Upward high-energy field-aligned electron beams above the polar edge of auroral oval: observations from the SKA-3 instruments onboard the Auroral Probe (Interball-2)

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Abstract. A new phenomenon was found at the polar edge of the auroral oval in the postmidnight–morning sectors: field-aligned (FA) high-energy upward electron beams in the energy range 20–40 keV at altitudes about $3\,R_E$, accompanied by bidirectional electron FA beams of keV energy. The beam intensity often reaches more than $0.5 \cdot 10^3$ electrons/s $\cdot$ sr $\cdot$ keV $\cdot$ cm^2, and the beams are observed for a relatively long time ($\sim 3 \cdot 10^2$–10^3 s), when the satellite at the apogee moves slowly in the ILAT-MLT frame. A qualitative scenario of the acceleration mechanism is proposed, according to which the satellite is within a region of bidirectional acceleration where a stochastic FA acceleration is accomplished by waves with fluctuating FA electric field components in both directions.

Key words. Ionosphere (particle acceleration; wave-particle interactions) · Magnetospheric physics (magnetosphere-ionosphere interactions)

1 Introduction

The Interball Auroral Probe carries the SKA-3 experiment whose goal was to investigate high energy particle intensities at high latitudes (i.e. above the auroral oval and inside the northern polar cap). In several cases at the polar edge of the oval in the postmidnight – morning sectors in the energy range 20–40 keV the SKA-3 instruments detected field-aligned high-energy upward electron beams (see Galperin, 1997; Stepanov et al., 1997). These beams were observed as field-aligned (FA) monodirectional (upward), while simultaneous measurements made by the ION spectrometer (data courtesy of

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J.-A. Sauvaud and R.A. Kovrazhkin, see Sauvaud *et al.*, this issue) showed that the keV energy electron fluxes were bidirectional. In some cases, upward accelerated ions (O$^+$) of 100–1000 eV energy (at least partly folded ion conics) were detected simultaneously with the SKA-3 upward electron beam detection. For one case, upward beam of low-energy (about 10 eV) H$^+$ was detected by the onboard thermal mass-spectrometer HYPERBOLOID (data courtesy of N. Dubouloz). However, interesting features of the low-energy ions observed simultaneously with the upward high-energy electron beams are beyond the scope of this study.

Several authors have reported observations of the upward electron beams in auroral regions (e.g., see Burch *et al.*, 1983; and references therein). Hultqvist *et al.*, 1988 were the first to observe relatively energetic (up to 8 keV) bidirectional field-aligned electron beams at altitudes $\sim 2\,R_E$, i.e., above the main region of downward auroral electron acceleration. They have presented measurements from VIKING of upward moving electrons and ions of comparable energy at altitudes about 13 500 km in the invariant latitude (ILAT) – magnetic local time (MLT) sector of 76° and ~ 9 h, respectively, where the field lines were most probably closed, thus implying the possibility of electron bouncing. Observations were made during quite magnetic conditions after a period with several substorms. The upward electron beams detected by VIKING had a conical distribution at energies of several keV, while at the lowest energies they were clearly beamed, and those electron conics were much narrower than ion conics. The lower energy electrons had much higher fluxes than those at high energies. It was suggested that the distributions of low-energy and high-energy electron beams were produced by different processes. Authors have proposed an interpretation in which the upward field-aligned acceleration of both electrons and ions was due to the fluctuating electric field with its mean parallel component different from zero.

The SKA-3 observations of energetic upward electron beams, presented in this work, in some aspects are

similar to those reported by Hultqvist *et al.* 1988, but at the same time are quite distinct from them. We present a case study of upward electron beams in the energy range 20–40 keV only, i.e., at energies which are substantially higher than typical auroral electron energies. Four orbits in the postmidnight sector were chosen for a detailed analysis during which the invariant latitude of the Auroral Probe exceeded 75°.

It is emphasized in this work that the upward acceleration of electrons to tens of keV observed by the Auroral Probe at altitudes of about 3 R_E at, or close to the polar boundary of the auroral oval, cannot be significantly influenced by a parallel quasi-DC electric field component and conjugate effects. These observations imply acceleration processes distributed in a wide altitude interval, both below and above the satellite apogee ($\sim$4 R_E geocentric), caused by wave turbulence which leads to a stochastic particle acceleration. This means that during the upward electron beam registrations, the satellite at its apogee was within such extended regions of intense plasma turbulence and auroral FA acceleration.

2 The SKA-3 instrumentation set

The SKA-3 set of particle detectors installed onboard the Auroral Probe is aimed to measure low and medium energy electrons and ions. It consists of two energy-angle analyzers EA-2 and EA-3 for low energy particles, and two identical oppositely directed time-of-flight (TOF) analyzers EM-1-1 and EM-1-2 for high energies. A short description of the instruments is given (for more information see Shuiskaya *et al.*, 1995, 1998).

All instruments are mounted on the back of the satellite, opposite to Sunward direction, with fields of view perpendicular to the satellite rotation axis (which is Sunward directed). The satellite spinning thus scans the range of the pitch angles depending on the angle between the Sunward direction and magnetic field. The spin period of the satellite is 120 s. Temporal resolution of observation modes varies from 0.1 to 0.8 s, spatial resolution at apogee is about 0.5 ÷ 10 km.

2.1 Analyzers of low-energy charged particles (EA-2 and EA-3)

EA-2 and EA-3 are energy-angle spectrometers based on electrostatic toroidal analyzers. Analyzers differ in polarity of voltages applied to systems of electrostatic deflection and microchannel plates (MCP) circuitry. EA-2 measures energy-angle distributions of electrons, EA-3 measure ion distributions, During a satellite rotation each window (of 22.5° width with a gap of 22.5° in between, and 5.7° height) scans all the phase angle range. The instruments allow us to measure simultaneously in eight angular sectors evenly distributed at the angle 2π perpendicular to the satellite rotation axis, and sequentially in seven energy intervals for each angular sector. The central energies of energy

intervals are as follows: 30, 85, 240, 680, 1900, 5300, 15000 eV, the energy resolution $\Delta E/E$ is 10%. Particles are recorded by means of the MCPs with spaced anodes for eight angular directions. In order to improve the angular resolution of the detector, a mask is applied to the MCPs corresponding to location of anodes, and a special sectioned collimator is attached to the entrance aperture. The calculated geometric factor is $6 \cdot 10^{-3}$ cm$^2 \cdot$ sr.

2.2 Analyzers of medium-energy charged particles (EM-1-1 and EM-1-2)

The instruments EM-1-1 and EM-1-2 are identical time-of-flight solid-state energy-mass spectrometers. Electrons are deflected from the ion aperture by a magnet. Ions are selected with masses, 1, 4 and 16 in seven energy intervals within energy range from 20 to 500 keV. Spectrometers are based on a combination of TOF device with a thick silicon semiconductor detector of the full energy at the end. Fields-of-view of these detectors are directed oppositely and are perpendicular to the satellite rotation axis. Each field-of-view is a cone of full angle 8°. Table 1 presents the ranges of energy intervals for each type of particles. For the 20–40 keV electrons the geometric factor is $5.7 \cdot 10^{-2}$ cm$^2 \cdot$ sr, and $3 \cdot 10^{-3}$ cm $\cdot$ sr for higher energy electrons.

3 Experimental results

Some results of observations made by the time-of-flight instruments EM-1-1 and EM-1-2 (hereafter TOF analyzers) are presented here. Only some cases of the observed phenomenon are presented, when the upward high-energy electron beams were easily identifiable and of long duration. There are other cases, not included here, when the beam identification was shorter, or less reliable. The EA analyzers data as well as data from other onboard instruments are now being used for a more detailed analysis of those cases, and will be reported elsewhere.

During a satellite spin period the field-of-view of each TOF analyzer scans a complete circle in a plane perpendicular to the satellite rotation axis (which is directed towards the Sun). Depending on the angle

Table 1. Ranges of energy intervals for EM-1-1 and EM-1-2

Interval	Energy ranges, keV			
	e	M = 1 (p^+)	M = 4 (α)	M = 16 (O^+)
1	20–40	30–50	35–55	55–90
2	40–70	50–85	55–90	90–130
3	70–110	85–115	90–130	130–185
4	110–150	115–170	130–185	185–245
5	150–220	170–225	185–240	245–315
6	220–290	225–300	240–315	315–395
7	290–390	300–395	315–415	395–510

between the satellite rotation axis and the magnetic field line, each analyzer scans a limited pitch-angle range $90° \pm \varphi$, $\varphi \leq 90°$, where $\varphi = 90°$ is a rather rare case. If a particle beam is more or less field-aligned, monodirectional and crosses the rotating field-of-view, it will be seen by the instrument once in a period. Then, as fields-of-view of the two analyzers point in opposite directions, that beam will be seen by both instruments once in a period but with a half-period shift.

Below we have used for comparisons some preliminary data from the ION onboard particle spectrometer (courtesy of J.-A. Sauvaud and R. Kovrazhkin, see Sauvaud *et al.,* this issue), and data from the onboard thermal mass-spectrometer HYPERBOLOID (courtesy of N. Dubouloz).

3.1 Overall data description

Case 1: pass 218 (see Fig. 1). The first of the events presented here was detected during the northern polar cap crossing on the 20 October, 1996. At 12:00 UT the satellite location was near the apogee (altitude about 19 200 km). The invariant latitude ILAT = 78.0°, magnetic local time MLT = 6 h at 12:00 UT, then the position changed to ILAT = 74.8°, MLT = 7 h at 12:30 UT. The *Kp* value during the beam observation was 2, *Dst* index was about -30 nT. This pass took place during a quieting after a long disturbed period. The data collected by both TOF analyzers revealed the presence of a beam of 20–40 keV electrons at large pitch angles (up to 175°, so the beam moved upward from the Earth). The beam was rather narrow, the angular width of its most intensive portion was about $\pm 20°$. Maximum beam intensity reached more than $0.5 \cdot 10^3$

electrons/s $\cdot$ sr $\cdot$ keV $\cdot$ cm^2 at 175° pitch angle, while at 90° it was not greater than 4 electrons/s $\cdot$ sr $\cdot$ keV $\cdot$ cm^2

The closest ground stations from which magnetic field data were available at that time were Fort Simpson (Latitude = 61.8°, Longitude = 238.8°, MLT ~3 h at 12:00 UT) and Leirvogur (Latitude = 64.2°, Longitude = 338.3°, MLT ~10 h at 12:00 UT). The magnetogram from Fort Simpson indicated a series of a moderate substorm-like bursts from 03:00 to 10:30 UT, and the moment of our observations corresponds to a quieting period or a recovery phase of a small substorm. The magnetogram from Leirvogur also indicated a disturbed period from 00:00 to 08:00 UT, and then quieting. The solar wind and IMF data from the WIND spacecraft showed southward turning of the IMF *Bz* at the time corresponding to our observations (delayed by 22 min according to the solar wind velocity). Previous three hours of data indicated frequent southward turnings of the IMF *Bz* (WIND position at 11:40 UT was $X_{GSE} = 112.4$ R$_E$, $Y_{GSE} = -69.8$ R$_E$, $Z_{GSE} = -1.6$ R$_E$, solar wind velocity $Vx = -535$ km/s).

The beam detection lasted for 15 min (i.e. for eight satellite rotation periods), with distinct field-aligned peaks and threshold fluxes around 90° pitch angle. Then at 12:17 UT both TOF instruments detected a 3-min interval with a burst of rather isotropic flux with intensity of $10^2 \div 10^3$ electrons/s $\cdot$ sr $\cdot$ keV $\cdot$ cm^2 at 20–40 keV. The isotropic burst gradually decayed and the flux returned to the field-aligned beam which was more intense than before the burst, and had some fine structure around 90° pitch angle. Its registration lasted until 12:30 UT.

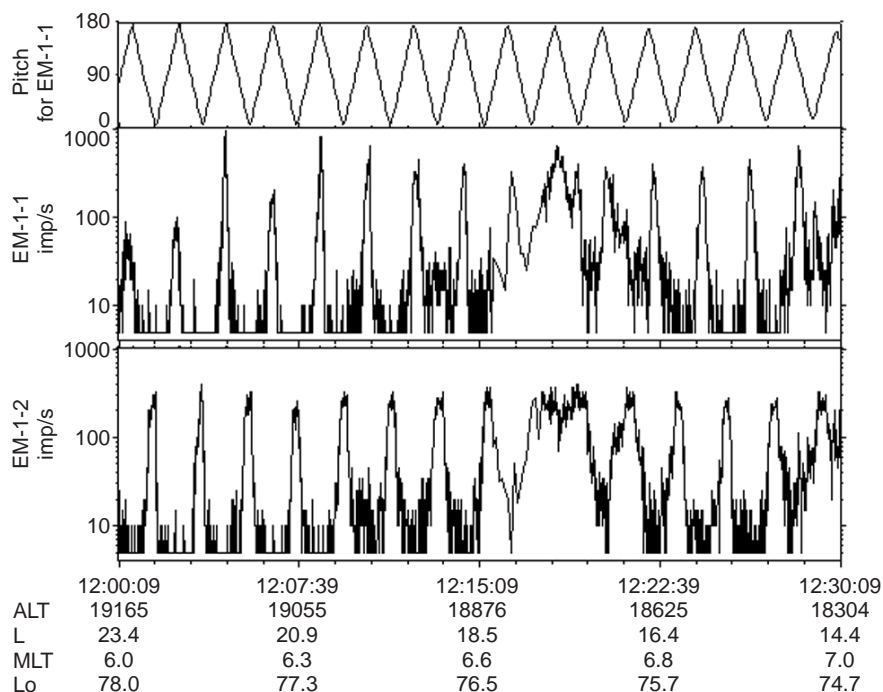Simultaneous measurements made by the ION instrument onboard the Auroral Probe (see Sauvaud *et al.,*

Fig 1. *Case 1,* October 20, 1996). Intensities of upward beam of electrons of 20–40 keV by time-of flight spectrometers EM-1-1 and EM-1-2 in counts per second. In the *top panel* the pitch angle for EM-1-1 is shown (the pitch angle for EM-1-2 is shifted by half period in respect to that of EM-1-1, see Sect. 2 for details). The *middle* and *lower panels* show the 20–45 keV electrons data from EM-1-1 and EM-1-2, respectively. At the *bottom* there are also shown (from *top* to *bottom*): universal time; *ALT* satellite altitude; *L*-shell; *MLT*, magnetic local time, and L_0, invariant latitude.

Time	12:00:09	12:07:39	12:15:09	12:22:39	12:30:09
ALT	19165	19055	18876	18625	18304
L	23.4	20.9	18.5	16.4	14.4
MLT	6.0	6.3	6.6	6.8	7.0
Lo	78.0	77.3	76.5	75.7	74.7

this issue) indicated presence of a combination of an isotropic plasmasheet-type background intensity with intermittent FA counterstreaming electron beams in the energy range of $100 \div 1000$ eV, at the time of the upward electron beam observations from the SKA-3. Also a beam of upward accelerated ions (H^+ and O^+) of $100 \div 1000$ eV energy was seen from 11:30 till 12:34 UT. At 12:17 UT, simultaneously with the isotropization burst observed by SKA-3, the ION spectrometer detected a 3-minute interval of isotropic flux of electrons in the energy range of $100 \div 1000$ eV. The velocity dispersed burst of H^+ ions was detected at 12:17 UT in the energy range of 800 eV–10 keV, along with the upward beam of H^+ in the range of $100 \div 1000$ eV. The superthermal ion data available (thermal mass-spectrometer HYPERBOLOID) did not show any significant features which could be correlated with the simultaneously observed upward high-energy electron beam.

Case 2: pass 247 (see Fig. 2). At 11:00 UT on 27 October, 1996 the satellite position was ILAT = 79.1° and MLT = 2 h, altitude about 17 800 km. The satellite was moving to the apogee (altitude about 19 000 km), at 11:30 UT it reached ILAT = 79.3° and MLT = 4 h. During this time interval both TOF analyzers detected an upward beam of 20–40 keV electrons with intensity of about 10 electrons/s · sr · keV · cm^2 at pitch angles of $130° \pm 20°$ since 11:00 UT. The flux around 90° was below the threshold. At 11:10 UT both instruments simultaneously detected a 3-min isotropic intensity burst with an intensity up to $0.5 \cdot 10^3$ electrons/s· sr · keV · cm^2. Then instruments continued to detect the upward electron beam, now with an intensity reaching $0.6 \cdot 10^2 \div 10^3$ electrons/s · sr · keV · cm^2, and a fine structure at pitch angles of 90° (intensity there was about 10 electrons/s · sr · keV · cm^2).

Simultaneous ION spectrometer measurements showed counterstreaming electron beams in the energy range of $40 \div 200$ eV after 11:10:30 UT and upward FA accelerated O^+ ions of ~ 100 eV after 11:11 UT. At 11:10:30 UT (ILAT = 79.5°, MLT = 2.8 h) a 3-min isotropic intensity burst of electrons of $100 \div 1000$ eV energy was seen, and at 11:11 UT a 3-min isotropic burst of intensity of H^+ ions of $400 \div 5000$ eV was detected. Before 11:10:30 UT the flux of ions in all energy ranges observed by ION was almost below the threshold, while the electron flux was detectable only in the range below 500 eV. From 11:05:30 UT till 11:09:30 UT, counterstreaming electron fluxes were seen in the range of $80 \div 500$ eV. Unfortunately, for this case there were no superthermal ion observations.

Ground magnetometer data from Fort Simpson (MLT ~ 2.1 h at 11:10 UT) indicated a local substorm from 07:30 to 10:30 UT, so the upward electron beam was detected during the recovery phase of that substorm. WIND IMF and solar wind data indicated a decrease of proton number density (from 25 cm^{-3} to 12 cm^{-3}) along with an increase of IMF $|B|$ magnitude and northward turning of the IMF Bz approximately at the moment corresponding to our observations (delayed according to solar wind velocity by 35 min). From 08:00 to 12:00 UT there were two broad peaks of the solar wind proton number density up to 30 cm^{-3} separated by a period of lower density from 10:35 to 11:15 UT (average proton number density during the day was about 10 cm^{-3}). The WIND position at 10:40 UT was $X_{GSE} = 121.7$ R$_E$, $Y_{GSE} = -57.2$ R$_E$, $Z_{GSE} = 1.9$ R$_E$, solar wind velocity $Vx = -369$ km/s. Value of Kp at the moment of observations was $1+$, *Dst* index was -8 nT.

Case 3: pass 250 (see Fig. 3). At 03:55 UT on 28 October, 1996 both TOF analyzers indicated a weak (less than 10 electrons/s · sr · keV · cm^2) beam of
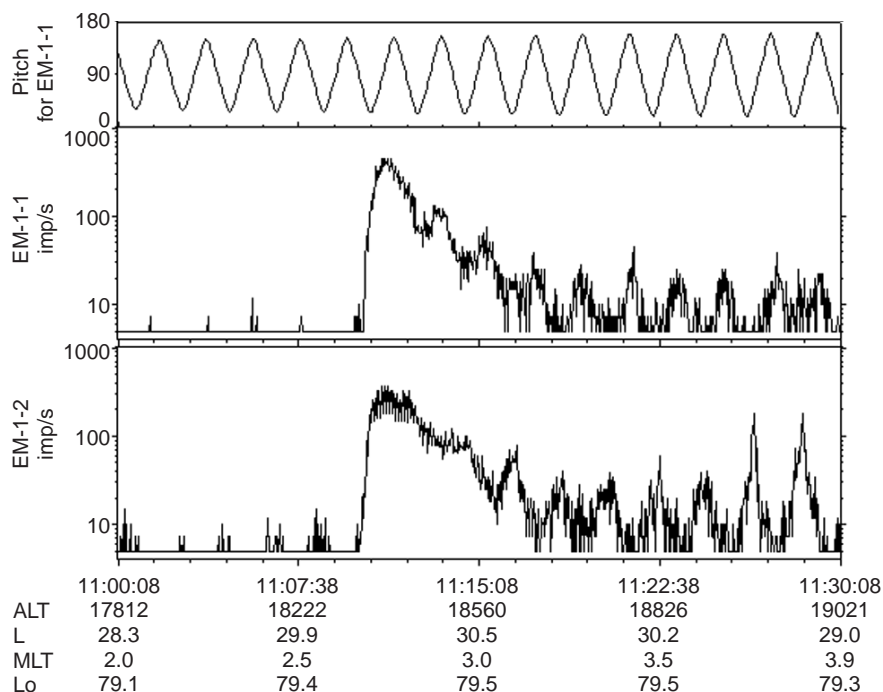

	11:00:08	11:07:38	11:15:08	11:22:38	11:30:08
ALT	17812	18222	18560	18826	19021
L	28.3	29.9	30.5	30.2	29.0
MLT	2.0	2.5	3.0	3.5	3.9
Lo	79.1	79.4	79.5	79.5	79.3

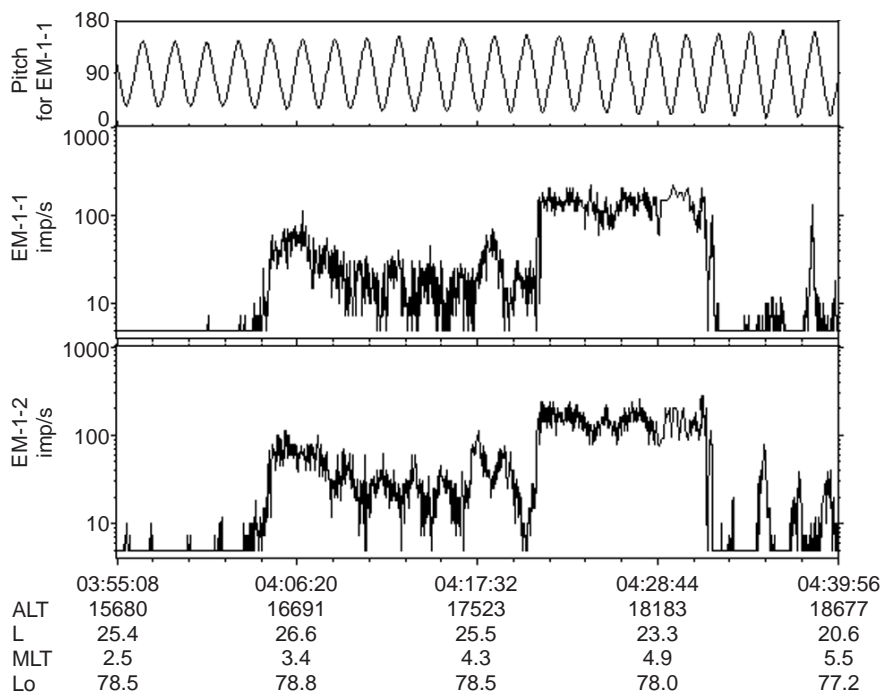**Fig 2.** (*Case 2,* October 27, 1996). For details see Fig. 1

Fig 3. (*Case 3,* October 28, 1996). For details see Fig. 1

20–40 keV electrons a pitch angles about $130° \pm 20°$, with almost no counts above the threshold around $90°$ of pitch angle. At 04:03 UT the TOF instruments detected a 3-min isotropic burst with an intensity of $0.5 \cdot 10^2$ electrons/s · sr · keV · cm². Then till 04:21 UT an upward electron beam was seen with peaks of the same intensity at pitch angles of $125° \pm 25°$. Around $90°$ the observed flux was fine-structured, while the intensity did not exceed 4 electrons/s · sr · keV · cm².

At 04:21 UT both TOF analyzers detected an 11-min isotropic intensity burst with intensities up to $0 \cdot 5 \cdot 10^3$ electrons/s · sr · keV · cm² with some fine structure. After that until 04:39 UT an upward electron beam was seen with rather distinct peaks at pitch angles of $135° \pm 15°$(intensity $0.5 \cdot 10^3$ electrons/s · sr · keV· cm²). At $90°$ the intensity was rather weak-number flux not greater than 10 electrons/s · sr · keV · cm². Other particle instruments of the Auroral Probe either were not operating at this time or the data is still unavailable.

The satellite position at 03:55 UT was 15 650km altitude, MLT = 2.5 h and ILAT = 78.5°; by 04 : 39 UT the satellite moved to an altitude of 18 600 km, MLT = 5.5 h and ILAT = 77.3°. *Kp* value was 3-, *Dst* was about −3 nT. The magnetogram from the nearest ground station Leirvogur (MLT ∼ 3.5 h) indicated a moderate disturbance or possible recovery phase of a small substorm. The WIND data indicated southward turning of the IMF *Bz* at the moment roughly corresponding to the observation time, shifted by the delay calculated from the solar wind velocity (26 min). The WIND position at 10:40 UT was $X_{GSE} = 122.1 \, R_E$, $Y_{GSE} = -55.5 \, R_E$, $Z_{GSE} = 2.3 \, R_E$, solar wind velocity $Vx = -500$ km/s.

Case 4: pass 251 (see Fig. 4). The last case we consider here took place at 10:12 UT on 28 October, 1996. After 10:12 UT for 40 min the TOF analyzers detected an

upward beam of 20–40 keV electrons with intensities up to $0.5 \cdot 10^2$ electrons/s · sr · keV · cm², pitch angles about $135° \pm 15°$. Then at 10:52 UT (ILAT = 79.1°, MLT = 4.8 h) some flux intensification began, up to $0.5 \cdot 10^3$ electrons/s · sr · keV · cm², along with isotropization and intensification of flux around pitch angles of $90°$. From 11:16:50 to 11:23:45 UT ($76.9° <$ ILAT $< 76.2°$, $5.8 <$ MLT < 6.0 h), distinct peaks at maximum pitch angles were seen and almost no detectable flux at $90°$ of pitch angle, after that a 3-min isotropic burst was seen.

Other particle instruments observations are available only after 11:00 UT. The ION particle spectrometer detected a rather isotropic flux of $100 \div 1000$ eV electrons until 11:13 UT. Then ION detected a series of isotropic $100 \div 1000$ eV electron bursts: from 11:16 till 11:17, from 11:19 till 11:21, from 11:24 till 11:27 UT. After that the electron flux became isotropized. Several velocity dispersed H^+ structures below 8 keV were also detected by ION from 11:03 till 11:16 UT, and then after 11:24 UT. An isotropic H^+ burst in the energy range $100 \div 3000$ eV was detected by ION from 11:16 till 11:18 UT. In addition, an upward 100 eV O^+ beam was detected from 11:00 till 11:53 UT. The measurements of the thermal plasma analyzer HYPERBOLOID showed an upward beam of 10 eV H^+ from 11:00 till 11:55 UT, slightly isotropized from 11:37 till 11:45 UT.

From the WIND data for the case an unstable IMF *Bz* behavior is seen: there was a 10-min southward IMF *Bz* turning near the moment corresponding to the observation time shifted by the appropriate delay (22 min). WIND position at 10:40 UT was $X_{GSE} = 122.1 \, R_E$, $Y_{GSE} = -54.7 \, R_E$, $Z_{GSE} = 2.5 \, R_E$, solar wind velocity $Vx = -585$ km/s. The Auroral Probe position was changing from 18 000 km altitude, MLT = 2 h and ILAT = 80° to 18 200 km, MLT = 6.2 h and
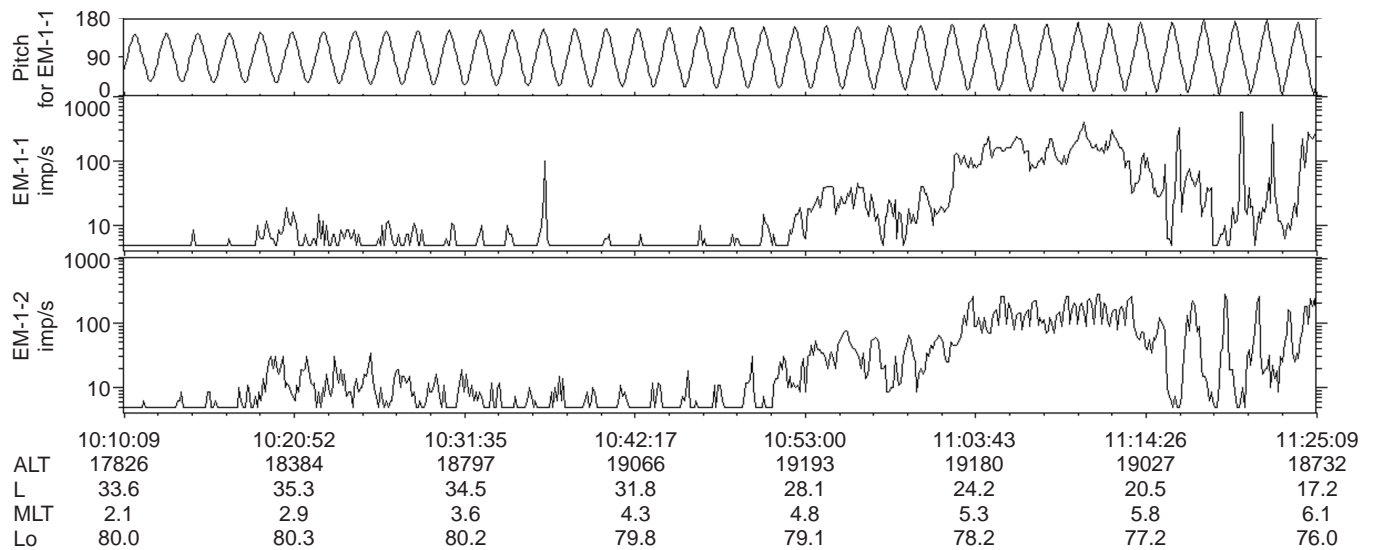
	10:10:09	10:20:52	10:31:35	10:42:17	10:53:00	11:03:43	11:14:26	11:25:09
ALT	17826	18384	18797	19066	19193	19180	19027	18732
L	33.6	35.3	34.5	31.8	28.1	24.2	20.5	17.2
MLT	2.1	2.9	3.6	4.3	4.8	5.3	5.8	6.1
Lo	80.0	80.3	80.2	79.8	79.1	78.2	77.2	76.0

Fig 4. (*Case 4*, October 28, 1996). For details see Fig. 1

ILAT = 75°. During the beam registration the satellite's orbit crossed its apogee at 11:03 UT, MLT = 5.4 h, ILAT = 78.5°. At the moment of observations Kp was 3-, Dst about −22 nT. Ground magnetometer data from College (Latitude = 64.8°, Longitude = 212.2°, MLT ∼0 h) and Fort Simpson (MLT ∼1.3 h) indicated that the beam was detected during a quieting period between two substorm-like bursts, or just before the breakup phase of a local activation.

3.2 Observations summary

As can be seen from the data description, the four cases detected were located from 2 to 7h MLT and from 75° to 80° ILAT near the apogee of the Auroral Probe orbit (i.e. at the polar edge of the auroral oval and/or inside the northern polar cap), during quieting, or moderate disturbance levels. ION particle spectrometer measurements onboard the Auroral Probe (Sauvaud *et al.*, 1997, this issue) for *Case 2* also show that the satellite probably crossed the poleward auroral oval boundary during, or before, the beam registration. Observations revealed the existence of narrow field-aligned upward beams of energetic electrons in that region interrupted by isotropic intensity burst of about 3 min duration, after which the upward beam intensity increased. At the same time, in the keV energy range, counterstreaming FA electron beams of variable intensity (generally much higher than that of the upward beam of 20–40 keV) were seen simultaneously with nearly isotropic intensity of plasmasheet-like electrons. Sometimes upward beams of low-energy ions (probably, conics narrowed in pitch angle due to magnetic moment conservation) were seen more or less simultaneously with the upward high-energy electron beam. From a limited set of the data available it is not clear whether the presence of such energetic upward electron beams is caused by some distinct signature in the IMF and solar wind. *Cases 1, 3*

and *4* probably correspond to the southward turnings of the IMF Bz, but *Case 2* seems to be detected during northward turning of the IMF Bz. Global magnetospheric conditions were not very disturbed, as is shown by Kp and Dst values, and loosely could be described as quieting periods. Ground magnetograms from the nearby stations correspond to intervals after or between disturbances of moderate activity levels, or probably to a recovery or late recovery phase of a small substorm-like bursts. There is no clear evidence that the events observed are a product of a preceding substorm activity. However this is not inconsistent with the data available.

Simultaneously with the energetic upward beam observations by SKA-3, measurements performed by the ION particle instrument show variable counterstreaming electron beams of 100 ÷ 1000 eV embedded in the plasmasheet-like background. An isotropic but fine-structured intensity bursts of 100 ÷ 1000 eV electrons and H^+ ions of up to some keV energy were observed after several minutes of the upward beam appearance at least for *Cases 1 and 2*. In addition an upward accelerated ion beam of keV energy was observed in *Case 1*, as well as a set of velocity-dispersed H^+ structures below 8 keV and upward 100 eV O^+ beam for *Case 4*. An upward beam of 10 eV H^+ was also detected by the thermal mass-spectrometer HYPERBOLOID in *Case 4*.

Further studies of features accompanying the upward high-energy electron beams require detailed analysis of simultaneous observations performed by other particle detectors onboard the Auroral Probe such as ION, PROMICS-3 and DOK-2, as well as wave and electric field instruments and onboard magnetometers. The work of data collection and analysis during the upward high-energy electron beam registrations and some modeling efforts are under way and will be reported elsewhere.

In the next section we propose a qualitative scenario of the mechanism which could be responsible for the

formation of energetic upward electron beams in that ILAT-MLT region above the polar ionosphere.

4 An interpretation scenario

4.1 Features of the upward high-energy electron beams

In an attempt to construct a plausible theoretical scheme for explanation of the observed FA upward beams of energetic electrons, the following morphological properties of the phenomenon will be taken into account:

1. The high-energy beams $(20 - 40 \, keV)$ are observed for a relatively long time $(\sim 3 \cdot 10^2\text{–}10^3 \, s)$, when the satellite stays almost at the same place, or moves slowly in the ILAT-MLT frame. Thus they may be considered as quasi-stationary.
2. The high-energy FA upward electron beam is nearly monodirectional, while the simultaneously present electron FA beams of keV energy are observed as bidirectional and highly variable. In some cases high-energy electron fluxes at $90°$ also appear, but are much weaker than the FA upward beam.
3. The ILAT-MLT location of the beams at, or close to, the polar border of the oval in the postmidnight-morning MLT sectors is consistent with a region of large-scale downward FA current (region I). But the preliminary onboard magnetometer data (courtesy of V. Styazhkin, IMAP-3 experiment) are inconclusive to prove the existence of the downward current. Recent results by FAST group (see, e.g., Carlson *et al.*, 1998, and references therein) show high wave activity and intermittent small-scale potential drops in the downward current region. The inference about the downward FA current at the upward beam locations is also consistent with the "Matreshka" scheme of nested FA current loops at the polar edge of the postmidnight oval (Timofeev and Galperin, 1991).
4. Simultaneous but preliminary data on ELF plasma waves (courtesy of M. Mogilevsky, IESP instrument) indicate that while some wave activity is usually present during an event, no straightforward correlations have been found so far.

4.2 A qualitative scenario

In view of these characteristics, a scenario for the high-energy acceleration phenomenon is proposed. In this scenario, during registration of the upward energetic electron beam the satellite is supposed to be within a bidirectional electron acceleration region, or at least, the FA acceleration of electrons occurs both above and below the satellite. This is evidenced by the counter-streaming low-energy electron beams embedded in the plasmasheet-like particle environment. Thus the FA low-energy electrons $(\sim 0.1 \div 1 \, keV)$, reaching the satellite from both directions, have been accelerated by some wave-particle interactions while crossing a part of

the acceleration region lying respectively below or above the satellite ("single transit").

The upward beam of high-energy electrons is presumed here to originate from the acceleration of a part of the FA accelerated plasmasheet electrons. Before the formation of the upward beam, those electrons have passed downward through the whole acceleration region both above and then below the satellite ("double transit"). As a result of the FA acceleration they formed electron beams, mostly reaching auroral altitudes, with excitation of respective auroral phenomena, probably in form of diffuse (or weakly structured) features, sometimes with additional activation. The portion of the accelerated electron distribution lying outside the loss cone, after being mirrored below the acceleration region (but above the ionosphere), and now moving upward, is able to reach the satellite again after passing the lower part of the acceleration region ("triple transit"). Thus particles that formed an upward beam of high-energy electrons have experienced much more effective acceleration in a "triple transit" than those registered at the satellite as counterstreaming electron beams which experienced only a "single transit", or auroral electrons at the footprint of the satellite that have experienced a "double transit" through the region of stochastic wave-particle acceleration within the downward FA current region. This scenario is shown schematically in Fig. 5.

4.3 On possible acceleration mechanisms

Consider now a possible mechanism for the particle acceleration process. For the scenario discussed it must be bidirectional, i.e., in these wave-particle interactions,
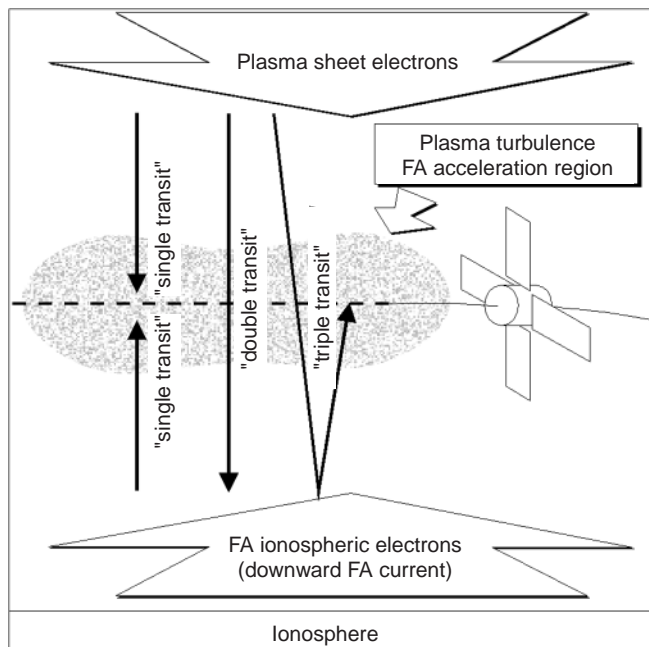

Fig 5. Schematics of the acceleration scenario

the acceleration is experienced by electrons moving either upward or downward through the layer of wave-particle interactions. For that, a stochastic type of FA acceleration is suitable if accomplished by waves with FA electric field components in either direction. At the same time, as no comparable acceleration effects are observed for ions, and considering the available wave and other particle data onboard, some restrictions probably may be devised for the choice of the wave-particle interactions involved. This work is in progress now.

According to our observations, the acceleration by wave-particle interactions is present in a wide range of altitudes along the particle trajectory. It occurs both above and below the satellite and is not confined in the altitude region of 0.5–2 R_E, where most of the auroral FA acceleration takes place. It is not clear at what altitudes above the satellite the FA downward acceleration of the plasmasheet electrons occurs. It must be confined at most to $\sim 6\,R_E$, because otherwise the magnetic moment conservation tendency will isotropize the electron distribution more than is observed. At the same time, the observed weakness of the high-energy electron intensities around 90° pitch angle in comparison to the FA component indicates that the perpendicular acceleration process by plasma waves is not local. Thus, we cannot expect a good correlation of the upward beam intensity with some particular type of waves registered by the Auroral Probe. A search for such waves, both from measurements on the Auroral Probe and from theoretical analysis, is in progress.

Turbulent acceleration processes in the aurora have been discussed in many papers (see, e.g., Bryant *et al.*, 1991; Tetreault *et al.*, 1995), however, no definite comparisons with the data are known so far. Intense IC and LH wave packets and their interaction with particles have been studied using a kinetic approach by many authors (see, e.g., Andre and Chang, 1992; Kintner *et al.*, 1992; Retterer *et al.*, 1994; and recently Dubouloz *et al.*, 1995 for LHR wave packets). Supposing the initial plasmasheet electron temperature of 0.5 keV, model results of Dubouloz *et al.*, 1995, show the possibility for such electrons to be FA accelerated up to several keV due to LH wave packets in a single particle transit through the upper part of the acceleration region (above the satellite), or through its lower part (below the satellite), if LH waves of sufficient intensity are present there. These accelerated electrons will then constitute the observed FA counterstreaming beams of about 1keV. However, the resonance condition for high-energy electrons of the upward beam requires very large wave phase velocities hardly achievable by the LH wave packets. But much higher energies, up to 20 or more keV, are observed to be attainable by a small part of the initial plasmasheet electron population which is presumed here to mirror above the ionosphere after traversing the whole accelerating layer, forming an upward accelerated energetic electron beam. Thus, the theory outlined already is unable to explain observations fully by itself and additional mechanisms are needed.

The described scenario seems to be qualitatively consistent with observations of the energetic upward electron beams as described, while the nature of the wave-particle interactions involved remains obscure. According to the scenario, the observed energetic upward beam is the extended tail of the FA accelerated electrons of lower energies, presumably with a power law spectral form. The accompanying feature expected from the scenario is a wave turbulence in extended regions somewhere above, and especially below the satellite, but not necessarily at its altitude. In addition, for the LHR wave packets e.g., a perpendicular ion heating and thus ion conic formation is another expected consequence. We are now studying the available data with respect to these inferences.

5 Discussion

5.1 Location in magnetosphere and time development

We have concentrated here on a few cases of long duration events when, during many satellite rotations (2 min each), both oppositely directed TOF analyzers indicated the presence of an upward high-energy electron beam. At this time no reliable statistics of such cases could be presented.

The four cases described occur in the postmidnight-morning sector of MLT near, or at, the polar edge of the auroral oval, or within the polar diffuse auroral zone (see, Feldstein and Galperin, 1985, 1996; Galperin and Feldstein, 1991). These magnetic flux tubes in stationary conditions are expected to be traced to, or close to, the open-closed magnetic field boundary, or the distant reconnection line. A suggestion about an extended region in the distant tail with turbulent magnetic field as an alternative to the single distant reconnection line was recently put forward by Galperin, (1995) and Galperin and Feldstein 1996. However, the conditions in which the four events studied here took place cannot be considered as stationary states of the magnetosphere. They all belong to some quieting period after, or between, substorm-like disturbances or activations, when the distant tail still could not be equilibrated, and filaments of plasma with different properties could extend from the plasmasheet to tail lobes, or plasmoid(s) in the tail could be still present, causing variable FA currents in the regions of beam observations. As there is no returning high-energy electron beam in these cases, a quasi-regular closed magnetic field along the beam plasma flux tube is excluded (in contrast to the late morning case described by Hultqvist *et al.*, 1988). Thus, either an open magnetic field, or a turbulent weak magnetic field in the distant tail where strong scattering of the high-energy electrons occurs, seem to be the alternatives for these plasma flux tubes.

Now let us consider the time development of the observed energetic electron beams and ambient plasma populations. In the four cases described qualitatively a very similar behavior was found: a weak upward beam of 20–40 keV electrons after several minutes was followed by an isotropic intensity burst that lasted for about 3 min. It occurred simultaneously with the

isotropic burst of electrons and ions in the keV energy range. After the burst the quasi-steady high-energy electron beam reappeared and was more intense than before the burst. We note that the 3 min interval of the burst is a characteristic time for the transit of protons of 0.3–3 keV from the distant tail region at 50–160 R_E. Thus, the origin of the burst in some active processes in the far tail seems plausible, and deserves further analysis.

5.2 A possible relation to energetic particle bursts in the distant tail

The Auroral Probe orbit is chosen so that the satellite at the apogee moves only very slowly in the ILAT-MLT frame for a relatively long time (~20 min), thus the time dependence of the events can be distinguished from the data more easily. This was the case during the registration of the upward electron beams. As could be seen from our case studies, there is each time a period of a relatively weak flux (as long as several satellite spin periods of 120 s) before an intensity burst and isotropization interval followed by subsequent upward beam intensification.

Sarris *et al.*, 1996, have reported Geotail observations of the high-energy electron and ion bursts in the deep magnetotail at a distance of $X_{GSM} = -128\,R_E$. The source location of these high-energy particles is reported to be at ~ −103 R_E. Then it could be of the same type as the isotropic intensity bursts observed by the SKA-3 after some time of quasi-steady upward beam existence. However, no sign of the preceding weak high-energy beam intensity was noted in Sarris *et al.*'s 1996, study. We note that if the source region was in the closed field line region, or a reconnection region, such a location could be mapped to the ILAT-MLT region of our observations. Thus energetic particle bursts in the tail during the SKA-3 observations cannot be excluded, and at least, in some cases, such checks will be possible from simultaneous Tail Probe data.

5.3 A speculation concerning possible local destabilization of the cross-tail current by high-energy electrons of the upward beam

It is known that bursts of energetic electrons occur in the distant tail (see Lui and Krimigis, 1984; Sarris *et al.*, 1996). It has been shown by Sitnov *et al.*, 1996, that the loss cone electron population could affect significantly the linear stability conditions of the tearing mode in the quasi-neutral magnetotail current sheet. So it might be speculated from this limited data set that the initial upward energetic electron beam (even while rather weak) could affect the distant tail stability conditions, as the field lines on which the measurements were performed map to more than −70 R_E geocentric according to the Tsyganenko-87 model. Supposedly, the induced local destabilization of the tearing mode in the

distant tail plasma and currents could cause the observed isotropic burst of energetic particles which is detected by the SKA-3 instruments. Presumably the plasma turbulence level at altitudes below and above the satellite, which is responsible for the acceleration of high-energy electrons, increases after the particle burst, and qualitatively it can cause the upward beam intensification after the burst.

One possibility to significantly alter locally the cross-tail current in the distant tail is to inject particles there with a Larmor radius comparable to the local magnetic field line curvature in the neutral sheet. According to the data from the ISEE-3 and GEOTAIL, the average magnetic field in the neutral sheet at ~100 R_E is about 0.3 nT (Fairfield, 1992, 1993; Nishida *et al.*, 1995; see also Lui and Krimigis, 1984) and the curvature radius can be less than 2 R_E. For a 25 keV electron the respective Larmor radius amounts then to about 1.7 R_E, so that its strong scattering due to non-adiabatic motion is quite feasible. It may be supposed that, due to appearance of new charge carriers with a different type of particle motion in the cross-tail current sheet, the charge neutrality and cross-tail current characteristics could be locally disturbed. It is speculated here that this disturbance could lead to the plasma particle burst observed in the middle of the upward beam observations.

Clearly this point is just a speculation based on the medium-altitude measurements and requires further analysis and comparisons with the data from other satellites and ground-based observations.

6 Summary and conclusions

1. A quasi-stable upward field-aligned electron beam with super-auroral energies (20–40 keV) was discovered at altitudes ~3 R_E, high above the post-midnight polar border of auroral oval (or at, or near, the open-closed magnetic field boundary) during quieting conditions.

2. From four case studies presented, the time development of the beam starts from a low monodirectional upward flux, but after 5–15 min an isotropic intensity burst appears, decays in ~3 min and the upward monodirectional beam reappears with higher intensity than before the burst.

3. The appearance of bidirectional electron beams at altitudes ~3 R_E during the upward high-energy electron beams demonstrates that electron FA acceleration processes, presumably by the wave-particle interactions, can encompass a very extended altitude range, up to the Auroral Probe apogee and higher, at least for the cases considered.

4. A qualitative scenario is proposed for FA acceleration of the tail of the plasmasheet electron distribution function both above and below the satellite altitude, by electron velocity diffusion due to unspecified wave-particle interactions. The scenario includes additional acceleration of the mirrored, upward moving, electrons, which gives them higher energy than those reaching auroral altitudes.

5. A local destabilizating action is suggested from the high-energy FA electron beam for the cross-tail current in the distant tail plasma sheet as a possible cause of the isotropic intensity burst observed after several minutes of the upward beam persistence.

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