DIFFUSION OF TRAPPED PARTICLES DUE TO THE BOUNCE-DRIFT RESONANCE INTERACTION IN THE MAGNETOSPHERE

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Abstract. Within the framework of the quasi-linear approximation, the hybrid diffusion process due to the bounce-drift resonance interaction between trapped particles and low-frequency field fluctuations is examined. The diffusion coefficients obtained, which are valid for particles with large pitch angles, cover the previous results in a few limiting cases. In general, the diffusion coefficients depend strongly on the spatial structure of the power spectrum along field lines, as well as the frequency dependence. The relative importance of the radial diffusion and field-aligned acceleration for ring-current particles is discussed. It is shown that the field-aligned acceleration exceeds the inward penetration of the particles near the plasmapause.

1. Introduction

Since the discovery of radiation belt particles there has been much observational and theoretical work on the transport of trapped particles in the magnetosphere (for review articles, see Hess, 1968; Roederer, 1970; Walt, 1971; Fälthammar, 1972; Williams, 1972; Schulz and Lanzerotti, 1974). Until now theoretical studies on radial diffusion of magnetospheric particles have been mainly concentrated on the drift-resonance interaction between particles and low-frequency, large-scale electromagnetic field fluctuations (for instance, Nakada and Mead, 1965; Fälthammar, 1965, 1966, 1968; Cornwall, 1968; Tverskoy, 1967; Birmingham, 1969).

Recent observations of ring-current particles have shown that these low-energy particles ($1 < w < 50$ keV) penetrate deep into the magnetosphere, say $L \sim 3$ to 4 Earth's radii, within a few hours of substorm onsets (Frank, 1967a, b; Frank and Owens, 1970; DeForest and McIlwain, 1971; Passignault et al., 1971; Hoffman, 1973). This effective penetration of ring-current particles correlates strongly with the inward shift of the plasmapause (Russell and Thorne, 1970), and is now attributed to the enhancement of the large-scale electric field within the magnetosphere during a substorm. It is inappropriate to apply the stochastic diffusion process due to the drift resonance of particles with the large-scale electric field to low-energy particles ($w \lesssim 10$ keV), since the drift time of these particles is longer than the typical time scale of the enhancement of the electric field during substorms (Tamao, 1972). Instead, the coherent convection due to the electric field drift motion of particles would be a rather

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more efficient process for such a case. As was shown by Swift (1971), however, due to the finite Pedersen conductivity in the ionosphere the primary large-scale electric field is shielded by the secondary induced field within the inner magnetosphere, and as a result the convection process is only applicable to the outer part of the magnetosphere. Thus, a further inward penetration of particles requires another transport process, that is, some stochastic interactions of particles with smaller-scale field fluctuations. Generally, small-scale disturbances are not uniform along magnetic field lines, except for the case of the flute-mode disturbance. There is another resonance interaction between the particle motion and field irregularities along field lines. This is the bounce resonance interaction of trapped particles. For instance, the bounce time of 1–50 keV protons at $L = 5 R_E$ is of about $\tau_b \approx 300 \sim 40$ s and 1–10 keV electrons have bounce periods of several seconds; the former covers the time scale of Pc 3–Pc 5 geomagnetic pulsations and the latter is nearly equal to that of Pi 1 pulsation.

In such a situation, it becomes necessary to consider the hybrid bounce-drift resonance interaction between trapped particles and field fluctuations. The problem of energy exchange between bounce-drifting particles and low-frequency waves in the magnetosphere was examined by Southwood et al. (1969). They derived a general relation between the radial displacement and energy change of the resonant particle to the first order of the perturbation fields. On the other hand, it has been pointed out that the pitch-angle diffusion through the bounce resonance is important for the loss of trapped particles with large pitch angles, because such particles do not have sufficient speed so as to match the cyclotron resonance with the electromagnetic waves (Roberts, 1969). Pitch-angle scattering through cyclotron resonance without change of particle energy has thus far been proposed as the main loss process of particles (Dungey, 1963; Cornwall, 1966, 1972; Kennel and Petschek, 1966; Cornwall et al., 1970; Lyons and Thorne, 1972). However, in the case of the resonant interaction of relatively low-energy particles and low-frequency waves, particle energy change is likely to occur simultaneously with displacement of the guiding center position. In the present paper, we shall formulate such a hybrid diffusion process due to the bounce-drift resonance, i.e. radial diffusion and field-aligned acceleration of trapped particles; both these processes are important for particle transport and wave generation in the magnetosphere.

2. Guiding Center Approximation and Drift Kinetic Equations

Within a frame of the drift approximation, let us now consider the interaction between charged particles and field fluctuations having low-frequencies and long scale-lengths. For such slowly varying fields, the particle motion can be separated into the rapid gyration component and the slow drift motion of its guiding center, $v = v_L + v_G$, where $v_L = dr_L/dt$ and $v_G = dr_G/dt$ are the Larmor and drift velocities, $r_L$ the Larmor radius vector, and $r_G$ the guiding center position vector. $v_G$ can further be divided into drift velocity components parallel and perpendicular to a field line, $v_G = v \| e + v_\perp$, where $\hat{e} = B/B$ is the local unit vector along the field line. The first order equation of motion