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主　論　文　の　要　旨

論文題目

Estimation of the neutron emissions during
the large flares of solar cycle 24
第２４太陽活動期における中性子放出量の評価

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論　文　内　容　の　要　旨

Solar flares are one of the efficient particle accelerators that exist in the universe. They are capable to release highly energetic particles, including electrons and ions, to relativistic speeds. The first one has been widely studied by the emission of X- and γ-rays, whereas the latter, especially the most energetic ones (>100MeV), is still unknown. To understand how these ions are accelerated, it is important to study a variety of observations such as ions themselves and secondary γ-rays and neutrons. In order to avoid the complexity of the interplanetary magnetic fields, it is useful to examine solar neutrons, because they are not affected by those magnetic fields when traveling to Earth. Solar neutrons are sometimes produced by the interaction of accelerated ions with the solar atmosphere. Some of the neutrons that escape from the Sun can reach the Earth. These neutrons can carry crucial information regarding the acceleration process occurred at the solar flare.

Ground-level detectors were installed to search for solar neutrons. During solar cycles 21, 22 and 23, thirteen solar neutron events were observed with high significance on the ground. The production time of the neutrons was associated to that of the X- and γ-rays. Those events were mostly found whenever statistically significant excesses were found in the data of Neutron Monitors (NM) and Solar Neutron Telescopes (SNT). Thus far, no systematic search for solar neutrons has been performed. Particularly, the relation between the solar neutron production and the scale of solar flares has not been discussed.

In the present work, a systematic method is developed to search for solar neutrons in association with large solar flares. The onset and maximum intensity time of soft X-rays observed by GOES (1.5-12keV) were used as the most probable production time of solar neutrons. The search was performed in two campaigns. In the first, three years (January 2010 to August 2013) of data collected by the Chacaltaya NM and twenty-eight M- and three X-class flares were used. The Chacaltaya NM has the highest efficiency to detect solar neutrons in the world. In the second, five years (January 2010 to December 2014) of data collected by the SNTs and the Chacaltaya NM were used. Thirty-five X-class flares were examined. In both campaigns, light curves were built for each studied flare. Based on these curves, a statistical analysis was performed. A significance level of greater than 3σ was set to identify an enhancement. The result of both campaigns produced no significant and positive excess attributable to solar neutrons. Therefore, upper limits on the greater than 100 MeV of the solar neutron emission for the 35 flares of the second campaign were estimated. A power-law shaped neutron energy spectrum and impulsive emission were assumed.

The estimated neutron emissions were compared with those of solar neutron events observed during solar cycle 23. The obtained results are consistent within one order of magnitude. The total energy release of solar neutrons was calculated for each of the 35 flares and compared with those of the radiated energy of soft X-rays. The newest understanding is: 1) in the strictest upper limit, neutrons are at most one order of magnitude lower than that of soft X-rays; 2) the lowest upper limit of neutrons is four orders of magnitude lower than that of soft X-rays; and 3) the neutron emissions for the successful detections observed during solar cycle 23, range from 10^{-4} to 10^{-3} of the soft X-ray fluxes.