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Advances in Space Research xxx (2016) xxx–xxx

ADVANCES IN SPACE RESEARCH
(a COSPAR publication)

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Gyrophase bunched ions in the plasma sheet

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Received 11 April 2016; received in revised form 10 July 2016; accepted 2 August 2016

Abstract

Gyrophase bunched ions were first detected in the upstream region of the Earth's bow shock in the early 1980s which is formed by the microphysical process associated with reflected solar wind ions at the bow shock. Inside the magnetosphere, the results of computer simulations demonstrated that nonlinear wave-particle interaction can also result in the gyrophase bunching of particles. However, to date direct observations barely exist regarding this issue occurred inside the magnetosphere. In this paper, we report for the first time an event of gyrophase bunched ions observed in the near-Earth plasma sheet. The nongyrotropic distributions of ions were closely accompanied with the electromagnetic waves at the oxygen cyclotron frequency. The phase of bunched ions and the phase of waves mainly have very narrow phase differences (<30°) when the O^+ band waves are remarkably enhanced, which indicates that the wave and particle are closely corotating. The "electric phase bunching" is considered to be a possible mechanism for the formation of the gyrophase bunched distributions in this case. The MVA analysis suggests that the oxygen band waves possess left helicity with respect to the propagation direction, which agrees with the characteristic of electromagnetic ion cyclotron waves. The observation of O^+ ions composition suggests that the oxygen band waves are excited due to the enhancements of the O^+ ion density. This study suggests that the gyrophase bunching is a significant nonlinear effect that exists not only in the bow shock but also in the inner magnetosphere.

Keywords: Gyrophase bunching; Oxygen band waves; Wave-particle interaction

1. Introduction

The concept of gyro-phase bunching of particles, defined as that all particles have phases within a very limited range in phase space, goes back to the last half of the 20th century when people studied triggered emissions of whistlers in the magnetosphere (Dysthe, 1971; Gendrin, 1974; Helliwell, 1967; Matsumoto, 1979). Gyrophase bunched ions were first detected at the upstream of the Earth's quasi-perpendicular bow shock (Eastman et al., 1981; Gurgiolo et al., 1981). After two decades of research, the formation mechanism of this observed structure had been well understood as due to one of two processes: (1) the nature of the process by which some fraction of the solar wind ions are reflected at the bow shock (Gosling et al., 1982; Paschmann et al., 1982), (2) the resonant nature of electromagnetic instability, which is driven by beams of ions reflected from the shock, leads to gyro-phase bunching of the beam ions (Gurgiolo et al., 1993; Hoshino and Terasawa, 1985; Meziane et al., 2001).

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http://dx.doi.org/10.1016/j.asr.2016.08.003
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Please cite this article in press as: Wang, Z., et al. Gyrophase bunched ions in the plasma sheet. Adv. Space Res. (2016), http://dx.doi.org/10.1016/j.asr.2016.08.003

In recent years, by using hybrid simulations Omidi et al. (2010) studied nonlinear evolution of electromagnetic ion cyclotron (EMIC) waves in the presence of multiple ion species in the plasma sheet at $L = 9$. They find that the nonlinear evolution of EMIC waves can generate electrostatic waves which are associated with strong gyrophase bunching of the cold protons (tens of eV). In the subsequent paper (Bortnik et al., 2010), these cold protons were shown to involve a nonresonant mechanism known as electric phase bunching, instead the hot protons (several keV) were scattered resonantly by the EMIC waves and experienced a moderate degree of bunching.

Liu et al. (2012) studied the interactions of relativistic electrons with EMIC waves by using test particle computations. They find that when the wave amplitude is sufficiently large, the electrons in or nearly in resonance with the wave are mainly phase trapped while the off-resonance electrons are only phase bunched duo to the $V \times B$ force. Their results suggest that electron phase bunching and trapping by large amplitude waves flatten the pitch angle distribution and reduce the loss rate for relativistic electrons trapped in the radiation belts, compared to the predictions of quasi-linear theory. Besides, in another simulation study the ring current protons are also found to be bunched in gyrophase when they interact with the EMIC waves, and the phase bunching can move protons toward the loss cone, tending to increase the overall loss rate estimated from quasilinear theory (Zhu et al., 2012).

Except the earlier observations in the upstream of the bow shock, most of the studies on this subject were made by computer simulations. The satellite observations are very rare inside the magnetosphere. In this study we present such an event observed by Cluster spacecraft in the near-Earth plasma sheet. The rest of this article is organized as follows. In Section 3, we present the Cluster observations of the non-gyrotropic ions associated with the concurrent oxygen band waves. In Section 4, we will use the cyclotron resonance theory to explain the observed phenomena. Section 5 gives a conclusion.

2. Instruments and data

The Cluster mission is comprised of four identical spacecraft (Cluster 1–4) flying generally in a tetrahedral formation on similar elliptical polar orbits (Escoubet et al., 2001). The apogee is 19.6 R_E and the perigee is about 4 R_E. The constellation has an orbital period of 57 h. Data collected by instruments on Cluster 1 (SC1) on 30 October 2006 are used in this study. To analyze the event comprehensively, we consider the magnetic field, ion energy flux, and ion distribution function data.

The magnetic field data are recorded by the Fluxgate Magnetometer (FGM) experiment (Balogh et al., 2001), which gives the magnetic field vector at a sampling rate up to 22.417 Hz. The full resolution (22.417 vectors/s) data were used in the wavelet analysis when we examine the magnetic field fluctuations at the gyrofrequency of O^+ ions. The ion data are from the Hot Ion Analyzer (HIA) of the Cluster Ion Spectrometry (CIS) experiment (Rème et al., 2001), which is capable of obtaining full three-dimensional ion distributions (about 5 eV/e to 32 keV/e) with a time resolution of one spacecraft spin, i.e. ~4 s.

3. Observation

3.1. Overview of the case

On 30 October 2006, there is a weak substorm during the period of 1500–1700 UT. The substorm AE index increased from 50 nT at about 1530 UT to the maximum of 300 nT at 1620 UT. Subsequently there followed a quiet interval of weak geomagnetic activity. The corresponding AE index decreased to 120 nT at around 1640 UT. At this time, the SC1 is located at $r = (-7.7, 4.7, 3.1)\ R_E$, and was crossing the nightside plasma sheet. Fig. 1 shows the overview of the data recorded by SC1 from 1642 UT to 1656 UT. The energy of the ions was mainly between 1 keV and 32 keV, and the ion number density was about 0.2 /cm^{-3}. From 1644:40 UT to 1652 UT, SC1 detected an ion rarefied region, which was characterized by the sudden decrease of energy flux of 1–32 keV ions (Fig. 1a). Some remaining ions at around 1–10 keV were distributed sporadically in this region. Associated with the ion rarefied region were the large magnetic field disturbances (Fig. 1b). The sudden decrease of B_x component and increase of B_z component at 1644:40 UT revealed that a magnetic field dipolarization process occurred. The B_z component increased in 1.5 min from 14 nT to 30 nT. The magnetic elevation angle θ which is defined as $\theta = \tan^{-1}(B_z/(B_x^2 + B_y^2)^{1/2})$ increased from 16°to 33°. During this period of magnetic field reconstruction, the magnetic field also fluctuated strongly. To identify the frequency distributions of the magnetic fluctuations, we performed the wavelet analysis to the total magnetic field (B_t) of SC1 (Fig. 1c). The power spectral densities (PSDs) show that between 1644:40 and 1647 UT, the broadband Ultra Low Frequency (ULF) waves below 0.2 Hz (~Ω_{He+}, He^+ ions gyrofrequency) were stimulated intensively, and a wave package at 0.06 Hz (~slightly above Ω_{o+}, O^+ ions gyrofrequency) was clearly seen. Between 1647 and 1648:20 UT, the broadband waves disappeared, and only the wave near the local Ω_{o+} still existed in the B field. The oxygen band waves grew over time and had a sudden enhancement between 1648:20 and 1649:40 UT. Later the waves continued to appear and finally vanished at 1652 UT. In a word, the oxygen band waves persisted for about 7 min from 1644:40 UT to 1652 UT (the shaded area in Fig. 1).

Fig. 2 shows the results of the Minimum Variance Analysis (MVA) of the magnetic field recorded at SC1 during two intervals of 1649:25–1649:53 UT and 1651:30–1652:00 UT on 30 October 2006. The method MVA

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