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LIFETIME OF A POLARIZATION JET DURING LONG-TERM MAGNETIC STORMS

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Abstract. The paper examines conditions of occurrence and typical time scales of a polarization jet by measuring ionospheric parameters from DMSP satellites (h~830 km) and using data from the ground-based ionospheric station Yakutsk (YA462) during strong and long-term geomagnetic storms. The polarization jet at the ionospheric station Yakutsk was recorded in the dusk sector at the background of substorm disturbances when the geomagnetic index *SME* reached values from 1000 to ~3000 nT, and, according to data from the magnetic observatory Yakutsk (YAK), there was a positive bay ~50–100 nT in the geomagnetic field H component and ~100–200 nT in its Z component. We show that the lifetime of the polarization jet or narrow troughs in ionospheric plasma in the subauroral ionosphere during strong and long-term magnetic storms can be as long as 12 hrs.

Keywords: ionosphere, magnetosphere, polarization jet, *SME* index, plasma drift, narrow trough, magnetic storm and substorm.

INTRODUCTION

The polarization jet (PJ) is a narrow band of ionospheric plasma moving rapidly (with a speed up to several kilometers per second) westward in the vicinity of the ionospheric projection of the plasmapause. PJ is most noticeable during magnetic storms [Stepanov et al., 2017 and references therein]. It causes structural modifications of the high-latitude ionosphere and thereby affects radio wave propagation conditions.

Westward fast ion drifts near the projection of the plasmapause at the F-region heights were first detected by Yu.I. Galperin et al. [1973] from Kosmos-184 satellite data; they were termed as "polarization jet". Since then, polarization jets (PJs), or fast westward drifts of ionospheric plasma in subauroral latitudes, have been actively studied by ground-based and satellite methods (see, e.g., [Galperin et al., 1990; He et al., 2014; Stepanov et al., 2017] and references therein). It has been found that the recording of characteristic traces of F3s reflections in ionograms of vertical and backscatter ionospheric sounding indicates the existence of a polarization jet or westward narrow jets of ionospheric plasma in the ionosphere near the zenith of the observation station.

Narrow plasma streams with velocities above 200–400 m/s have been demonstrated to lead to the formation of narrow ion density troughs in the dusk sector due to the transport of ionospheric plasma to the dusk-afternoon sector. Many ground-based and satellite measurements of PJs have shown that the trough has a latitudinal size 100–200 km, or 1°–2°, is observed mainly in the dusk-pre-midnight sector of local time (18:00–24:00 MLT) at invariant latitudes 55–65°; the typical plasma drift velocity in PJ is ~1–1.5 km/s [Stepanov et al., 2017], and the maximum one can be as high as 4–5 km/s.

In the work of 1979, Spiro R.W., Heelis R.A., and Hanson W.B. from the Center for Space Sciences at the University of Texas called the narrow fast plasma streams at subauroral latitudes, observed by the satellite Atmosphere Explorer C, "SubAuroral Ion Drift" (SAID) [Spiro et al., 1979].

A polarization jet is always observed to the equator of the boundary of auroral electron precipitation and shifts to lower latitudes as geomagnetic activity increases [Anderson et al., 1991]. Recently, a relationship has been established between PJ and Strong Thermal Emission Velocity Enhancement (STEVE), i.e. with "strong increases in the rate of thermal emission" [MacDonald et al., 2018]. Using an all-sky camera on July 25, 2016, MacDonald et al. [2018] detected a STEVE event as a narrow subauroral visible structure south of the auroral oval. According to simultaneous data from the SWARM satellite, STEVE was located along the same field lines as the narrow band of strong westward ion flux, situated higher in the ionosphere.

The terms "polarization jet" and "SAID" are still the most common for designating westward narrow fast ionospheric plasma streams at subauroral latitudes. Along with these terms, the term SubAuroral Polarization Stream (SAPS) is often used. It was introduced by Foster and Burke [2002] to emphasize that under conditions of moderate and weak magnetic disturbances PJ/SAID exists in the form of a wider and less intense plasma stream at subauroral latitudes.

Note that the time scales of polarization jets during intense and long-term magnetic storms have not been studied yet.

The purpose of this work is to examine the time duration of narrow ionization troughs and increased plasma drift velocities during the development of a polarization jet from measurements made by DMSP satellites and at the ground-based ionospheric station Yakutsk (YA462).

METHODS OF OBSERVATION AND DATA ANALYSIS

The work is based on data from satellites of Defense Meteorological Satellite Program (DMSP), which provides on-line solar and geophysical information [https://dmsp.bc.edu]. The satellites are located at an altitude of ~ 830 km in an almost circular polar orbit with an inclination of 98.8° and have an orbital period of 102 min. To analyze geomagnetic conditions, the K_p index is used which is a quantitative measure of auroral intensification [https://wdc.kugi .kyoto-u.ac.jp/kp/index.html].

Ground-based data was obtained by stations of the Yakutsk—Zhigansk—Tixie chain equipped with automatic ionosondes of the AIS type [Vasiliev et al., 1961] and with RH antenna systems for backscatter sounding [Aizenberg, 1962], which significantly increases the amount of information received by expanding the range of probed latitudes. In 2002–2003, the stations Yakutsk and Zhigansk were equipped with digital ionosondes DPS-4 [Reinisch, 1987; Reinisch et al., 1992].

To identify PJs from ground-based data, additional F3s reflections have been used at lower frequencies and at a longer distance than regular background traces in vertical sounding ionograms. The F3s reflections correspond to narrow fast plasma streams near the zenith of the observation station (see [Khalipov et al., 2001; Stepanov et al., 2017] and references therein). After the appearance of such reflections in ionograms, critical frequencies of the background F2 layer decrease by 2–4 MHz or more for 15–30 min, i.e. a frequency “fall” occurs which is clearly drawn in daily *f*-plots [Stepanov et al., 2016, 2019].

The October 20, 1989 event

Increases in the intensity of energetic ions due to the passage of a shock wave, accompanied by strong magnetic storms and magnetospheric substorms, are historically called energetic storm particle events. Such an event occurred on October 20, 1989 [Lario, Decker, 2002]. The K_p indices on that day were 2+, 3, 4+,7–, 8, 8+, 7, Σ K_p=47.

A polarization jet in the Northern Hemisphere was detected on October 20, 1989 by two DMSP satellites — F8 and F9. In Figure 1, panels with numbers in the top right corner correspond to the successive passages of the F8 satellite; and the bottom right panel, to the passage of the F9 satellite.

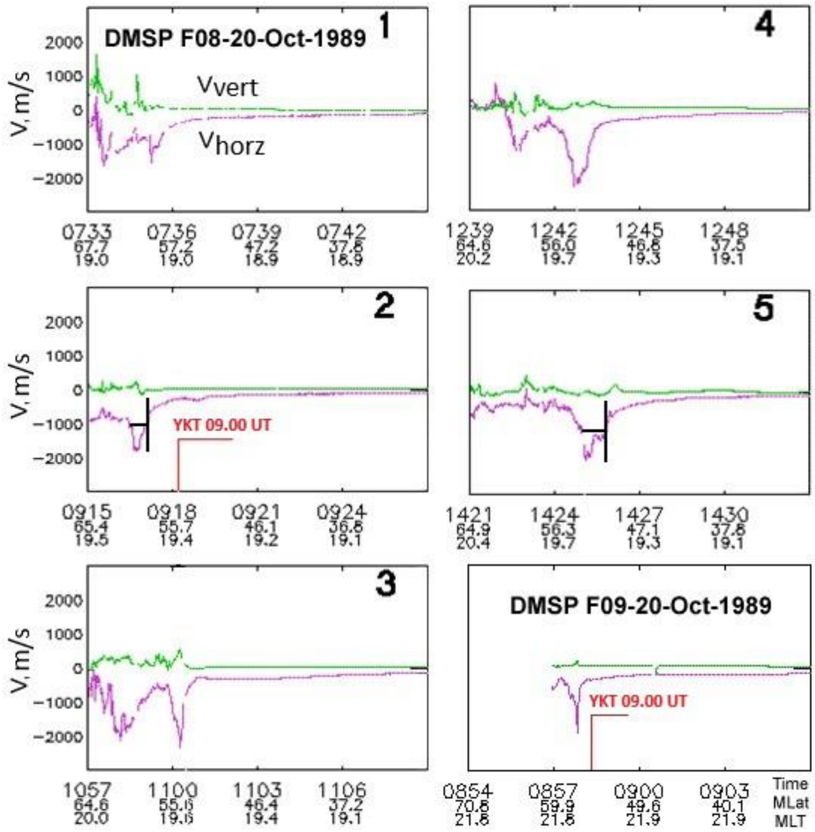

Figure 1. Parameters of PJ plasma in the subauroral ionosphere. Numbers in the top right corner indicate the numbers of DMSP F8 satellite passages; arrows show the magnetic latitude of the station Yakutsk; perpendicular black lines, the half-width and horizontal velocity of the jet. Along the Y-axis are horizontal V_{horz} (pink curve) and vertical V_{vert} (green curve) ion drift velocities; along the X-axis are the universal time (UT), magnetic latitude (MLat), and magnetic local time (MLT)

On the Y-axis, negative values indicate westward movement of ionospheric plasma. Black perpendicular lines in Figure 1 denote PJ half-width and horizontal velocity respectively; the arrow marks the magnetic latitude of the station Yakutsk.

The first signature of the PJ, according to F8 satellite data, was recorded at ~56° MLat at 07:35 UT when the horizontal plasma drift velocity was as high as ~1500 m/s (see Figure 1, Panel 1). During the next passage of the same satellite, a formed narrow plasma stream with a half-width ~2° is already visible (half-width is the width of PJ at half the horizontal velocity, which is schematically shown in the second passage of the satellite). The position of the ground station Yakutsk (MLat=55.6°), where the PJ signature was recorded at 09:15 UT (18:15 LT), is also indicated here. At 14:26 UT, the half-width of PJ (the region of high horizontal ion velocities or narrow ionization troughs) increased to 4° magnetic latitude, i.e. the narrow trough begins to transform into a wide one, or into the main ionospheric trough [Khalipov et al., 1977; Mamrukov, Filippov, 1988].

The F9 satellite (Figure 1, bottom right) detected the PJ in only one passage that day — at 08:58 UT, almost simultaneously with the ground station Yakutsk, where the PJ was observed at 09:15 UT, despite the fact that the difference in longitude with this station was almost 4 hrs or ~60°.

The F8 satellite recorded narrow ionization troughs during five passages, from 07:35 to 14:26 UT, i.e. ~7 hrs.

We employ the auroral activity index *SME* that allows us to estimate the auroral electrojet intensity more accurately than the *AE* index [Newell, Gjerloev, 2011; Boroyev, Vasiliev, 2021]. The formulas for calculating the *AE* and SME indices are the same, but *AE* is calculated using the *H* component at twelve high-latitude magnetovariation stations located in a narrow band of geomagnetic latitudes 65°–70°, whereas more than 100 SuperMag stations at geomagnetic latitudes from 40° to 80° are employed to calculate the SME index [Gjerloev, 2009, 2012; Newell, Gjerloev, 2014; http://supermag.jhuapl.edu/info].

Figure 2 illustrates *SME* variations on October 20, 1989; the interval of continuous observations of the PJ according to satellite measurements (DMSP F8 and F9) is marked with a horizontal line. The vertical arrow indicates the time of PJ recording at the station Yakutsk.

Recording of the PJ on October 20, 1989 at 09:15 UT in Yakutsk almost coincided with the sudden commencement of a very strong magnetic storm (Storm Sudden Commencement, SSC) at 09:16 UT. Note that earlier in our works [Khalipov et al., 2001; Stepanov et al., 2008] we compared the appearance of a PJ with a sharp increase in the *AE* index, i.e. not with SSC, but with the substorm onset.

The *Dst* index at 09:00 UT was –45 nT, and Dst_{min}=–202 nT was observed at 16:00 UT, i.e. after detecting the PJ in Yakutsk.

The *SME* variations exhibit two short-term increases in magnetic activity with intensity higher than 750 nT at 05:50–08:00 UT. Recording of the PJ in Yakutsk at 09:15 UT coincided with the beginning of a sharp increase in magnetic activity: *SME* increased from ~500 nT at 09:15 UT to 2000 nT at 11:00 UT. Figure 2 also indicates that recording of the PJ by satellites began even before its observation at the ground-based station.

The August 26, 1998 event

At ~06:51 UT on August 26, 1998, solar flare plasma interacted with Earth's magnetosphere, causing SSC of a strong geomagnetic storm, which lasted until August 29 [Magnetic Storms, 2005]. The K_p indices for August 26, 1998 were 2, 2+, 5–, 6–, 5–, 6–, 6–, 6+, ΣK_p=37.

Figure 3 presents spectrograms of ion and electron precipitation, variations in ion density N_i, horizontal V_{horz} and vertical V_{vert} ion drift velocities during a satellite passage near the meridian of the station Yakutsk on August 26, 1998. The vertical line in Figure 3 indicates the time of PJ recording (12:35 UT), which corresponds to a narrow deep trough in the ion density and a sharp increase in the westward horizontal ionospheric plasma drift velocity to ~3 km/s. The half-width of the subtrough is 1.63°. These phenomena are seen to occur at the equatorial edge of ion and electron precipitation (see, e.g., [Stepanov et al., 2017]).

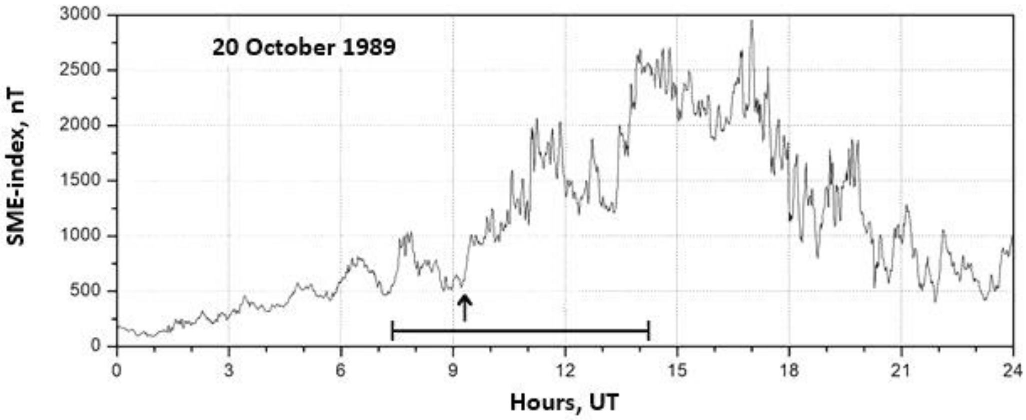

Figure 2. Variations in the *SME* index on October 20, 1989: the horizontal segment is the interval of PJ detection from satellite measurements; the vertical arrow is the time of PJ recording at the station Yakutsk

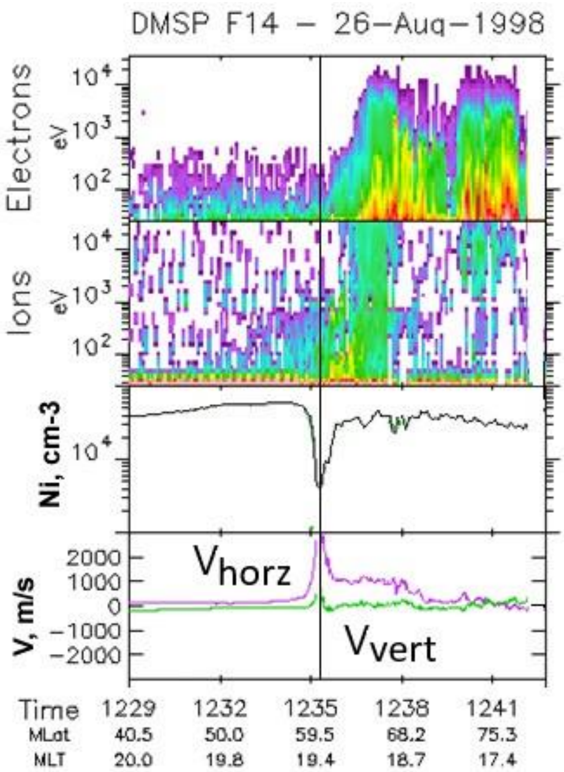

Figure 3. Parameters of the August 26, 1998 PJ, measured by the DMSP F14 satellite during the passage near the meridian of the station Yakutsk: horizontal V_{horz} (pink curve) and vertical V_{vert} (green curve) ion drift velocities, ion density N_{i} (black curve), and spectrograms of ion and electron precipitation. The vertical line marks the time of PJ detection

Figure 4 exemplifies the plasma parameters recorded by the DMSP F14 satellite on August 26, 1998. The middle left panel (passage 2, numbers of the passages are given at the bottom) shows the position of the station Yakutsk, where PJ signatures were detected in ionograms at 13:00 UT (22:00 LT). During passage 3 there were two peaks of horizontal velocities similar to those studied in [Sinevich et al., 2021]. The maximum half-width of the PJ was observed during passage 5 and was ~4° MLat, while the horizontal ion drift velocity decreased to 1500–1600 m/s.

In Figure 4, positive velocity values correspond to the westward ionospheric plasma drift. On DMSP satellites, according to drift meters, the velocity is determined in the coordinate system linked to the ion Retarding Potential Analyzer (RPA) [https://dmsp.bc.edu/html2/ssiesgeneral.html]. Since the F14 satellite flew in the opposite direction than F8 and F9, the velocities, according to F14, change sign to the opposite relative to the velocities shown in Figure 1 [https://dmsp.bc.edu/html2/ssiesdriftcartoon.gif]. Thus, the F8, F9, and F14 satellites detect a westward narrow band of ionospheric plasma, which should be observed in a polarization jet.

The impact of the solar wind shock wave front on Earth's magnetosphere is manifested in *SME* variations (Figure 5) as a short-term burst with intensity higher than 2000 nT from 06:51 to 08:00 UT [Magnetic Storms, 2005]. The PJ in Yakutsk on August 26, 1998 was detected at 13:15 UT (vertical arrow in Figure 5),

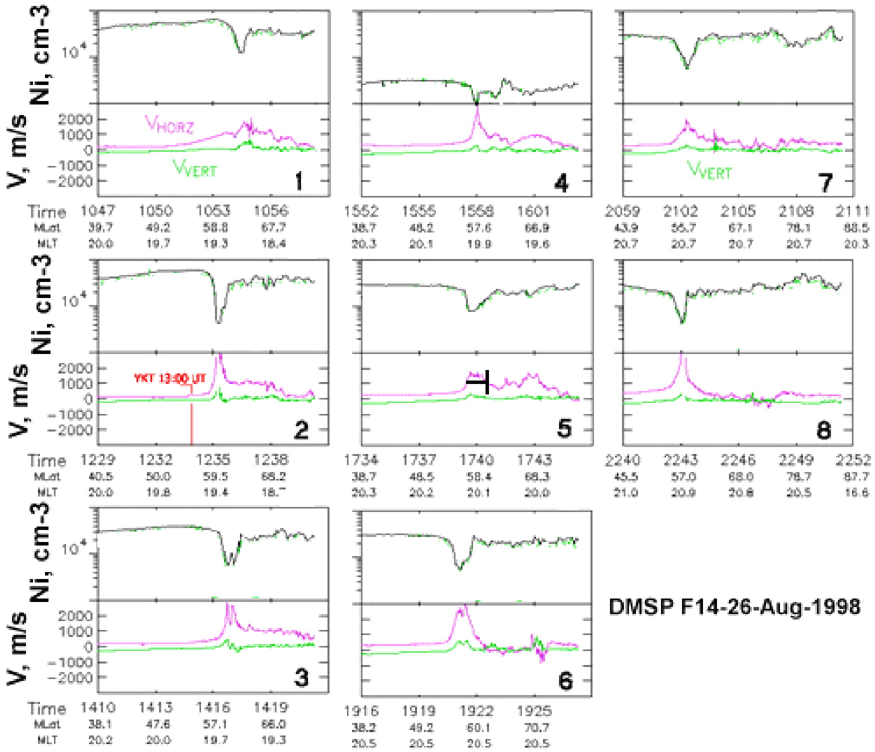

Figure 4. Horizontal V_{horz} (pink curve) and vertical V_{vert} (green curve) ion drift velocities, ion density N_{i} (black curve) on August 26, 1998, recorded by the DMSP F14 satellite, which observed the PJ for 12 hrs. During passage 3 there were two horizontal velocity peaks above 2000 m/s

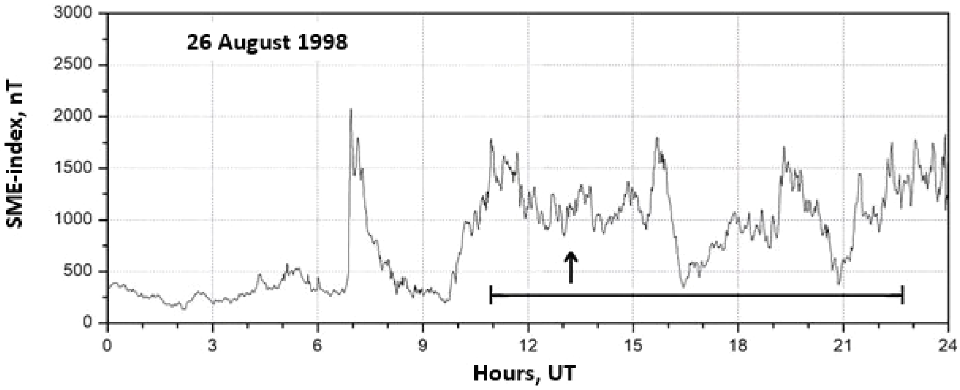

Figure 5. Variations in the *SME* index on August 26, 1998: the horizontal segment is the interval of PJ observation from F14 satellite measurements; the vertical arrow is the time of PJ recording at the station Yakutsk

which coincides with the period of increasing magnetic activity from 09:40 to 16:15 UT when *SME* exceeded 1000 nT.

The DMSP F14 satellite observed narrow troughs in N_i and high horizontal ion drift velocities (polarization jets) on August 26, 1998 for 12 hrs, from ~10:40 to ~22:40 UT inclusive (horizontal segment in Figure 5).

At that time, according to the Yakutsk Magnetic Observatory (YAK), there were positive bays ~50–100 nT in the geomagnetic field *H* component and ~100–200 nT in its *Z* component.

Previously, in our works [Khalipov et al., 2001, 2016], we have compared the PJ detection at the station Yakutsk with a sharp increase (>500 nT) in the geomagnetic index *AE*. It has been shown that the delay in the appearance of PJ relative to the *AE* index sharp increase was minimum when the observation station was located near the local magnetic midnight during substorm events. At the same time, in many cases these events occurred during the substorm explosive phase.

In this paper, we deal with the events when PJ signatures were simultaneously observed at the station Yakutsk and by the DMSP satellites, and the *SME* index is utilized as a characteristic of auroral activity. Between 2010 and 2015, 13 such events were detected in the dusk sector of MLT. Figure 6 illustrates variations in the *SME* index for these events, generalized by the epoch superposition method. The moment of PJ detection (F3s reflection) at the station Yakutsk was taken as 0 hour [Stepanov et al., 2017]. The simultaneous observation varies within 30 min before and after the PJ signature detection at the station Yakutsk. The time of the PJ detection at the ionospheric station is seen to be preceded by a peak of geomagnetic activity with a maximum of *SME*=1000–1050 nT approximately 1.5 hrs before the occurrence of the event on the meridian of Yakutsk.

Thus, analysis of *SME* variations has shown that the maximum index value of ~1000 nT was recorded 1.5 hrs before the start of PJ detection at the station Yakutsk in the dusk sector of MLT (see Figure 6).

We can, therefore, state that the PJ was detected at the station Yakutsk during increased substorm activity, mainly in the main phase of a strong magnetic storm.

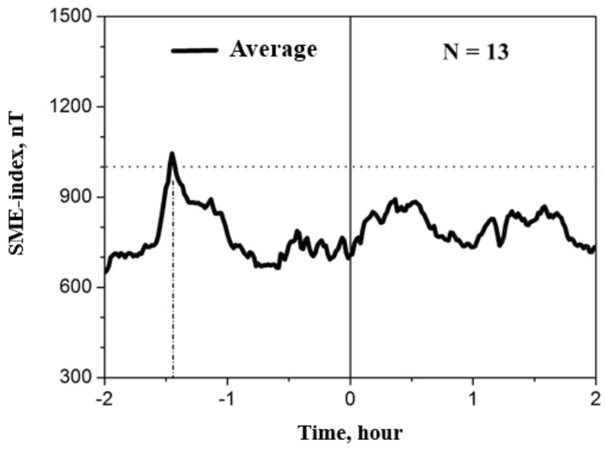

Figure 6. Variations in the *SME* index for 13 events obtained by the epoch superposition method: 0 — time of PJ detection in Yakutsk

DISCUSSION

Fairly large number of works has been devoted to the study of PJ and SAID. Time duration of PJ is mentioned in the monograph [Stepanov et al., 2017]. A narrow ionization trough was recorded over the station Tixie on October 07, 1981 at 09:15 UT (see Figure 1.13 from [Stepanov et al., 2017]). From 09:15 to 11:15 UT on October 07, 1981, the narrow ionization trough shifted from the latitude of the station Tixie (InvLat=65°) to the latitude of the station Zhigansk (InvLat=60°). The authors attributed this shift to an increase in the intensity of geomagnetic disturbances. At 12:30 UT, the narrow trough further shifted toward the equator and was located between Zhigansk and Yakutsk. Thus, on October 07, 1981 an almost continuous observation of the PJ at the ionospheric stations of the Yakutsk chain lasted for more than three hours. Note that all the ionospheric stations were operating in a patrol mode, i.e. sounding was carried out every 15 min.

From numerous series of ground-based measurements of this type it follows that the characteristic lifetime of a narrow ionization trough and high horizontal ion drift velocities is several hours (~2–4 hrs), during which the trough can noticeably shift in latitude, and almost always equatorward.

As statistical analysis of data from the Dynamics Explorer 2 (DE-2) satellite for 1.5 years shows [Anderson et al., 1991], the lifetime of SAID varies from 30 min to 3 hrs. Furthermore, SAIDs were observed after a significant increase in the *AE* index, i.e. they are associated with the development of substorm activity [Khalipov et al., 2001, 2016; Stepanov et al., 2008].

Sinevich et al. [2021] have studied the PJ small-scale structure in a subauroral region during a moderate (Dst_{min}=–69 nT) magnetic storm on April 20, 2018. The authors reported the results of measurements of plasma parameters inside the PJ from 10:00 to 21:00 UT, using Langmuir probes installed on board the NorSat-1 microsatellite. From the *SME* values that were as large as 1400 nT at a maximum we can assume that the lifetime of PJ is 11 hrs, but passages of the NorSat-1 microsatellite occurred during the recovery phase of a moderate magnetic storm.

The two cases of PJ development discussed above took place at increased *SME* values in the main phases of very strong (October 20–23, 1989) and strong (August 26–28, 1998) magnetic storms. The extreme ring current intensity values and hence the numerous repeated bursts of substorm activity caused a long-term (7 and 12 hrs) recording of PJ from satellite data.

CONCLUSION

Joint analysis of simultaneous satellite and ground-based observations of a polarization jet/SAID during strong geomagnetic storms has shown that narrow ionization troughs and high horizontal ion drift velocities in the subauroral ionosphere can be observed for 12 hrs. The formation of a polarization jet in the magnetic storm main phase and its long-term observation are due to the extreme ring current intensity during strong magnetic field disturbances.

Long-term data from both the ground-based chain of ionospheric and magnetometric stations and DMSP satellites have revealed that the detection of the polarization jet at the station Yakutsk in the dusk sector starts ~1.5 hrs later than the abrupt variations in the *SME* index.

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