Analysis of Radiation Damage in On-orbit Solar Array of Venus Explorer Akatsuki

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Abstract

This paper describes an analysis of radiation damage in solar array of Venus explorer Akatsuki observed on orbit. The output voltage of the solar array have shown sudden drops, which are most reasonably associated with radiation damage, three times since its launch. The analysis of these radiation damages is difficult, because no direct observation data of the spectra and the amount of the high-energy particles is available. We calculated the radiation damage using the relative damage coefficient (RDC) method assuming a typical spectral shape of protons.

1. Introduction

JAXA has been operating a Venus explorer Akatsuki, which is on the orbit similar to that of Venus at the moment, since its launch in 2010. We have observed sudden drops in the solar array output voltage three times so far. We presumed that solar energetic protons caused the voltage drops as described later. In this paper, we report the telemetry data and analytical results of the radiation damage. On-orbit observation of radiation damage on solar arrays is limited, though the radiation damage is one of the most important issues of solar arrays. We believe the telemetry data of the Akatsuki is very valuable.

2. Mission Overview

The Akatsuki in flight configuration is depicted in Fig. 1. The spacecraft mass is 502 kg, including the fuel and the oxidizing agent of 189 kg and the observation cameras of 33 kg. It is equipped with two solar array paddles, which are mounted on the north and the south surfaces of the body and rotate to track the sun. Each panel is 1.43 m wide and 1.036 m long, with a boom about 0.9 m long. The front side of the panels are covered by triple junction solar cells with an efficiency of 28.3% from SHARP Corp., recognized as JAXA-QTS-2130/502. The solar cells are covered by 100 μm-thick CMG cover glasses with AR coats. The predicted generated power is more than 480 W at 1.0781 AU and more than 660 W on the Venus orbit. The rear side is covered by optical solar reflectors (OSRs) to lower albedo input from Venus. The designed temperature range of the solar array is –170°C - +184°C. The output voltage of the solar arrays are regulated not by a shunt regulator but by a series switching regulator, because the distance between the spacecraft and the sun varies from 0.7 AU to1.07 AU, resulting in large output voltage variation.

The main objective of the Akatsuki mission is to observe a mysterious atmospheric circulation on Venus

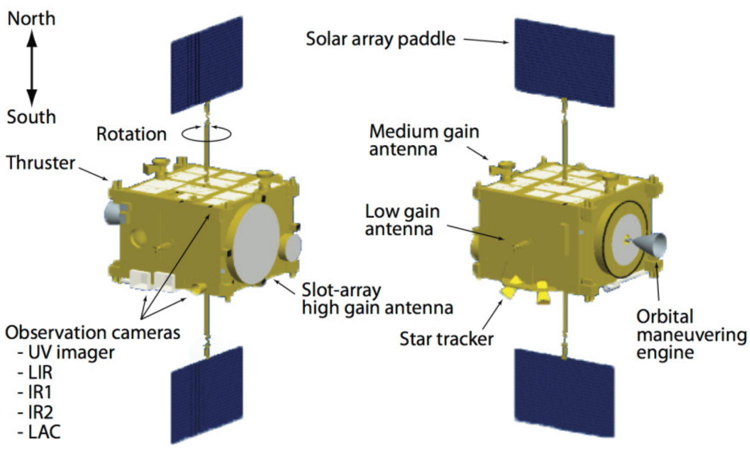


Fig. 1. Venus Explorer Akatsuki

using five cameras covering from ultraviolet to near infrared light.

3. On-orbit Performance of Solar Array

3.1 Operation history

The Akatsuki was launched on May 20, 2010 (UTC) by the H2A launch vehicle. The solar array-related telemetry of the Akatsuki is shown in Fig. 2. At first, the spacecraft went away from the sun to the distance of 1.07 AU, where the solar array temperature was +33ºC. After that, the solar array temperature increased as the spacecraft went nearer to the sun, and reached at +106ºC when it met Venus on December 6, 2010 (UTC). Regrettably the Akatsuki failed in the orbit insertion and is on a orbit around the sun with the perihelion distance of 0.61 AU and the aphelion distance of 0.7 AU. The solar array temperature is between +100ºC and +140ºC, which is below the expected temperature of +144ºC on the orbit around Venus. The output voltage of the solar arrays has been changing according to the temperature. The Akatsuki is expected to meet Venus in November, 2015 again. The mission life extended by 2 years and temperature raise near the perihelion are the important problems for the Akatsuki.

3.2 Radiation damage analysis

The output voltage of the solar arrays have shown sudden drops three times so far as indicated in Fig. 3. Fig. 4 shows the output voltage trend during the first voltage drop on June 5, 2011. It fell gradually by 1.63 V in about two hours.

We examined three possible causes: failure in the electronic circuits, change in the solar array temperature and/or the load, and radiation damage. The possibility of the failure in the electronic circuits was denied, because it is unlikely to cause gradual voltage drop. No change in the solar array temperature or the load that could cause the voltage drop was not observed. Radiation damage could cause the gradual voltage drop shown in Fig. 3, and we confirmed occurrence of two large solar flares that correspond to the voltage drop.

It is, however, difficult to analyze the solar flares and the voltage drop for two reasons: the output voltage of the solar arrays are regulated by a series switching regulator, and almost no observation data of solar energetic protons (SEP) generated by the flares are available. When output voltage of solar array is regulated by a series switching regulator, the operation point on the current and voltage (IV) curve comes to the constant voltage part, resulting in difficulty in estimating the entire IV curve or at least the short circuit current (I_{sc}), the open circuit voltage (V_{oc}) or the maximum power (P_{max}). Fig. 4 shows the positions of the Akatsuki, the sun and the earth, and the direction of the corona mass ejection (CME) which could cause the voltage drop. The Akatsuki was on the opposite side of the sun from the earth when the CME was released, therefore, the energy spectrum of the SEP was not observed by any satellites. Optical images captured by the STEREO satellite of NASA were the only

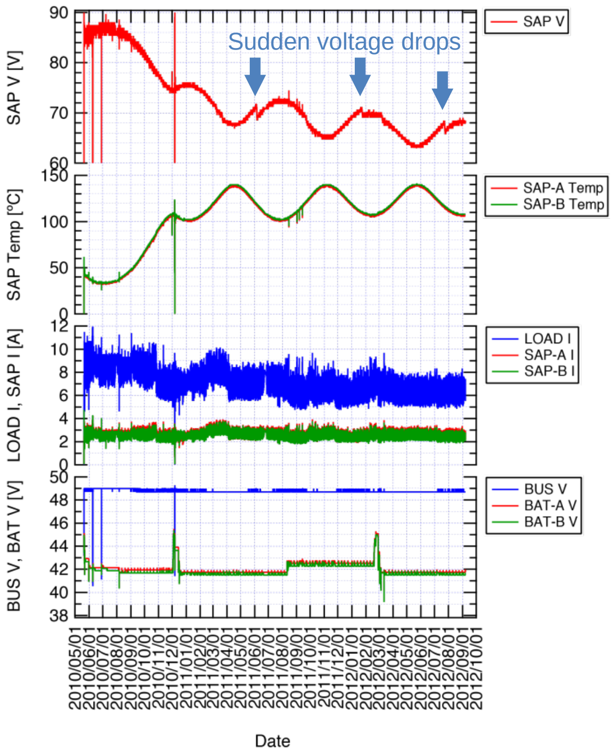


Fig. 2 Solar array-related telemetry data since launch.

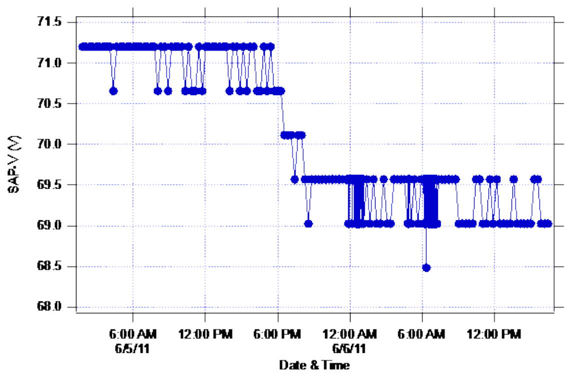


Fig. 3 Solar array output voltage trend showing sudden voltage drop on June 5, 2011.

observation data available. We took two approaches to estimate the SEP spectrum. Firstly we estimated the SEP spectrum from the CME speed, but the calculated degradation did not agree with the observation. Then we calculated a SEP spectrum which gives degradation which agrees with the observation. The following is the procedure and the results of the analysis. We used the relative damage coefficient (RDC) method to estimate the degradation of the solar cells in both approaches.

Fig. 5 shows ultraviolet (UV) images and white-light coronagraphs taken by the STEREO/Ahead satellite. Fig. 5 (a) and (b) shows the first flare (flare 1), which occurred at around 6:50 on June 4, 2011, and (c) and (d) shows the second flare (flare 2), which occurred at around 21:50 on the same day. From successive pictures captured by the STEREO/Ahead satellite, we estimated the speed of the CME 1 and the CME 2 to be 1200 km/s and 2200 km/s respectively at their occurrence. The CME 2 is supposed to catch up the CME 1 and they were merged before hitting the Akatsuki. Fig. 6 shows the relationship between the proton intensity and the CME speed when two CMEs occurs successively [1]. We assumed a typical SEP spectrum shown in Fig. 7 [2]. Actually we estimated the degradation of the solar cells based on several different shape of SEP spectra, but they did not make a significant difference, because the degradation is dominated by protons of 4-5 MeV as seen from the RDC shown in Fig. 8. From the relationship shown in Fig. 6, the Proton intensity is estimated to be 10^2-10^4 cm^{-2} s^{-1} sr^{-1}, because the speed of the CME 2 was 2200 km/s. We changed the SEP fluence so that the integral proton fluence over 10 MeV is 10^4 cm^{-2} s^{-1} sr^{-1} keeping the spectral shape shown in Fig. 7. Calculated IV curves before and after the voltage drop are shown in Fig. 10 as a green and a blue line respectively. The telemetry data are also shown as green and red crosses. The estimated degradation is too small to explain the observed voltage drop.

Next, we calculated a SEP spectrum which causes the same amount of degradation in the solar cells as the observation. Fig. 9 shows the result. The degraded IV curve is shown as a red line in Fig. 10. The SEP spectrum

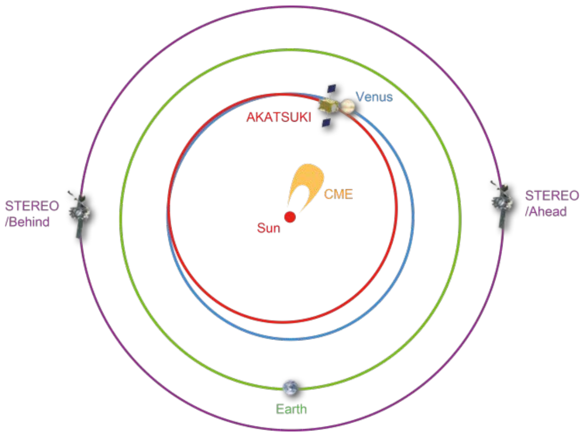
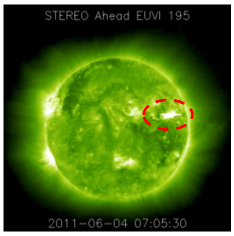
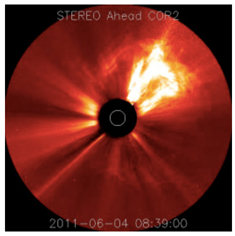


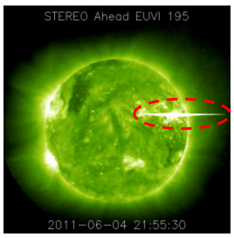
Fig. 4 Position of Akatsuki, Earth and Venus when solar array voltage dropped.



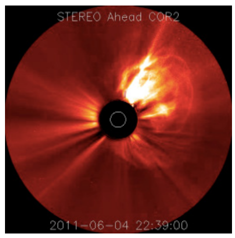
(a) UV image of flare 1.



(b) White-light coronagraph of flare 1.



(c) UV image of flare 2.



(d) White-light coronagraph of flare 2.

Fig. 5 Optical images of solar flares that could cause voltage drop captured by STEREO/Ahead satellite.

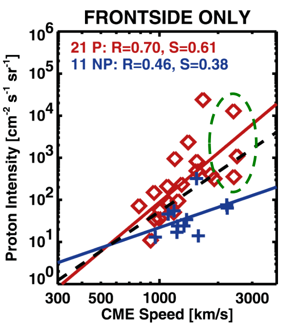


Fig. 6 Proton intensity over 10 MeV vs corona mass ejection (CME) speed [1].

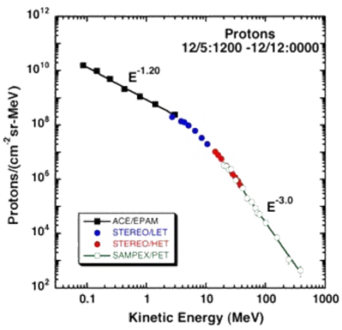


Fig. 7 Solar proton spectrum used for analysis [2].

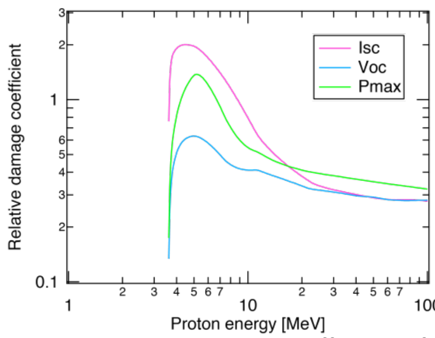


Fig. 8 Relative damage coefficients of solar cells for Akatsuki.

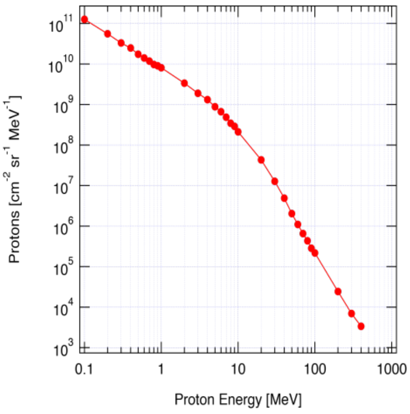


Fig. 9 Solar proton spectrum which gives radiation damage corresponding to observed voltage drop.

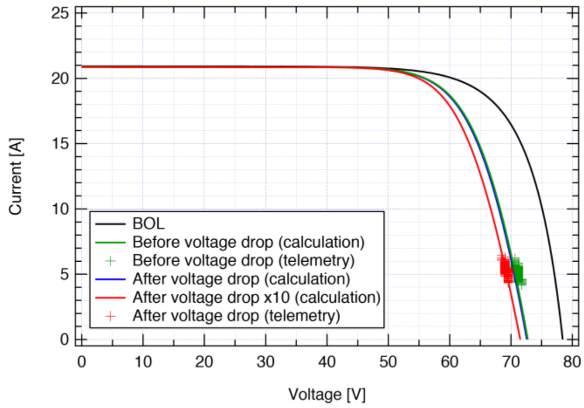


Fig. 10 IV curves calculated using RDC method and telemetry data before and after solar array output voltage drop.

shown in Fig. 9 is ten times as intense as that shown in Fig. 7 and at the same level as the most intense SEP on record. Though no proof of this SEP spectrum can be shown, it is at least within the realm of possibility.

4. Summary

This paper reported telemetry data of the solar arrays for our Venus explorer Akatsuki, which is on a orbit similar to that of Venus. Sudden voltage drops of the solar array were observed three times so far. Since estimating the entire IV curve is difficult due to the use of a series switching regulator and no observation data on the solar energetic protons are available, we calculated the spectrum of the protons which could cause the observed voltage drop using the relative damage coefficient method. The calculated spectrum was at the same level as the most intense one on record.

Acknowledgments

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