Chorus variation during the compression of magnetosphere

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Abstract

Chorus is important in space science due to its role in generation of relativistic electrons in the Van Allen radiation belts, which are hazardous to satellites and astronauts. Although chorus has been studied for several decades and many theories have been proposed, its generation and growth mechanisms are still not well understood. In this manuscript, we show an unexpected observation, based on measurements from the NASA THEMIS satellites, that chorus can be significantly amplified when an interplanetary shock that originates from Sun hits Earth's magnetosphere. The shock-induced anisotropic distribution of energetic electrons leads to the growth of chorus.

1. Introduction

On the morning side of Earth, a type of electromagnetic emission in the frequency range of sound waves can usually be heard by a radio[1]. It sounds much like a simultaneous crow from hundreds of birds in the morning time, thus it is named chorus[2]. Chorus consists of a sequence of discrete elements with rising or falling tones in the frequency-time spectrogram. It appears usually as two bands in the region near the inner boundary of plasmatrough (also called plasmapause): a lower, more intense, band in the range of 0.1 - 0.45 f_{ce}, and an upper band of 0.5 - 0.7 f_{ce}, where f_{ce} is the frequency with which electrons gyrate about the Earth's magnetic field line[3]. In the region with L shell (distance measured in R_E, from the center of the Earth to the point where a magnetic field line crosses the equator) greater than 8, however, the upper band usually disappears[4]. Recently chorus has received increasing attention due to its key role in accelerating electrons to relativistic energies in the outer Van Allen radiation belt, producing a disastrous space environment for humans and spacecrafts. Besides, chorus is also considered to be responsible for the source of hiss according to ray-trace simulations[3] and observations[5]. Four kinds of mechanisms have been proposed as candidates to explain the generation and growth of chorus during the past half-century: (1) the Cerenkov process, which takes effect when the electron velocity $V_{//}$ is larger than the phase velocity of the chorus, (2) gyro-resonant interaction[6] that requires a coherent whistler-mode wave to be the seed first, (3) interaction with background thermal noise which is induced by the energetic electrons, and (4) the backward wave oscillator regime. Most of these mechanisms, however, are based upon theoretical analysis and simulation methods, hence requiring lots of observations to confirm the feasibility. The NASA THEMIS D (ThD) satellite provides an excellent opportunity for solving this problem since it traverses the chorus-dominant region once per day.

2. Observations of chorus

Figure 1a and 1b describe the geomagnetic environment, in terms of D_{st} and K_p index, for the period from 19 November to 21 November 2007. The geomagnetic condition is very quiet at the early time of November 19, thereafter however, it is strongly disturbed. The sudden drop of D_{st} index from 6 nT to -70 nT on November 20 indicates the main phase of a moderate magnetic storm as seen from Fig. 1a. Before the main phase, a storm sudden commencement (SSC) is clearly seen at 1807 universal time (UT) on November 19. Meanwhile, K_p index jumped from 0 to 2, a typical feature of the beginning of disturbed geomagnetic conditions. SSC is usually a response of the Earth's magnetosphere to the interplanetary shock which can be seen from Fig. 1c - 1f as the sudden increasing of solar wind density (N_{sw}, from 4 cm^{-3} to 13 cm^{-3}), solar wind velocity (V_{sw}, 372 km/s to 415 km/s), Z component of the interplanetary magnetic field ($IMFB_z$, 1 nT to 5 nT), and the solar wind dynamic pressure (P_{sw}, 1 nPa to 4.5 nPa) at 1807 UT.

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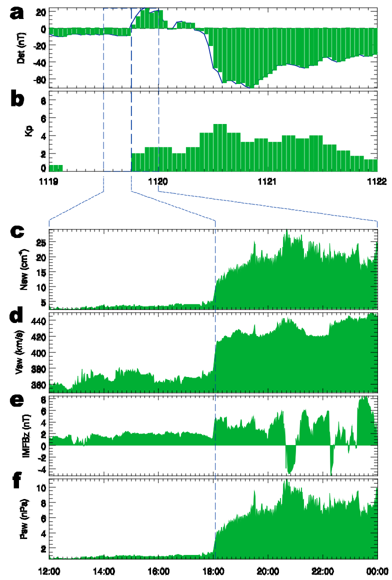

Figure 1. Geomagnetic environment and the associated solar wind conditions.

The chorus has a corresponding response when the interplanetary shock hits the Earth's magnetosphere. Fig. 2a and 2b show, respectively, the magnetic and electric field components of electromagnetic waves measured by ThD in the frequency range of 2.26 - 2689 Hz from 1740 to 1840 UT on 19 November, when the satellite was located in the Earth's dawn side plasmatrough region. White lines in Fig. 2 represent, from top to bottom, electron's gyrofrequency f_{ce}, 0.45 f_{ce} and 0.1 f_{ce} on the equatorial plane. Between the two bottom lines (from ~100 Hz to ~900 Hz), intensive discrete signals expressed on a logarithmic scale are clearly seen. They are just the lower-band whistler-mode chorus. The upper-band one is absent because during this period the L shell was larger than 8 as indicted by the previous study. Fig. 2c shows the observations of the magnetic field during the same period. When the interplanetary shock hits the Earth's magnetopause, a compressional wave is excited and propagates toward Earth. Its wave front causes the increase of magnetic field, as the jump observed by ThD at 1810 UT (vertical dashed line). Due to propagation of the wave front from the magnetopause to the location of ThD, the enhancement of magnetic field encountered by ThD is about 3 minutes after the interplanetary shock measured at the nose position (Fig. 1c - 1f). At the same time, the plasma density decreases from 6.2 cm^{-3} to 3.2 cm^{-3} (indicated by the spacecraft floating potential, dotted lines in Fig. 2a and 2b). The chorus is amplified significantly. This amplification occurred before the storm main phase. The center frequency of the lower-band chorus before and after the shock is ~150 Hz and ~600 Hz, respectively.

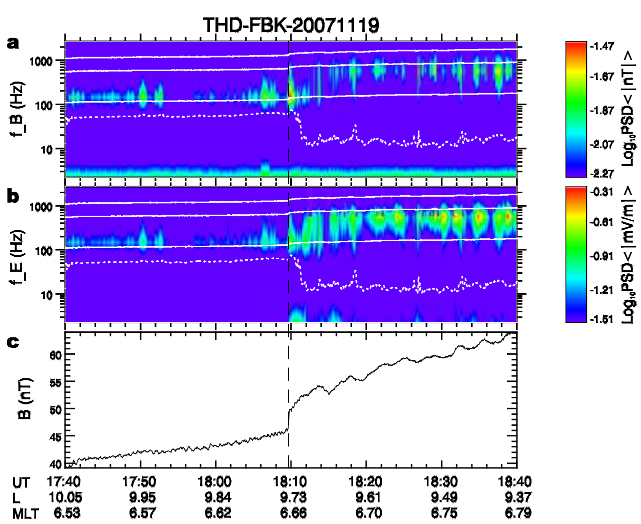

Figure 2. Magnetic and electric field components of chorus.

Fig. 3a and 3b display the velocity space density (VSD) of the electrons with energy from 30 keV to 300 keV at 1800 UT (before the shock) and 1820 UT (after the shock), respectively. Prior to the shock arrival, the electrons' velocity distribution is approximately isotropic (Fig. 3a). The gradient of the VSD along the diffusion curve is not large, indicating a less effective diffusion process according to the diffusion equation. Even if the electron with energy of 95.4 keV is scattered from the resonance point to the low density region (PA ~ 0 or 180°), its energy loss is very small due to the lower frequency (150 Hz, indicates a lower phase velocity) of chorus. Less energy of electrons are thus transferred to the chorus, resulting in the weak intensity of chorus before the shock. The electron's VSD distribution after the arrival of shock is considerably different from that before the arrival of shock. It is almost concentrated near the region PA ~ 90° (Fig. 3b). There are fewer electrons near the region PA ~ 0 (or 180°). This significant anisotropic distribution is unstable and can easily scatter the electrons to become isotropic (from the resonance point to the low-density region) when interacting with the chorus. Larger density gradient means a more effective diffusion. During the diffusion process, the resonant electrons lose much energy, which can be seen from the difference between the blue half-circle and black half-circle in the low-density region near PA ~ 0 (or 180°). The prominent energy loss is attributed to the larger phase velocity (blue dots) of the chorus caused by the larger frequency (600 Hz) at this time. The lost energy was subsequently transferred to amplify the chorus. Thus we observed the intense chorus emission after the shock.

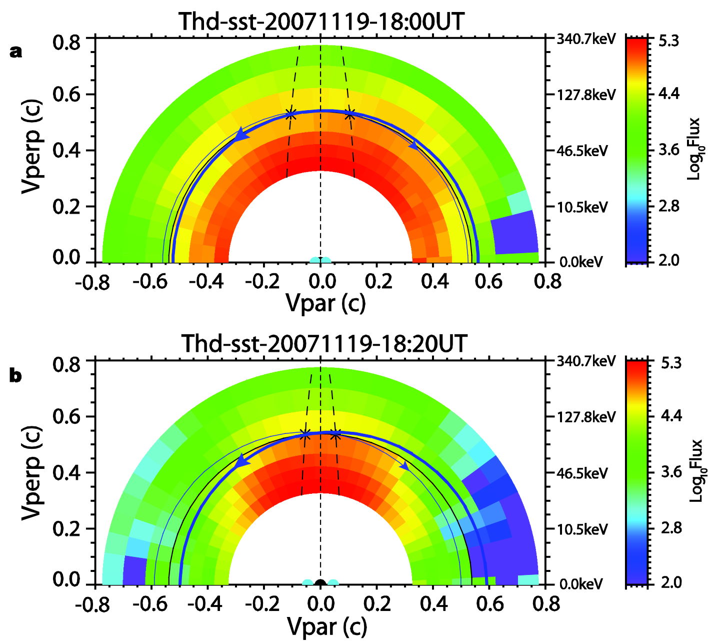

Figure 3. Velocity space density (VSD) of the 30-300 keV electrons

Fig. 4 schematically illustrates the evolution of the electrons' anisotropic distribution. During the quite time, ThD that locates in the inner magnetosphere measured a regular geomagnetic field. When the interplanetary shock arrives, the Earth's magnetosphere is compressed significantly. ThD measures an enhanced magnetic field at this time as shown in Fig. 2c. Since the compressional disturbance lasts for ~12 s, much longer than the relativistic cyclotron period of the 95.4 keV electrons (about 1.0×10^{-3} s), the first adiabatic invariant $\mu = \frac{1}{2} m v_\perp^{\ 2} / B$ is conserved when the magnetosphere is compressed at 1810 UT. In this way, the enhanced magnetic field after the shock denotes the increase of the electrons' perpendicular velocity. This increase is actually caused by the azimuthal electric field that is generated by the shock-induced time-varying **B** according to the Maxwell equation $\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$. During this process, however, the electron's parallel velocity is constant since almost no field-aligned force takes effect. The increased component $V_\perp$ and constant component $V_\parallel$ leads to the significant increase of the electron's pitch angle, hence explains well the anisotropic distribution shown in Fig. 3b.

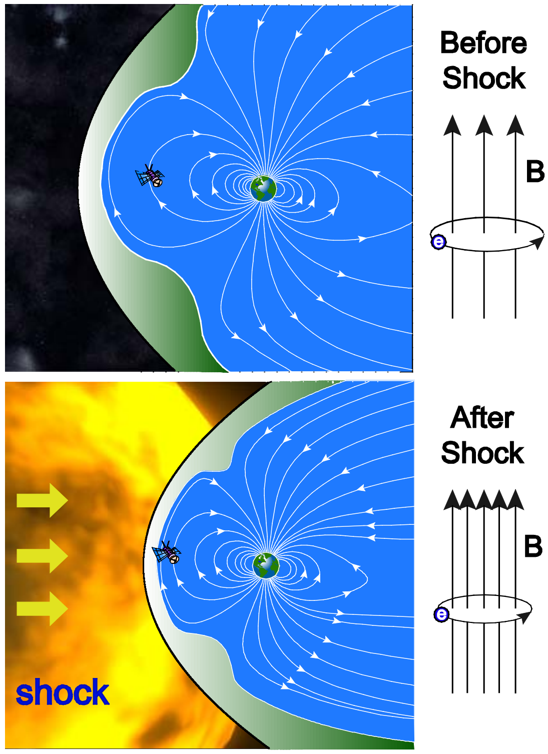

Figure 4. Schematic of the anisotropization process of electrons' VSD

3. Conclusion

The present study shows for the first time the observational evidence of chorus's intensification in response to the interplanetary shock on the morning side. The wave-particle interaction plays an important role in the whole process. Chorus growth before the storm main phase may result in the formation of the Van Allen radiation belt at an early time. This observation can also be a reference to studying the space environment of other planets such as Venus, Mercury and so on.

4. References

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