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Prompt responses of magnetospheric whistler-mode waves to solar wind dynamic pressure pulses

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Whistler-mode waves play a critical role in shaping the Earth's radiation belts, and their spatiotemporal distribution is vital for forecasting and modeling geospace weather. Previous works have extensively investigated the influences of geomagnetic activities, such as storms and substorms, on the modification of whistler-mode waves, but the direct impacts of solar wind disturbances have received relatively less attention. Recently, increasing research has highlighted the prompt impacts of solar wind dynamic pressure pulses on magnetospheric whistler-mode waves. This paper reviews the current progress in this field, specifically the prompt responses of chorus waves and plasmaspheric hiss to the solar wind dynamic pressure pulses. It will summarize the underlying mechanisms and pose some outstanding questions.

KEYWORDS

whistler-mode waves, solar wind-magnetosphere coupling, chorus, plasmaspheric hiss, plasma wave instability

1 Introduction

Whistler-mode waves are very low-frequency (VLF) right-handed circularly polarized electromagnetic emissions that are commonly observed in the magnetosphere (Laakso and Blomberg, 2005; Anderson and Vasko, 2018). Depending on their spatial location, whistler-mode waves are divided into chorus (outside high-density plasmasphere) and plasmaspheric hiss (inside high-density plasmasphere or plume). Chorus waves typically exhibit a structured and discrete emission pattern, with a frequency range of 0.1–0.8 f_{ce} (equatorial electron cyclotron frequency) (Tsurutani and Smith, 1974; Tsurutani and Smith, 1977; Meredith et al., 2001; Santolík et al., 2003; Gao et al., 2017). In contrast, plasmaspheric hiss is typically observed as an incoherent and structureless band, with a frequency range from ~0.1 kHz to several kilohertz (Russell et al., 1969; Thorne et al., 1973; Hayakawa and Sazhin, 1992; Summers et al., 2008). Once plasmaspheric hiss leaks out of the plasmasphere, it is referred to as exohiss (Russell et al., 1969; Thorne et al., 1973). Note that low frequency chorus below 0.1 f_{ce} (Meredith et al., 2014; Cattell et al., 2015; Gao et al., 2016) and coherent plasmaspheric hiss with fine structures (Summers et al., 2014; Tsurutani et al., 2015; Su et al., 2018; Liu et al., 2020a) have also been reported. The fundamental role of whistler-mode waves in radiation belt dynamics has made them a subject of considerable interest in the space-physics community. Through cyclotron resonance, whistler-mode waves contribute to the acceleration and loss of radiation belt electrons (Summers et al., 2002; Horne et al., 2005; Reeves et al., 2013; Thorne et al., 2013b; Su et al., 2014a; c; Xiao et al., 2014; Lyons and Thorne, 1973; Abel and Thorne, 1998; Albert, 1994; Su et al., 2011; Nishimura et al., 2013; Kasahara et al., 2018; Thorne et al., 2013a; Ni et al., 2014; Breneman et al., 2015; Zhu et al., 2015; Li et al., 2017; Ma et al., 2017; Zhang et al., 2019; Liu et al., 2020b). Through landau resonance, plasmaspheric hiss is able to accelerate suprathermal electrons (Woodroffe et al., 2017; Li et al., 2019; Wang et al., 2020), and probably transfer energy toward the ionospheric plasma (Wang et al., 2020). Thus, a detailed understanding of the spatiotemporal distribution of whistler-mode waves is of great importance for forecasting and modeling geospace weather.

Storms and substorms are remarkable geomagnetic activities caused by solar wind disturbances (McPherron et al., 1986; Gonzalez et al., 1989; Gonzalez et al., 1999; Sergeev et al., 2012). Their important role in modifying whistler-mode waves has been extensively investigated (Wilson et al., 2011; Agapitov et al., 2013; Li et al., 2013b; Tsurutani et al., 2018; Shi et al., 2019; Liu et al., 2020a; Meredith et al., 2020; Meredith et al., 2021). However, previous works commonly highlight the influences of electron injection in the course of storms and substorms. In fact, there might be variations in the magnetospheric plasma environment during the initial phase of a storm (Gosling et al., 1967; Tsurutani et al., 1995; Gonzalez et al., 1999; Samsonov et al., 2007) which could also impact whistler-mode waves. Moreover, regarding solar wind disturbances that are incapable of triggering storms or substorms, there is a relative lack of studies on their influence on whistler-mode waves. One of the most frequently observed solar wind disturbances at 1 AU is the solar wind dynamic pressure pulses (Wu et al., 1993; Dalin et al., 2002; Neugebauer, 2006; Zuo et al., 2015). They are characterized by abrupt jumps or depressions in solar wind dynamic pressure, corresponding to the positive or negative pressure pulse, respectively. Solar wind dynamic pressure pulses are usually associated with interplanetary shocks or other discontinuities (Hudson, 1970; Dalin et al., 2002; Neugebauer, 2006; Zuo et al., 2015). The fast-forward interplanetary shock (simply termed interplanetary shock in the following), which is the most common type of interplanetary shock, can be treated as a positive pressure pulse (Kennel et al., 1985). As important manifestations of solar wind-magnetosphere coupling, the prompt impacts of solar wind dynamic pressure pulses on the magnetospheric current systems (Zesta et al., 2000), particle fluxes (Lee et al., 2004; Zong et al., 2009; Li et al., 2013a), and auroral activities (Zhou et al., 2009; Zhou et al., 2017) have been investigated. Given the geoeffective nature of solar wind dynamic pressure pulses, it is reasonable to expect the prompt responses of magnetospheric whistler-mode waves to these disturbances.

This paper reviews the recent progress in the prompt responses of magnetospheric whistler-mode waves to solar wind dynamic pressure pulses. Here the “prompt response” refers to variations in whistler-mode waves occurring within several minutes (depending on solar wind velocity) after the arrival of pressure pulses at the magnetopause. Advanced magnetospheric missions such as the Van Allen Probes (Mauk et al., 2013) and THEMIS (Angelopoulos, 2008), which carry various instruments including the Electric and Magnetic Field Instrument Suite and Integrated Science suite (EMFISIS) (Kletzing et al., 2013), the Energetic particle, Composition and the Thermal plasma suite (ECT) (Spence et al., 2013), the Electric Field and Waves (EFW) (Wygant et al., 2013), the Search Coil Magnetometer (SCM) (Le Contel et al., 2008), and the Electric Field Instrument (EFI) (Bonnell et al., 2008), have provided high-quality and comprehensive data, allowing for a detailed investigation into the underlying mechanisms.

2 Prompt responses of chorus waves

Anisotropic energetic electrons from a few to tens of keV provide the free energy for the excitation of chorus waves (Kennel and Engelmann, 1966; LeDocq et al., 1998; Li et al., 2009; Su et al., 2014b). Though the generation mechanism of chorus waves has not been fully revealed, current works have proposed a widely accepted scenario: the background thermal noise grows linearly to a specific threshold wave amplitude for the further amplification through nonlinear process (Omura et al., 2008; Katoh and Omura, 2013; Tao, 2014; Nakamura et al., 2016; Omura, 2021). By modifying the linear and nonlinear wave growth processes, solar wind dynamic pressure pulses can cause the prompt response of chorus waves.

The modification of equatorial energetic electron fluxes by pressure pulses can alter the chorus wave intensity. Fu et al. (2012) reported a chorus intensification in response to an interplanetary shock using THEMIS observations. The shock compression increased the magnetic field strength and triggered PC4-5 ultra-low-frequency (ULF) waves, which further enhanced the temperature anisotropy of energetic electrons through local betatron acceleration and radial diffusion processes. These increased the maximum linear growth rate by 50%, resulting in chorus intensification. Peng et al. (2020) also reported such compression-related chorus intensifications associated with adiabatic acceleration of energetic electron fluxes using MMS observations. In contrast, Liu et al. (2017a) reported a sudden disappearance of chorus waves triggered by an interplanetary shock. The shock produced a drastic increase in dynamic pressure which compressed the dayside magnetopause earthward to about $L = 7$, abruptly eliminating the preexisting dayside chorus waves and the associated source electrons.

As well as impacting the local energetic electron populations, solar wind dynamic pressure pulses can also affect the background magnetic field configuration and consequently the nonlinear growth process of chorus. Zhou et al. (2015) analyzed 20 interplanetary shock events which occurred between 1 January 2008 and 31 December 2014 with simultaneous observations of chorus waves made by three THEMIS satellites, and found that the chorus intensification events preferentially occurred at high L shells (greater than 8) and on the dayside (MLT from 6 to 18). Utilizing the TS04 geomagnetic mode (Tsyganenko and Sitnov, 2005), they showed that the background magnetic field configurations became more homogeneous (a smaller background magnetic field gradient) following shock compression, which is favorable for the nonlinear growth of chorus (Omura et al., 2008; Katoh and Omura, 2013). Zhou et al. (2015) claimed there were no significant changes in the energetic electron distribution to be responsible for the chorus intensifications, contrary to the interpretation of Fu et al. (2012). Liu et al. (2017b) reported a sudden disappearance of chorus waves triggered by a negative pressure pulse using THEMIS observations. The negative pulse caused no significant changes in the background plasma populations associated with the generation of chorus waves, but an increase in background magnetic field inhomogeneity. Liu et al. (2017b) proposed that the dayside geomagnetic field configuration with the enhanced inhomogeneity became unfavorable for the nonlinear growth of chorus, which can be interpreted as an "inverse" process of that described in Zhou et al. (2015).

Recently, a statistical study was conducted by Jin et al. (2022) to investigate the immediate impacts of dynamic pressure pulses, both positive and negative, on inner magnetospheric chorus waves. The study analyzed Van Allen Probes data from 2012 to 2019 and demonstrated that a stronger pulse has a greater likelihood of changing the chorus amplitude particularly on the dayside. Specifically, positive pulses were associated with an enhancement in chorus amplitudes, while negative pulses resulted in a weakening of these waves. The disappearance of chorus waves triggered by positive pulses due to the losses of source electrons to the magnetopause (Reeves et al., 2003; Ukhorskiy et al., 2006; Turner et al., 2012) has not been observed in the inner magnetosphere in this work. As supported by direct observations, these pulses alter the linear growth of waves by modifying energetic electron distributions. On the other hand, geomagnetic field modeling indicates no significant changes in the background magnetic field inhomogeneity controlling the nonlinear growth threshold of waves. The inconsistency between this result and previous works (Zhou et al., 2015; Liu et al., 2017b) which investigated chorus waves in the outer magnetosphere ($8 < L < 12$) can be attributed to the low sensitivity of equatorial magnetic field inhomogeneity to solar wind disturbances in the inner magnetosphere.

3 Prompt responses of plasmaspheric hiss

The generation mechanism of plasmaspheric hiss remains a topic of intense debate. Two main categories of candidate mechanisms have been proposed: 1) internal generation, which involves the linear or nonlinear amplification of ambient electromagnetic noise by unstable energetic electrons inside the plasmasphere (Thorne et al., 1979); 2) external origination, which involves the entry of lightning-associated whistlers or source chorus to the plasmasphere (Church and Thorne, 1983; Draganov et al., 1992; Green et al., 2005; Bortnik et al., 2008; Bortnik et al., 2009; Chen et al., 2009; Li et al., 2015). An identification of plasmaspheric hiss with different generation mechanisms is based on the wave Poynting fluxes, where the internally-generated hiss has poleward uni-directional Poynting fluxes near its source region before undergoing magnetospheric reflections, and the externally-originated hiss has bi-directional Poynting fluxes. Studying the prompt impacts of solar wind dynamic pressure pulses on plasmaspheric hiss provides an opportunity to examine the wave generation mechanisms.

For the externally-originated plasmaspheric hiss, variations of source chorus triggered by solar wind pressure pulses can subsequently cause corresponding responses within the plasmasphere. As introduced in the previous section, an intense interplanetary shock can eliminate energetic electrons and chorus waves on the dayside outer magnetosphere (Liu et al., 2017a), and a negative solar wind dynamic pressure pulse can cause the disappearance of chorus waves by enhancing the dayside magnetic field inhomogeneity (Liu et al., 2017b). In both cases, the plasmaspheric hiss ceased as a result of the quenching of source chorus. A similar event to that of Liu et al. (2017a) has been lately reported by Chakraborty et al. (2021). It also should be mentioned that, by using the conjunctive observations from three satellites of Van Allen Probes and THEMIS, Liu et al. (2017b) observed for the first time the simultaneous disappearances of chorus, plasmaspheric hiss, and exohiss over a vast region on the dayside, providing direct observational evidence for the link between different types of magnetospheric whistler-mode waves.

Another important factor affecting the externally-originated plasmaspheric hiss is the propagation of source chorus into the plasmasphere. Su et al. (2015) gave the first report on the shock-induced disappearances of plasmaspheric hiss observed by the Van Allen Probes. The hot electron fluxes were expected to be increased through adiabatic process after shock, which could favor the excitation of chorus. However, the increased hot electron fluxes also enhanced the Landau damping for obliquely propagating chorus waves, thus leading to the quenching of plasmaspheric hiss by damping the chorus before it can enter the plasmasphere. Later, Yue et al. (2017) conducted a statistical study on the prompt responses of whistler-mode waves to fast forward shocks using the Van Allen Probes and THEMIS missions. The statistical results showed that chorus waves were intensified following shock arrival at all MLTs, which is consistent with the results for positive pressure pulses in Jin et al. (2022). In contrast, plasmaspheric hiss mainly disappeared/weakened on the dayside and intensified on the nightside, which cannot be explained solely by the variations of source chorus. Such different dependences of chorus and plasmaspheric hiss on the solar wind dynamic pressure have also been reported recently by Tang et al. (2023). Through simple ray tracing modeling, Yue et al. (2017) found that a more stretched magnetic field configuration on the nightside caused by shock compression favors the entry of chorus waves with more field-aligned wave normal into the plasmasphere, which are generally the majority of observed chorus waves in the equatorial region (Burton and Holzer, 1974; Goldstein and Tsurutani, 1984; Santolík et al., 2014a; Santolík et al., 2014b; Hartley et al., 2019). It also should be noticed that the occurrence of oblique chorus waves increases close to the plasmapause on the nightside (Li et al., 2016), which may make this less favorable. Generally, these results qualitatively explain the enhancements of plasmapsheric hiss on the nightside. Yue et al. (2017) proposed that the weakening of plasmaspheric hiss on the dayside can be attributed to the enhanced Landau damping from the observed enhancements in suprathermal electron flux (Su et al., 2015). Another possibility could be related to the abrupt erosion of the plasmapause caused by the shock compression. It has been shown that the presence of azimuthal density gradients associated with plasmaspheric plumes allows for a broader range of chorus wave normal angles to propagate into the plasmasphere (Chen et al., 2009; Hartley et al., 2019; Hartley et al., 2022). As such, the absence of azimuthal density gradient or plume after shock compression might reduce the amount of source chorus that can propagate into the plasmasphere and evolve into plasmaspheric hiss.

Compared to the externally-originated plasmaspheric hiss, there has been relatively little research on the prompt response of internally-generated hiss to solar wind dynamic pressure pulses. Two plausible explanations for this are: 1) some solar wind dynamic pressure pulses may not be strong enough to affect the plasma environment associated with whistler-mode wave generation in the plasmasphere within synchronous orbit; 2) due to the overlapping of different whistler rays, it is difficult to identify internally-generated plasmaspheric hiss through uni-directional Poynting fluxes. Nonetheless, there is still observational evidence showing the direct impact of dynamic pressure pulses on internally-generated plasmaspheric hiss. Fu et al. (2021) reported a frequency-dependent response of plasmaspheric hiss to an interplanetary shock. Based on wave Poynting fluxes, they found that hiss waves with frequencies below 3.5 kHz (~0.18f_{ce}) probably originated from chorus waves outside the plasmasphere, while hiss waves with frequencies above 3.5 kHz were generated near the local magnetic equator. A recent statistical work has proposed the combination of these two different generation mechanisms as the origin of banded plasmaspheric hiss (Ni et al., 2023). The interplanetary shock changed magnetic field configuration and weakened hiss waves below 3.5 kHz by preventing the entry of source chorus into the plasmasphere, which is coincident with the scenario in Yue et al. (2017). Note the shock compression could also change the position of minimum B pockets where source chorus is generated (Tsurutani et al., 2019) and the Landau damping rate along the raypaths (Su et al., 2015), which both affect the propagation of the source chorus into plasmasphere and need further studies. In contrast, the shock-induced acceleration of hot electron fluxes intensified the hiss waves above 3.5 kHz. Recently, Liu et al. (2022) reported the evolution of internally-generated plasmaspheric hiss during a heliospheric plasma sheet (HPS) in the dusk-side plasmasphere (L ~6.7, MLT ~16.8). The long duration impingement of high-density solar wind HPS onto the magnetosphere produced hot anisotropy electrons and caused excitation of plasmaspheric hiss. The subsequent cessation of the HPS led to decreases in hot electron fluxes and the prompt disappearance of the compression-related plasmaspheric hiss. Here, the cessation of the HPS can be treated as a negative solar wind dynamic pressure pulse. The hot proton fluxes and EMIC waves also exhibited similar evolutions in this event, highlighting the importance of solar wind conditions for Earth's space weather.

4 Discussion and conclusion

As a new consequence of solar wind-magnetosphere coupling, the prompt responses of magnetospheric whistler-mode waves to solar wind dynamic pressure pulses has attracted increasing interest in recent years. The prominent effects of solar wind dynamic pressure pulse on the magnetospheric plasma environment associated with whistler-mode waves include: 1) influences of magnetopause movements on electron drift paths; 2) adiabatic variations of energetic electron fluxes caused by sudden changes in magnetic field intensity; 3) acceleration of energetic electrons by compression-related ULF waves; 4) the variation of magnetic field configuration due to the movement of field lines; 5) variations of cold plasma density and plasmasphere structure. In general, the influences to the whistler-mode waves can be summarized as: 1) variations of electron populations can modify the linear wave growth process or the Landau damping (Fu et al., 2012; Su et al., 2015; Jin et al., 2022); 2) variations of both electron populations and magnetic field configuration control the nonlinear growth process (Omura et al., 2008; Katoh and Omura, 2013; Omura, 2021); 3) the magnetic field configuration and cold plasma density determine the raypaths of whistler-mode waves (Chen et al., 2009; Yue et al., 2017; Hartley et al., 2019; Hartley et al., 2022). For chorus waves and internally-generated plasmaspheric hiss, their prompt responses to the solar wind dynamic pressure pulse are directly linked to the local linear or nonlinear growth processes. For plasmaspheric hiss originated from chorus waves, their prompt responses are associated with both the intensity of source chorus and the accessibility of source chorus into the plasmasphere.

Recent studies investigating the prompt impacts of solar wind dynamic pressure pulses on magnetospheric whistler-mode waves have enhanced our understanding of the wave spatiotemporal distribution and generation mechanism. However, several questions remain open, for instance, whether there is a frequency dependence in the response of chorus waves to solar wind dynamic pressure pulses? Can we make a further step in clarifying the plasmaspheric hiss generation mechanisms by statistically analyzing their prompt response to solar wind dynamic pressure pulses? Current studies mainly focus on the variations of wave intensity triggered by pressure pulses, are there any variations in wave frequencies? How do solar wind dynamic pressure pulses affect the propagation process of whistler-mode waves by altering the background magnetic field configuration? The impacts of solar wind dynamic pressure pulses on whistler-mode waves can last for how long, and to what extent do these affect radiation belt electron dynamics? In the future, detailed simulations including the event-specific parameters and statistical analyses using more comprehensive data set are required for a better knowledge.

Author contributions

ZS and NL designed the study. NL wrote the manuscript with contributions from ZS. All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication. All authors contributed to the article and approved the submitted version.

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Conflict of interest

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