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THE DEVELOPMENT OF THE AURORAL SUBSTORM

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Abstract—A working model of simultaneous auroral activity over the entire polar region is presented in terms of the auroral substorm. The substorm has two characteristic phases, an expansive phase and a recovery phase. Each phase is divided into three stages, and characteristic auroral displays over the entire polar region during each stage are described in detail. Further, all the major features seen at a single station are combined into a consistent picture of large-scale auroral activity.

1. INTRODUCTION

The aurora tends to have a stable form, namely, that of a quiet homogeneous arc. Different active features added to the quiet form produce various forms of the aurora[1]. Simultaneous all-sky camera records from an area of intercontinental scale (e.g. Siberia–Alaska–Canada) indicates that the aurora simultaneously shows various active features at different places, different from place to place[2,3].

A certain active feature at a particular place is closely related to active features at other places. For example, the break-up is the most violent form of display and is most often seen around the midnight sector, but at the same time, or a little later, quiet arcs in the evening sky may brighten or become folded by westward travelling surges coming from the eastern sky[3]. Also at the same time, in the auroral cap encircled by the auroral zone, active bands move from the auroral zone towards the geomagnetic pole.

The sequence of auroral events over the entire polar region during the passage from auroral quiet through the various active phases to subsequent calm is called an auroral substorm*: it coincides with a magnetic (*DP*) substorm[4], with which it has some close relationships.

One of the aims here is to construct a reasonable model of simultaneous auroral activity over the entire polar regions, and to show how the various types of auroral display at different places are inter-related. For this purpose, I began by examining all the available Alaskan, U.S. sub-auroral zone and Canadian all-sky films, as well as some Antarctic ones. Auroral displays differ greatly from one to another; no two are exactly alike. Nevertheless, several characteristic features of active displays have been recognized; their appearance depends on the geomagnetic latitudes (gm. lat.) of the stations, and on their local time. After completing this first part of the study, I used the films of the Alaskan stations to examine how each major feature at a single station is related to displays at other stations. As has already been recognized, the major features occur on a scale comparable with the size of Alaska. The third step was to examine the Siberian and Canadian all-sky films when major features were seen over the Alaskan sky. Unfortunately this step was hindered by several difficulties, such as bad weather and malfunction of all-sky cameras. Further, the network of stations was not always close enough to examine in detail some of the essential features. These difficulties have been partly oversome by examining a large number of individual displays.

* The author owes the term auroral substorm to Dr. S. CHAPMAN.

These efforts have now led me to propose a working model of simultaneous auroral activity over the entire polar region in terms of the auroral substorm. All the major features are combined into a consistent picture of large-scale auroral activity (a number of examples used in this study are illustrated in the Annals of IGY, Vol. XX, Part 4: "Auroral morphology as shown by all-sky photographs"). Some of the earlier extensive statistical studies of the aurora are also discussed in the light of the present analysis of individual display and are included to construct the model.

2. THE AURORAL SUBSTORM

2.1 *General*

Each auroral substorm has a life time of order 1–3 hr, and consists of two phases. It always originates around the midnight meridian at the place where quiet arcs exist. The first phase is characterized by a sudden increase in the brightness of the part of a quiet arc that is near the midnight meridian and by subsequent rapid motion of the arc towards the geomagnetic pole. This expansive phase is rapid, taking place within only about 10–30 min.

After a certain lapse of time such abrupt and violent activity affects the aurora in various ways in both the evening and morning sectors. When bands moving rapidly polewards attain their northernmost point (in the northern hemisphere) they begin to return to their original location. This is the beginning of the second or recovery phase. During this phase various after-effects of the first expansive phase propagate towards both the evening and morning sectors. The second phase may last more than 2 hr and at its end there may be a few quiet arcs in the region where the arcs were originally located just before the auroral substorm began.

Several auroral substorms occur at intervals of a few hours or less during a moderately disturbed period. In more complicated occurrences a new substorm may start before the second phase of the preceding substorm is over. As the proposed working model of an auroral substorm is based on IGY data it corresponds to a time of rather high magnetic activity, although not necessarily to a time when a distinct sudden commencement storm is in progress. In fact, such substorms were almost daily events during the IGY. During sudden commencement magnetic storms, however, the frequency and the intensity of the substorm increases considerably. As a result the second phase may not be completed before a new substorm begins.

In the following, the model is described in detail. It is convenient to divide the whole sequence of the substorm into the following seven stages, including the quiet phase just before the substorm.

(a) $T = 0$ the quiet phase
(b) $T = 0 \sim 5$ min
(c) $T = 0 \sim 10$ min — the first phase (the expansive phase) [(b)–(d)]
(d) $T = 10 \sim 30$
(e) $T = 30$ min ~ 1 hr
(f) $T = 1 \sim 2$ hr — the second phase (the recovery phase) [(e)–(g)]
(g) $T = 2 \sim 3$ hr

Figure 1 shows schematically some of the essential features of the auroral substorm at each stage.

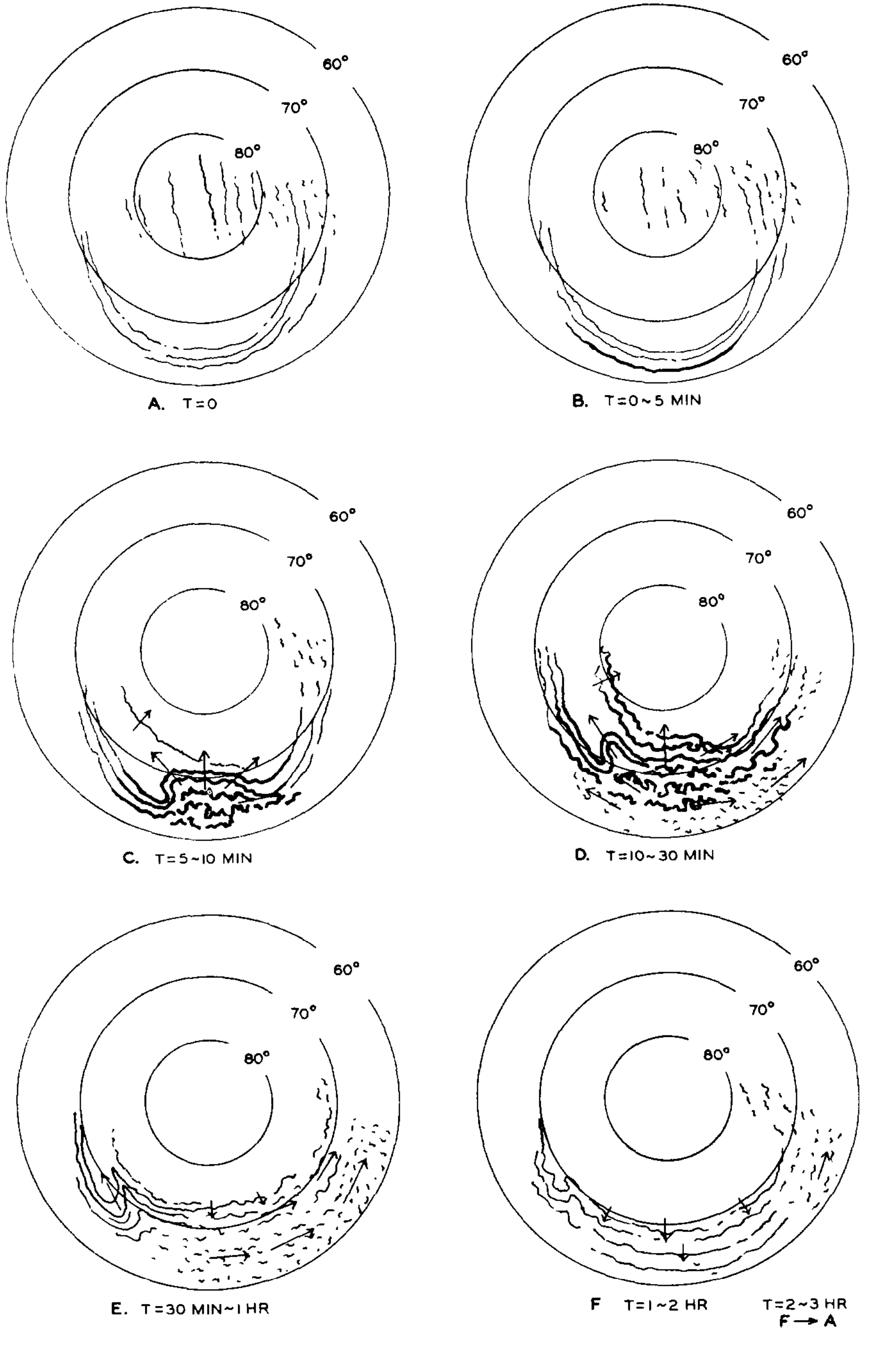

FIG. 1. SCHEMATIC DIAGRAM TO ILLUSTRATE THE DEVELOPMENT OF THE AURORAL SUBSTORM. THE CENTER OF THE CONCENTRIC CIRCLES IN EACH STAGE IS THE NORTH GEOMAGNETIC POLE, AND THE SUN IS TOWARD THE TOP OF THE DIAGRAM.

2.2 *The expansive phase*

(a) *The quiet phase:* $T = 0$ (*Fig.* 2). When the auroras in the polar region are free from activity for about 3 hr, most of these around midnight in the auroral zone become quiet and homogeneous arcs: some of them may be barely visible. They are approximately parallel to the geomagnetic latitude circles there.

One most characteristic feature of auroral cap bands is that they do not lie along the geomagnetic latitude circles. Even quite close to the auroral zone on the poleward side, arcs or bands do not lie along the gm. latitude circles in the twilight hours. Bands closer to the gm. pole, around gm. lat. 80° and beyond, tend to lie along the Sun–Earth line(5). Further, the location of an instantaneous auroral distribution can differ greatly from the statistical auroral zone(6–8).

If, however, the auroral zone is free from a significant substorm for about half a day or more, the situation may be quite different; at such times the auroral cap may be occupied by fairly active bands, whereas only faint arcs lie in the auroral zone. Typical examples of this are the displays on 23 and 28 December 1957; on those days the maximum *Kp* was only 1+.

The minimum gm. latitude at which quiet arcs finally settle after their slow equatorward motion during the second recovery phase of a substorm, depends on the intensity of the ring current(9). When this is moderate, e.g. when $D_{st}(H)$ is of order -30 γ, the latitude is likely to be between 60 and 65°. Between two auroral (and *DP*) substorms during a great magnetic storm, quiet arcs may descend to a gm. latitude as low as 50°. Typical examples are the arcs seen in the North American Continent during the storms of 13 September 1957 and 11 February 1958(10).

(b) *The expansive phase* (*Stage I*): $T = 0 \sim 5$ *min* (*Fig.* 3). The first indication is a sudden brightening (within a few minutes) of one of the quiet arcs a few thousand kilometers in length approximately centred at the midnight meridian. Other arcs may remain faint and diffuse until the brightened arc starts to move poleward: in some cases a barely visible arc may abruptly become bright, as if a new arc is suddenly formed in the midnight sky. The brightening is usually accompanied by the development of a distinct ray structure.

(c) *The expansive phase* (*Stage II*): $T = 5 \sim 10$ *min* (*Fig.* 4). If the substorm is very weak the brightening and some development of irregular folds are the only consequences. In most cases the brightening of an arc is followed by its rapid poleward motion. This results in a "bulge" around the midnight sector. When the substorm is weak the poleward motion lasts only for a few minutes and other arcs not may be seriously affected. Such a substorm results in the pseudo break-up(11): this is often the case when one of the arcs other than the southernmost one is activated. If, however, the southernmost arc is the first to become active, the poleward motion is usually most violent, resulting in a great bulge rapidly expanding poleward, westward and eastward. In general, the bulge, even when the substorm is only of medium intensity, covers an area large compared with the field of view of a single station.

The speed of the poleward motion depends on the intensity of the substorm. It is usually of order 20 $\sim$ 100 km/min. However, in some cases, it can be as fast as 200 km/min or even more. The center of the bulge in most cases is near the midnight meridian. In some cases, however, it can be shifted ± 1 hr to either side of the midnight meridian.

From a station located in the evening sector, the expanding bulge is seen as a motion of bright bands from the eastern sky. If the original location of the activated arc is equatorward of a station, the bulge is seen as a rapid motion of bright bands from the south-eastern sky (in the northern hemisphere). If a station is located just to the north of the auroral zone, the

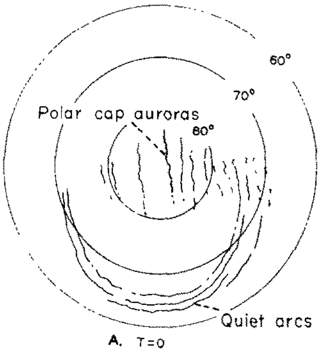

FIG. 2. THE DISTRIBUTION OF THE AURORAS DURING THE QUIET PHASE.

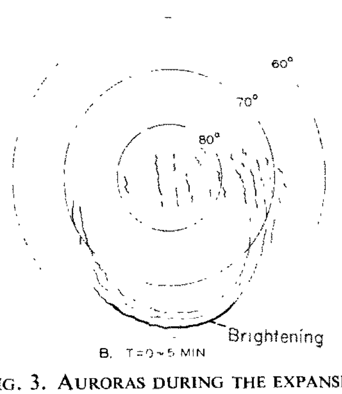

FIG. 3. AURORAS DURING THE EXPANSIVE PHASE (STAGE I).

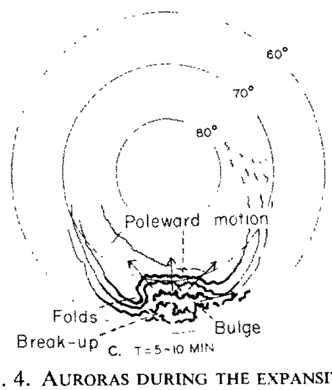

FIG. 4. AURORAS DURING THE EXPANSIVE PHASE (STAGE II).

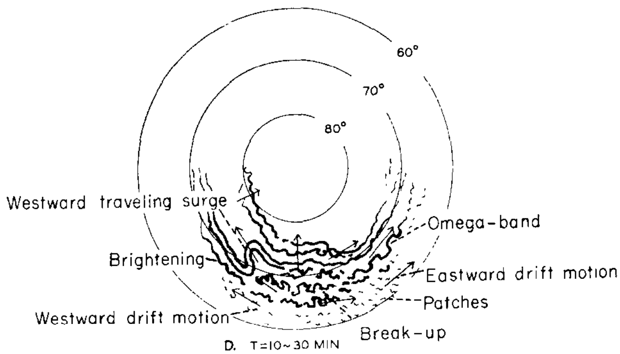

FIG. 5. AURORAS DURING THE EXPANSIVE PHASE (STAGE III).

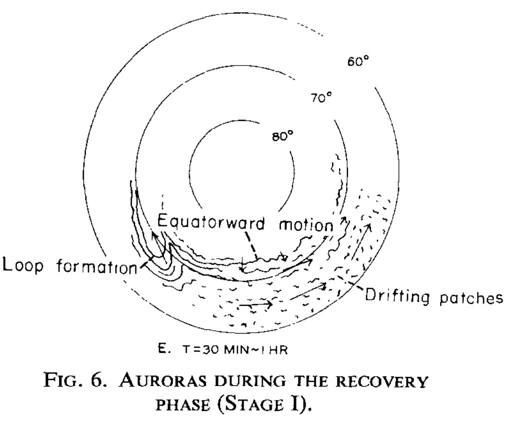

FIG. 6. AURORAS DURING THE RECOVERY PHASE (STAGE I).

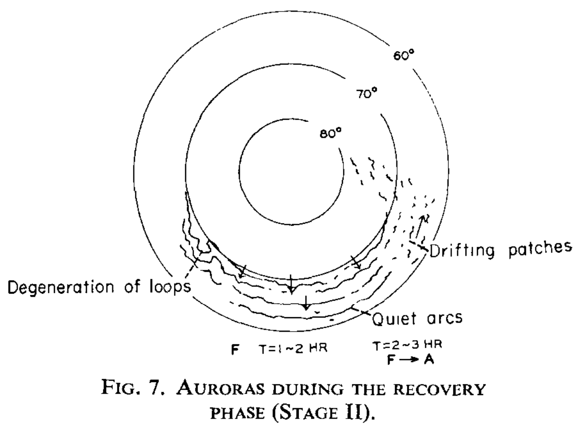

FIG. 7. AURORAS DURING THE RECOVERY PHASE (STAGE II).

original location of the activated arc is likely to be south of the station. Therefore, at such a station (like Barrow, Alaska) a rapid motion of bright bands from the south-eastern sky in the evening is almost a daily event.

In the morning sector the expansion occurs simultaneously over a greater range of longitude than on the evening side. Therefore, the folds or the loop seen in the evening sky can seldom be seen in the morning sky, although the expansion is often seen as a rapid motion of a bright band from the south-western sky.

Arcs or bands lying near the evening and morning twilight sectors are still unaffected at this stage of the substorm; faint arcs in the polar cap beyond gm. lat. 80° tend to disappear. An excellent example of this type of display was observed on 13 December 1958. This negative correlation between the polar cap auroras and magnetic activities has been studied by Feldstein(12) and Davis(13).

(d) *The expansive phase* (*Stage III*): $T = 10 \sim 30$ *min* (*Fig.* 5). At this stage of the substorm, the front of the expansive bulge around the midnight meridian reaches its northernmost point. The highest gm. latitude attained by active bands depends on the intensity of the substorm. When this is weak, the bands go up to between gm. lat. 70 and 75°, or even lower. For a medium substorm, it is around 75° but if the substorm is extremely intense the bands can go as high as gm. lat. 80° or even beyond. Within the bulge the bands are extremely active.

As mentioned already, the region beyond the auroral zone around the midnight sector is characterized by the absence of the aurora during the quiet phase. Particularly, in the midnight region between 75 and 80° auroras rarely appear even during fairly disturbed periods; few of the expanding arcs reach that far. Thus the occurrence frequency of the aurora in this region has a distinct minimum around midnight. In this region the daily variation of occurrence frequency of overhead auroras has a distinct double peak, in the early evening and late morning. The former corresponds either to active bands moving poleward during the substorm or to faint arcs and patches present during quiet periods: the morning peak is due mostly to faint arcs and patches during quiet periods(14,15).

In the evening sky, following the formation of the bulge, the folds are formed. The folds move rapidly westward because of the expansion of the bulge. In all-sky films, the folds are seen first as a mass of light at the eastern end of an arc. In about 5–10 min, they pass the zenith along the arc, and then disappear over the western horizon. These propagating folds are called a westward travelling surge(16,3). If a substorm is very weak, it generates only wavy motions of an arc, and there is little displacement of the arc after the surge passes on. The pseudo break-up is usually associated with a surge which is propagated along a brightened arc, without affecting others, During an intense substorm, most of the arcs lying near the midnight sector are much folded seriously, and the surge speed is rapid. The bands along which the surges move are greatly displaced poleward after the passage of the surges(16).

The speed of the surges depends greatly on the intensity of the substorm; it is of order $10 \sim 100$ km/min or $0{\cdot}17 \sim 1{\cdot}7$ km/sec. Because westward surges are the western edge of the expanding bulge, they are associated with the break-up to the east. It is very common to observe surges travelling westward across the Siberian sky (e.g. Wrangel Island, gm. lat. 64·7°N, gm. long. 133·8°W) about $10 \sim 20$ min after the expansive phase is seen in Alaska (e.g. Fort Yukon, gm. lat. 66·7°N, gm. long. 102·9°W); similarly, the expansive phase in Canada (e.g. Uranium City, gm. lat. 67·7°N, gm. long. 55·6°W) is seen as a westward surge in the Alaskan sky about 10–30 min later.

Most of the arcs lying in the early evening sector become bright and develop the ray structure and folds at this stage of a substorm. Particularly, an arc along which westward surges are propagated may become extremely bright; it often shows a slight equatorward motion a few minutes before the surge appears in the eastern horizon. Such active features seen in the evening sky are not independent of active displays at other places; they are closely related to auroral activity to the east.

The range of longitude in which surges and active bands are seen is another index of the intensity of a substorm. When this is extremely intense, westward travelling surges can be seen even in the evening twilight sky[16]. Such an event occurs, however, only during an intense magnetic storm.

One most important feature of the substorm at this stage is the appearance of westward drift motions of active or broken up bands in the evening sky, and eastward drift motions in the morning sky. This type of drift motion may appear in the second stage of the expansive phase, but in Stage III it becomes more significant. Well-defined bands, the so-called Ω bands, drift rapidly eastward.

Another interesting feature of the substorm at this stage is the break-up process of arcs near the dawn meridian. After becoming brighter for a few minutes, and showing a slight equatorward shift, arcs then break up without violent motions. The resulting patches are isolated and cloud-like, resembling a group of cumulus clouds. They drift away towards the twilight meridian. It is common to observe such a phenomenon in the Canadian sky corresponding to active displays in the Alaskan sky. To the south of the bulge, patches appear at this Stage III. They drift rapidly westward or eastward, depending on the local time; in the evening sector, it is mostly westward, but sometimes eastward; in the morning side it is always eastward[5].

2.3 *The recovery phase*

(e) *The recovery phase (Stage I): $T = 30$ min ~ 1 hr (Fig. 6).* As soon as the northernmost active band attains its highest latitude, it may start to return southward. Often, however, it stays at its northernmost point for as long as $10 \sim 30$ min and then starts to return. The size of the bulge is thus reduced. The speed of the return motion is usually less than that of the poleward motion, but sometimes it is as great as 50 km/min.

The speed of westward surges is also reduced during this stage. Westward surges may degenerate directly into small-scale irregular folds, if their intensity is weak. However, irregularly-shaped westward surges often become well-defined loops in a few minutes. A kind of bifurcation seems to take place during the loop formation, often resulting in a group of loops. The location of the loop formation is also an important indicator of the intensity of the substorm. If this is weak, loops can be formed a few minutes after the beginning in a region close to the midnight meridian. If the substorm is intense, the loops form after the westward surges have travelled a substantial distance, say $1000 \sim 2000$ km, in the middle of the evening sector.

The average drift speed of the loops is of order 30 km/min or 500 m/sec. A group of loops may be fairly stable and can drift a great distance, as much as 2000 km, with little deformation. During the 14 February 1958 display, a set of loops drifted from Central Canada to Eastern Siberia, a distance of about 4000 km.

The brightness of the arcs lying in the evening twilight sector is reduced at this stage; folds and the ray structure may disappear. In the morning sector, to the south of the auroral zone, most of the arc or band structure disappears, and patches spread over a wide area. They drift eastward with a speed of order 20 km/min or roughly 300 m/sec. In the morning sky, it is common to observe groups of patches drifting to the zenith from the western horizon and disappearing over the eastern horizon. This does not often occur to the north of the auroral one. Band forms are maintained without disruption.

(f) *The recovery phase* (*Stage II*): $T = 1 \sim 2$ *hr* (*Fig.* 7). The equatorward motion of the arcs continues over a wide range of latitude and longitude. New arcs form in the auroral cap and also in the patches, and join in the equatorward motion. Many of them become barely visible, however, during the motion. Sometimes, groups of patches seem to converge to form homogeneous arcs.

The drifting loops often become irregular bands at this stage; this irregularity is reduced in from 10 to 20 min, leaving quiet arcs.

Arcs that brightened during the expansive phase in the far western sector become faint, and some become barely visible.

In the morning sector, drifting patches may still be seen at this stage (II) to the south of the auroral zone. To the north of the auroral zone, faint arcs or patches reappear.

(g) *The recovery phase* (*Stage III*): $T = 2 \sim 3$ *hr*. This stage is also characterized by slow equatorward motion of arcs. No eastward or westward motion of the aurora is seen. The brightness of arcs may be considerably reduced. During a fairly disturbed period, this stage may not be seen at all.

3. DISCUSSION

3.1 *The sequence of auroral displays during the course of a night*

A single observer moves with the Earth with an angular speed of 15°/hr under a continuously changing pattern of the aurora. During a fairly disturbed period, there may be four or more substorms in about 12 hr. In each, the whole sequence A → B → C → D → E → F → G → A may be followed while the observer is in darkness.

The field of view of a single observer being limited, he can see only a small portion of the auroral displays at each stage of the substorm; he cannot discern more than 500 km away.

In the early evening sector, substorms manifest themselves by only an intermittent increase of the brightness of arcs or a little development of rays or folds. Hence arcs with occasional minor activity are the main auroral features in the evening sky.

As the night progresses and the observer moves towards the midnight sector, he will see westward travelling surges, drifting loops or even broken-up bands, depending on his location and the intensity of the substorm. Between two such active periods, an equatorward motion of arcs is seen.

If a substorm begins when he is around the midnight meridian or in the early morning sector, he will see its most brilliant phase. Later, he will see mostly drifting patches during the substorm; between two substorms quiet arcs will be seen. Such a sequence of auroral display as seen from one station during the course of a night has been well studied(17).

It is interesting to note that although the actual pattern of the aurora is continuously changing, as is seen in Fig. 1, many of the characteristic features of the substorm are local time dependent. For this reason, the active features of the aurora have often been said to be 'fixed' with respect to the Sun(5).

3.2 *Magnetic disturbances*

Medium westward surges are often accompanied by a short positive impulsive change in the magnetic record of H, the horizontal component. Its magnitude is of order $100 \sim 200\,\gamma$, and it lasts for 10–20 min. However, if the surge is very intense, there may be a sharp negative change of H of order $100 \sim 300\,\gamma$; its duration is usually not more than 1 hr. These are characteristic features of magnetic records in the evening.

The poleward expansion around midnight and in the early morning is always accompanied by a large negative change (a negative bay) of order $100 \sim 2500\ \gamma$. Rapid fluctuations superposed on negative bays are characteristic features of the magnetic records when drifting bands and patches are observed in the early morning sky. Thus, the whole nightly sequence of magnetic disturbances in most of the magnetic records obtained during the IGY at magnetic stations in the auroral zone, shows small positive impulses and occasional large negative impulses in the evening, sharp negative bays around midnight, and bays with rapid fluctuations in the morning. Between two substorms, the H-component returns approximately to a quiet day level.

Further extensive study is needed to improve the working model here presented and to study the relationships between the auroral and magnetic (DP) substorms.

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Резюме—Рабочая модель одновременной активности полярных сияний над всей полярной зоной представляется в условиях вызванной полярным сиянием суб–бури. У суб–бури имеются две характерные фазы—фаза расширения и фаза регенерации. Каждая фаза распадается на три стадии и дается детальное описание типичных полярных сияний над всем полярным районом во время каждой стадии. Далее, все главные характеристики, наблюдаемые на одинарной станции, совмещены в согласованном изображении широкой активности полярных сияний.