論文内容の要旨

Studies on Variability of Non-Thermal Emissions in Solar Flares

(太陽フレア非熱放射変動の研究)

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Many observations of hard X-rays (HXRs) and microwaves in solar flares have told that a significant amount of non-thermal electrons are produced. However, their kinematics of acceleration and transport is still an open question. The determination of the energy and pitch-angle distribution of accelerated electrons from the observations is essential to solve this problem. From both observational and theoretical studies, we determined the distribution of injection electrons and addressed electron acceleration mechanisms in solar flares.

We performed a comparative analysis of non-thermal emissions of HXRs and microwaves in the impulsive phase of the 2003 May 29 flare, to reveal characteristics of non-thermal electrons in a wide energy range. We focus on the higher energy HXRs above 100 keV that have been less studied and thus less understood so far. We found that the spatial distribution of the higher energy HXRs coincides with that of the lower energy HXRs below 100 keV while the time profile of the spectrum of the higher energy HXRs is similar to that of the microwaves. This analysis showed characteristics of higher energy HXR-emitting electrons (in intermediate energy range) as well as lower energy HXR-emitting electrons (in lower energy range) and microwave-emitting ones (in higher energy range).

To explain the observed variability and determine the injection pitch-angle distribution, we developed a general treatment of the electron transport model called trap-plus-precipitation, by solving the Fokker-Planck equation in space, energy, and pitch angle. Comparing the calculations and observations, we showed that the trap-plus-precipitation model in the weak diffusion regime can explain the variability of the observed non-thermal emissions. By the observed characteristics of the higher energy HXRs, we concluded that the electrons are accelerated more perpendicular to than parallel to the magnetic field line. We suggest a possible mechanism of the betatron acceleration to yield this pitch-angle distribution.

We performed a detailed analysis of the spatial distribution of non-thermal emissions in the early impulsive phase of the 2003 May 29 flare. We found an energy-dependent asymmetric distribution of footpoint HXR sources appeared at the southeast and northwest sites. The northwest footpoint HXR source is brighter (weaker) for lower (higher) energy than the southeast one, and its time profile leads the southeast. This variability could not be explained by previously proposed scenarios. We showed that this could be explained if the injected electrons have an asymmetric pitch-angle distribution in direction parallel to the magnetic field. A field-aligned electric field is a candidate to yield this pitch-angle distribution.

We numerically studied the electron propagation along the loop based on the observation of the 1999 August 28 flare. From the refined modeling of the electron propagation with the Fokker-Planck equation and the gyrosynchrotron radiation, we concluded that the injected electrons have to be widely distributed in pitch-angle space to yield the observed propagating feature of the microwave source. We suggest that the electrons are almost isotropically accelerated in this flare.

By the observational and theoretical studies, we addressed the pitch-angle distributions of injection electrons in three cases. These are different from each other, implying that a different acceleration mechanism efficiently works in a different physical condition. A macroscopic magnetic field configuration is one of the keys. During the impulsive phase of the 2003 May 29 flare, the flare geometry shows a simple two-dimensional configuration, which is close to the dipole magnetic field or is described by the Petschek-type magnetic reconnection model. In such geometry, the adiabatic betatron acceleration works more efficiently than the adiabatic Fermi acceleration. Consequently the electron pitch-angle distribution is concentrated perpendicular to the magnetic field line.

On the other hand, the geometries in the early impulsive phase of the 2003 May 29 flare and the 1999 August 28 flare are different from the two-dimensional picture. They show a complex three-dimensional configuration. In such geometries, the betatron acceleration might not play a dominant role. Different electron acceleration mechanisms might efficiently work and then yield different pitch-angle distributions.