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(Eds.)

Geospace Electromagnetic Waves and Radiation

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Preface

The "Ringberg Workshop on High Frequency Waves in Geospace" convened at Ringberg Castle, Bavaria, from July 11 to 14, 2004. Approximately 30 attendees from 11 countries gathered at the castle for a program of invited talks and posters focussed on outstanding problems in high-frequency waves, defined broadly as waves exceeding a few kHz in frequency. Thirteen invited presentations comprise the contents of this volume. These articles provide introductions to current problems in geospace electromagnetic radiation, guides to the associated literature, and tutorial reviews of the relevant space physics. As such, this volume should be of value to students and researchers in electromagnetic wave propagation in the environment of the Earth at altitudes above the neutral atmosphere, extending from the ionosphere into outer space.

The contributions are broadly grouped into three parts. Part I, entitled "High-Frequency Radiation" focusses on radiation processes in near-Earth plasmas. Benson et al. present a tutorial review of Z-mode emissions, which so far have received relatively little attention and are the subject of few such reviews despite their abundant presence in geospace. Hashimoto et al. continue with another tutorial review on the terrestrial continuum radiation, the relatively weak radio emissions that fill the entire outer magnetosphere and provide information about the magnetospheric plasma boundaries and the state of the magnetospheric plasma density. Louarn reviews the ideas relevant to the generation of Auroral Kilometric Radiation (AKR), by far the most powerful and significant of the high-frequency radiations in the magnetosphere. Fleishman introduces the topic of diffusive synchrotron radiation, a mechanism not widely appreciated by geophysicists, but which may play a role in several magnetospheric, heliospheric, and even astrophysical settings. Pottelette and Treumann end this chapter with a discussion of the latest ideas about the relationship between auroral acceleration processes and radiation processes such as AKR, a subject which has been transformed in the last decade due to observations with the FAST and CLUSTER satellites.

Part II of this monograph, entitled "High-frequency waves," focusses on wave physics. Sonwalkar presents a lengthy and comprehensive review of whistler-mode propagation in the presence of density irregularities. James' paper deals with recent results from the OEDIPUS-C sounding rocket, combined with recent innovations in antenna theory, which lead to the provocative but significant conclusion that field strengths measured by many previous observations of auroral hiss using dipole antennas may need to be revised downward. Lee et al. present a novel theoretical method for analyzing mode-coupling and mode-conversion of high-frequency waves, with applications to geophysical plasmas. Yoon et al. treat the subject of mode-conversion radiations, which are replete in the Earth's environment, both in the ionosphere, magnetosphere, and solar wind. Vaivads et al. conclude this part with a review of high-frequency waves related to magnetic reconnection as the generator region of high-frequency waves and radiation in geospace, a very important and hot topic, especially in the light of recent CLUSTER satellite observations.

Part III of the monograph is devoted to new analysis techniques and instrumentation transforming research on high-frequency waves. Pécseli and Trulsen discuss novel ideas on the forefront of linking wave observations to theoretical models. Santolík and Parrot apply sophisticated wave propagation analysis tools to the study of AKR. Finally, Kletzing and Muschietti discuss wave particle correlators, describing the physics that can be investigated with them and including results from a recent state-of-the-art wave-particle correlator flown in the Earth's auroral ionosphere.

This monograph would not have been possible without the assistance of the many referees. Special thanks are due to M. André, R.E. Ergun, J.R. Johnson, E.V. Mishin, R. Pottelette, O. Santolík, V.S. Sonwalkar, and A.T. Weatherwax. We thank Dr. Axel Hörmann and his team for creating the gracious, welcoming environment at Ringberg Castle, which allowed a creative workshop to take place and thereby inspired this volume. We also thank the International Space Science Institute Bern for support. Finally, the editors at Springer, especially Dr. Christian Caron, deserve thanks for supporting the timely publication of this work and helping to assure its high quality.

Hanover, New Hampshire, and Munich
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James LaBelle
Rudolf Treumann

Contents

Part I

High-Frequency Radiation

1

Active Wave Experiments in Space Plasmas: The Z Mode

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Abstract. The term Z mode is space physics notation for the low-frequency branch of the extraordinary (X) mode. It is an internal, or trapped, mode of the plasma confined in frequency between the cutoff frequency f_z and the upper-hybrid frequency f_{uh} which is related to the electron plasma frequency f_{pe} and the electron cyclotron frequency f_{ce} by the expression $f_{uh}^2 = f_{pe}^2 + f_{ce}^2$; f_z is a function of f_{pe} and f_{ce}. These characteristic frequencies are directly related to the electron number density N_e and the magnetic field strength $|\mathbf{B}|$, i.e., $f_{pe}(\mathrm{kHz})^2 \approx 80.6 N_e(\mathrm{cm}^{-3})$ and $f_{ce}(\mathrm{kHz})^2 \approx 0.028|\mathbf{B}|(\mathrm{nT})$. The Z mode is further classified as slow or fast depending on whether the phase velocity is lower or higher than the speed of light in vacuum. The Z mode provides a link between the short wavelength λ (large wave number $k = 2\pi/\lambda$) electrostatic (es) domain and the long λ (small k) electromagnetic (em) domain. An understanding of the generation, propagation and reception of Z-mode waves in space plasma leads to fundamental information on wave/particle interactions, N_e, and field-aligned N_e irregularities (FAI) in both active and passive wave experiments. Here we review Z-mode observations and their interpretations from both radio sounders on rockets and satellites and from plasma-wave receivers on satellites. The emphasis will be on the scattering and ducting of sounder-generated Z-mode waves by FAI and on the passive reception of Z-mode waves generated by natural processes such as Cherenkov and cyclotron emission. The diagnostic applications of the observations to understanding ionospheric and magnetospheric plasma processes and structures benefit from the complementary nature of passive and active plasma-wave experiments.

Key words: Auroral kilometric radiation, Z-mode, free space radiation, wave transformation, radiation escape, cavity modes, active experiments

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1.1 Introduction

According to cold plasma theory, at high frequencies there are two characteristic electromagnetic (*em*) waves, or modes, that can propagate in a magnetoplasma. They are often referred to as the free-space ordinary (O) and extraordinary (X) modes because waves propagating in these modes can smoothly connect to free space. The X mode has two branches. In addition to the free-space mode, it has a mode called the slow branch. This name is used because it is restricted to propagation velocities less than the vacuum speed of light c. Since this mode only exists within a plasma, there was considerable interest in explaining observations indicating that it was responsible for a unique signature on early ground-based radars designed to probe the ionosphere. In their most common application these radars, called ionosondes, operate by transmitting a radio pulse of short time duration at a particular frequency and receiving, at the same frequency, for a time interval sufficient to receive an echo from the ionosphere overhead. This process is repeated over a range of frequencies likely to produce reflections. The resulting record is called an ionogram.

Normally, there are two ionospheric reflections, one due to the O mode and one due to the X mode. "On rare occasions", as first reported by Eckersley [23], there is a third reflection with the same polarization as the O mode. This third reflection trace, corresponding to the slow X-mode branch, was dubbed the Z mode in ionospheric research; a designation commonly used in space physics. In order to explain the presence of the Z mode at ground level, i.e., far below the ionospheric plasma, and the polarization (same as the O mode), a Z-O mode coupling process involving obliquely-propagating O-mode waves was introduced by Ellis [24] as discussed in Sect. 13.5 of Ratcliffe [57]. An ionogram showing this triple splitting of the ionospheric reflection is schematically illustrated in Fig. 1.1. Here the apparent height h' (or apparent, or virtual, range) corresponds to $ct/2$, where t is the round trip echo delay time, and the frequency f is the sounding frequency. For a description of the sounding technique, and the inversion from $h'(f)$ to $N_e(h)$, where N_e is the electron number density and h is the true altitude, see Thomas [64] and Reinisch [58] and references therein.

In order to understand how the Z mode is related to the free-space O and X modes it is necessary to discuss plasma-wave dispersion. This topic will be addressed in Sect. 1.2. Since the Z mode is an internal (or trapped) mode of the plasma, the emphasis in this paper will be on the reception of the Z mode by space-borne receivers during active and passive experiments. Sections 1.3 and 1.4 will deal with sounder-stimulated Z-mode waves in the ionosphere and the magnetosphere, respectively. Particular attention will be given to the information that the sounder-stimulated Z-mode waves provide concerning magnetic-field aligned N_e irregularities (FAI). FAI are irregularities in N_e transverse to the direction of the background magnetic field **B** that are maintained for long distances along **B**. They efficiently scatter and

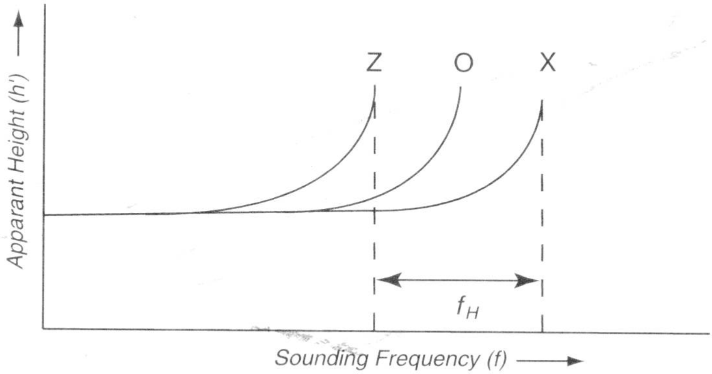

Fig. 1.1. Ground-based ionogram schematic illustrating Z-, O-, and X-mode reflection traces. Here the ionospheric notation for the electron cyclotron frequency, f_H, is used [adapted from 57]

duct sounder-stimulated Z-mode waves. Section 1.5 discusses a combined active/passive investigation of Z-mode waves generated by natural processes. A summary is presented in Sect. 1.6.

There have been many spacecraft that have generated Z-mode waves in the ionosphere and magnetosphere using radio sounders. Similarly, there have been many satellites that have detected Z-mode waves of magnetospheric origin using plasma wave receivers [LaBelle and Treumann, 43, included a review of auroral Z-mode observations and theory]. Our goal is not to review the Z-mode observations from all of these missions. Rather, it is to select specific examples that illustrate the range of Z-mode phenomena observed in active space wave-injection experiments and to demonstrate their diagnostic capability. In the case of the ionosphere, we will mainly use data from two missions, namely, (1) the ISIS (International Satellites for Ionospheric Studies) satellites [Jackson and Warren, 33] and (2) the OEDIPUS sounding rocket double payloads (Observations by Electric-field Determinations in the Ionospheric Plasma-A Unique Strategy) [see, e.g., 30, 36]. In the case of the magnetosphere, data from the Radio Plasma Imager (RPI) [Reinisch et al., 59] on the IMAGE (Imager for Magnetopause-to-Aurora Global Exploration) satellite [Burch, 15] will be used.

1.2 Plasma Wave Dispersion

Waves in a cold plasma are described by a dispersion relation, i.e., the scalar relation expressing the angular frequency $\omega = 2\pi f$ in terms of the propagation vector $\mathbf{k}$, which is related to the refractive index $\mathbf{n}$ by $\mathbf{n} = \mathbf{k}c/\omega$ where $k = |\mathbf{k}| = (2\pi/\lambda)$ and λ is the wavelength.This description has been given in a number of books and review papers [see, e.g., 1, 19, 27, 39, 57, 63]. Figure 1.2 presents dispersion curves for waves propagating in a homogeneous cold

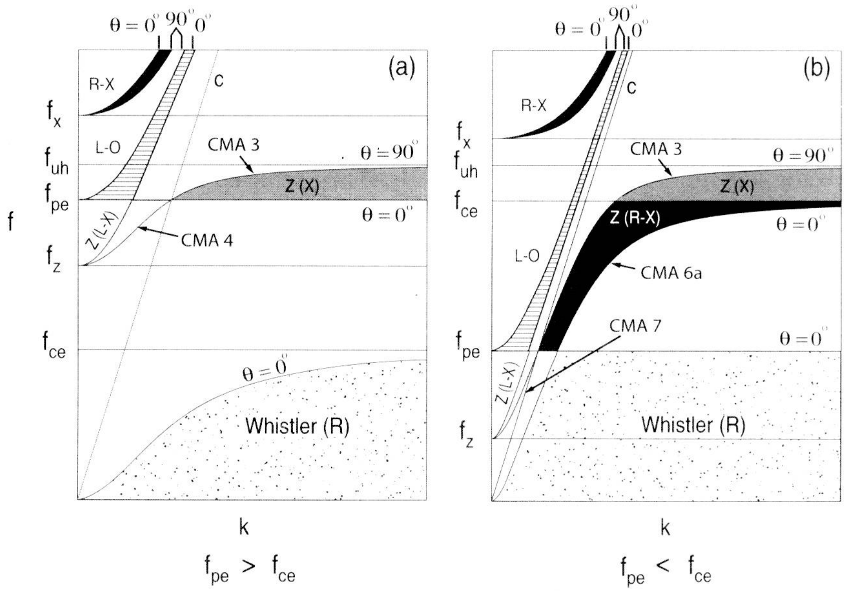

Fig. 1.2. Schematic dispersion diagrams. (**a**) Example when $f_{pe}/f_{ce} > 1$. (**b**) Example when $f_{pe}/f_{ce} < 1$ [adapted from 27, 62] (Reprinted with permission of the American Geophysical Union)

plasma, where ion motions are neglected, with **k** making an angle θ relative to **B**. The figure shows the dispersion curves for $\theta = 0$ and $\theta = \pi/2$ cases for a range of frequency and wave number. The region between these two limiting cases is shown by various shades of gray – indicating various modes – where the propagation at oblique wave normal angles is permitted. The waves are labelled based on their polarization for parallel or perpendicular propagation, i.e., R or L for right- or left-hand polarization (with respect to the direction of **B**) when $\theta = 0$, and X or O for extraordinary and ordinary mode polarization when $\theta = \pi/2$. In some regions, only one letter is used indicating that propagation is not possible for both $\theta = 0$ and $\theta = \pi/2$. Thus Z(X) indicates that the Z mode does not include the condition $\theta = 0$ in the region indicated based on the cold-plasma approximation. The Z-mode regions in Fig. 1.2 are also labelled with the CMA designation using the notation of Stix [63]. Thus Z(X) occurs in CMA region 3 where k, and thus $n = |\mathbf{n}|$, can become large leading to a condition ($n = \infty$) known as *resonance*; the condition $k = 0$ (or $n = 0$) is known as a *cutoff*.

The plasma resonances and cutoffs in Fig. 1.2 are given by the following expressions:

$$f_{ce}(\mathrm{kHz}) = \frac{|e|}{2\pi m_e)}|\mathrm{B}| \approx 0.028\,|\mathbf{B}(\mathrm{nT})| \quad (1.1)$$