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Interactive comment on "The increase of curvature radius of geomagnetic field lines preceding a classical dipolarization" *by* Osuke Saka

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I very much appreciate the review and comments of referees #2.

Statistical studies of geomagnetic field variations in geosynchronous orbit show that they can be clearly understood in the nighttime sector when they are timed by the Pi2 onset at the conjugate equatorial stations [Saka et al., J. Atomos. Solar Terr. Phys., 72, 1100-1109, 2010]. For the case studies of field line dipolarization at geosynchronous altitudes, please refer to [Saka and Hayashi, Longitudinal expansion of field line dipolarization, J. Atmos. Solar Terr. Phys., 164, 235-242., 2017]. The following replies are summarized in a comment-response format.

Comment 1: Why ballooning instability could develop in geosynchronous orbit? Comparison between the scale of pressure gradient and curvature radius is necessary.

Response: We used calculation results of Ballooning instability given in [Rubtsov et al., Physics of Plasmas 25, 102903, doi:10.1063/1.5051474, 2018]. In a distance from L=5 to 10Re, instability threshold is given approximately as k∼-1.0 Reˆ-1 (k denotes reciprocal spatial scale of radial inhomogeneity of plasma pressure) for beta defined by the ratio of plasma pressure and magnetic pressure exceeding 0.1. This suggests that the Ballooning instability develops at the geosynchronous altitudes (curvature radius R is 2.2 Re) when spatial scale of the earthward pressure gradient caused by the inflows becomes steeper than 1.0 Re. With the field line stretching, instability is more likely to develop because stretching introduced offset in the earthward pressure gradient.

Comment 2: Substorm onset is usually believed triggered at _10 Re, and the auroral beads which manifest ballooning instability is also believed to map to _10 Re but not at geosynchronous orbit. The geosynchronous orbit initiation of dipolarization is not supported by observations.

Response: Please refer to [Saka and Hayashi, Longitudinal expansion of field line dipolarization, J. Atmos. Solar Terr. Phys., 164, 235-242., 2017] for a case study of geosynchronous initiation of field line dipolarization.

Comment 3: Why the hypothesis must be applied in geosynchronous but not 10Re? The magnetic stretching process is also clearly shown in 10Re region, for example, the substorm event shown in Sergeev et al. 2011, doi:10.1029/2010JA015689.

Response: The proposed scenario was deduced from the geosynchronous observation and cannot be readily applied to the onset scenario beyond the geosynchronous orbit. Nevertheless, if dawn-dusk expansion of the flux tubes in our scenario caused by the Ballooning instability is applicable to the formation of dipolarizing flux bundles (DFBs) propagating within fast earthward flows (BBFs) [Liu et al., JGR, 120, 2516-2530, 2015], the results from geosynchronous observations we presented can be extended further tailward in upstream.

Comment 4: The dawn dusk stretching flux tube is a common feature ahead of dipolarization front, (e.g., Figure 4 in Yao et al. 2013 doi:10.1002/2013JA019290 and Figure 6 in Liu et al. 2013 doi:10.1002/jgra.50092).

Response: The above references will be added to the revised version.

Comment 5: It has been reported that BBFs decelerate dramatically when they propagate towards the Earth [Shiokawa et al., 1997]. And It could be hardly for DFs arrival at geosynchromous. Thus, the hypothesis that westward electric fields on DFs trigger instability at geosynchromous should be not universal. The author needs to discuss in which conditions the proposed scenarios could be applied.

Response: We proposed that substorm onset is a transitional state lasting 10 min after the Pi2 onset followed by formation of the substorm current wedge by reduction of cross-tail currents. We can assume that DFs arrive in the transitional interval and the flow braking may occur afterwards in association with the reduction of cross-tail currents, viz., subsequent formation of the substorm current wedge. The flow braking does not affect the arrival of DFs.

Comment 6: line 100: It requires more explanation for Eq. 1:

Response: At geosynchronous altitudes, field line stretching started 90 minutes prior to the substorm onset [Figure 1 of Saka, Ann Geophys., 37, 381-387, 2019]. The stretching decreased the field line inclination by 7 degrees from 40.6 to 33.6 in this 90-min interval. This gives angular velocity of rotation of field line inclination in Equation (1) as 1.4E-3 rad/min. Total parallel flux gained in T min may be given by the integral of equation (1) with time from 0 to T. Substituting T=60 min and 1.4E-3 rad/min for angular velocity of field line inclination, this yields F_para=8.2E-2*F_perp. Gain of F_para is about 10% of the perpendicular flux (F_perp). This is consistent with the parallel temperature anisotropies (20% gain) observed at geosynchronous orbit [Birn et al., J. Geophys. Res., 102, A2, 2309-2324, 1997].

Comment 7: line 258-262: it is unclear why the change of curvature radius of field lines is different from the flux pileup dipolarization. Both are caused by current disruption, can we distinguish between them in observations?:

Response: Changes of curvature radius occurred in the geosynchronous orbit in association with longitudinal expansion of flux tubes which decreased field magnitudes therein. It lasted about 10 minutes after the Pi2 onset. The change of curvature radius is thought to be caused by the transition of the flux tubes to a new equilibrium configuration. Of course, cross-tail currents decrease according to Ampere's law. The flux pileup characterized by the increase of the field magnitudes at geosynchronous altitudes began after this 10-min interval. This post 10-min-interval is organized by reduction in cross-tail currents (formation of the substorm current wedge) which were deduced from the field line observations by Goes 5 and Goes 6 satellites at different latitudes from the equatorial plane. Please refer to [Saka et al., J. Atmos. Solar Terr. Phys., 72, 1100-1109, 2010].

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