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1. SUBSTORM CURRENT SYSTEMS

The polar magnetic substorm is one of several manifestations of the magnetospheric substorm. It is a magnetic perturbation with a peak magnitude of a few hundred gammas and a duration of about an hour. At times of high magnetic activity the substorms become more intense, occur frequently and a sequence of substorms may build up a magnetic storm.

The global distribution of the magnetic perturbation field during a substorm may be described by means of an equivalent current system, to be discussed later. The geometry of the real physical current system is as yet unknown, but it certainly must include the auroral electrojets in the ionosphere and Birkeland currents flowing along the geomagnetic field lines connecting the electrojets to the source regions in the outer magnetosphere. Figure 1 shows one simple model. The field computed for models of this kind shows good agreement with the field observed during isolated substorms (BIRKELAND, 1908, 1913; BOSTRÖM, 1968, 1969; AKASOFU and MENG, 1969; BONNEVIER et al., 1970). In fact the magnetic perturbation field from a model of this kind is equivalent to that of the classical purely horizontal ionospheric system (BIRKELAND, 1908, 1913; FUKUSHIMA, 1969).

In a model where the ionosphere is homogeneously conducting the field-aligned Birkeland currents will be coupled only to the Pedersen currents in the ionosphere. Together these currents produce a magnetic disturbance field mainly

above the ionosphere. In such a model the ground level magnetic perturbation field is produced almost solely by horizontal Hall currents circulating in the ionosphere. However, in a model like the one shown in Figure 1, where the ionospheric conductivity is assumed to be enhanced along the auroral oval, the Birkeland and Pedersen currents give a significant contribution to the ground level geomagnetic effect.

The current system shown in Figure 1 represents the change in the magnetospheric current system at the substorm onset. Before the substorm onset a westward current flows in the outer magnetosphere on the night side. This westward current may be a segment of a symmetric ring current (AKASOFU and MENG, 1969) or of the current in the neutral sheet. At the substorm onset a disturbance occurs in this part of the magnetosphere and a discharge to the ionosphere takes place. The magnetospheric westward current is then redirected and flows through the ionosphere. To represent this change of the state of the magnetosphere we must add the current system of Figure 1 to any already existing currents. Thus, in Figure 1, the eastward current segment in the outer magnetosphere does not represent the real currents flowing there. Initially the substorm current system has a short east-west extent and thus the circuit has a small inductance and short time constant. During the expansive phase the upward and downward flowing Birkeland currents separate and the westward electrojet in the ionosphere extends in longitude, as seen from ground based observations.

Several observations indicate that changes occur in the state of the magnetosphere during some hours before the substorm onset. PUDOVKIN et al. (1968) reports low latitude magnetic perturbations preceeding the substorm onset. COLEMAN and McPHERRON (1970) finds a general depression of the H field component on the night side at the ATS orbit before the substorm followed by a recovery at the time of the substorm. HONES (1970) reports a

thinning of the tail plasma sheet during the development of a substorm and CARPENTER and STONE (1967) find an inward drift of plasma around the plasmasphere before the substorm.

A magnetospheric current system is built up before the substorm onset and at the onset a discharge to the ionosphere occurs which changes the geometry of the current system.

Field-aligned Birkeland currents play an important role in the substorm phenomenon. Current densities of about 5×10^{-5} amp/m² have been inferred from rocket and satellite magnetometer measurements (ARMSTRONG and ZMUDA, 1970; CLOUTIER et al., 1970). There is evidence that the upward flowing current may be carried by the precipitating keV auroral electrons.

Indirect evidence for Birkeland currents may be found in Ba cloud electric field measurements over the polar cap (WESCOTT et al., 1970; HAERENDEL and LÜST, 1970). The current that would be produced by the local electric field could not explain the magnetic perturbations seen in the polar cap. The perturbations are produced by currents flowing somewhere else, for example along the field lines. In the magnetosphere the ATS magnetometer has recorded D component spikes, that may be caused by field-aligned currents, during the expansive phase of substorms (COLEMAN and McPHERRON, 1970).

2. SPACE CHARGE REGIONS ABOVE THE AURORA

If the current density of the Birkeland currents exceeds a critical limit instabilities may occur which drastically decrease the effective conductivity along the field lines. The two-stream instability has been suggested (SWIFT, 1965) but another possibility which often occurs in laboratory plasmas is that a space charge region is formed. This has a high potential drop over a very short distance. The electric fields associated with the space charge

region will accelerate auroral electrons and give rise to horizontal motions of the visual aurora (CARLQVIST and BOSTRÖM, 1970).

Space charge regions are expected to form when the drift velocity of the electrons exceed the thermal velocity. The critical current density estimated for the upper ionosphere, 3×10^{-5} amp/m², is of the same order as current densities inferred from rocket and satellite experiments.

It has been suggested (ALFVÉN and CARLQVIST, 1967, CARLQVIST, 1969) that the space charge regions may account for solar flares, and AKASOFU (1969) suggested that the same mechanism might occur on the field lines to the auroral oval. Magnetic energy stored in the magnetospheric current circuit would then be released in the space charge region. Due to the high inductance of the pre-substorm circuit this acts as a constant current source and where the circuit is broken the energy is released. Properties of space charge regions have also been discussed by BLOCK (1969).

Figure 2 shows a schematic cross-section of the proposed space charge region. The relation between the voltage drop across the space charge region and the current density is for a one dimensional model given by a relation similar to that for a vacuum diode. In Figure 2 the vertical voltage drop is maximum in the center of the space charge region and zero outside of it. Thus the potential varies along the upper (cathode) boundary. Since the magnetic field lines may be considered to be equipotential lines outside of the space charge region horizontal electric fields must exist in a column above the space charge region. No intense fields are formed below the space charge region since the lower ionosphere with high Pedersen conductivity would short circuit such fields. Provided the vertical field in the space charge region is directed so it accelerates auroral electrons downward, the horizontal field will be directed from

the boundaries toward the center of the column above the space charge region. These fields will set the plasma into a motion that may be seen as drifts of irregularities in visual auroral forms. For a filamentary field-aligned current structure we get a rotational motion in a clockwise sense viewed in the direction of the magnetic field, while for a sheet structure we get a streaming toward east on the poleward side of the auroral form and toward west on the equatorward side. Such motions, with the predicted direction, have been observed in TV auroral pictures (CARLQVIST and BOSTRÖM, 1970; HALLINAN and DAVIS, 1970; DAVIS, 1971). The velocities were in the range 4-20 km/sec, corresponding to electric fields of 0.2-1 volt/m, over regions about 10 km wide. Thus, we have a voltage drop of about 1-5 k volt between the center and outer boundary, and a similar voltage drop along the field lines in the space charge region.

Provided we interpret the auroral motions as electric field drifts it is necessary to introduce a mechanism by which the intense fields are prevented from penetrating into the E layer. This can only be done by introducing a voltage drop along the magnetic field lines, possibly in the form of a space charge region. The magnitude of the voltage drop estimated, 1-5 kvolt, falls in the range of typical energies for the monoenergetic peaks which often are seen in auroral electron fluxes. Thus the space charge region might in addition to giving rise to the motions also contribute to the acceleration of auroral particles.

3. TEMPORAL DEVELOPMENT OF SUBSTORMS

For a complete description of the magnetic perturbation field observed on the ground during a substorm the three field components H, D, and Z should be given as function of time, latitude and longitude. It is not possible to show the dependence on all three variables in one figure, but various plots where one or two of the variables are

kept constant may be used (ZAITZEV and BOSTRÖM, 1970).

Figure 3 shows isointensity contours for the H, D, and Z component in a latitude-time diagram. The longitude is constant; recordings along a north-south chain of stations through the Scandinavian and Soviet countries have been used to construct the plot. The plot shows the development and decay of four substorms. One of the most noticeable features in the plot of the H component is the rapid northward expansions of the region of negative H component, indicating a broadening of the electrojet region. The real electrojet is not as broad as the region of negative H perturbation, but when this region expands the electrojet expands northward. Positive H component peaks north and south of the electrojet are most pronounced in the early phase of the substorm. These peaks are caused by the field-aligned Birkeland currents at the eastern and western ends of the westward electrojet. In the later phase of the substorm, when the electrojet is extended in longitude, the Birkeland currents are further away from the north-south chain of stations and give a smaller contribution. The latitude of the peak of the negative H component varies with time and is lowest around 2100 UT, which is close to local magnetic midnight. This shows that the electrojet flows along the auroral oval and not at constant latitude. The vertical Z component is positive north of the center of the electrojet and negative to the south. The north-south motions of the center of the electrojet are not as pronounced as the northward expansion of the northern boundary seen in the Z component as well as in the H component. The D component was generally small indicating that the chain of stations was close to the center line of the current system.

Figure 4 shows in a polar plot isointensity contours for the scalar magnetic potential for various phases of a substorm. The contours are everywhere perpendicular to the horizontal component of the magnetic perturbation

vector at ground level and the separation between the contours is inversely proportional to the magnitude of the horizontal perturbation. These curves are generally referred to as equivalent overhead current systems, because a purely horizontal ionospheric current system of this form would give a perturbation field similar to the observed one. Plots of this kind may be used to represent at the same time both the H and D component as a function of latitude and longitude for constant time. The plots contain no observational information about the vertical Z component and should in general be supplemented by plots showing this component.

A computer program has been developed for automatic evaluation of the plots and has been used to prepare a movie showing the temporal development of the substorm. Figure 4 shows some frames of the movie. In the program no smoothing of the data is performed, so the contours are forced to be exactly perpendicular to observed field at the 36 observatories used. For this reason, and due to the uneven distribution of the observatories, the contours are somewhat irregular.

In the peak phase of the substorm the current system has one cell and a westward equivalent current flows around the auroral oval. The current is most intense (electrojet) in the midnight sector. In the early phase of the substorm the westward electrojet has only a short east-west extent. In between the substorms, or in the last phase of the substorms, weak current systems with two or more cells may exist. In this study of isolated substorms no indication of any confined intense eastward electrojet was found. However, the eastward jet may possibly be more typical for intense magnetic perturbations (storms). In a recent study of an intense magnetic storm GRAFE (1969) found that the eastward electrojet sometimes was dominant and sometimes absent.

Obviously the substorm current system may have very different forms. A concept like the "typical" or "average" system is not really very useful, although the appropriate form of this has been discussed over the last few years. In the future emphasis should be laid more on the study of individual events and the temporal development of these, including studies of possible magnetic effects of precursors to the substorm and the spatial and temporal development and decay of the electrojets.

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Figure captions

Figure 1. Three dimensional substorm current system.

Figure 2. Schematic cross-section of the space charge region.

Figure 3. Isointensity contours for the three field components for a sequence of 4 substorms on September 21, 1965, observed along a north-south chain of stations. (a) Northward H component. (b) Eastward D component. (c) Downward Z component.

Figure 4. Polar plots of isointensity contours for the scalar magnetic potential ("equivalent current system"). The frame of reference is geographic with 10° between latitude circles and the Greenwich meridian downwards. The universal time is given at the top. The distance between isointensity contours is equal to the length of one latitude degree when the horizontal perturbation is 100 gammas (about 18 kamp per equivalent current line). (a) Peak phase. (b) Weak current system between two substorms. (c) Electrojet starts to develop again. (d) Peak phase of new substorm.

Fig. 1

Fig. 2

FIG. 3a

FIG. 3b

FIG. 3c

561-T650921 00 2050.0

189-T650921 00 2140.0

FIG. 4c

189-T650921 00 2150.0

FIG. 4d