Evidence of near-Earth breakup location

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[1] We report a detailed study of an isolated substorm onset with the FAST spacecraft crossing the equatorward = most auroral arc just when/where it starts to break up. Comprehensive ground (optical, riometer and magnetometer) data combined with the space borne field and particle high resolution observations allowed to infer the following properties of the breakup onset region in this well-documented event: (1) The arc flux tube stays in the region of considerable plasma pressure gradient wherethe pressure values are close to ~1–2 nPa. The arc was located (2) just 0.4° poleward of the proton isotropic (b2i) boundary (which roughly gives ~40 nT estimate for the equatorial magnetic field) and (3) close to the peak of the diffuse electron precipitation. (4) Tsyganenko 96 model for these particular solar wind conditions (which correspond well to both the observed b2i boundary and estimated plasma pressure) maps the arc to the equatorial distance of $\sim 8R_E$. All these facts in mutual agreement evidence that the auroral breakup in this particular case was launched in the near-Earth domain of the magnetotail at r $\sim 8R_E$. *INDEX TERMS:* 2788 Magnetospheric Physics: Storms and substorms; 2716 Magnetospheric Physics: Energetic particles, precipitating; 2730 Magnetospheric Physics: Magnetosphere—inner; 2731 Magnetospheric Physics: Magnetosphere—outer; 2704 Magnetospheric Physics: Auroral phenomena (2407). **Citation:** Dubyagin, S. V., V. A. Sergeev, C. W. Carlson, S. R. Marple, T. I. Pulkkinen, and A. G. Yahnin, Evidence of near-Earth breakup location, *Geophys. Res. Lett.*, *30*(6), 1282, doi:10.1029/2002GL016569, 2003.

1. Introduction

[2] The location and type of the plasma instability that triggers the substorms and auroral breakups are still disputed subjects. Magnetic reconnection at the near-Earth neutral line (NENL) and tail current disruption (TCD) are the most popular candidates. Recent statistical analysis of the plasma flows from Geotail observations gave a strong support to the NENL model and showed that the preferable origin of diverging (Earthward and Tailward) flows typically occurs between X = $-22R_E$ and $-30R_E$ [*Machida et al.*, 1999]. Close association between fast plasma flows and auroral breakups (in both timing and longitude range [e.g., *Ieda et al.*, 2001]) seems to expand this conclusion to the breakup phenomenon. At the same time, in other events the signatures of the TCD (such as turbulent magnetic field dipolarization) were observed just at the substorm onset at closer distance, $\leq 10\ R_E$ and a number of arguments have been proposed [e.g., *Kennel*, 1992; *Persson et al.*, 1994; *Pulkkinen et al.*, 1998] to argue for the near Earth location of the auroral breakup. Most difficulties arise because magnetospheric and ionospheric observations alone are not sufficient to solve the problem of source location in event studies. Single magnetospheric spacecraft can not locate and time reliably the onset, whereas although this can be done with 2D ionospheric observations it is difficult to map the onset location accurately to the magnetotail with the standard models available.

[3] There are two ways to help perform the accurate mapping. The first is to modify the standard model to fit the observed characteristics [e.g., *Kubyshkina et al.*, 1999]. The second is to use the low altitude signatures of the different plasma sheet domains (e.g. precipitation boundaries, CPS/BPS precipitation regions etc) which itself could be used as a reference mark of the radial distance. One such example is the proton pressure value which is constant along the field line in the isotropic plasma sheet and, since the pressure decreases monotonously with the distance in the plasma sheet [*Lui et al.*, 1994], its value is a useful landmark [*Dubyagin et al.*, 2002]. While each landmark taken alone may have interpretational problems, their cross-checks increase the reliability of the mapping procedure. In this paper we apply this method to obtain information in the case of a well-observed auroral breakup.

2. Observation

[4] *Event description*: The breakup occurred at the end of the growth phase of an isolated substorm on January 28, 2000 (21:22 UT). As observed by the Wind spacecraft at [11, −58, 18] R_E, it nearly coincided with the northward IMF turning at 21:20 UT which followed a half an hour of southward IMF ($B_z \sim -2$ nT). The auroral forms were observed by two cameras of the MIRACLE network (Kilpisjärvi and Kevo, with 20 s time resolution) as well as by two (more sensitive, high time resolution) TV cameras at Kola Penninsula (Loparskaya and Lovozero). This provides an excellent optical coverage of the breakup area which was this time near local midnight, see Figure 1. Prior to the breakup there were a few faint discrete arcs moving equatorward, it was the equatorwardmost discrete arc that disrupted. The arc brightening and subsequent formation of a street of spirals with a longitudinal scale 100–130 km started to appear first at Kilpisjärvi at 21:21:20 UT (see

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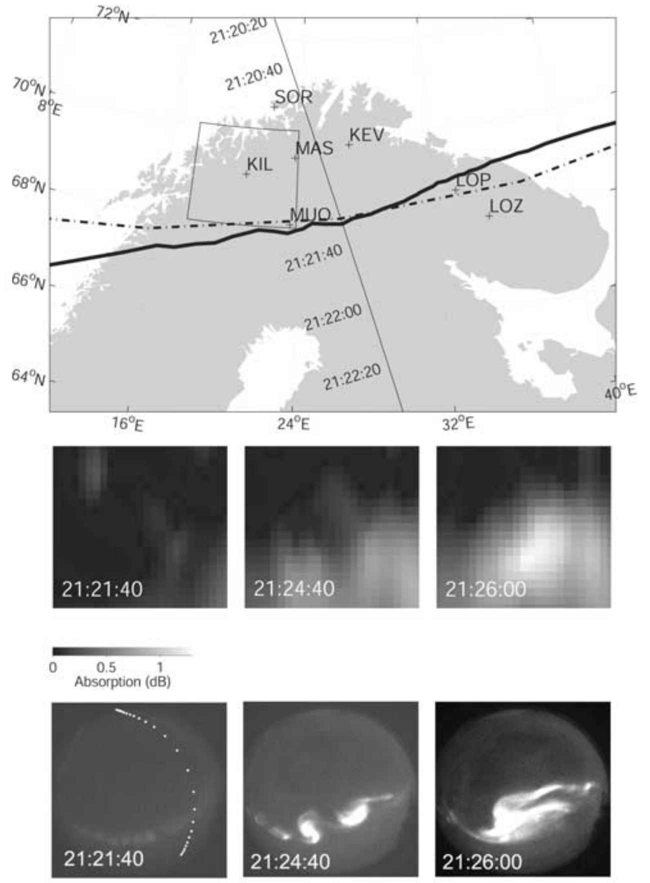

Figure 1. Top: Map showing the stations, FAST trajectory with the time labels (thin line) and the arc projection (at 21:21:40 UT, h = 110 km altitude was assumed, thick line) in geographic coordinates. Three consecutive ASC images (bottom row) and IRIS riometer images (center row), both taken at KIL characterize the breakup development. The north (and east) are at the top (and right side) of images. Points at KIL ASC image at 21:21:40 indicate the projection of FAST trajectory with 10 s steps. The ionospheric mapping of the cross-tail current line is shown by the dash-dot line. The square centered at Kilpisjärvi presents the riometer field of view.

KIL image in Figure 1) progressing then to the east. Three images in Figure 1 just correspond to the first arc intensification (coinciding with the FAST crossing), the spiral development and the arc breakup. (The 20 s resolution of Kilpisjärvi camera does not allow us to say certainly whether the spirals formed above the stations or they came from the west.).

[5] In addition, the imaging riometer at Kilpisjärvi (IRIS 7 × 7 beams system operates at a frequency of 38.2 MHz with 1 sec. sample interval) monitored the distribution of energetic electron precipitation (see the square diagram in Figure 1). Its recordings confirm that intensification of accelerated energetic electrons started at the South-East corner of IRIS diagram at 21:22 UT (Figure 2), just where the initial brightening was developed. (The orientation of the arc relative to riometerbeams does not exclude the possibility that arc came to the FOV from the west.). Figure 2 also presents data from IMAGE meridional magnetometer chain. The moments of arc brightening and sharp depression of the horizontal (X) magnetic field component (22:24 UT) are marked by dashed and solid lines respectively.

[6] *The FAST observations*. FAST spacecraft traversed the auroral zone along the midnight meridian equatorward at an altitude of 390 km and crossed the equatorward most auroral arc at 21:21:30 UT, just at the moment when it first became discernible in the Kilpisjärvi all-sky camera data. The FAST plasma spectrometers [*Carlson et al.*, 2000] measure the ion and electron fluxes at good (11.2°) pitch angle resolution with a coverage of 360° and temporal resolution up to 78 ms (burst mode was available just during the breakup arc crossing allowing to resolve well the auroral arc - see Figure 3). The energy range is 0.003–24 keV for ions and 0.004–32 keV for electrons. Besides, we use three components of magnetic and two (field-aligned and orbital) components of electric field at time resolution ~0.032 s which are available from the FAST flux gate magnetometer and electric field sensors [*Ergun et al.*, 2000].

[7] The burst mode spectrogram of precipitated electrons at the top of Figure 3 shows the narrow energy peak at 1–2 keV (indicating field-aligned acceleration) at the expected arc location between 21:21:29 and 21:21:31 UT, that corresponds to arc thickness of ~16 km. The next panels show the southward electric field component, with a short spike just preceding the arc crossing, and a triple system of field-aligned currents (down-up-down). The first pair is more intense and surrounds this short intense spike of the southward electric field. The arc itself coincides with the upward FAC region. The analysis of the horizontal magnetic variations showed that the FAC sheet has a well-defined orientation which corresponds to the orientation of the optical arc. The arc could be ascribed to the "morning side" type according to the classification given by *Timofeev and*

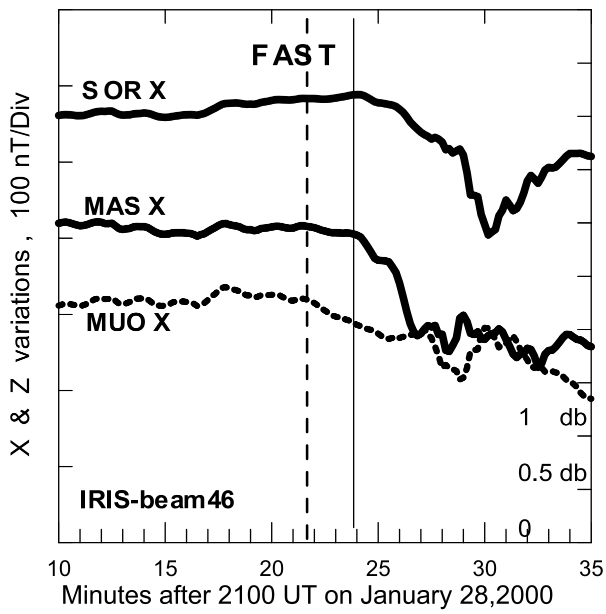

Figure 2. Selected IMAGE magnetograms and riometer traces (from southernmost beam), vertical lines indicate the time of FAST crossing and major intensification of ionospheric current at 21:24 UT.

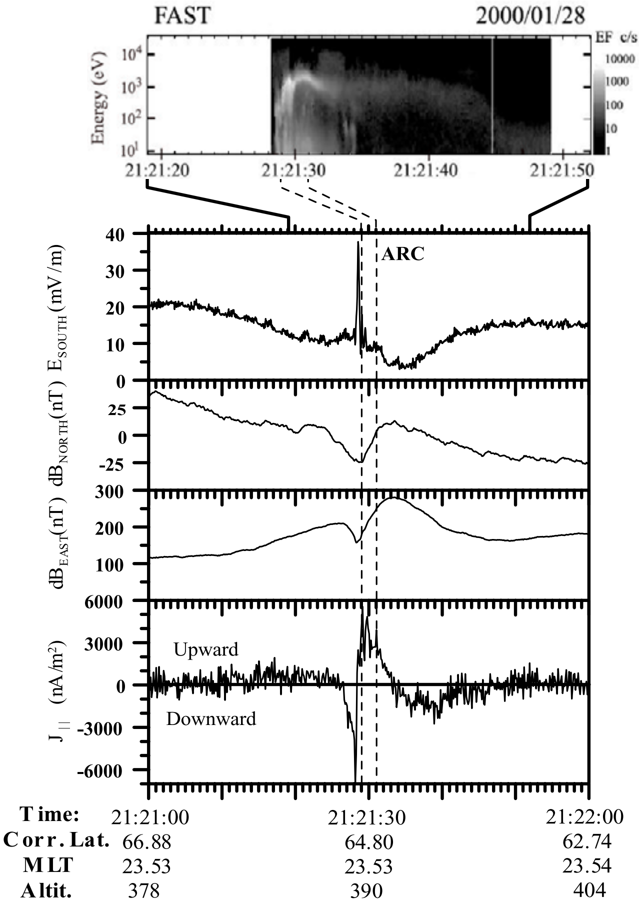

Figure 3. Summary of the FAST particle and field observations. From top to bottom: 0°-pitch angle electron energy flux spectrogram, Southward electric field component, northward and eastward magnetic variations and field-aligned current density computed assuming sheet-like geometry for the FAC system.

Galperin [1991] as inferred from enhanced southward electric field (convection stream along the arc)located poleward of the arc.

[8] Figure 4 presents the proton pressure and electron energy flux obtained by analyzing the measured distribution functions. Direct integration (thin line in Figure 4 top) gives only a small part of the proton pressure since the peak in energy flux is close to the 24-keV upper limit of the spectrometer. Therefore we approximated the measured part by both Maxwell and Kappa (with κ = 5, [*Christon et al.*,1991]) distribution functions assuming angular isotropy. Furthermore, we computed temperature and density from the flux values taken at the maximum of energy flux spectrum E_m (suggesting $E_m = 2T$ for Maxwellian distribution). Minimum and maximum of these three pressure values are shown with the error bars on the plot together with the pressure integrated over the measured 0.01–24 keV part of the spectrum, which gives the lowest limit (shown by the solid line). The following characteristics important for establishing the equatorial location could be inferred from particle measurements:

1. *Proton pressure*. The arc is situated in the region of strong Earthward gradient on the pressure profile where the pressure value lies in the range 1–3 nPa. Such values are typical for inner magnetosphere rather than the current sheet (where it is about a few tenths of nPa).

2. *Isotropic boundary location*: The isotropic boundary (IB) indicates the outward limit of proton adiabatic motion and the inward limit of their strong nonadiabatic pitch-angle scattering in the current sheet. It approximately corresponds to the condition $R_c/\rho = 8$ taken in the equatorial plane (using the minimum B-curvature radius and maximum particle gyroradius [e.g., *Sergeev et al.*, 1993]). In our case FAST was at low ~390 km altitude near perigee where the proton interaction with the atmosphere is essential. Thus, there was no large difference between the fluxes at local 0° and 90° pitch angles. Nevertheless, like the b2i boundary in DMSP observations [e.g., *Newell et al.*, 1996] the isotropic boundary is clearly expressed as the maximum of the integral proton pressure on the top plot of Figure 4, which stays at 64.4° CGLat. The arc is thus very close, being only 0.4° poleward of the isotropic boundary. The condition R_c/ρ = 8 gives for 20-keV proton the equatorial magnetic field of about 40 nT for a nominal current sheet thickness of 1–2 R_E (it can exceed 60 nT if the current sheet is extremely thin, h ~ 0.1 R_E). These values give the upper limit for the equatorial magnetic field at the source region of thebreakup arc in our event.

3. *Diffuse electron precipitation*: In Figures 3 and 4 the arc is clearly embedded within the broad diffuse electron precipitation and stays near the energy flux maximim, with peak energy decreasing towards lower latitudes. This location is commonly interpreted as the Alfven convective boundary for the hot electrons (e.g., *Newell et al.* [1996]) which always stays in the inner magnetosphere. Although the Alfven layer location depends also on the large-scale electric field (which is not exactly known in this case) it gives strong additional evidence of near-Earth location of the breakup source.

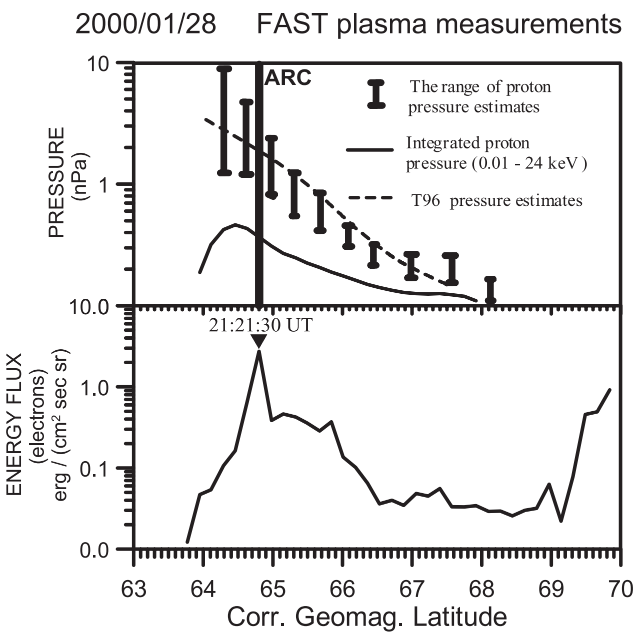

Figure 4. Latitudinal profiles of the proton pressure (top) and precipitated electron energy flux (bottom) according to FAST observations. Vertical line indicates the breakup arc position.

4. *Mapping with the magnetospheric model*: We used Tsyganenko 96 model with input parameters which are close to the values during previous half an hour, P_d = 3.25 nPa; Dst = −9 nT; B_y = 3 nT; B_z = −4 nT). To check its consistency with real observations we compared the locations of observed isotropic boundary and those computed from model according to the condition $R_c/\rho = 8$. Their difference appeared to be small, within 0.1°. Encouraged by this agreement we computed the pressure profile in the equatorial plane by integrating the x-component of the Ampere's force $\nabla P = j \times B$, starting from the point $X = -25\ R_E$ at the neutral sheet at the midnight meridian. (The pressure value here was initialized according to the lobe magnetic pressure at this distance [see *Kubyshkina et al.*, 1999] for more discussion). This computed pressure profile mapped to the ionosphere along the model field lines is shown by dashed line in the Figure 4. This profile agrees with experimental pressure estimates in both its shape and value, which is ∼2 nPa at the arc location. With such good agreement we believe that this T96 model is consistent with the real magnetic field in our event and that the arc is really mapped to the equatorial region at the distance $\sim 8\ R_E$.

[9] We searched but could not find any evidence that the breakup arc could be associated with the narrow flow burst intruding from the midtail into the near-Earth region. The orientation of the arc agrees within 15° with the ionospheric mapping of the cross-tail current. (The current line passing through the point $X = -8\ R_E$ at midnight equator, was computed from T96 model and mapped to the ionosphere, as shown by dot-dashed line in Figure 1). The amount of rotation in the process of mapping [see *Sergeev*, 2002] is small for equatorial magnetic fields of tens nanotesla inferred in the breakup region. Thus this arc could only be the mapping of the flow burst after it has been diverted azimuthally. The sensitive TV observations at Loparskaya did not support the latter option since the faint arc (predecessor of the breakup arc) has been already seen in the sky for about ten minutes.

3. Conclusions

[10] We have reported an event where the initial development of an auroral breakup was recorded reliably by the ground network at the end of the substorm growth phase and where the arc breakup region was probed with high time resolution by a few instruments on board the FAST spacecraft. The T96 model is consistent with observations in this case. The other methods of the source location determination showed the complementary results. Based on their mutual agreements we conclude that in this particular case the processes causing the auroral breakup took place in the near Earth region at $\sim 8\ R_E$ distance at midnight where: (1) the pressure value is ∼2 nPa and displays a strong Earthward gradient; and (2) the equatorial magnetic field strength is a few tens nT as strong. Such position is not consistent with the magnetic reconnection as the direct cause of the breakup, although the results do not rule out the operation of reconnection firmly established with Geotail observations [*Machida et al.*, 1999; *Ieda et al.*, 2001]. Our results do not reject a possibility that the breakup originates in the quasineutral thin current sheet, but this requires the transition region to be extremely sharp. Otherwise, as suggested by *Ohtani* [2001] the reconnection and current disruption may operate simultaneously in a coordinated way.

[11] **Acknowledgments.** Wind observations have been made available through CDAWeb. The Imaging Riometer for Ionospheric Studies (IRIS), operated by the Department of Communications Systems at Lancaster University (UK), funded by the Particle Physics and Astronomy Research Council (PPARC) in collaboration with the Sodankyla Geophysical Observatory. The work by SVD and VAS was supported by RFBR grant 03-05-64807 and InterGeophysics program.

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