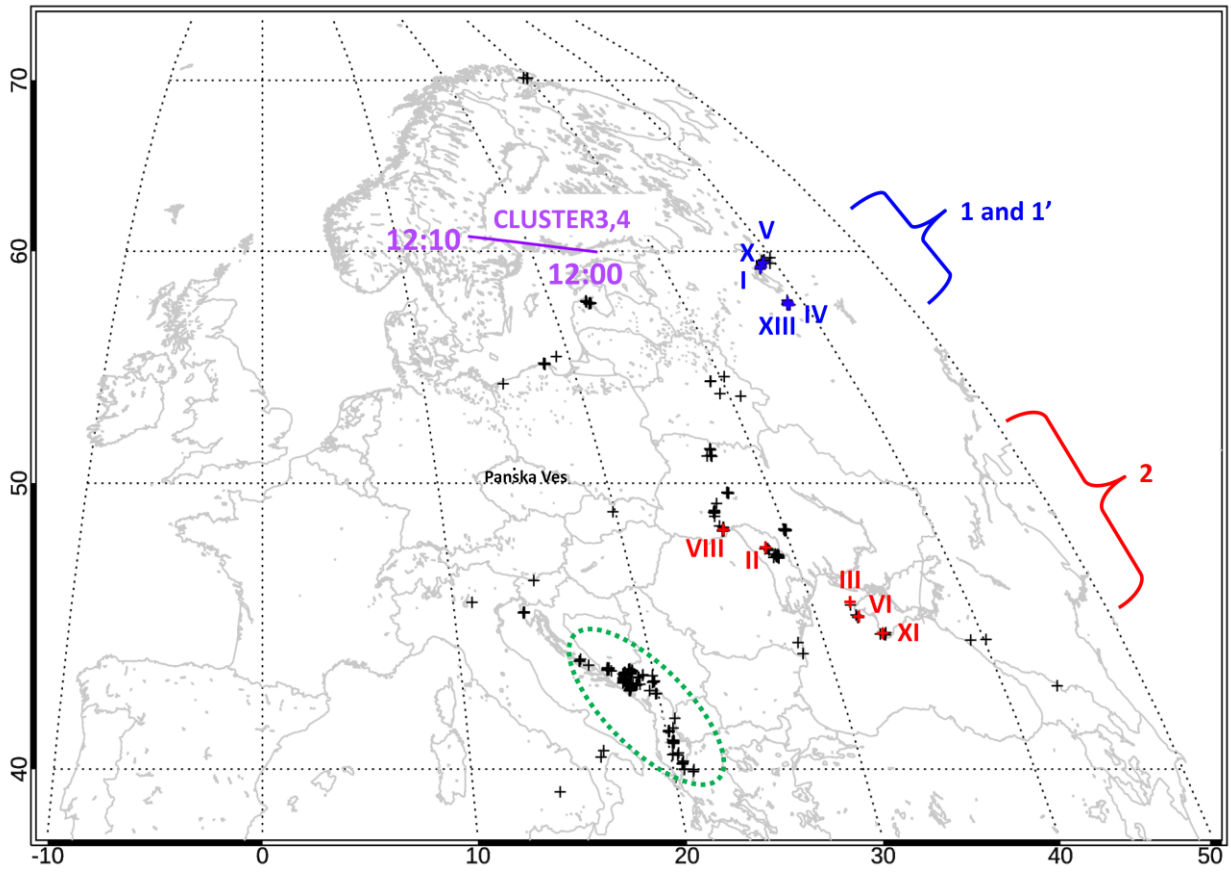

Figure 5. *Map of WWLLN lightning locations (shown as black '+' signs) over Europe on 4 July 2013 between 12:00 and 12:10 UT. The magnetic footprints of the Cluster 3 and Cluster 4 orbits (purple line) are nearly identical. Identified source strokes for type 1 and type 2 whistlers are respectively shown in blue and red, annotated by the roman numerals corresponding to the analyzed intervals. Strokes from an Adriatic storm at lower latitudes are encircled by a green dotted line.*

Black '+' signs in Fig. 5 show all WWLLN stroke locations in the geographic region at latitudes above 30°N and longitudes between 10°W and 50°E, obtained on the 4th of July 2013 between 12:00 and 12:10 UT. From this set of 377 individual lightning strokes we have selected those, which have their WWLLN stroke time within 400 ms from the time t_0 obtained from the Cluster 3 data using equation (1). Out of the analyzed 13 whistler intervals, for 3 we didn't find any corresponding WWLLN stroke, for 2 we found a single corresponding stroke, for 6 we

found two candidate strokes, for 1 we found three strokes, and for the remaining one four strokes.

In these cases, where we obtained two or more possible strokes fulfilling our criterion, all but one corresponded to multiple strokes from the same lightning flash at the same location. We have then selected the strongest stroke, which always was the first one in the sequence. Table 1 summarizes the positions and equivalent peak currents of these estimated source strokes. Their positions are plotted in Fig. 5 which clearly shows that the causative lightning return strokes for type 1 whistlers are found closer to the magnetic footprint of the spacecraft, at higher geographic latitudes of 57.5°-59.5°N, corresponding to 53.0°-54.8° of the geomagnetic dipole latitude. The causative lightning return strokes of type 2 whistlers are found at lower latitudes of 44.5°-48.3°N (41.1°-45.9° of the geomagnetic dipole latitude). We also found an intense thunderstorm activity in the Adriatic region between 40° and 43.5°N (38.9° - 43° of the geomagnetic dipole latitude).

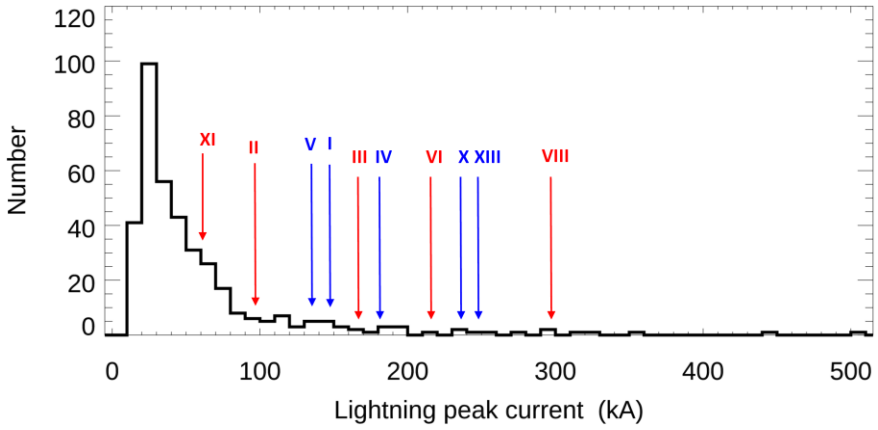

Figure 6. *Histogram of WWLLN equivalent peak currents obtained from 377 lightning strokes shown as black '+' signs in Fig. 5. Arrows with roman numerals show the peak currents of identified source strokes for the type 1 (blue) and type 2 (red) whistlers.*

Noting that the sources are displaced from the spacecraft magnetic footprint, we expect that only strong lightning strokes can feed sufficient electromagnetic energy into the Earth-ionosphere waveguide, so that the resulting atmospherics can travel to a distant exit point and generate the observed whistlers. Relation of the equivalent peak current of the identified source

strokes for the type 1 and type 2 whistlers to the overall distribution of peak currents in the analyzed geographical region and time interval is given in Fig. 6. The results confirm that the whistler source lightning strokes tend to be placed on the tail of the distribution at high peak currents, with no clear differences of the source peak currents for the two types of whistlers.

5 Discussion

Although source lightning discharges of the type 2 whistlers are located at larger distances from the spacecraft magnetic footprint (1400 to 1900 km) compared to sources of the type 1 whistlers (800 and 1300 km), they do not tend to be generated by stronger lightning. At the same time, the spectral forms of the two types of whistlers are different. A plausible explanation of both these observations is as follows:

(i) the lightning discharges generate atmospherics with a broadband frequency spectrum which propagate in the Earth-ionosphere waveguide to all horizontal directions radially from their source;

(ii) part of their electromagnetic power continuously leaks into the ionosphere during this subionospheric propagation;

(iii) the leaked power quickly decreases with the distance of the ionospheric exit point from the source lightning discharge but the measurable affected area has a radius of at least 2000 km around a strong lightning (Fišer et al., 2010; Burkholder et al., 2013);

(iv) the Snell's law implies wave vector directions which are very close to the local vertical direction at the exit points, determining thus boundary conditions for their subsequent propagation into the magnetosphere;

(v) the waves propagate in an unducted mode (Kimura, 1966; Smith and Angerami, 1968; Edgar, 1976; Shklyar and Jiříček, 2000; Santolík et al., 2009) upward from their exit points, each frequency along a slightly different path;

(vi) the type 1 whistler traces observed by the spacecraft correspond to the half-hop propagation from the ionosphere to the equator - the whistlers are then composed of different frequencies from the same source, each of them arriving from a slightly

364 different ionospheric exit point at higher latitudes, which the atmospherics from the
365 type 1 source lightning discharges reach with acceptably low attenuation;

366 (vii) another set of ionospheric exit points corresponds to separate frequencies of type 1′
367 or type 2 whistlers which are observed after the first magnetospheric reflection: lower
368 frequencies observed in type 2 case would also correspond to lower latitudes of the
369 corresponding ionospheric exit points;

370 (viii) hiss bands are triggered by these whistlers (Sonwalker and Inan, 1989), but also by
371 whistlers reflecting many times in the magnetosphere (Bortnik et al., 2003) where
372 discharges at yet lower latitudes of the Adriatic storm might contribute to an
373 embryonic sourceof hiss below 1.5 kHz.

374 To verify if these scenarios are realistic for both types of whistlers we performed a
375 schematic ray-tracing simulation, based on the procedure of Cerisier (1970) with a diffusive
376 equilibrium model of the plasma density distribution, modified to include an adaptive integration
377 step by Santolík et al. (2006, 2009). The model in our case was set to an exospheric temperature
378 of 700K and calibrated to a plasma density of 10^4 cm^{-3} at a reference altitude of 700km. This
379 model is necessarily only a crude approximation of the real plasma density distribution in the
380 magnetosphere but it is sufficient to demonstrate the properties of wave propagation, which lead
381 to the observed effects.

382 Figure 7a shows that only a relatively narrow interval of 3.2° for ionospheric exit points
383 at higher latitudes is needed to account for an unducted half-hop propagation of different
384 frequency components to a spacecraft located at the magnetic equator at a radial distance of 3.5
385 Earth radii. The waves arrive with wave vectors that are obliquely inclined from the focal
386 magnetic field line by 58-60°, which is still sufficiently far from the whistler mode resonance
387 cone to account for the electromagnetic nature of these waves. These rays would correspond to
388 the half-hop (trace 1) part of type 1 whistlers whose source discharges have been detected at
389 higher latitudes. Following the rays past the spacecraft we may notice them undergoing a
390 magnetospheric reflection and returning to the equator at different places far from the spacecraft:
391 low frequencies, represented by the ray at 1 kHz return to larger radial distances, and high
392 frequencies (4, 6, and 8 kHz) return to lower radial distances than the spacecraft position.
393

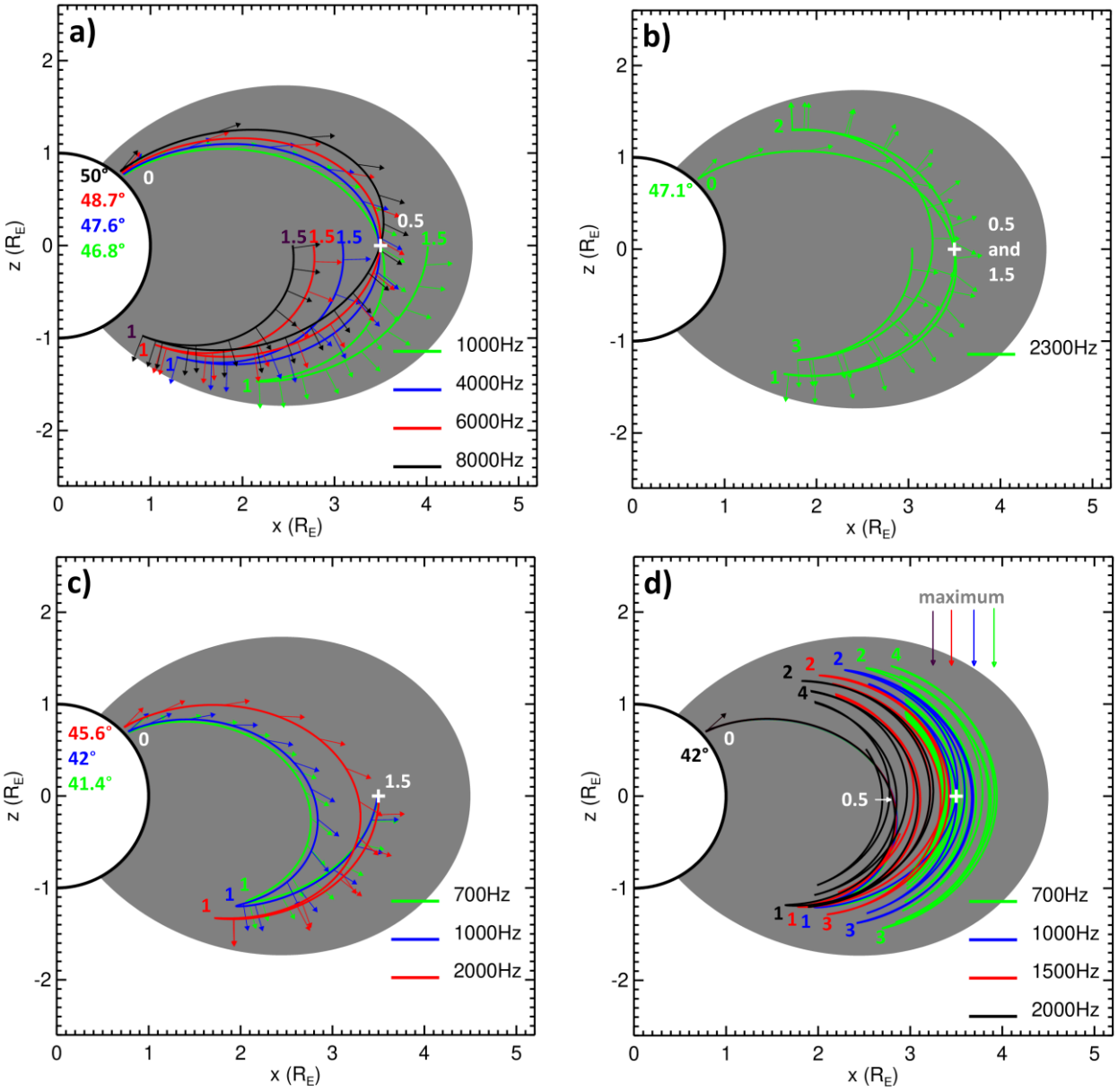

Figure 7. *Schematic ray tracing simulation from the ionosphere to the Cluster spacecraft shown by a white '+' sign at the equator and at a radial distance of 3.5 Earth radii. The plot is drawn in the plane of the local magnetic meridian containing the spacecraft position in Cartesian coordinates x-z where z is parallel to the magnetic dipole axis. (a) Type 1 whistler trace for color coded frequencies 1-8 kHz (b) Ray for a frequency of 2.3 kHz (c) Type 2 whistler trace for color coded frequencies 0.7-2 kHz (d) Rays exiting from the geomagnetic dipole latitude of 42° trace for color coded frequencies 0.7-2 kHz during 10s of the group time, with their maximum radial distances shown on the top. Geomagnetic dipole latitudes of the ionospheric exit points of the separate rays are given on the left hand side of each panel. Exit points are marked by white*

405 *"0", equatorial passes are marked by "0.5" and "1.5", magnetospheric reflections are*
406 *identified by color coded numbers 1, 2, 3, and 4. Arrows are added to the rays to show the wave*
407 *vector directions with an interval of 100 ms of the group time. Grey area follows the magnetic*
408 *field line passing through the equator at a radial distance of 4.5 Earth radii.*

409

410 A frequency between 1 and 4 kHz must therefore exist, for which the corresponding ray
411 passes through the spacecraft not only as a half-hop whistler but also after the magnetospheric
412 reflection. Fig. 7b show such a ray for a frequency of 2.3 kHz, which would then contribute to
413 both type 1 and type 1' traces. Further evolution of the ray during first three magnetospheric
414 reflections indicates that the waves gradually move to lower radial distances.

415 Fig. 7c corresponds to possible propagation of type 2 whistlers. Waves at frequencies
416 below 2.3 kHz, all of them launched from lower latitudes than in the previous case, initially miss
417 the spacecraft position and converge at the spacecraft location only after the first magnetospheric
418 reflection. Their wave vector directions at that point are inclined by 77-79° from the local field
419 line. This is still far enough (5-11°) from the resonance cone, which explains the observed
420 electromagnetic nature of these waves. Occasional very weak half-hop whistlers preceding the
421 type 2 traces could be explained by a long propagation and strong attenuation of the lightning
422 generated atmospherics in the Earth-ionosphere waveguide.

423 Finally, a long lasting hiss emission below 1.5 kHz might be, at least in part, attributed to
424 embryonal sources from whistlers originating in the Adriatic storm at geomagnetic latitudes
425 below 43°. Unducted whistlers can bounce in the magnetosphere back and forth with many
426 reflections. Bortnik et al. (2003) showed that the lifetime of these waves is limited by the wave
427 damping caused by the low energy component of the electron distribution function. At the
428 equatorial distance of 3.5 Earth radii, their results give lifetimes of at least 20 s, which accounts
429 for many reflections. Fig. 7d shows rays propagating for 10 s from an exit point at a geomagnetic
430 latitude of 42°, from which the 2 kHz waves always stay at lower radial distances and do not
431 reach the spacecraft but waves below 1.5 kHz propagate to larger radial distances up to the
432 spacecraft position.

433

6 Conclusions

Detailed analysis of high cadence multi-point measurements of electromagnetic field by the Cluster spacefleet allowed us to reconstruct the chain of events leading to the occurrence of triggered hiss in the outer edge of the equatorial dayside plasmasphere. Sources of triggering waves for these emissions are found in lightning discharges localized by the Word Wide Lightning Location Network to different thunderstorms spread over 15° of geomagnetic latitude. The location of the source lighting determines the spectral shapes and frequencies of the resulting unducted whistlers. Our case study demonstrates that lightning whistlers penetrating the ionosphere at latitudes around 40° of geomagnetic latitude and propagating unducted should be considered as one of the embryonic sources of plasmaspheric hiss below 2 kHz.

Acknowledgments and Data Availability

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