Opponent's report on the doctoral thesis of Miroslav Hanzelka:

Nonlinear processes in space plasmas and their effects on the generation and propagation of electromagnetic waves

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This thesis discusses, from a theoretical perspective, naturally occurring very low frequency (VLF) radio waves termed chorus (because they sound like birds singing at dawn) which can be observed both on the ground and aboard satellites travelling through the Earth's magnetosphere. The Abstract provides a clear and concise summary of the work in space plasma physics that is presented. There is a review of the cyclotron resonant interaction between energetic electrons trapped in the Van Allen belts and these radio waves which propagate in the whistler mode. Important properties of whistler mode waves, such as their dispersion (both cold plasma and hot plasma) and amplification (both linear and non-linear), are considered. New and significant original results are presented: the style and quality of the written English throughout is excellent.

The thesis consists of five numbered chapters and an un-numbered chapter which summarises the Conclusions and briefly considers the outlook for future research in the field. The bibliography of 13 pages contains 179 important references, 4 of which have Hanzelka as their first author, and 2 have him as a co-author; there are references to 12 monographs. Two impressive papers published in JGR Space Physics with Hanzelka as the first author are appended to the thesis; there are 7 other publications where Hanzelka is either the first author or a co-author.

The two-page Introduction gives a clear outline of the physics of energetic electrons trapped in the magnetosphere, explaining that these electrons constitute a radiation hazard both to astronauts and to various electronic components aboard satellites. The magnetospheric electron lifetimes are determined by interactions with whistler mode waves. Two quite long paragraphs summarise the contents of the thesis and present in outline the main results obtained.

The first chapter of the thesis introduces the time dispersion of the different frequencies in a radio signal, electromagnetic ion cyclotron (EMIC) waves and their dispersion, ray tracing studies, the linear theory of whistler mode wave growth, and some satellite observations (using both electric and magnetic field antennas) of such signals (both below and above half the electron cyclotron frequency). Examples of the dynamic spectra (spectrograms) of chorus and EMIC emissions are shown.

1. **What is the parameter L shown in Fig. 1.7?**

Chapter 2 introduces the concept of the trapping of electrons by a wave, and reviews the cyclotron resonance between whistler-mode waves and energetic electrons.

1. **Can you list, starting with the most important, and in order of decreasing importance, all the forces acting upon an energetic electron which is trapped on an L=4 flux tube?**
2. **On an L=4 flux tube, where is the region that an efficient cyclotron interaction between an energetic electron and a whistler-mode signal is most likely to occur? Why is that so?**

Chapter 3 presents some typical examples of the dynamic spectra of chorus signals observed by satellites in the Earth's magnetosphere. The non-linear theory of the amplification of such signals using numerical simulation is elaborated; this involves the resonant electron current. The spatial inhomogeneity of the plasma distribution along particular flux tubes is an important parameter in the non-linear growth of chorus signals.

1. **In what ways should the non-linear growth theory of Omura et al. (2008) and Omura (2021) be extended in the future?**
2. **Is it likely that the step in the energetic electron distribution function required by the backward wave oscillator theory of chorus generation could be observed experimentally?**
3. **What are the advantages (and disadvantages) of the Zonca et al. (2022) theory of chorus generation?**
4. **What are the limitations of the Helliwell (1967) theory?**

Chapter 4 presents original research, giving a theoretical model for the rising tone of an element of chorus emissions. This is based upon the non-linear growth theory described earlier; it explains how the chorus waves modify the distribution of energetic electrons. The flow chart shown in Figure 4.2 is especially helpful. The results obtained (Figure 4.6) demonstrate good agreement with observations made aboard a satellite (Figure 4.8). The final paragraph of the Chapter suggests future useful work.

Chapter 5 considers numerical simulations of the non-linear behaviour of energetic electrons interacting with a chorus emission whose frequency rises rapidly. Changes of the kinetic energy and of the pitch angle of the cyclotron resonant electrons are calculated. The possibility of different space-borne instruments being able to observe such changes is discussed. It is shown that the energy resolution and/or the pitch angle resolution of current instruments in space are insufficient. Figure 5.10f interestingly demonstrates how an improved instrument could measure the likely energy and pitch angle changes associated with an element of a chorus signal. Section 5.6 considers the important topic of the scattering of cyclotron resonant energetic electrons into the loss cone and their consequent precipitation into the atmosphere. Section 5.7 is a very clear and concise summary of the main significant results derived in this thesis, and relates them to several very recent papers written by scientists in different countries. The most important one of these, in my opinion, is that a new space mission dedicated to the detailed study of chorus is needed to pinpoint the space plasma physics mechanism responsible for its generation and the consequent loss of energetic electrons from the Van Allen belts.

The final Conclusion and future outlook chapter is a short one which sets the valuable results obtained in this thesis in a broader context, namely that of magnetospheric dynamics. The thesis closes with a comprehensive list of the symbols used and their definition/explanation.

I consider that this thesis clearly demonstrates the author's ability to carry out independent and creative scientific work, and also his deep understanding of the phenomenon of chorus, together with its generation and propagation mechanisms. Without any hesitation, I recommend it for the author's defence.

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