Special Contributions, Geophysical Institute, Kyoto University, No. 7, 1967, 15-21

ON THE PERIODIC MODULATION OF ENERGETIC ELECTRONS IN THE MAGNETOSPHERIC SKIRT REGION

By

Kunitomo SAKURAI

(Received October 24, 1967)

Abstract

The acceleration mechanism of the energetic electrons in the magnetospheric skirt region is considered. It is inferred that the periodic modulation of these electrons is due mainly to the pulsative change of geomagnetic field lines in the skirt region, and that the cause of such periodicity is intimately connected with that of the X-ray burst, cosmic noise absorption with the periods, 4 to 6 minutes and geomagnetic pulsation, Pc-5, which are usually observed in the auroral latitudes.

It is suggested that all electromagnetic disurbances are most violent at the dawn side of the skirt region compared with the other side, since the modulation mentioned above is strongest at the dawn side. As regards such disturbances, the rapid change of the geomagnetic field lines there with space and time may be most effective on the generation of energetic electrons. The acceleration mechanism of these electrons is examined in relation to the behavior of geomagnetic field lines.

1. Introduction

The skirt region, located between the magnetopause and the Van Allen trapping zone, is filled up with a vast of energetic electrons (Anderson [1965]; Anderson, Harris and Paoli [1965]). The fluxes of these electrons change instantaneously, and the width of such flux change occasionally attains about 1000 times.

The periodic modulation for the flux of these electrons has oftenly been observed by the satellites, IMP-I and II (Lin and Anderson [1966]). It has been shown that the period of such modulation is almost of the order of 4 to 6 minutes, based on the time-harmonic analysis of the observed data. Since the order of this period is well coincident with periods for geomagnetic pulsation, Pc-5 and cosmic noise absorption (Barcus and Rosenberg [1965]), existence of some relationships among them is inferred. For instance, the behavior of energetic electrons in the skirt region may be strongly related with the electron influxes oftenly observed at the geomagnetic high-latitude region and with other geophysical phenomena (O'Brien [1964]; McDiarmid and Burrows [1963]).

2. The Energetic Electrons in the Skirt Region

The occurrence of the periodic modulation of energetic electrons is most significant at the dawn side of the skirt region as is shown in Fig. 1 (Lin and Anderson [1966]). The period of this modulation almost ranges from 4 to 6 minutes, and this modulation oftenly continues repeatedly for two to three hours.

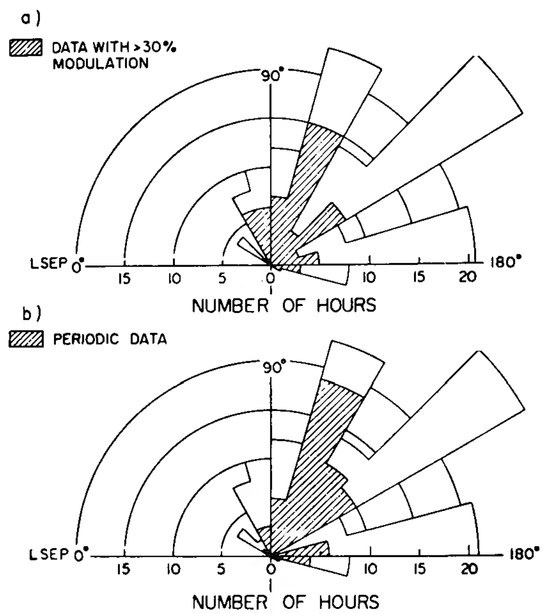

Fig. 1. The ratio of the observed duration of periodically modulated electrons to the total sounding duration, based on the results by Lin and Anderson [1966].

The order of the electron flux with energy >40 kev in the skirt region is always lower than that in the trapping zone. Even when the maximum for electron flux is attained in the skirt region, this flux is at most nearly equal to or lower than that for the outer fringe of the trapping zone (Anderson [1965]; Anderson, Harris and Paoli [1965]; Fan, Groeckler and Simpson [1965]). In general, the electron flux in the skirt region tends to become lower with going away from the outer boundary of the trapping zone. Both this distribution and the periodic modulation of energetic electrons are, therefore, useful for understanding the cause of such electrons.

The geomagnetic field lines passing through the skirt region go across the earth's surface in the latitude regions higher than the auroral zone. As has been described by O'Brien [1962], the geomagnetic field lines going across the earth's surface between the latitudes 67° and 82° close at day side from the northern to the southern hemispheres, but at night open into the magnetic tail. Hence the length of these magnetic field lines usually repeats a violent daily variation. In other words, the geomagnetic field lines, which are opened to the magnetic tail during night, close during daytime as is shown in Fig. 2· On account of this, the plasmas in the skirt region would vary violently at the dawn side in association with the reconnecting action and its resulting motion of the geomagnetic field lines.

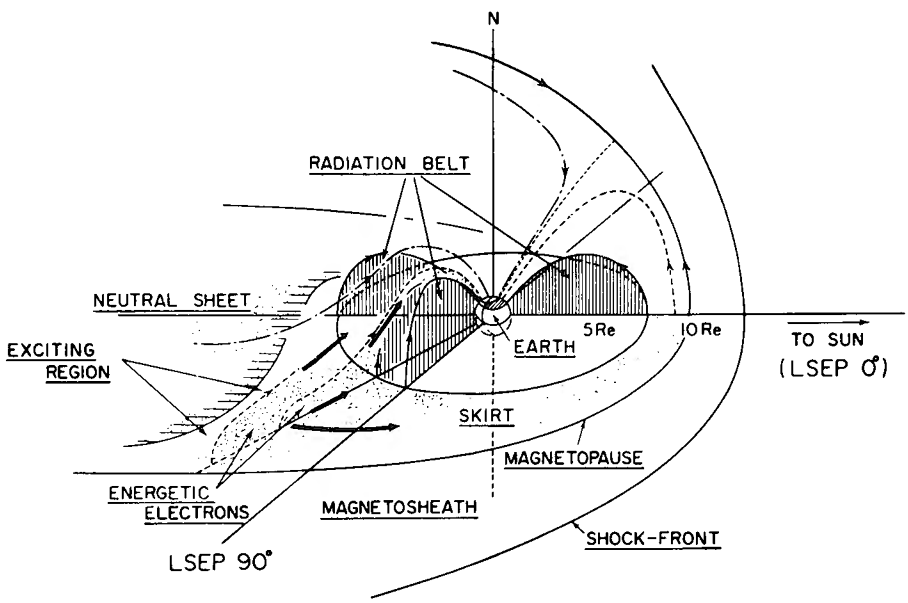

Fig. 2. The motion of the geomagnetic field lines and the behavior of the energetic electrons in the skirt region on the dawn side of the magnetosphere. The arrows indicate the movement of those electrons.

The geomagnetic field lines thus reconnected would contract toward the interior of the skirt region while releasing the magnetic energy accumulated as a result of the extension of these lines. Then, this magnetic energy would be transfered to the kinetic energy of the electrons and protons being trapped by these field lines by means of some acceleration mechanisms. Especially, the electrons would rapidly be accelerated in association with the contraction of these field lines. This circumstance is shown schematically in Fig. 2. These energetic electrons are estimated to precipitate oftenly into the high latitude regions along these geomagnetic field lines.

These geomagnetic field lines, as contracting, would reach near the outer boundary of the trapping zone. The momentum transported by this contraction is transfered to the plasmas and magnetic lines of force there. Through this

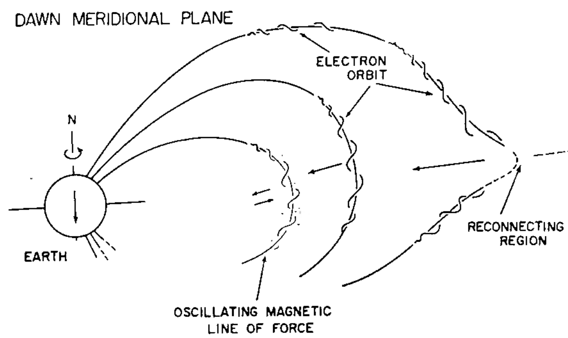

Fig. 3. The motion and oscillation of the geomagnetic field lines in the skirt region on the dawn side. The arrows show the pattern of the motion of those field lines.

transfer, the oscillations of the geomagnetic field lines near the outer fringe and just outside of the trapping zone are subsequently excited. The pattern of the motion of these oscillating magnetic field lines is indicated by the arrows in Fig. 3. Since the geomagnetic field lines near the outer fringe and just outside of the trapping zone oscillate periodically to and fro, the period of this oscillation would roughly be determined by dividing the length of field lines with the propagation speed of oscillation along the field lines, being identified with the resonating one. This oscillation is much efficient in accelerating the electrons and ions being trapped by those field lines. It seems, therefore, that the cause of the periodic modulation of energetic electron flux with the periods, 4 to 6 minutes mentioned earlier lies in such periodic oscillation of geomagnetic field lines.

Such oscillation with the periods, 4 to 6 minutes has oftenly been observed at the auroral latitudes, and the occurrence frequency of this oscillation is much higher in the fornoon hemisphere (Kokubun and Nagata [1965]). This oscillation is now called the geomagnetic pulsation, Pc-5. The periodic change of the above pulsation, Pc-5, the X-ray burst and the cosmic noise absorption, mentioned in section 1, may all be causatively connected with the modulating action of the energetic electron fluxes in the skirt region referring to the fact that the periods of them are all 4 to 6 minutes.

3. The Electron Acceleration and Hydromagnetic Waves

The oscillation of geomagnetic field lines generates hydromagnetic waves which accelerate the electrons and ions being trapped by field lines. Since this oscillation, being indentified with the geomagnetic pulsation, Pc-5, perhaps has some characteristics similar to the oscillation of the elastic string, the both ends of which are just fixed, the period of this oscillation is roughly determined by dividing the length of these field lines connecting between the north and south hemispheres with the mean propagation speed of hydromagnetic wave along the geomagnetic field lines. This means that these lines of force oscillate as a whole with a kind of resonant period. Therefore, the magnetic intensity changes periodically at any point in the magnetosphere with such period. Thus, the electrons and ions, while being trapped by those oscillating field lines, are accelerated in such a manner as the betatron mechanism.

As regards the electron acceleration, the betatron mechanism is most effective compared with the other mechanisms such as the Fermi one in the non-relativistic energy range (Sakurai [1965]). It is, therefore, expected that the accelerating process mentioned above is more favorable for the electron acceleration in the skirt region. Now, the energy equation for an electron is given by

$$\frac{\partial W}{\partial t}=e(\boldsymbol{v}\cdot\boldsymbol{b})(\boldsymbol{b}\cdot\boldsymbol{E})+M\boldsymbol{u}_E\cdot\nabla B+m(\boldsymbol{v}\cdot\boldsymbol{b})\boldsymbol{u}_E\cdot\frac{d\boldsymbol{b}}{dt}+m\boldsymbol{u}_E\frac{d\boldsymbol{u}_E}{dt}+M\frac{\partial B}{\partial t}, \tag{1}$$

where W is the electron energy, e and m, the charge and mass of electron, B, the magnetic intensity, $\boldsymbol{b}$, the unit vector of magnetic field lines, and $\boldsymbol{v}$ is the velocity of electron. Further,

$$\boldsymbol{E}+\frac{1}{c}\boldsymbol{u}\times\boldsymbol{B}=0, \tag{2}$$

and so,

$$\boldsymbol{u}_E=c\left(\frac{\boldsymbol{E}\times\boldsymbol{b}}{B}\right)=\boldsymbol{u}_\perp. \tag{3}$$

Since M is the magnetic moment, and the time-change of magnetic field is given by

$$\frac{\partial B}{\partial t}=-\boldsymbol{u}\cdot\nabla B, \tag{4}$$

the eq. (1) is transformed to, by considering the result by Northrop [1963],

$$\frac{\partial W}{\partial t}=-M(\boldsymbol{u}\cdot\boldsymbol{b})(\boldsymbol{b}\cdot\nabla)B+mv_{/\!/}^{*2}\boldsymbol{u}\cdot\frac{\partial\boldsymbol{b}}{\partial s}, \tag{5}$$

where $\partial\boldsymbol{b}/\partial s$ expresses the curvature vector for field lines. The efficiency of accelerations given by both the first and second terms of right side in the eq. (5) is equal each other (Sakurai [1965]). In consequence, the mean acceleration rate for electrons is given by

$$\frac{\partial W}{\partial t}=4\left(\frac{u}{c}\right)^2\frac{W}{\tau}, \tag{6}$$

where τ is the repeating time interval of acceleration. This formula is identical with the result for the Fermi acceleration since the time change of magnetic field is always rewritten by using the motion of field lines expressed as the eqs.

(2) and (4).

The electrons seem to be trapped by geomagnetic lines of force in such a manner as is shown in Fig. 3. After acceleration, these accelerated electrons would escape from the both ends of the geomagnetic field lines by which they are trapped.

The energy spectrum of these electrons after acceleration is given as

$$N(W)=\frac{\tau}{4(u/c)^2}W^{-\left(1+\frac{\tau}{T}\frac{1}{4(u/c)^2}\right)}\int_0^W q(W')W'^{\frac{1}{4(u/c)^2}\frac{\tau}{T}}dW', \qquad (7)$$

if the duration that electrons continue to be trapped and their initial flux are defined by T and q, respectively. As is evident from the above equation, the spectrum is given by a power law, which is favorable to the interpretation of the results observed by Fan, Groeckler and Simpson [1966]. That the index of the observed energy spectra becomes larger with the increase of geomagnetic activity (Fan *et al.* [1966]) could well be explained by taking into account that the duration for trapping becomes shorter with the increase of geomagnetic activity.

Since the intensity of geomagnetic fields is varied periodically with the oscillation of geomagnetic field lines, the electrons being trapped there repeat acceleration and deceleration in turn. As a result, the periodic modulation for electron flux is produced. Further, the period just mentioned must be coincident with the oscillation period of geomagnetic field lines. The periodic modulation for energetic electrons that has been found out by Lin and Anderson [1966] in the skirt region would be naturally generated in association with the oscillation of geomagnetic field lines such as geomagnetic pulsation, Pc-5.

4. Discussion

It has been inferred in the section 2, that in the skirt region the energetic electrons are generated through the reconnection and motion of geomagnetic field lines. Since the period of the modulation of these electrons is well coincident with those observed for X-ray bursts and cosmic noise absorption in the auroral latitude, it is, furthermore, deduced that these latter phenomena occur in association with the precipitation of those electrons along geomagnetic field lines.

The generation of the energetic electrons in the skirt region is perhaps due mainly to the oscillation of geomagnetic field lines, which is identified with some types of geomagnetic pulsation. It is thus inferred that these electrons are oftenly injected together into the upper atmosphere in the conjugate north and south high latitude regions. In consequence, it may be concluded that the phase for geomagnetic pulsation, Pc-5 is nearly coincident with that for the modulation of electron influx.

In conclusion, I wish to express my hearty thanks to Prof. Y. Tamura for his interest and stimulation. I am much indebted to Prof. K. Maeda, Prof. T. Obayashi and Dr. T. Hirasawa for their valuable discussion and criticisms on this work.

References

Anderson, K. A., 1965; Energetic electron fluxes in the tail of the geomagnetic field, J. Geophys. Res., **70**, 4741–4763.

Anderson, K. A., H. K. Harris and R. J. Paoli, 1965; Energetic electron fluxes in and beyond the earth's outer magnetosphere, J. Geophys. Res., **70**, 1039–1050.

Barcus, J. R. and T. J. Rosenberg, 1965; Observations of the spatial structure of pulsating electron precipitation accompanying low frequency hydromagnetic disturbances in the auroral zone, J. Geophys. Res., **70**, 1707.

Fan, C. Y., G. Groeckler and J. A. Simpson, 1966; Acceleration of electrons near the earth's bow shock and beyond, J. Geophys. Res., **71**, 1837–1856.

Kokubun, S. and T. Nagata, 1965; Geomagnetic pulsation Pc-5 in and near the auroral zones, Rep. Ionos. Space Res. Japan, **19**, 158–176.

Lin, R. P. and K. A. Anderson, 1966; Periodic modulation of the energetic electron fluxes in the distant radiation zone, J. Geophys. Res., **71**, 1827–1835.

McDiarmid, I. B. and J. R. Burrows, 1964; High latitude boundary of the outer radiation zone at 1000 km, Canad. J. Phys., **42**, 616–626.

Northrop, T. G., 1963; The Adiabatic Motion of Charged Particles, Interscience, New. York, pp. 109.

O'Brien, B. J., 1962; A large diurnal variation of the geomagnetically trapped radiation, SUI 62-23-A, State Univ. of Iowa.

O'Brien, B. J., 1964; High-latitude geophysical studies with satellite Injun 3. 3. Precipitation of electrons into the atmosphere, J. Geophys. Res., **69**, 13–44.

Sakurai, K., 1965; The adiabatic motion of charged particles in varying magnetic fields, Rep. Ionos. Sapce Res. Japan, **19**, 421–432.