Pergamon

Phys. Chem. Earth (C), Vol. 25, No. 1-2, pp. 63–66, 2000

1464-1917/00/$ - see front matter

PII: S1464-1917(99)00038-0

Satellite and Ground-Based Measurements of the SAR-Arc Phenomena

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Received 9 October 1998; revised 12 March 1999; accepted 5 April 1999

Abstract. Data of the Intercosmos 24 (IC 24) satellite and the ground-based complex optical and ionospheric measurements in the region of the stable auroral red (SAR)-arc are presented. Photometric observations were carried out at the Maimaga station (invariant latitude Λ =56.5°, geomagnetic longitude λ_m=200°) and vertical incidence ionospheric soundings were made at Yakutsk (Λ =55.6°, λ_m=200°) and Zhigansk (Λ=60.4°, λ_m=195°) stations. It is shown that when SAR-arc arises for the interval ~ 15 min, the local minimum of the F-region electron density is formed, and in the ionograms typical signatures of the polarization jet or SAID are observed. Simultaneously, the height of the regular F2 layer increases. This evidences that strong electric field (E ~ 100 mV/m) exists at the F2 layer heights. In this case, in addition to the SAR-arc energy sources, the effect of the ion-frictional heating is turned out to be important. Simultaneous measurements aboard the IC-24 satellite at the altitudes ~500 km above the SAR-arc also show 3÷5 times decreased electron density.. The electron temperature elevates up to ~ 4500 K. At altitudes of 2400 km the ion density increases by 30 – 40 % and T_e rises up to 6300 K.

1 Introduction

Midlatitude stable auroral red arcs are the most vivid manifestation of the processes of ring current energy dissipation in the inner magnetosphere. SAR occur on L-shells, which map to the region where ring current formed by energetic ions, overlaps with plasmasphere consisting of cold ions. Morphology, energetics, and possible generation mechanisms of SAR arcs were considered (Cornwall, 1971; Rees, 1975; Kozyra, 1997).

Recent complex measurements of Millstone Hill radar, the DMSP F9 satellite, and ground based all-sky optical imaging system provide new experimental data on physical processes in the region of SAR arc formation (Foster, 1994). It was found that in the evening sector SAR arc develops in the region of intense west ion drift with velocity of 1000 m/s. Fast ion drifts (polarization jet or subauroral ion drifts (SAID) events) were first described by Cosmos-184 data (Galperin, 1973) and then their characteristics were studied in the experiments aboard AE-C (Spiro, 1979) and S3-2 (Rich, 1980) satellites. The value of northward electric fields in these structures is 50 – 70 mV/m on average, but sometimes it can be as high as 250 mV/m. They are observed in time sectors 18.00 - 02.00 MLT and have a latitude dimension of ~ 2 degrees.

According to DE 2 satellite measurements on ionospheric heights (~400 km) in the region of polarization jet electron density N_e is reduced by 5-10 times, electron (T_e) and ion (T_i) temperatures are significantly increased and upflowing fluxes of O^+ ions with the velocity of 500 – 800 m/s are observed (Anderson, 1991).

In ionosphere signatures of polarization jet were studied in detail with the data of Yakutsk ionozond chain and simultaneous satellite data (Galperin, 1986). Development of polarization jet close to the zenith of ionospheric station causes a formation of additional traces on ionograms ($F3_s$ – reflections) due to rapid (15- 30 min.) electron density decrease in ionosphere F – region. Coordinate optical and ionospheric measurements carried out in Yakutsk showed that SAR arc appearance is accompanied by the development of polarization jet (Alexeev, 1994).

Thus, experimental data suggest that the processes of SAR arc generation occur in the ionosphere modified by strong electric field of polarization jet. Below the parameters of thermal plasma in ionosphere SAR arc region are analysed using synchronous measurements aboard the IC 24 satellite and ground-based ionozond and photometric data.

2 Instrumentation

The satellite IC 24 was launched on September 28, 1989

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into an orbit with apogee of 2500 km and perigee of 500 km. Ion temperature and electron density were provided by the Faraday cup with retarding potential. The altitude of the satellite orbit near above a meridian of ground-based observations was 500 – 1000 km. The data obtained were mapped to the height of SAR arc along the lines of geomagnetic field.

The optical data were obtained by the Maymaga station situated 100 km northward of Yakutsk. SAR arcs were observed by 2-channel scanning photometer with the angle of the field of view ~ 3°. Distribution of emissions on wave lengths λ = 630 nm and 557.7 nm were recorded along the geographical meridian every 2 min. Half bandwidth of the interferential light filter is 1.5 – 3.0 nm. For the following analysis the data of scanning photometer were drawn as isolines of surface brightness of emissions in coordinates: time – zenith angle (invariant latitude). The records of a signal with amplitude resolution of 10 – 20 R permitted to observe confidently the SAR arcs with 50 R intensity.

Characteristics of the ionosphere were provided by vertical and oblique backscatter sounding every 15 minutes from the stations in Yakutsk (Λ_0 = 55.6) and Zhigansk (Λ_0 = 60.4). The local time (LT) at the meridian of ground-based observations LT = UT + 9 hours.

3 Case study

On December 4, 1989 since 12.00 UT (Fig.1a) the photometer detected the SAR arc in the zenith of Yakutsk station (Ievenko,1993). During 6 hours afterwards the arc slowly drifted equatorward, and this drift grew up abruptly when at 18.00 UT the substorm began to develop. The southward boundary of diffuse aurora determined by the brightness level of 0.5 kR in the line 557.7 nm, was located northward from the station zenith during the whole period of observations. Ionospheric measurements (Fig.1b) showed that immediately since 12.00 UT close to the zenith of Yakutsk station $F3_s$ – reflections were observed, and their critical frequencies were by 2.6 MHz less than background critical frequency of F2 layer (f_0F2). This corresponds to the formation of local minimum in electron density typical for polarization jet structure (Galperin, 1986). This additional trace of $F3_s$ – reflections was seen till 15.00 UT and then merged with the main F2 – reflection. Beginning from 12.30 UT the electron density in F2 layer fell down abruptly and the height of the layer rose significantly relative to its quiet time position. At 19.00 UT the actual height of F2 layer h'F2 close to the polar edge of SAR arc was ~ 440 km, that is by 180 km higher than it unperturbed value, and the critical frequency f_0F2 is less by 1.2 MHz, correspondingly.

Approximately at the same time the satellite IC 24 crossed the region of the observed SAR arc in the early morning sector of MLT at the height 1000 km, by 1.5 hour in MLT

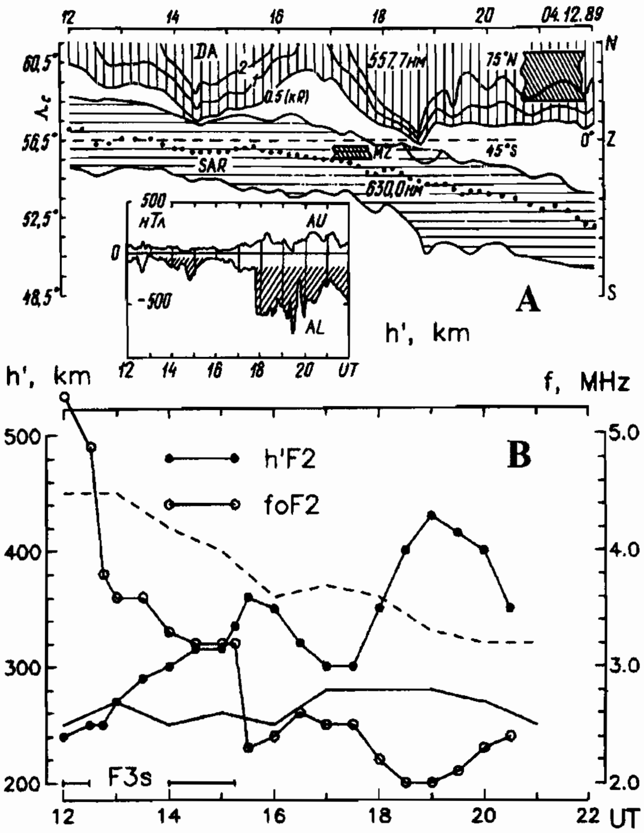

Fig. 1 a –Latitude profiles of constant intensity (marked in kR) of diffuse auroral emission of 557.7 nm and the SAR arc on Dec. 4, 1989 as measured by the photometer. Dotted line refers to maximum SAR arc intensity Dashed line marks the location of the station of optical observations and MZ denotes the magnetic zenith of the station. Additional window shows variations of geomagnetic indices AU and AL.

b – Time variations of the parameters of F2 layer measured by ionospheric station in Yakutsk. Solid and dashed lines present the layer height and its critical frequency on the closest unperturbed day. Lines with full and empty circles show these parameters during the SAR arc observation.

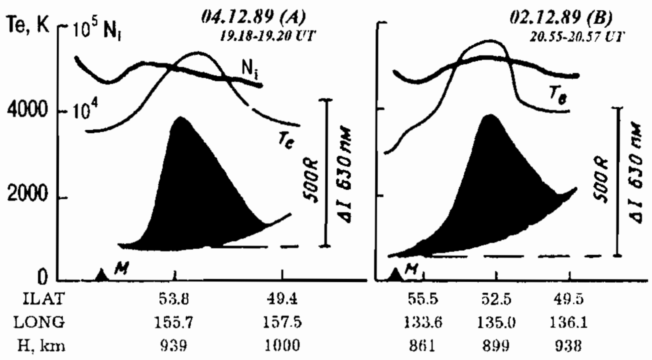

Fig.2 Latitude profile of electron temperature, ion density and SAR arc intensity on December 4, 1989 (a) and December 2, 1989. M – marks the zenith of station of optical observations in Maymaga.

eastward from the meridian of ground-based observations. Fig.2a presents latitude distributions of electron temperature, ion density, and emission for this IC 24 overflight. It is seen that the shape of T_e latitude profile is similar to the shape of meridional profile of surface brightness in 630.0 nm line of the arc. N_i variations above the arc are insignificant. In the next orbit at 21.14 UT IC 24 was close to Yakutsk meridian. The latitude parameter

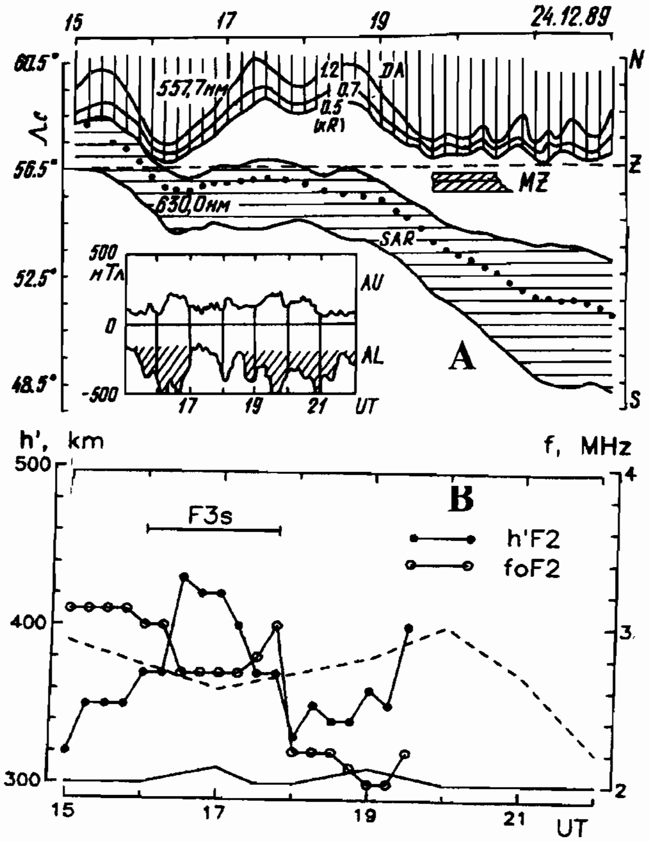

Fig.3 Optical and ionospheric measurements on December 24, 1989. The notations are the same as in Fig.1

distributions were practically the same, only the ion density had a slight minimum above the SAR arc. During the satellite measurements in these passes the D_{st} index was –43 nT and –52 nT, respectively, and K_p was equal to 4_+

IC-24 measurements in the Southern hemisphere at 19.48 UT and 21.46 UT on Dec.4, 1989 showed T_e enhancement from 5000 K up to 6300 K and a small but quite obvious by 30 – 40 % rising of N_i in the region magnetically conjugate with the Northern SAR arc region. In the Southern hemisphere the height of the orbit was 2400 km.

Fig. 2b demonstrates another example of satellite measurements above the SAR arc on Dec. 2, 1989. Geophysical conditions on December 2 and 4 were similar and approximately equal arc intensity is related to nearly the same T_e increasing.

The IC 24 satellite measurements at the altitude ~ 510 km above the SAR arc on 02.12.1989 at 11.02 UT occurred exactly above the meridian of ground based stations. The electron density above the SAR arc region is reduced by a factor of ~ 2.5 and T_e increased up to ~ 4600 K. Like in other cases the ionozond detected reflections typical for polarization jet. The satellite measurements during the SAR arc region overflights at the altitude ~ 500 km on 3 other days showed 3 – 5 times N_i decreasing and the increasing of T_e up to 4500 – 4700 K. Measurements at different heights in similar geomagnetic conditions revealed significant altitude gradient of T_e.

Fig. 3a presents another example of the SAR arc development, when the magnetic activity was high. Through the period of observations and preceding 6 hours the geomagnetic activity indices K_p = 4 and D_{st} = -18 nT. The starting of SAR arc formation was monitored at 15.00 UT after the beginning of the substorm 'break up' phase at 14.04 UT. The later was determined by the appearance of Pi2 pulsations detected at the magnetic observatory in Yakutsk. SAR arc had an intensity of 200 R and adjoined directly to the equatorward boundary of the diffuse auroral emission. At 15.54 the second substorm onset occurred and the SAR arc emission intensified from 200 to 400 R during 20 min. Through the time interval 16.15 – 18.30 UT the SAR arc intensity peaked nearly at the Yakutsk latitude, and then the arc moved continuously southward with the velocity ~ 40 m/s. On December 24, 1989 the SAR arc occurred close to midnight and that is why the changing of the ionospheric parameters were observed for the low background f_0F2 values (Fig. 3b). The F2 layer started to rise at 15.15 UT and at 16.30 UT h'F2 was 130 km higher, than its undisturbed value. Approximately in 15 min. after the SAR arc displacement to the zenith of the Yakutsk station, $F3_s$ reflections specific for the polarization jet formation appeared in the ionograms. At 19.45 UT the diffuse aurora boundary moved to Maymaga station and the ionograms detected reflections from the regions of enhanced electron density on the poleward edge of the main ionospheric trough.

The variations of ionospheric parameters in the SAR arc region were also checked in details for a set of other events using the observations at Zhigansk station. They also demonstrated the close relationship of the SAR arc and polarization jet phenomena in the dusk and near midnight sectors.

4 Discussion

The observational results considered above and also the results of Foster et al. (1994) demonstrated that the SAR arc appearance in the dusk and near midnight sectors is associated with the polarization jet formation (or SAID events) and the presence of poleward electric field (E ~ 50 – 100 mV/m). We have also analyzed 3 events of SAR arc development during intense magnetic storms on February 15 – 16, 1967 and October 21 and 23, 1981 using the satellite data (La Valle, 1972; Craven, 1982) and the data of some ionospheric stations in Russia. In all these cases SAR arcs were again associated with polarization jet formation. Such an association between these two phenomena agrees well with the mechanism of polarization jet formation in the region between the ring current and inner plasma sheet boundary as a result of separation of space charges (Southwood, 1978; Deminov, 1988; Anderson, 1993).

In the region of plasma drift with the velocity > 1 km/s fast frictional heating of ions and electrons occurs. This mechanism is quite effective and it alone provides 630.0 nm emission with the intensity > 100 R (Megill, 1963). In the polarization jet region the rates of recombination processes and losses due to field aligned and cross-field ionization transfer increase essentially, and, hence, deep trough in the N_e latitude profile forms with characteristic time of 15 – 30 min. (Deminov, 1988; Sellek, 1991). This seems to be the main reason of fast and rather significant variations of F layer in the region of SAR arc development (Fig.1b, 3b). The value of N_i, obtained from satellite measurements at different heights above SAR arc, can be also explained in the frames of model calculations. Enhancement of N_i at high altitudes is likely to be connected with general plasma heating in field tubes above the SAR arc region and the following field aligned plasma transport. Experimentally observed high values of T_e could be obtained in the model (Moffet, 1998) only in a case of heat flux of $\sim 10^{10}$ eV/cm^{2}s. This energy flux is a specific feature of the SAR arc observed simultaneously by ground-based monitors. Polarization jet appears in time sector 18 – 02 MLT and its life time is 2 – 3 hours, but the created trough structure exists during many hours in the dark ionosphere. Such a distinct structure channels the 630.0 nm emission, which is caused by the ring current energy input.

Polarization jet can also affect essentially the temperature of the neutral atmosphere (T_n). The electric field E = 100 mV/m results in energy output of ~ 0.5 erg/cm^{2}s (Sellek, 1991). In the region of SAR arc the interferometric measurements show the enhancement of T_n by 200 – 300 K (Watanabe, 1984; Alexeyev, 1994). The ring current energy input is not enough to account for the observed T_n variations. Physical effects in the ionosphere resulted from the polarization jet formation have to be studied carefully using the models of SAR arcs which are being developed now.

5 Conclusions

- Complex optical and ionospheric measurements show, that the SAR arc development in the F layer of the ionosphere is associated with the formation of local electron density minimum and the appearance of the reflections in the ionograms specific for the polarization jet structure.
- The formation of the SAR arc occurs in the ionosphere modified by the intense electric field (E~100 mV/m). In such conditions additional energy source associated with frictional ion heating is important.
- Measurements of the parameters of thermal plasma in the SAR arc region at different heights resulted in the following:

  - in the region of the F layer maximum and at the height of 500 km the plasma density is decreased by a factor 3-5.
  - at the height of 2400 km the ion density is enhanced by 30 – 40 %
  - at the height of 500 km the electron temperature is increased up to 4500 K, at the height of 2400 km T_e reaches 6300 K

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