Transpolar Arcs: Summary and Recent Results

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This review summarizes the current understanding of transpolar arcs. The following topics are covered: (1) transpolar arcs types; (2) influence of IMF B_y and B_z on shape and motion of transpolar arcs; (3) temporal intensifications of transpolar arcs; (4) substorms and transpolar arcs; (5) solar wind energy coupling; (6) ionospheric convection and source regions of transpolar arcs; (7) interhemispheric differences caused by IMF B_x and (8) the Earth dipole tilt; (9) magnetotail topology during transpolar arcs.

1. INTRODUCTION

The first (ground-based) observations of high-latitude polar arcs have been documented already in the early 20th century [*Mawson* 1925]. In the 1970s it became clear that such small-scale (a few km wide) typically sun-aligned arcs appear frequently during quiet geomagnetic conditions poleward of the main oval [e.g., *Ismail et al.,* 1977]. Large-scale polar arcs were not discovered until global auroral satellite images became available. In 1982, *Frank et al.* [1982] published an image from the DE 1 satellite, showing an auroral band that stretches over the entire polar cap connecting the nightside oval with its dayside counterpart. As this auroral configuration resembles the Greek letter "theta", *Frank et al.* [1982] suggested the name "theta aurora". Today, the expression "transpolar arc" (TPA) is more commonly used.

In this review, we refer to all polar arcs as TPAs, that can be detected on global auroral imagers poleward of the main oval, although not all large-scale polar arcs are (during their entire existence) attached to the noon oval or appear in the center of the polar cap. Many TPAs that seem to be clearly separated from the oval when looking at global imagers, are in fact attached to one oval side, as can be seen from particle detectors [e.g., *Makita et al.,* 1991; *Newell et al.,* 2009]. TPAs can have considerable fine structure. An auroral structure looking like one single TPA on global imagers corresponds often to multiple individual arcs when using ground based all-sky cameras [*Feldstein et al.,* 1995] or particle detectors [e.g., *Makita et al*., 1991; *Cumnock et al*., 2009].

As it is not possible to summarize 30 years of TPA research within a few pages, I refer here to the excellent review paper by *Zhu et al.* [1997] for a comprehensive coverage of the scientific knowledge about polar auroral arcs until 1997. In the present review the knowledge until the mid 90s regarding TPA types and their IMF dependence is briefly summarized. The main focus is on research results during the last 15 years.

2. MORPHOLOGY OF TRANSPOLAR ARCS

TPAs separate typically from the dawn- or duskside oval and move poleward. When reaching the noon-midnight meridian, they form a true theta aurora. Some TPAs even move over the entire polar region until they reach the opposite oval side [e.g., *Huang et al.,* 1989; *Cumnock et al.,* 1997]. However, most TPAs do not move considerably poleward after separation from the dawn- or duskside oval. *Murphree and Cogger* [1981] referred to these as oval-aligned arcs. When oval-aligned arcs appear simultaneously on both oval sides, the polar cap area becomes tear-drop shaped with the narrow end of the tear trop pointing towards the sun [*Meng*, 1981]. *Hones et al.* [1989] called such a configuration “horse-collar” aurora. Although TPAs are in general sun-aligned [*Frank et al.,* 1986] occasionally, they strongly bent at their nightside oval connection point. Such hook-shaped arcs have been reported by *Ismail and Meng* [1982], *Murphree et al.* [1982], and *Gusev and Troshichev* [1986]. In rare occasions TPAs evolve from the nightside oval [*Craven et al.,* 1986, *McEwen and Zhang,* 2000; *Kullen et al.,* 2002; *Goudarzi et al.,* 2008]. A few cases have been reported, where several arcs appear simultaneously in the polar cap which may emerge from both oval sides and/or the nightside oval [*Newell et al.,* 1999, *Kullen et al.*, 2002].

With the launch of the Polar spacecraft in 1996, global UV images of the auroral oval became available with a time resolution of 1-4 min between the images, which allows to study the temporal evolution of TPAs in detail. Based on 200 large-scale polar arcs that were identified in 3 winter months of Polar UV images, *Kullen et al.* [2002] proposed a new classification of large-scale polar arcs (expanding on an earlier classification by *Gussenhoven*, 1982): oval-aligned TPAs (including those arcs that are clearly separated from the oval, but do not move considerably poleward before they disappear), moving TPAs, bending TPAs, midnight (nightside originating) TPAs and multiple (3 or more) TPA events. Examples of each arc type are given in Figure 1. Bending TPAs (Figure 1, row 3) are extremely faint, hook-shaped arcs where the tailward connection point (often at the dawn or duskside oval) stays nearly fixed while the dayside part bends more and more into the polar cap, i.e. they do not become transpolar. Due to the weak auroral intensity, these arcs are extremely difficult to discover using global imagers. Bending TPAs should not be confused with the hook-shaped TPAs reported earlier. Often, moving TPAs become during part of their lifetime hook-shaped (Figure 1, row 2). During one third of all TPA events, a small oval-aligned arc appears simultaneously on the opposite oval side (see, e.g., the small dusk arc in row 2 of Figure 1).

Newell et al. [2009] suggested a much different classification. They consider there exist only three types of polar arcs: small-scale sun-aligned arcs, TPAs attached to one oval side and in rare cases true theta aurorae that are clearly detached from both oval sides. This classification has its difficulty as it does not take into account the temporal evolution of TPAs. For example, true theta aurorae start their evolution by separating from one oval side, i.e., during part of their lifetime, they are attached to the oval as well.

TPAs are rare events. They occur during only 10% of the time. For comparison, small-scale sun-aligned arcs appear during at least 40% of the time [*Valladares et al*., 1994]. The average lifetime of TPAs lies at 2 hours. However, some oval-aligned and moving TPAs last up to 4-6 hours [*Kullen et al.*, 2002; *Cumnock*, 2005].

3. TRANSPOLAR ARC DEPENDENCE ON IMF B_y AND IMF B_z

Different TPA types are not randomly occurring but they arise in specific situations, as a response of the magnetosphere to specific IMF and solar wind conditions. It is known since a long time that polar arcs are a predominantly northward IMF phenomenon which includes both, small-scale sun-aligned arcs [*Lassen and Danielsen*, 1978; *Valladares et al*., 1994] and TPAs [*e.g., Frank et al., 1982; 1986; Gussenhoven*, 1982; *Ismail and Meng*, 1982]. *Kullen et al*. [2002] showed, in nearly all cases IMF B_z is predominantly northward during the last 2 hours before (87%) and during TPA events (75%). After a southward turning of the IMF TPAs fade within 15-65 min [*Rodriguez et al.*, 1997].

The dawn-duskward motion of both small-scale sun-aligned arcs [*Valladares et al*., 1994] and TPAs [*Kullen et al.* 2002] is controlled by the direction of IMF B_y. In the northern hemisphere most TPAs move into the direction of IMF B_y [*Frank et al.,* 1986; *Huang et al.*, 1989]. Only those TPAs that have emerged close to the dusk oval side during duskward IMF (on the dawn oval side during dawnward IMF) remain as oval-aligned TPAs close to the oval [*Elphinstone et al*., 1990]. This includes even those static TPAs that are separated by quite many degrees latitude from the oval [*Kullen et al.* 2002]. The few existing interhemispheric studies show that TPAs may exist simultaneously in both hemispheres, and that IMF B_y has an opposite effect on location and motion of TPAs in the southern hemisphere [*Gorney et al.,* 1986, *Mizera et al.,* 1987; *Obara et al.*1988; *Craven et al*., 1991; *Cumnock et al.*, 2006].

In the mid 90s it was discovered that an IMF B_y or B_z rotation may trigger TPAs to move poleward. *Newell and Meng* [1995] proposed that a change from northward to southward IMF is responsible for the occurrence of TPAs, *Cumnock et al*. [1997] assumed that TPAs appear due to a sign change of the IMF B_y component. *Chang et al.* [1998] suggested that either large variations in IMF B_y or an IMF turn to weakly southward IMF may trigger TPAs, a view later also shared by *Newell et al*. [1999]. Most events shown in these early reports about possible IMF triggers appear during varying IMF B_y and B_z conditions, which makes it difficult to draw clear conclusions. Finally, *Cumnock* [2005] was able to show with a large statistical study, selecting 55 time periods with at least 3 hours northward IMF and one clear IMF B_y sign change that theta aurora almost always occur during such conditions. *Newell et al.* [1997] and *Kullen et al.* [2002] each presented a polar arc event that appears in connection with an IMF B_z southward rotation during constant IMF B_y, which shows that an IMF B_z southturn may trigger a TPA as well. Furthermore, *Kullen et al.* [2002] discovered that nearly all bending TPAs occur in connection with IMF B_z sign changes.

The rare multiple TPAs events appear commonly during strongly varying IMF conditions [*Kullen et al.* 2002]. A nice example where several arcs fill the polar cap during the northward phase of a CME storm is presented in *Newell et al*. [1999]. However, it is extremely difficult to discern which IMF change triggers which arc in such events, especially as the reaction delay between solar wind changes and TPA evolution is not exactly known. From observations of solar wind pressure pulses that cause intensifications of a TPA, a time delay of 40 minutes can be estimated [*Liou et al.*, 2005]. *Kullen et al.* [2002] observed that bending arcs appear soon (1-20 min) after an IMF B_z sign change, while moving TPAs appear on average 60 min after an IMF B_y sign change. This indicates that different creation mechanisms may be responsible for different types of arcs.

4. TEMPORAL INTENSIFACTION OF TRANSPOLAR ARCS

TPAs are never continuously bright. The point of insertion of the TPA into the nightside auroral zone appears often as a bright spot [*Murphree et al.*, 1987]. *Hubert et al.* [2004] observed these in 90% of all studied TPA events. As can be seen in Figure 1, 1st row, such an auroral intensification may expand along the TPA. Localized brightenings in the nightside oval sector are common during quiet times [*Fillingim et al*., 2000]. They can be elongated up to several degrees MLT and may exist between 15 and 60 minutes. About one third of all quiet time intensifications appear in connection with TPAs [*Kullen and Karlsson*, 2004]. It is to date unclear what triggers these [*Hubert et al.,* 2004; *Kullen et al.*, 2010]. *Murphree et al.* [1987] interpreted auroral brightening at the nightside end of a TPA as pseudobreakups, while *Hubert et al.* [2004] assumed, these are different from usual pseudobreakups as they are dominated by proton injections.

The magnitude of solar wind density and pressure seem to have no influence on the TPA frequency. [*Kullen et al.,* 2002]. High density has only a weak (negative) effect on TPA luminosity [*Kullen et al.,* 2008]. However, a sudden solar wind pressure pulse may change temporarily the brightness of a TPA. *Liou et al.* [2005] shows a pressure pulse event during a preexisting TPA. The pressure pulse leads to a temporal intensification of the auroral oval which starts at noon within minutes after the pulse hits the magnetopause and spreads along the dawn oval to the nightside sector and further along the TPA. That the TPA brightens as the last part of the oval, indicates that TPAs map to far tail regions. It is well-known that a pressure pulse may cause a temporal intensification of the auroral oval [*Elphinstone et al*., 1990; *Zhou and Tsurutani*, 1999]. The sudden compression of the magnetosphere by shock impact probably causes more particles to enter the loss cone although the exact mechanism is not known. *Zhou and Tsurutani* [1999] suggested that it is connected to wave particle scattering, [*Liou et al.*, 2005] proposed a temporal widening of the loss cone due to a magnetic field line reconfiguration as a possible explanation for the auroral enhancement.

5. TRANSPOLAR ARCS AND SUBSTORMS

Although TPAs are a quiet time phenomenon, they may survive several 10s of minutes up to two hours after substorm onset [*Kullen et al.*, 2002] until they fade gradually in antisunward direction [*Rodriquez et al*., 1997]. Smaller substorms during predominantly northward IMF have been observed to take place without causing a preexisting TPA to disappear. Instead, the most intense substorm region may spread along the nightside part of the TPA [*Cumnock et al*., 2000]. These observations fit to the assumption that TPAs are a far tail phenomenon [e.g., *Frank et al.*, 1986; *Elphinstone et al*., 1990], whose existence is affected only 10s of minutes after the onset of large substorms during which the entire tail undergoes large-scale topological changes.

About one third of all TPAs occur at the end of substorm recovery, most of these are oval-aligned TPAs [*Kullen et al.*, 2002]. Typically, IMF has turned northward at onset or during the expansion phase of substorms that are followed by TPA events. Such northward IMF recoveries are very dynamic and multiple intensifications (PBIs) [*Lyons et al.,* 1999] occur along a strongly deformed poleward oval boundary that has reached highest latitudes. When returning to the ground state, the poleward boundary remains often active while the region between poleward and equatorward boundary already starts to erode, resulting in a double-oval [*Elphinstone et al*., 1995]. For those recoveries where a double-oval like structure occurs, the evolving TPA is connected to the poleward oval. PBIs are often observed at the TPA intersection point with the oval, and may spread along the arc (note the similarity with quiet time intensifications appearing on TPAs). On global images, this gives occasionally the impression as if the TPA evolution does not only include a separation from the oval side, but also expands from the nightside towards noon.

In rare cases, a TPA appears to evolve from the nightside oval boundary into the empty polar cap. Such nightside originating arcs (in *Kullen et al.* [2002] referred to as midnight arcs) appear at the end of a dynamic substorm recovery and develop within minutes from a bright bulge at the oval boundary (maybe a PBI) that extends several degrees latitude into the polar cap (Figure 1, last row). Such TPAs show often a messy, patchy structure. A nice example of such an unusual TPA is given in *Goudarzi et al.* [2008]. Whether or not such TPAs form at a preexisting (on global imagers subvisual) much poleward expanded oval, remains to be shown. Theoretical studies have shown that the evolution of nightside originating arcs could be possible on highly curved magnetic field lines where ballooning instabilities can occur that could cause plasma sheet filaments to stretch tailward [*Rezhenov*, 1995] or high into the lobes [*Golovchanskaya et al.,* 2006].

6. SOLAR WIND ENERGY COUPLING DURING TRANSPOLAR ARC EVENTS

An important factor for TPAs to occur is that enough energy is available in the solar wind which is transferred into the magnetosphere. The results of *Cumnock* [2005] demonstrate this nicely. Of the 55 time periods with IMF conditions that are favorable for TPA formation, TPAs occur in all cases except in those two cases where the magnetic solar wind energy flux vB^2 has lowest values [*Kullen et al.*, 2008]. Furthermore, *Kullen et al.* [2008] showed that vB^2 controls the luminosity of (dayside) TPAs. A possible interpretation of these observations is that for low values of vB^2 there is not enough energy available to draw high-latitude field-aligned currents (FAC) that produce aurora, while the magnetosphere topology is such that a TPA could occur.

That high IMF magnitude and fast solar wind speed are favorable for polar arcs to occur has already been reported by *Makita et al*. [1988] and *Gussenhoven* [1982], respectively. *Kullen et al.* [2002] discovered the combination of high solar wind speed, strong IMF magnitude and northward IMF gives the highest occurrence frequency of TPAs. The best correlation with TPA occurrence appears for a solar wind energy coupling parameter, *Kullen et al.* [2002] referred to as *anti-epsilon* ~ $vB^2\cos(\theta/2)^4$ with theta defined as the clock angle between IMF B_y and B_z (high for northward, zero for southward IMF). The anti-epsilon parameter corresponds to the Akasofu-Perreault epsilon parameter [*Perreault and Akasofu*, 1978] with the sine function replaced by cosine. A similar coupling parameter [*epsilon** ~$(B_y^2+ B_z^2)^{1/2}\cos(\theta /2)$] has been suggested already by *Iijima et al.* [1984] to describe the correlation between solar wind and the intensity of field-aligned currents appearing in the dayside polar cap during northward IMF (NBZ currents). This current system is generally believed to be connected to polar arcs [e.g., *Iijima and Shibaji*, 1997].

7. IONOSPHERIC CONVECTION AND SOURCE REGIONS OF TRANSPOLAR ARCS

For northward IMF, reconnection takes place in the high-latitude lobes [*e.g., Reiff and Burch*, 1985; *Crooker*, 1992], resulting in two or more reverse convection cells at highest latitudes and two viscous cells on lower latitudes that appear completely on closed field lines. The result is sunward flow on the dayside of the polar cap region [*Heppner and Maynard*, 1987]. On the nightside, weak flows with irregular patterns are observed. The global convection pattern during northward IMF is characterized by a variety of configurations with the number of cells increasing with increasing ratio of B_z/B_y. The convection pattern becomes additionally distorted by the occurrence of polar arcs. TPAs are known to be associated with upward FAC, as they nearly always lie on a location with div E<0 [e.g., *Burke et al.,* 1979; *Frank et al.,* 1986; *Nielsen et al.,* 1990]. The field-aligned currents associated with TPAs do not always close locally, which has been observed to have an effect on the large-scale convection pattern [*Marklund and Blomberg*, 1991; and references therein]. There exists no general valid model about how the convection pattern changes globally during a TPA event. Based on satellite passes through the dayside polar cap, it has been reported that moving TPAs occur at the convection reversal boundary or inside the sunward part of a distorted 2-cell [*Nielsen et al*., 1990; *Chang et al*., 1998] or 3–cell pattern [*Jankowska et al.,* 1990]. *Cumnock et al*. [1997] observed how a large dominant cell changed to a four-cell pattern while a TPA moved poleward.

The similar particle characteristics of TPAs and auroral arcs of the main oval and numerous reports of sunward flow on TPAs is the reason why it was commonly assumed that TPAs appear on closed field lines that origin in the plasma sheet or its boundary layer [e.g., *Frank et al.*, 1986; *Peterson and Shelley*, 1984]. As pointed out by *Liou et al.* [2005], most of these TPA studies are based on satellite paths through the dayside polar cap. On the nightside TPA part, a different flow direction has been observed. *Nielsen et al* [1990] reported a case with sunward flow on the dayside part of the TPA, while the nightside endf of the same TPA is collocated with antisunward flow. *Liou et al.* [2005] observed that the plasma flow direction on the dayside TPA was changing with IMF B_y between sunward and dawn-duskward (as expected from convection models), while the strong tailward plasma flow on the nightside TPA was not affected by the IMF orientation (see Figure 2). The existence of TPAs with anti-sunward flow along the nightside part suggests the low-latitude boundary layer (LLBL) along the magnetotail flanks as a possible source region for these events, an idea already put forward by *Murphree et al.* [1982] for horse-collar aurora. The (during northward IMF thick) LLBL contains plasma sheet like particles that drift tailward along the outer part of the LLBL. *Liou et al.* [2005] proposed, the entire TPA maps to the LLBL, but the dayside part may be dominated by current states of dayside merging. *Eriksson et al.* [2005] observed separate convection cells at the dayside and nightside parts of a duskside oval-aligned TPA. They suggested two different drivers, with merging poleward of the cusp as the driver of the sunward (dayside) cell. This would mean that dayside and nightside parts of the TPA map to different magnetospheric regions.

8. IMF B_x EFFECTS ON TRANSPOLAR ARCS

IMF B_x has an asymmetric effect on high-latitude lobe reconnection in the different hemispheres. For negative (tailward) IMF B_x, solar wind and magnetospheric field lines become more antiparallel in the northern than in the southern hemisphere. Theoretical studies [e.g., *Crooker*, 1992] indicate that northward IMF coupling with the magnetopause is stronger in one hemisphere when B_x/B_z is large. This has an impact on the polar cap potential. *Taguchi and Hoffman* [1995] observed an IMF B_x effect on the polar cap potential drop during northward IMF, which they interpreted as a signature for a larger reconnection area in one hemisphere.

The more favorable reconnection in one hemisphere effects the occurrence frequency of high-latitude aurora. Small-scale polar arcs [*Lassen and Danielsen*, 1978], localized high-latitude dayside aurora (HilDA) [*Frey et al.*, 2004; *Frey,* 2007 and references therein], and TPAs [*Kullen et al.*, 2002] are in the northern hemisphere more commonly observed during negative than during positive IMF B_x. This has an effect on TPA conjugacy. *Ostgaard et al.* [2003] presented two cases where a bright TPA appears only in the hemisphere with favorable sign of IMF B_x. The authors suggested that flow shears associated with convection reversal boundaries along TPAs are too weak to draw currents in the hemisphere with non-favorable reconnection during strong IMF B_x. This is in agreement with observations of a strong IMF B_x dependence of NBZ currents intensities [*Iijima et al.,* 1984].

Although not mentioned in their report, in *Ostgaards et al.'s* [2003] second example polar arcs appear even in the non-favored hemisphere (in their other example the image quality is too poor to detect similar structures). Instead of one bright TPA, two faint bending-type arcs and one small oval-aligned arc appear at the dawn and dusk oval sides, respectively. This is in agreement with statistical results by *Elphinstone et al.* [1990] and *Kullen et al.* [2002]. *Elphinstone et al*. [1990] found weak polar arcs to occur on both oval sides in the by IMF B_x non-favored hemisphere, and one bright sun-aligned arc in the B_x favored hemisphere. *Kullen et al.* [2002] reported that bending arcs are the only TPAs that appear typically in the by B_x non-favored hemisphere, and are commonly accompanied by a small oval-aligned arc on the opposite oval side. This suggests that (in addition to an IMF B_x dependence of FAC strength), interhemispheric differences in the field line topology during non-zero IMF B_x are such that FACs map far into the polar cap only in the B_x-favored hemisphere, but polar arcs may still occur close to the oval in the other hemisphere.

9. DIPOLE TILT EFFECTS ON TRANSPOLAR ARCS

The Earth dipole tilt has a similar effect on the magnetospheric topology as IMF B_x. It is defined as positive when the northern part of the Earth's dipole axis points sunward. Positive dipole tilt not only results in a more favorable magnetic field topology for high-latitude lobe reconnection, it also results in a larger solar illuminated polar cap area in the northern hemisphere. The question appears whether seasonal (dipole tilt) effects on TPAs have their cause in the magnetospheric field line topology or the illumination of the ionosphere.

The UV illumination of the ionospheric plasma results in enhanced conductivity. This is known to have a strong influence on the brightness of the oval. While diffuse auroral regions of the oval are brighter in the sunlit hemisphere [*Liou et al.*, 2001; *Shue et al.,* 2001] due to a positive correlation with ionospheric conductivity [*Fujii and Iijima*, 1987], discrete arcs (appearing preferably in the pre-midnight oval region) are suppressed in sunlight [*Newell et al.*, 1996]. This may be connected to the extremely low conductivity in that region, allowing for particle acceleration via the feed-back instability mechanism [*Newell et al.*, 1996].

Kullen et al. [2008] observed that TPAs appearing during completely quiet times are brighter in the sunlit than in the dark hemisphere, i.e., they have the same dipole tilt dependence as diffuse aurora. A clear correlation between TPA luminosity and dipole tilt could only be established in the sunlit hemisphere. Even for large dipole tilts, TPAs do not disappear completely in the dark hemisphere, as can be seen, e.g., from the conjugate TPA example in *Craven et al*. [1991]. No correlation between TPA luminosity and IMF B_x has been found [*Kullen et al.*, 2008]. This suggests, the TPA brightness depends much more on the ionospheric conductivity than on a favorable reconnection topology.

There is a general tendency that only the dayside part of the polar cap is directly influenced by the solar wind. TPA luminosity [*Kullen et al.*, 2008], plasma flows on TPAs [*Liou et al.*, 2005], NBZ currents [*Iijima et al.,*1984], polar rain [*Newell et al.*, 2009] as well as the cross polar cap potential [*Reiff et al.,* 1981] all show clear correlations with solar wind and IMF parameters in the dayside part of the polar cap, but not in the nightside part.

10. MAGNETOTAIL TOPOLOGY DURING TRANSPOLAR ARCS

[*Meng,* 1981] proposed already in the early 80’s that polar arcs appearing close to one oval side lie on the boundary of a poleward expanded closed field line region. *Makita et al.* [1991] confirmed this observationally. As closed field lines map to the plasma sheet or its boundary layer [e.g., *Frank et al.,* 1986], the appearance of an (oval-aligned) TPA would require a highly contracted polar cap and a dawn-dusk asymmetry or a twisting of the tail plasma sheet [*Makita et al*., 1991]. *Cowley* [1981] proposed that IMF B_y exerts a torque on the magnetosphere about the Earth-sun line such that the entire plasma sheet becomes increasingly twisted with distance from the Earth. Statistical studies [*Kaymaz et al.,* 1994] and MHD simulations [*Kaymaz et al*., 1995] confirm such a twist. Later on it was shown both observationally [*Owen et al.*, 1995] and by simulations [*Walker et al.*, 1999; *Kullen and Janhunen*, 2004] that the tail twist is much larger during northward than during southward IMF, which explains the northward IMF dependence of (oval-aligned) TPAs. The stronger twist occurs due to high-latitude lobe reconnection during northward IMF: B-field lines originating in the northern hemisphere are connected to solar wind field lines south of the magnetosphere. When the solar wind drags these field-lines in an anti-sunward direction, the open field lines exert (in case of nonzero B_y) a strong torque on the magnetotail. For positive IMF B_y, the duskside (dawnside) far tail plasma sheet flanks map to highest latitudes in the northern (southern) hemisphere (see Figure 3a). This explains why most oval-aligned TPAs appear on the duskside (dawnside) of the northern (southern) auroral oval during constant positive IMF B_y.

Frank et al. [1982; 1986] and *Huang et al.* [1989] suggested that TPAs that are clearly separated from the oval (theta aurora) map to a bifurcated tail plasma sheet with a tongue of plasma reaching high into the northern and southern tail lobes. Observation of filamentary plasma sheet extensions into the lobes during a TPA event [*Huang et al.*, 1989] shows that such a plasma sheet topology is possible.

Based on observations that an IMF B_y sign change can trigger a moving TPA [*Cumnock et al.,* 1997], *Kullen* [2000] developed a TPA model which is based on the idea that after an IMF By rotation, the magnetotail changes its twist not at once, but successively from near-Earth to far-tail regions. Modifying the *Tsyganenko* [1989] magnetosphere model, *Kullen* [2000] showed that opposite twists of near-Earth and far-tail plasma sheet cause a field line topology where closed field lines from the distant tail map to a finger of closed field lines that bifurcates the polar cap (see Figure 3b). The “finger” of closed field lines moves from one oval side to the other while the new magnetotail twist direction expands tailward. Assuming that TPAs occur on (or at the boundary of) closed field lines, the polewardly moving “finger” represents the possible location of a moving TPA.

MHD simulations with the Winglee model [personal communication], the Fedder and Lyons model [*Slinker et al.,* 2001], the Gumics-3 MHD code [*Kullen and Janhunen*, 2004], the BATSRUS MHD model [*Naehr and Toffoletto*, 2004], the Tanaka model [*Tanaka*, 2004] and ISM model [*Maynard et al*., 2003] differ in many details but all confirm the appearance of a closed field line strips in the northern and southern polar cap for an IMF B_y sign reversal during northward IMF (for southward IMF the tail twist is too weak to cause a polar cap bifurcation). The closed field line strips develop at opposite sides of the oval and move into opposite directions in the different hemispheres, while a rotation of the tail twist into the opposite direction takes place. Thus, the observed conjugacy of TPAs in different hemispheres [e.g., *Craven et al.,* 1991] appears in all MHD models. Possible dipole tilt and IMF B_x effects [*Kullen et al*., 2008; *Ostgaard et al*., 2003] on the conjugacy of TPAs have not been studied with these simulations. In *Kullen and Janhunen* [2004] the reconfiguration of the tail is examined in detail. They find that the twist change does not only propagate tailward (as predicted by *Kullen* [2000]) but also from the flanks to the tail center, which additionally complicates the resulting tail topology (see Figure 3b). Furthermore, the (closed field line region) tail expands during the B_y rotation. As the closed field line strip bifurcating the polar cap, maps to the most distant tail regions, an increase of the tail length explains in part the long TPA lifetime (however, the MHD model TPAs last only 40 minutes as compared to real TPAs). The closed field line strips do not reach the dayside oval in any of the different MHD runs. In case this reflects a physical reality, it would mean that the dayside TPA part does not lie on closed field lines. Due to numerical diffusion and low resolution in the tail, it is not possible to reproduce thin FACs or reliable convection maps of the high-latitude ionosphere (the convection pattern deviate extremely between the different MHD codes for similar IMF B_y change runs). Thus, the MHD models should not be used for detailed studies of the convection and current pattern during TPA events.

As predicted in the conceptual TPA models by *Newell et al.* [1997] and *Chang et al*. [1998], a new region of open field lines appears in the simulations at the duskside polar cap close to noon after the reconnection site jumped from dusk to dawn due to an IMF B_y flip. A closed field line strip appears between the old (dawnside) polar cap and the new (duskside) open flux region (see Figure 3b). An expansion of the new open flux region at the expense of the old open flux region is connected to the poleward motion of the closed field line strip.

MHD simulations of an IMF B_z southward turning during nonzero IMF B_y failed to produce any signatures that could explain how a TPA emerges after an IMF B_z southturn [personal communication with Janhunen, Maynard et al., 2003]. As suggested by *Newell et al.* [1997] and *Chang et al*. [1998], even in this case a merging line jump (from northward high-latitude to southward dayside reconnection) would lead to a new region of open flux to appear poleward of the cups. How this could be connected to a long-lasting TPAs or explain their poleward motion, remains to be shown.

Other recent TPA models involve the concept of a return flow blockage in convection cells due to an IMF B_y sign change, which would lead to a pileup of closed flux that protrudes into the polar cap due to the simultaneous existence of old and new open-field line regions [*Tanaka et al.,* 2004], or due to competition between the conjugate hemispheres [*Milan et al*., 2005].

Despite comprehensive knowledge about TPAs, a global model is still missing that explains consistently how ionospheric convection, TPA associated currents, particles and magnetospheric source regions are linked together. Simultaneous imaging of the northern and southern auroral ionospheres with help of high-resolution global imagers (combined with data from low-altitude orbiting satellites such as DMSP) would help to answer many open questions regarding the ionosphere-magnetosphere coupling during TPA events.

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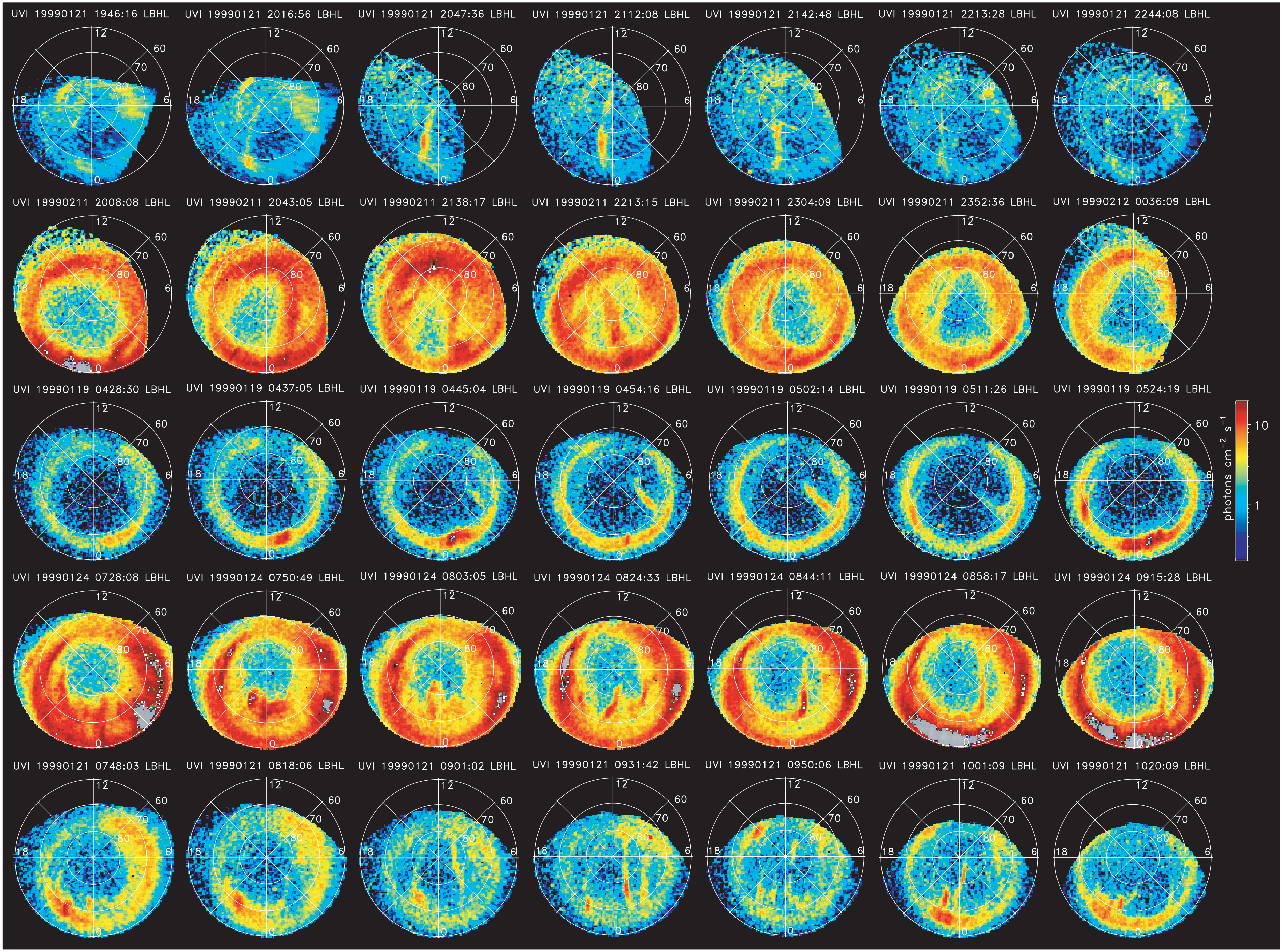
FIGURE CAPTIONS

Figure 1. The temporal evolution of 5 different TPA types, seen on the Polar UV imager (from top to bottom row): oval-aligned TPA, moving TPA, bending TPA, nightside originating TPA, and multiple TPA event. Reproduced from *Kullen et al.* [2002].

Figure 2. Horizontal ionospheric plasma flows observed with SuperDARN in the northern hemisphere during a TPA event (IMF B_z ~ 7 nT, IMF B_y ~ 1 nT). The colored dots indicate the location of the measurements and the colored “sticks” indicate the magnitude and direction (away from the dot) of the plasma flow. Plotted on the background is a 2-min average UVI image for the same time period. The field of view for each radar is plotted as dashed lines. Reproduced from *Liou et al.* [2005].

Figure 3. (a) Tail topology for oval-aligned TPAs: An IMF B_y>0 induced (due to northward IMF strong) tail twist causes the high-latitude dusk (dawn) far tail flank to map to highest latitudes in the northern (southern) hemisphere. The blue line at each polar cap boundary indicates the possible location of an oval-aligned TPA. (b) Tail topology for moving TPAs: A (tailward propagating) change in the tail twist, caused by an IMF B_y sign reversal during northward IMF, leads to a bifurcation of the closed field line region in the near-Earth tail which maps to a (polewardly moving) closed-field line strip in the northern and southern polar cap (blue lines) on which a moving TPA may appear.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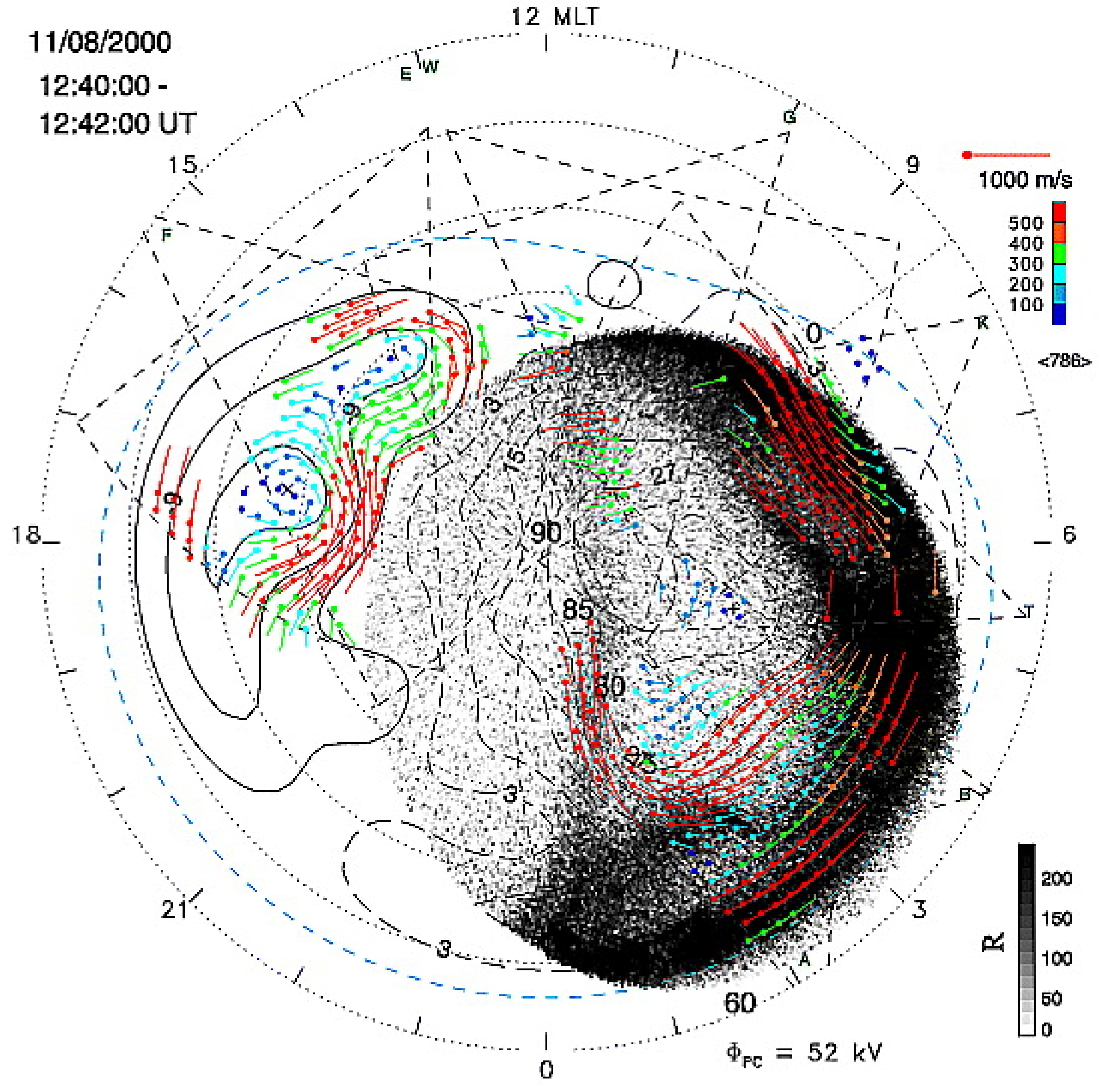

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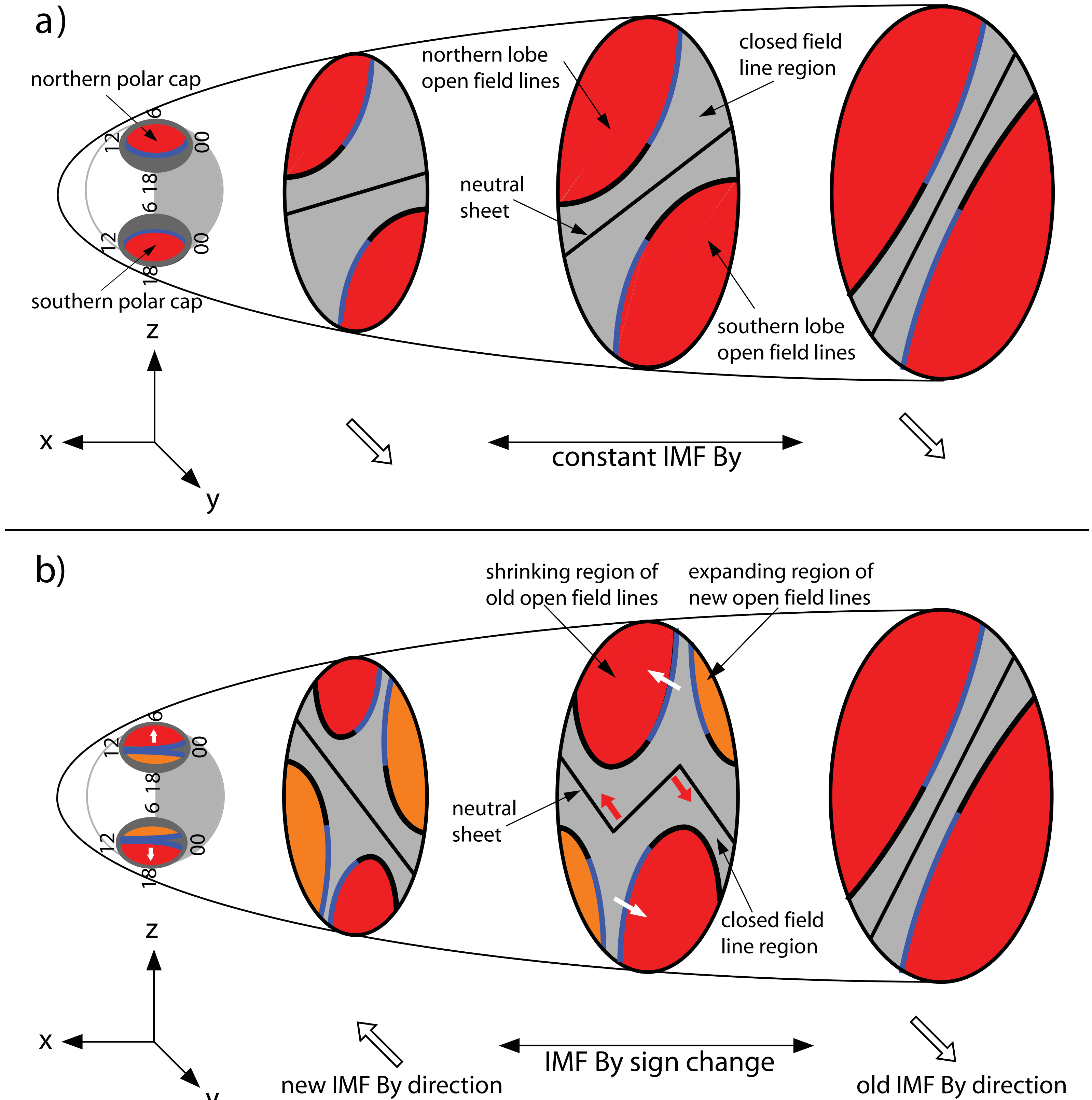

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expanding region of
new open field lines
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