Reply to comment by T. Kikuchi and T. Araki on "Propagation of the preliminary reverse impulse of sudden commencements to low latitudes"

P. J. Chi,[1] C. T. Russell,[1] J. Raeder,[1] E. Zesta,[2] K. Yumoto,[3] H. Kawano,[3] K. Kitamura,[3] S. M. Petrinec,[4] V. Angelopoulos,[5] G. Le,[6] and M. B. Moldwin[1]

Received 8 March 2002; revised 12 July 2002; accepted 8 August 2002; published 24 December 2002.

INDEX TERMS: 2708 Magnetospheric Physics: Current systems (2409); 2784 Magnetospheric Physics: Solar wind/magnetosphere interactions; 2752 Magnetospheric Physics: MHD waves and instabilities; 2736 Magnetospheric Physics: Magnetosphere/ionosphere interactions; 2712 Magnetospheric Physics: Electric fields (2411); *KEYWORDS:* sudden impulses, preliminary reverse impulse, MHD waves, inhomogeneous magnetosphere, magnetic pulsations

Citation: Chi, P. J., et al., Reply to comment by T. Kikuchi and T. Araki on ''Propagation of the preliminary reverse impulse of sudden commencements to low latitudes,'' *J. Geophys. Res.*, *107*(A12), 1474, doi:10.1029/2002JA009369, 2002.

[1] We appreciate *Kikuchi and Araki*'s [2002] giving us the opportunity to compare in more detail the two different models of how the preliminary reverse impulses (PRI) of sudden commencements (SC) propagate to the ground. The inconsistency between the Earth-ionosphere waveguide model [*Kikuchi and Araki*, 1979a, 1979b] and our observations [*Chi et al.*, 2001] is most clearly demonstrated by the discontinuity in PRI arrival time at approximately the plasmapause latitude as shown in Figure 1. Neither the waveguide mode nor any SC-related current (including the Chapman–Ferraro current and the field-aligned current) can result in this jump in arrival time across the plasmapause latitude. On the contrary, this discontinuity is well explained by Tamao's MHD waves model [*Tamao*, 1964] because the wave slows down as it encounters the dense plasmasphere.

[2] Although the MHD wave model of *Chi et al.* [2001] was only applied to the arrival time of PRIs, it can explain also the observed onset time of PRIs. The onset signals the first wave front reaching the observer, whereas the arrival time, defined by the time at maximum amplitude, represents the arrival of wave energy coming from all possible propagation paths. In the MHD waves model, the first wave front arriving at the ground observer travels along a path very close to the line connecting Q, P_1, and P (see Figure 2). For any different location on the Earth, the corresponding wave path only shifts slightly in space, and therefore the travel time would almost be identical. This explains why the onset occurs simultaneously across all latitudes. The travel path that conserves the greatest wave energy varies more significantly as the location of ground station changes, and therefore there is a more visible differentiation in the arrival time.

[3] The notion of the invisibility of the converted transverse (CT) mode for ground observers is unlikely to be applicable in reality. A fast-mode wave can be converted into Alfvén waves in the inhomogeneous magnetosphere [*Southwood and Kivelson*, 1990; *Itonaga and Yoshikawa*,

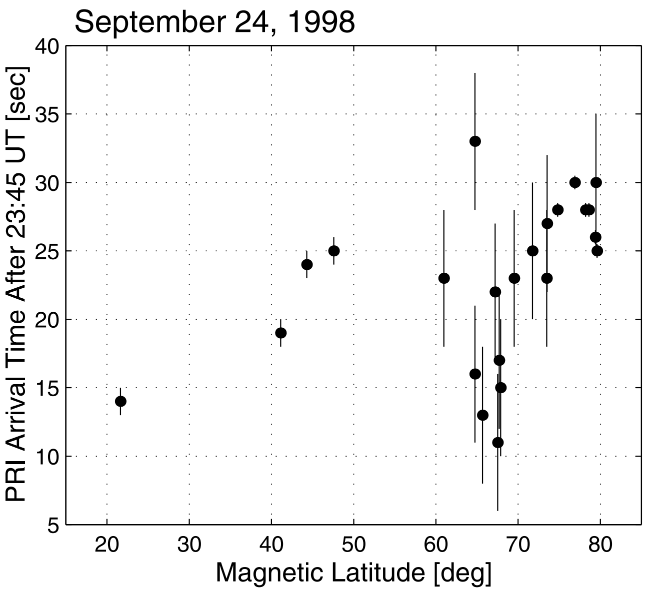

Figure 1. The PRI arrival time observed at 23 magnetometer stations for the SC event on September 24, 1998. A slowdown of PRI propagation is clearly seen near the plasmapause latitude, an important feature that can be explained only by the MHD waves model. The error bars indicate the time resolution of magnetometer data.

[1] Institute of Geophysics and Planetary Physics, University of California, Los Angeles, California, USA.
[2] Department of Atmospheric Sciences, University of California, Los Angeles, California, USA.
[3] Department of Earth and Planetary Sciences, Kyushu University, Fukuoka, Japan.
[4] Lockheed Martin Advanced Technology Center, Palo Alto, California, USA.
[5] Space Science Laboratory, University of California, Berkeley, California, USA.
[6] NASA Goddard Space Flight Center, Greenbelt, Maryland, USA.

0148-0227/02/2002JA009369$09.00

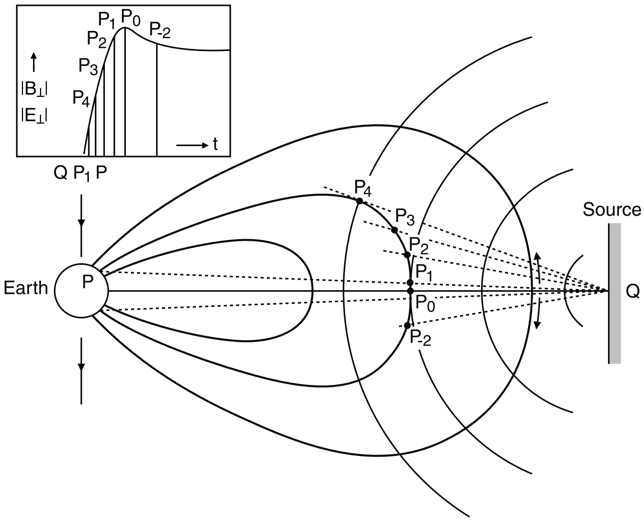

Figure 2. Tamao's model of PRI propagation from the source location to a ground observer at P via multiple paths in the magnetosphere. The inset shows the temporal variation of $|B_H|$ at P. The first wave front reaches the ground observer through the path $\overline{QP_1P}$, whereas the path that conserves the most wave amplitude is $\overline{QP_0}$ followed by a field-aligned propagation to P. (After *Tamao* [1964]. Graphics taken from *Chi et al.* [2001]).

1996]. As a consequence, the MHD waves that carry the PRI signal to low latitudes can no longer be perfectly screened by the ionosphere. The observation of an SC signal (mainly in the transverse mode) above the E region and the PRI simultaneously recorded by ground stations below the spacecraft path [*Araki et al.*, 1984] provides strong evidence that transverse SC signals in space can be seen on the ground.

[4] It is important to note that the MHD waves model also explains the propagation of the magnetic pulsations driven by solar wind pulses. Studies have found that some ground magnetic pulsations have one-to-one correspondence to solar wind pressure variations [*Korotova and Sibeck*, 1994, 1995; *Matsuoka et al.*, 1995], and travel time analysis indicates that the wave signals travel in the magnetosphere at MHD wave speeds. In particular, *Weygand et al.* [2001] showed that the solar wind-driven Pc5 pulsations observed by a chain of ground stations at different latitudes exhibited the same arrival-time pattern as the zigzag profile shown in our PRI study. These driven pulsations and SCs have many similarities in physics because both of them originate from changes in solar wind pressure. However, it does not appear that the Earth-ionosphere waveguide model can explain the propagation of these pulsations.

[5] In addition to our study that shows inconsistency with the Earth-ionosphere waveguide model, the observations of ground electric fields associated with PRI signals contradict what the waveguide model predicts. *Yumoto et al.* [1997] presented a case in which the amplitude of the preliminary impulse signal is $\simeq$1 nT. The vertical electric field would have had a perturbation $\sim$$10^2$ mV/m if the signal were a zeroth-order TM mode, but the observation shows that it was less than 1 mV/m. Further study on the Earth-ionosphere waveguide, such as numerical simulation of the subject, could be valuable in examining the model in detail.

[6] In summary, we believe it is correct to say that MHD waves provide the dominant scheme for PRI signals to propagate to low-latitude regions. The MHD theory of PRI propagation can certainly be refined in several aspects, such as the effect of inhomogeneous plasma and the propagation of signals through the realistic ionosphere. However, the Earth-ionosphere waveguide theory requires very significant changes if it is to explain the timing of PRI propagation and resolve the differences between its theory and observations.

References

Araki, T., T. Iyemori, and T. Kamei, Sudden commencements observed by MAGSAT above the ionosphere, *J. Geomagn. Geoelectr.*, *36*, 507–520, 1984.

Chi, P. J., et al., Propagation of the preliminary reverse impulse of sudden commencements to low latitudes, *J. Geophys. Res.*, *106*, 18,857–18,864, 2001.

Itonaga, M., and A. Yoshikawa, The excitation of shear Alfvén waves and the associated modulation of compressional wave in the inner magnetosphere, *J. Geomagn. Geoelectr.*, *48*, 1451–1459, 1996.

Kikuchi, T., and T. Araki, Transient response of uniform ionosphere and preliminary reverse impulse of geomagnetic storm sudden commencement, *J. Atmos. Terr. Phys.*, *41*, 917–925, 1979a.

Kikuchi, T., and T. Araki, Horizontal transmission of the polar electric field to the equator, *J. Atmos. Terr. Phys.*, *41*, 927–936, 1979b.

Kikuchi, T., and T. Araki, Comment on "Propagation of the preliminary reverse impulse of sudden commencements to low latitudes" by P. J. Chi et al., *J. Geophys. Res.*, doi:10.1029/2001JA009220, in press, 2002.

Korotova, G. I. and D. G. Sibeck, Generation of ULF magnetic pulsations in response to sudden variations in solar wind dynamic pressure, in *Solar Wind Sources of Magnetospheric Ultra-Low-Frequency Waves*, *Geophys. Monogr. Ser.*, vol. 81, edited by M. J. Engebretson et al., pp. 265–271, AGU, Washington, D.C., 1994.

Korotova, G. I., and D. G. Sibeck, A case study of transient event motion in the magnetosphere and in the ionosphere, *J. Geophys. Res.*, *100*, 35–46, 1995.

Matsuoka, H., K. Takahashi, K. Yumoto, B. J. Anderson, and D. G. Sibeck, Observation and modeling of compressional Pi3 magnetic pulsations, *J. Geophys. Res.*, *100*, 12,103–12,115, 1995.

Southwood, D. J., and M. G. Kivelson, The magnetohydrodynamic response of the magnetospheric cavity to changes in solar wind pressure, *J. Geophys. Res.*, *95*, 2301–2309, 1990.

Tamao, T., The structure of three-dimensional hydromagnetic waves in a uniform cold plasma, *J. Geomagn. Geoelectr.*, *18*, 89–114, 1964.

Weygand, J. M., M. B. Moldwin, and D. Berube, A sudden impulse driven compressional Pc5 wave in the Earth's magnetotail lobe, *Eos Trans. AGU*, *82*(20), Spring Meet. Suppl., SM62A-07, 2001.

Yumoto, K., V. Pilipenko, E. Fedorov, N. Kurneva, M. De Lauretis, and K. Kitamura, Magnetospheric ULF wave phenomena stimulated by SSC, *J. Geomagn. Geoelectr.*, *49*, 1179–1195, 1997.

V. Angelopoulos, Space Science Laboratory, University of California, Grizzly Peak Blvd. at Centennial Dr., Berkeley, CA 94720, USA.

P. J. Chi, M. B. Moldwin, J. Raeder, and C. T. Russell, Institute of Geophysics and Planetary Physics, UCLA, Box 951567, Los Angeles, CA 90095, USA. (pchi@igpp.ucla.edu)

H. Kawano, K. Kitamura, and K. Yumoto, Department of Earth and Space Sciences, Kyushu University 33, 6-10-1 Hakozaki, Fukuoka 812-8581, Japan.

G. Le, Laboratory for Extraterrestrial Physics, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA.

S. M. Petrinec, Lockheed Martin Advanced Research Center, 3251 Hanover Street, Palo Alto, CA 94304, USA.

E. Zesta, Department of Atmospheric Sciences, UCLA, Los Angeles, CA 90095, USA.