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Key Points:
- Discovery of a nightside polar arc at Saturn
- Earth-like transpolar arc can occur in internally influenced magnetosphere
- Saturn's polar arc might be related to solar wind driven tail reconnection

Supporting Information:
- Readme
- Movie S1

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Saturn's elusive nightside polar arc

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Abstract Nightside polar arcs are some of the most puzzling auroral emissions at Earth. They are features which extend from the nightside auroral oval into the open magnetic field line region (polar cap), and they represent optical signatures of magnetotail dynamics. Here we report the first observation of an arc at Saturn, which is attached at the nightside main oval and extends into the polar cap region, resembling a terrestrial transpolar arc. We show that Earth-like polar arcs can exceptionally occur in a fast rotational and internally influenced magnetosphere such as Saturn's. Finally, we discuss the possibility that the polar arc at Saturn is related to tail reconnection and we address the role of solar wind in the magnetotail dynamics at Saturn.

1. Introduction

A planetary magnetotail is the region where plasma and energy is built up and released in an explosive way. Earth's magnetotail dynamics are mainly controlled by solar wind driven magnetic reconnection via the Dungey cycle (opening and closure of magnetic flux) [*Dungey*, 1961]. Reconnected open flux tubes are transported over the poles by the solar wind, before reconnecting in the tail. The newly closed field lines in the tail are then expected to convect along the flanks back to the dayside. Saturn's magnetotail may be influenced by a combination of Dungey and *Vasyliūnas* [1983] reconnection cycles [i.e., *Jackman et al.*, 2011]. The Vasyliūnas cycle is an internally driven process, in which the planet's rapid rotation combined with the mass loading of flux tubes fed by internal plasma sources (Enceladus and its neutral cloud) lead to reconnection on closed field lines. The closed field lines are then accelerated back to the dayside via the dawn flank. Another process that is suggested to influence Saturn's magnetotail dynamics is the viscous interaction of the solar wind with the planetary magnetosphere [*Delamere and Bagenal*, 2013]. Unlike the Earth, Saturn is a fast rotator and thus the magnetospheric lobes are speculated to become twisted by a rotational torque applied to the ionospheric ends of the open field lines while the other end is anchored in the solar wind [*Isbell et al.*, 1984; *Cowley et al.*, 2005; *Milan et al.*, 2005b]. The magnetotail lobes house the open magnetic flux, which is stored in the tail and maps to the ionospheric polar caps.

The process of magnetic reconnection accompanied by expansion or contraction of the polar cap gives evidence of the mechanisms which couple solar wind mass, energy, and momentum into the magnetosphere both at Earth [*Milan et al.*, 2004] and Saturn [*Badman et al.*, 2005; *Radioti et al.*, 2011; *Badman et al.*, 2014]. A simplified view of the polar cap changes in response to dayside/nightside reconnection is illustrated in Figure 1a. Low-latitude magnetopause reconnection (blue arrows, Figure 1a), which occurs for northward IMF at Saturn, creates new open flux and increases the polar cap size [*Cowley et al.*, 2005; *Badman et al.*, 2005; *Radioti et al.*, 2011]. Dipolarizations in the tail are identified as localized small-scale intensifications in the nightside aurora region [*Jackman et al.*, 2013] and are believed to be precursors to a more intense activity following tail reconnection [*Mitchell et al.*, 2009]. Dungey-type tail reconnection at Saturn (green arrows, Figure 1a) is expected to result in bright aurorae, which expand poleward in the dawn sector, accompanied by reduction of the size of the polar cap and closure of magnetic flux [*Cowley et al.*, 2005; *Badman et al.*, 2014; *Nichols et al.*, 2014], while tail reconnection of closed field lines (Vasyliūnas type) does not correspond to polar cap size changes. High-latitude reconnection (southward IMF) does not change the amount of open magnetic flux, in contrast to subsolar dayside magnetopause reconnection which adds open flux, or Dungey-type nightside reconnection which closes flux. Therefore, estimates of the overall size of the polar cap do not reveal the high-latitude reconnection rate but rather the net amount of magnetic flux

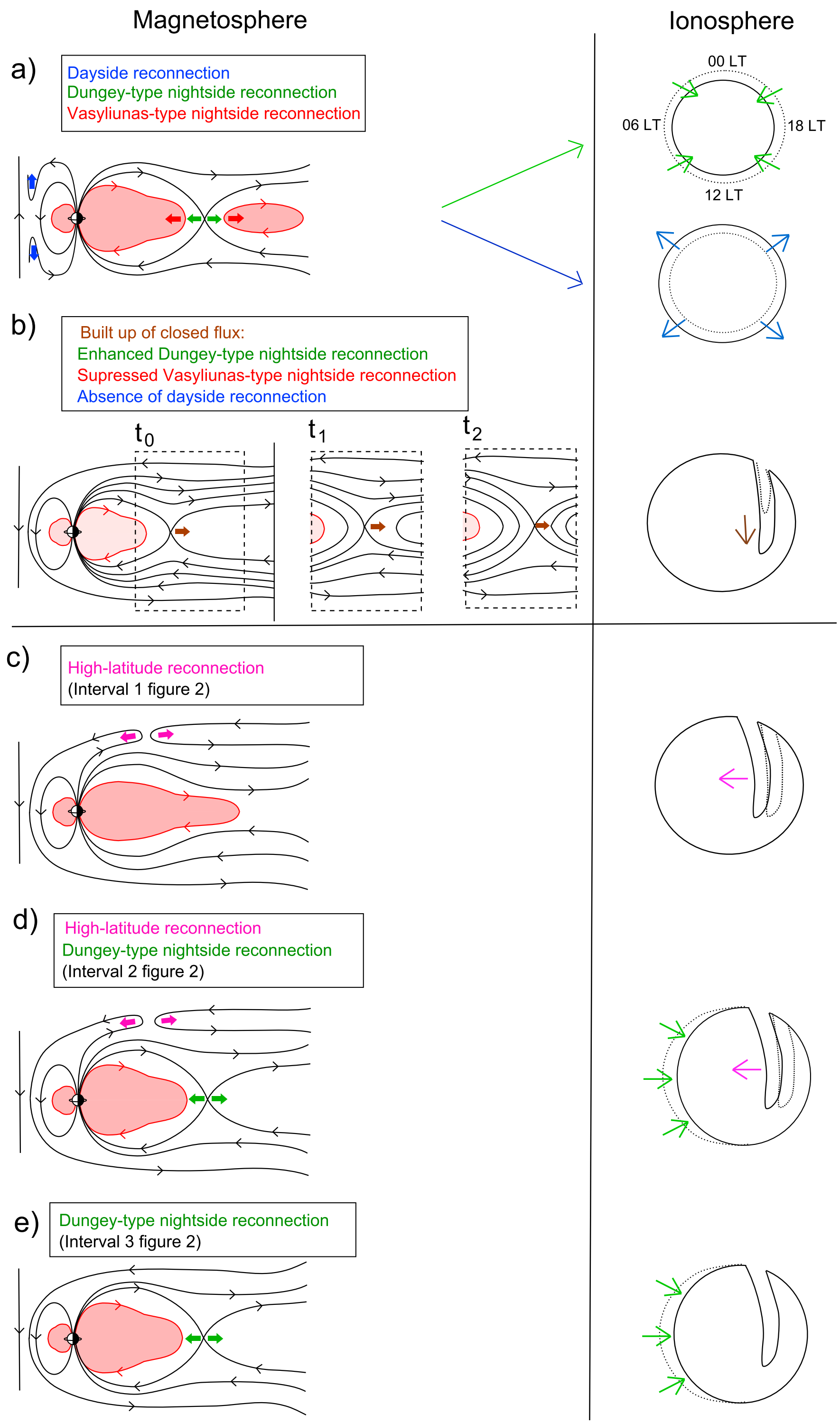

Figure 1. Cross sections in the magnetosphere illustrating five possible combinations of Dungey type, Vasyliunas type, and high-latitude reconnection, together with the associated polar cap changes in the ionosphere. The schematics are not to scale. (a) Illustration of a combination of Dungey- and Vasyliunas-type tail reconnection at Saturn. (b) Illustration of a magnetospheric configuration which favors the formation of a nightside polar arc at Saturn. (c)–(e) Illustrations of magnetospheric configurations, which correspond to intervals 1, 2, and 3 of the auroral observations shown in Figure 2.

content. The high-latitude reconnection rate at Earth has been quantified based on the motion of transpolar arcs [*Milan et al.*, 2005a].

Nightside polar arcs, often described as transpolar arcs, are commonly detected in the Earth's aurora. They are morphologically defined as auroral features that extend from the nightside auroral oval (18 to 06 LT) into the open magnetic field line region (the polar cap) and often reach the dayside auroral oval [e.g., *Frank et al.*, 1982; *Kullen et al.*, 2002; *Milan et al.*, 2005a]. Several mechanisms have been proposed for the formation of the terrestrial transpolar arcs, which suggest that they are formed by a poleward extended closed field line region in response to large deformations of the tail plasma sheet [*Makita et al.*, 1991; *Rezhenov*, 1995; *Kullen and Jahnunen*, 2004]. *Milan et al.* [2005a] suggested that they are formed by magnetotail reconnection closing lobe flux which is then unable to convect back to the dayside in the textbook manner. The validity of this mechanism is supported by ionospheric flow measurements [*Fear and Milan*, 2012b], indicating the occurrence of magnetotail reconnection, as well as the time delay in the correlation between the IMF B_y component and the location of the formation of the arc [*Fear and Milan*, 2012a]. In this mechanism, when magnetotail reconnection occurs, the northern and southern hemisphere footprints of the newly closed magnetic field lines straddle the midnight meridian. The return flow of field lines crossing the plasma sheet near midnight is prevented as the northern and southern halves of the field lines experience opposing forces in the dawn/dusk direction [*Milan et al.*, 2005a]. The field line experiences no net dawn/dusk component of force, and the return flow of the closed flux then becomes more complicated than originally thought [*Dungey*, 1961]. This results in a build up of closed flux in the tail and the formation of a transpolar arc. According to the *Milan et al.* [2005a] mechanism the formation of the arc requires the absence of dayside reconnection. This is because dayside reconnection adds open flux to the lobes (and polar cap), leading to the excitation of flows which would cause the closed field lines threading through the arc to convect back to the dayside in the usual Dungey cycle manner.

2. Saturn's Nightside Polar Arc

Figure 2a shows the northern aurora at Saturn obtained by the FUV channel (111–191 nm) of Cassini UVIS instrument, on 11 August 2008 (day of year (DOY) 224) [*Esposito et al.*, 2004]. During the sequence, the subspacecraft planetocentric latitude increased from 57 to 64° and the spacecraft altitude, which is considered to be the distance from the surface of the planet, changed from 9.4 to 8.3 R_S. The projections are constructed by combining the slit scans, which provide 64 spatial pixels of 1 mrad (along the slit) by 1.5 mrad (across the slit), using the method described by *Grodent et al.* [2011].

While nightside polar arcs are frequently observed at Earth, Saturn's aurora, which has been investigated remotely and in situ since 1995 [e.g., *Gérard et al.*, 1995], has not revealed the occurrence of such a polar arc until now. Figure 2a shows an auroral arc attached to the quasi-continuous nightside main emission which separates the region of open flux (polar cap) into two compartments dawnward and duskward of the arc. It resembles morphologically the terrestrial transpolar arc [i.e., *Milan et al.*, 2005a]. The polar arc observed here extends from the latitude of the main emission ($\sim$ 75°) up to 82° latitude, and its longitudinal length is $\sim$ 100°. Its brightness can reach values up to 21 kR. The equatorward edge of the arc is observed to be influenced by the planetary rotation, while the poleward part of the arc moves dawnward with a displacement of 2–3° of latitude at a given longitude during the 3 h interval (see Movie S1 in the supporting information). The arc reported here should not be confused with arcs observed to detach from Saturn's dayside aurora (bifurcations of the main auroral emission), which are related to the dayside reconnection process [*Radioti et al.*, 2011, 2013; *Badman et al.*, 2013].

We do not have the observational means to test how the polar arc at Saturn is formed, and we cannot claim whether it protruded from the nightside or "peeled off" from the duskside, while it remained attached to the nightside. Thus, several possible interpretations could be considered about the origin of the arc. Twisted tail plasma sheet due to dawn-dusk asymmetry proposed at Earth [*Makita et al.*, 1991] does not predict the motion of the arc and also requires a highly contracted polar cap, which is not the case in our observations. Alternatively, nightside polar arcs at Earth are proposed to be formed during substorm recovery by the magnetotail interchange instability creating a tailward motion of a tongue of plasma sheet plasma [*Rezhenov*, 1995]. This possibility is less likely as auroral signatures of interchange events at Saturn following tail reconnection are observed to rotate from midnight to dawn [*Mitchell et al.*, 2009], while the polar arc is observed in the dusk side. Additionally, this mechanism does not predict the motion of the arc. Finally, the formation

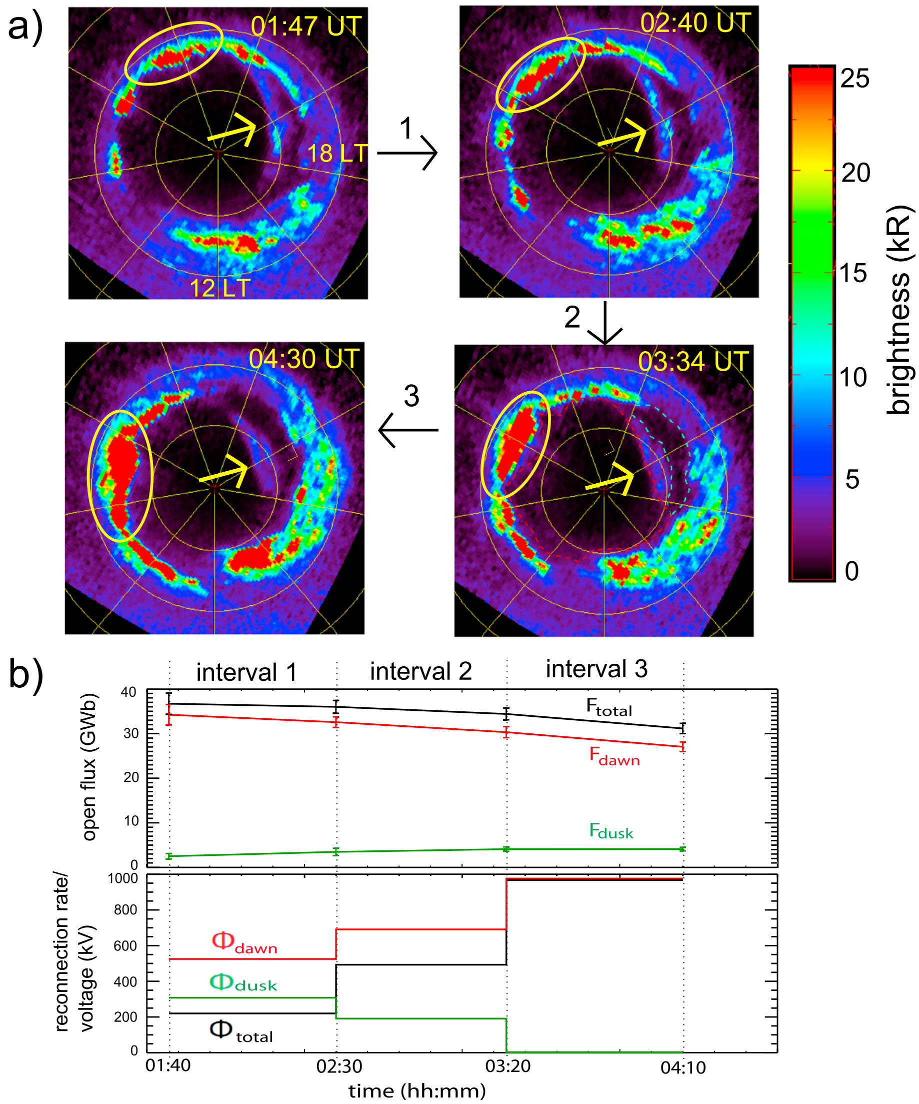

Figure 2. (a) Sequence of polar projections of Saturn's northern aurora obtained with the FUV channel of UVIS on board Cassini. The first image starts at 0147 UT and the last one at 0430 UT on DOY 224, 2008. For all images, noon is to the bottom and dusk to the right, as indicated on Figure 2a. The grid shows latitudes at intervals of 10° and meridians of 40° of local time. Arrows indicate the *nightside* polar arc, an optical emission associated with closed field lines embedded within a region of open magnetic flux. The ellipse marks an intensification on the main oval emission, interpreted as an auroral signature of tail reconnection. The red and green dashed lines on the third polar projection define the surfaces used to estimate the open magnetic flux in the dawn and dusk compartment of the polar cap, respectively. (b) Open magnetic flux and (c) reconnection rates as a function of time for the interval corresponding to the auroral images in Figure 2a. The colors stand for the total (black) flux and reconnection rates, dawn (red) and dusk (green) side of the polar. The error bars in the magnetic flux variations are estimated by varying randomly the auroral detection threshold from 0.85 to 2.55 kR for each local time. This variation range corresponds to Poisson error related to the number of counts associated with the initial threshold of 1.7 kR. Perpendicular dashed lines indicate three separate intervals which correspond to the polar projection and flux variations indicative of (1) high-latitude reconnection, (2) combined nightside and high-latitude reconnection, and (3) nightside reconnection.

of the polar arc could be also attributed to a rotation of the twisted tail plasma sheet leading to a bifurcation of the closed field lines [*Kullen and Jahnunen*, 2004]. This mechanism appears more possible than those proposed by *Makita et al.* [1991] and *Rezhenov* [1995]. However, it might not be appropriate as there are no observations yet which give evidence of a twisted tail plasma sheet at Saturn.

In the following, we make a working assumption that the nightside polar arc at Saturn is formed by magnetotail reconnection closing lobe flux which is then unable to convect back to the dayside, similar to what has been suggested by the transpolar arc model at Earth of *Milan et al.* [2005a]. Under this assumption, the rarity of the polar arc at Saturn implies that the conditions for build up of closed flux at Saturn are not regularly satisfied. This could be mainly attributed to internally driven mass loading processes and strong centrifugal forces at Saturn which complicate the magnetotail dynamics and differentiate them from the solar wind driven terrestrial paradigm. As a consequence, plasma properties in the duskside tail at Saturn suggest that the Dungey cycle is likely inhibited on the duskside [*Thomsen et al.*, 2013]. Additionally, the fast planetary rotation is thought to limit the ionospheric convection [*Cheng and Krimigis*, 1989] thus restricting the role of the Dungey cycle in the magnetotail dynamics. Finally, it is possible that the IMF B_y at Saturn does not have a very significant effect in terms of inducing a large azimuthal component in the tail field [*Jackman et al.*, 2014].

The present observations demonstrate that the conditions for the formation of a nightside polar arc at Saturn which resembles an Earth-like transpolar arc are occasionally satisfied. Assuming that magnetotail reconnection results in the formation of the arc as suggested by *Milan et al.* [2005a], this could be likely at Saturn during an interval of enhanced nightside reconnection which closes flux (Dungey type); suppressed tail reconnection on closed field lines (Vasyliūnas type) and absence of dayside reconnection. In the scenario of suppressed closed field line tail reconnection (Vasyliūnas type), solar wind driven tail reconnection (Dungey type) would be less inhibited [*Thomsen et al.*, 2013]. Vasyliūnas tail reconnection might be suppressed for low-ion mass production rate from internal plasma sources. The ion mass production rates at Saturn vary quite widely, resulting in mass unloading rates, in the Vasyliūnas cycle manner, of 8–18 h [*Rymer et al.*, 2013]. Additionally, dayside reconnection can be absent for a period of southward IMF. This configuration, is illustrated in Figure 1b, where enhanced nightside reconnection results in the building up of flux (brown arrow in the left-hand side sketch) and the formation (protrusion) of a nightside polar arc (brown arrow in the right-hand side sketch).

Following the formation of the transpolar arc at Earth, according to *Milan et al.* [2005a] mechanism, the polar cap is divided by a tongue of closed flux extending from the nightside auroral oval with the two compartments of the polar cap mapping to the bifurcated lobes. The observations indicate that the arc is located at high latitudes and the closed field lines, threading through the arc, map farther downtail. The farther downtail the magnetic field lines map, the less they are influenced by the planetary rotation. Its motion is controlled by the rate of high-latitude reconnection, which transfers open flux from one polar cap compartment to another [*Milan et al.*, 2005a]. The arc is expected to gradually disappear after the redistribution of flux caused by dayside reconnection (northward IMF) which will cause a reassimilation of the closed flux of the arc with the closed flux of the plasma sheet.

3. Auroral Burst of Tail Reconnection

In the same auroral sequence, starting at approximately midnight LT, the dawnside oval of the main emission (marked by the ellipse in Figure 2) locally intensifies and spreads poleward into the polar cap region, indicative of closure of open magnetic flux. The brightness of the region reaches values in excess of 330 kR and its rotational motion is close to 70% of the rigid corotational velocity. The observed picture here is indicative of auroral signature of bursts of tail reconnection resulting in the closure of flux and hence contraction of the polar cap [*Cowley et al.*, 2005; *Nichols et al.*, 2014]. Following the action of the ionospheric torque, the newly closed flux tubes are expected to subcorotate in the outer magnetosphere in accordance with the present observations [*Cowley et al.*, 2005]. This is a consequence of the Dungey-type nightside reconnection, which closes open flux, or a combined scheme of Dungey and Vasyliunas-type reconnection [*Jackman et al.*, 2011]. This event of tail reconnection is probably unrelated to the formation of the transpolar arc, since the auroral arc is already present when the intensification in the main emission appears. However, we note that solar wind driven tail reconnection events are commonly observed simultaneously with transpolar arcs at Earth [e.g., *Milan et al.*, 2005a; *Kullen et al.*, 2002].

4. Open Flux and Reconnection Rates

Based on our working assumption that the nightside polar arc is formed by magnetotail reconnection, we can estimate the magnetic flux variations and the reconnection rates (Figure 2). For the estimation of the amount of open magnetic flux considered to be contained within the polar cap region we use a flux function, which is described in detail in *Radioti et al.* [2011]. The polar cap boundaries are estimated automatically based on the cutoff intensity (∼ 1.7 kR), which corresponds to an average value of the day and night glow emission. An example of the boundaries is drawn on the third projection (03:34 UT) of Figure 2. The error bars in the magnetic flux variations are estimated by varying randomly the auroral detection threshold from 0.85 to 2.55 kR for each local time. This variation range corresponds to Poisson error related to the number of counts associated with the initial threshold of 1.7 kR. The sequence is discussed in three intervals.

During the first interval, the total amount of open magnetic flux remains almost constant. The arc moves dawnward during this interval, and the open flux in the dawnside of the polar arc decreases (from 34.2 to 32.5 GWb), while that in the duskside increases (from 2.5 to 3.5 GWb). Assuming that the process resulting in the motion of the polar arc at Saturn is the same as at Earth [*Milan et al.*, 2005a], this behavior is indicative of reconnection between the magnetosheath and lobe magnetic field lines (high-latitude reconnection). This reconnection type does not change the amount of total flux but stirs the already existing open flux. The process is illustrated in Figure 1c, where the purple arrows on the left-hand sketch correspond to the plasma moved away from the high-latitude reconnection site and the arrow on the right-hand sketch shows the respective movement of the arc in the ionosphere. The rate at which flux is transferred from the dusk to dawn polar cap regions corresponds to the lobe reconnection rate associated with the dawn lobe cell and is estimated to be ∼ 300 kV (1 kV = 10^{-6} GWb s^{-1}).

In the second interval, nightside reconnection on closed field lines is enhanced, as inferred from the enhancement and expansion of the bright region at the dawnside oval (ellipse in Figure 2). As a consequence, the polar cap compartment dawnward of the arc contracts and the decrease in area is balanced by the poleward expansion of the bright region at dawn, indicative of tail reconnection (Dungey type) with a flux closure rate of ∼ 500 kV. Simultaneously, the open flux in the dawnward side of the polar arc decreases, while the flux on the duskward side increases, indicative of high-latitude reconnection rate of ∼ 200 kV. This magnetic flux pattern is consistent with a combination of magnetotail reconnection and lobe reconnection: the tail reconnection process closes lobe flux and hence causes the area of the polar cap to decrease, while lobe reconnection transfers open flux from one side of the arc to the other, but does not change the total amount of open flux. The process is illustrated in Figure 1d, where in addition to the sketch depicted on Figure 1c, green arrows on the left-hand sketch correspond to the plasma moved away from the tail reconnection site and the green arrow on the right-hand sketch shows the contraction of the polar cap in the ionosphere.

During the third interval, high-latitude reconnection seems to have ceased. The nightside polar arc stops moving and the open flux in the dusk compartment of the polar cap remains constant. This process is illustrated in Figure 1e. The changes in the global auroral pattern indicate that tail reconnection in the presence of nightside polar arc is confined to the dawnward part of the polar cap, and the flux closure rate could be as high as 1000 kV. Previous studies [*Jackman et al.*, 2004] have estimated tail reconnection rates at Saturn to range from 50 kV up to 450 kV in strong solar wind compressions, while during short and active intervals this rate might be significantly higher than the average [*Jackman et al.*, 2011]. The total amount of magnetic flux closed along the 3 h sequence is estimated to be ∼ 5.5 GWb, comparable to the flux closed during average tail reconnection events (0.26–2.2 GWb flux closure per a 27 min event [*Jackman et al.*, 2014]). The flux closure rates reported here (500 kV in the second interval and 1000 kV in the third interval) are very significant when compared to the average values.

5. Summary and Conclusions

This study presents the first observation of a nightside auroral polar arc at Saturn, an arc that extends from the nightside auroral oval into the open magnetic field line region. We assume, in accordance with the transpolar arc model by *Milan et al.* [2005a], that the arc is formed by flux closure due to magnetotail reconnection (Dungey type) during an interval of suppressed closed field line tail reconnection (Vasyliūnas type) and in the absence of dayside reconnection. This configuration is shown schematically in Figure 2b. This process should have operated before the beginning of the present observations. Our interpretation does not contradict studies that question the significance of large-scale solar wind driven reconnection at Saturn, since we demonstrate that the occurrence of the transpolar arc at Saturn is rare. Assuming that the polar arc is formed by the mechanism proposed by *Milan et al.* [2005a], we demonstrate that lobe reconnection stirs the already existing open magnetic flux (Figure 1c). Based on the motion of the arc we estimate, for the first time at Saturn, the rate at which magnetic flux is transferred from dusk to dawn polar caps (high-latitude reconnection rate) and we found it to range between ~ 200 kV and 300 kV. The observations suggest that Saturn's magnetotail is undergoing high-latitude reconnection for about at least 2 h. In the same sequence, the auroral pattern indicates that nightside reconnection, likely unrelated to the formation of the arc, shrinks the polar cap size and closes flux, schematically shown in Figures 1d and 1e. We show that tail reconnection in the presence of a nightside polar arc appears to be confined to the dawnward part of the polar cap (dawnward of the arc), and the flux closure rate could be as high as 1000 kV.

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