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研究課題名（和文）Fighting the Cosmic Ray Effect in the Next Generation of Space Missions

研究課題名（英文）Fighting the Cosmic Ray Effect in the Next Generation of Space Missions

研究代表者
Ｓｔｅｖｅｒ　Ｓａｍａｎｔｈａ（Stever, Samantha）

岡山大学・自然科学学域・特任助教

研究者番号：２０８４２９９１

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研究成果の概要（和文）：本研究プロジェクトでは、次世代CMB望遠鏡における宇宙線システマティック効果の評価に関連する多くの実験とシミュレーションタスクを実施した。CMBを大きな角度スケールで測定する必要があるため、宇宙からの測定が必要となり、望遠鏡は宇宙線の影響を受ける.

本研究では、ライトバードの宇宙線による系統的な影響を評価するためのエンドツーエンドのシミュレータを作成しました。宇宙環境、焦点面の熱応答、検出器の電熱応答、時間順に並んだデータの地図への伝搬を考慮することで、CR効果の深刻さを軽減するためのレベルを見つけることができます。

研究成果の学術的意義や社会的意義
The next generation of cosmology telescopes seeks to measure primordial B-modes, which would provide direct evidence of cosmic inflation, and the human understanding of how we came to exist. This has fundamental impacts on the origins of humanity. The removal of CR effects makes this goal possible.

研究成果の概要（英文）：During the course of this research project, we have carried out a large number of experiments and simulation tasks relating to evaluating cosmic ray systematic effects in next-generation CMB telescopes. Because it is necessary to measure the CMB at large angular scales, measurements must be taken from space, and telescopes are therefore subject to cosmic radiation. Detectors on such telescopes are very sensitive and are kept at cold temperatures in order to reduce noise and measure the small sky signal very precisely.

In our study, we have produced an end-to-end simulator for evaluating the systematic effects produced by cosmic rays in LiteBIRD. By accounting for the space environment, the thermal response of the focal plane, the electrothermal response of the detectors, and the propagation of time-ordered data into maps, we can find the level of CR effects in order to reduce the severity of them.

研究分野：astrophysics instrumentation

キーワード：astrophysics　cosmology

１．研究開始当初の背景

Space-borne telescopes offer a large number of advantages to ground or balloon-based telescopes; the astronomical signal is not contaminated by the atmosphere, the full angular scale of the sky is able to be observed, and the environmental conditions in space are very stable. Some wavebands are further restricted into space by atmospheric absorption, as is the case with X-rays and gamma rays. In Cosmology, future missions rely on full-sky mapping and will therefore have their measurements taken in space.

Of course, with the benefits also come drawbacks. It is extremely important to have an operational system at launch, because something in space is not easily repaired. These systems have to have precision control over systematic effects ahead of the launch, or the results could be disastrous. One systematic effect is that arising from cosmic rays within and outside of the Galaxy.

Future cosmology space missions make use of very sensitive detectors which operate by measuring the change in heat from the light incident upon them. However, cosmic rqays will be continuously impacting these telescopes during their orbit. These cosmic rays are charged particles which will deposit their energy into the telescope focal plane as heat, which is then confused with the sky signal.

It is therefore vitally necessary to characterise and study this systematic effect in order to predict, mitigate, and eventually remove it from the science data. The goal of this study is to do this in the form of an end-to-end simulator which will be used to predict cosmic ray systematic effects in a next-generation Cosmology space telescope.

２．研究の目的

The objective of the study is to couple macroscopic and microscopic factors in order to produce a wide perspective on the issue of cosmic ray systematic effects in next-generation Cosmology experiments. This is done using both experiments and simulations, although the bulk of the finished work is simulated due to COVID-19 restrictions on travel.

The study uses the next-generation JAXA-led space telescope LiteBIRD as the working example. LiteBIRD will be launched in the 2030s, and seeks to measure primordial gravitational waves (B-modes) which are the footprints of cosmic inflation in the early Universe. LiteBIRD uses very sensitive detectors which will also be very sensitive to cosmic rays.

The study therefore aims to predict and characterise the scale and the vulnerability of LiteBIRD to cosmic radiation, which informs mission design and mitigation methods.

３．研究の方法

The first stage of the research involves evaluating the cosmic ray environment during the time that the LiteBIRD spacecraft will be actively observing. LiteBIRD will fly at an orbit at the second Earth-sun Lagrange point, during a time in which the magnetic activity of the Sun will be minimal. The magnetic activity of the Sun is important to consider in relation to cosmic ray flux because the magnetic field of the sun attenuates cosmic rays coming from outside of the solar system. The late 2030s will during the peak of a solar minimum, i.e. the time of minimal solar activity and the highest cosmic ray flux.

In order to predict the flux, we use the publicly available data of the PAMELA satellite which measured proton flux on a monthly basis during the period of the last solar minimum. We choose the end-2009 case, or worst case scenario, as the sample flux for our study. From this we draw a probability distribution function in order to draw our expected energies from. This PDF allows us to generate a list of events which are then used to make simulated time-ordered data. The proton flux is shown in Figure 1.

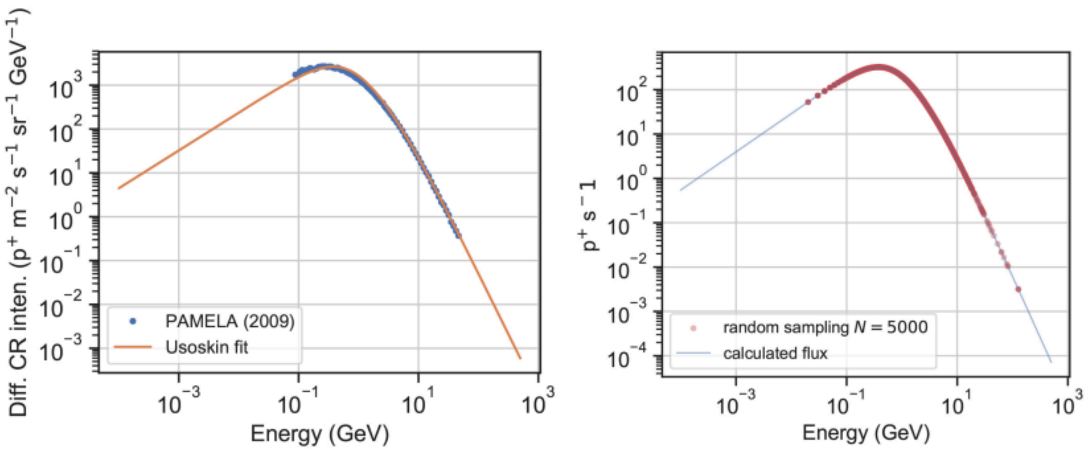

Figure 1: [Left] PAMELA end-2009 differential cosmic ray intensity (blue dots) and a model fit (Orange) extended to low energy regime. [Right] Probability density function of CR flux arriving at the detector wafer (blue line) and N = 5000 random sampling.

The next stage of the study involves evaluating the response of the focal plane of LiteBIRD to energy depositions in specific locations. Specifically, we simulate a wafer of the Low Frequency Telescope (LFT) on which many detectors are situated. This is done using the software package COMSOL which was purchased using this grant. The simulation tool allows for us to find how energy moves through the wafer and how the temperature changes depending on the location and energy of the deposition. A diagram of the wafer and the model is shown in Figure 2.

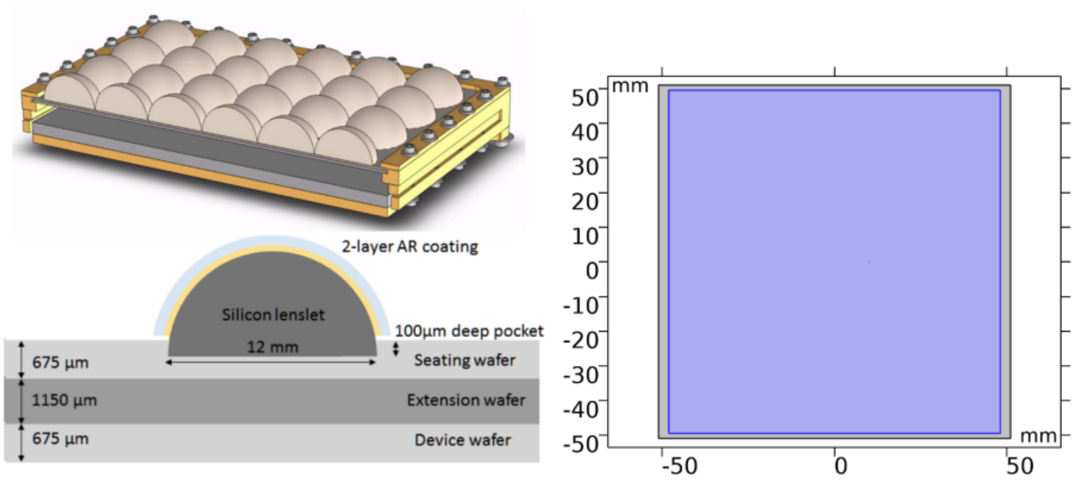

Figure 2: [Left] LiteBIRD LFT wafer design. [Right] Thermal model developed in COMSOL.

In the next stage, these elements are combined to generate time-ordered data (TOD). Using the event tables in the first step, we find which thermal response corresponds to the event in the second step. We iterate over the number of events and add each one to the timeline. This results in time-ordered data for 16 detectors, an example of which is shown in Figure 3.

Finally, all of this is turned into 3 years of simulated data and converted into maps of the CR effect observed as LiteBIRD measures the sky. We take into account the strong thermal coupling between all detectors in the wafer (with/without) and the case with a spinning half wave plate (with/without). The maps are shown in Figure 4.

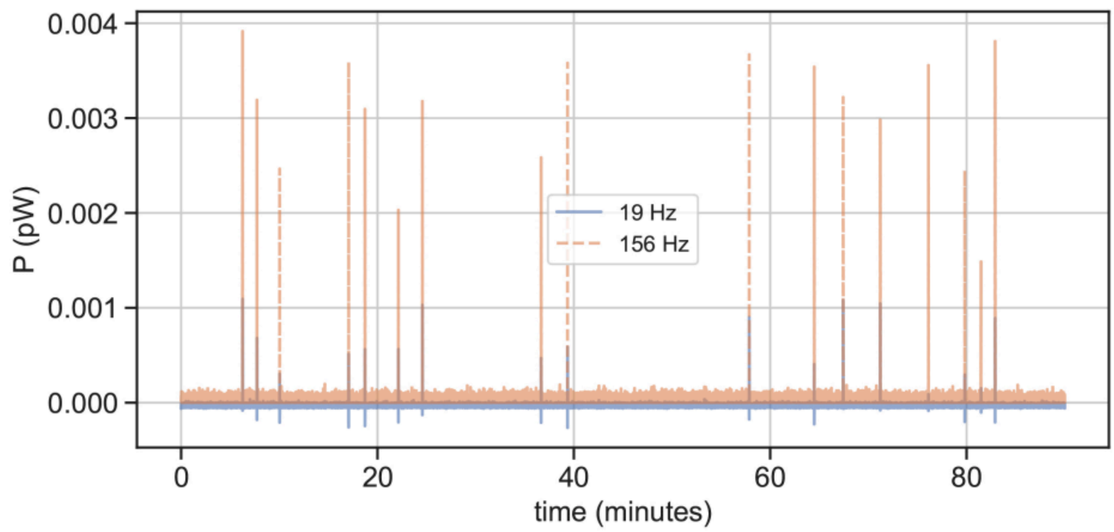

Figure 3: Time ordered data for one detector at 156 Hz and 19 Hz sampling rates.

４．研究成果

The result of the study is the degradation of the measured scientific signal, r, as a function of the number of detectors for the data simulated as above. We find that the case of the inclusion of the strong thermal coupling of the detectors on the same wafer is a better outcome than without it. This is because two detectors in one pair will see a very similar thermal profile, and the pairs are attached to opposite weights in the process of the mapmaking.

We also find that the largest degradation to the science signal is an outcome of uncommon direct hits on the detector, which can be removed using a simple filtering method. We show a summary of these results in Figure 4.

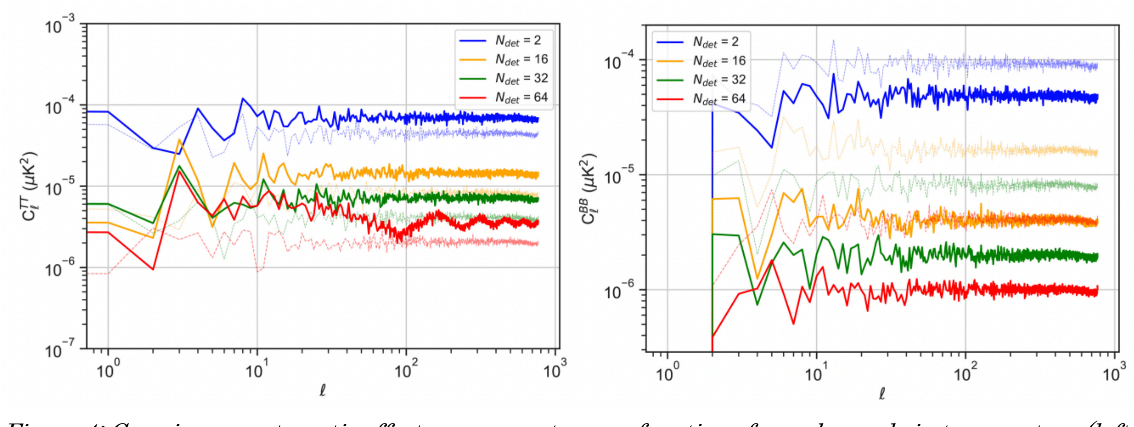

Figure 4: Cosmic ray systematic effect power spectra as a function of angular scale in temperature (left) and polarisation (right) for varying numbers of detectors, with and without strong thermal coupling (solid and dashed lines, respectively).

These results are important because they inform the design of the LiteBIRD space mission, and help the team to prevent a systematic effect which could make it impossible to measure cosmological B-modes.

５．主な発表論文等

〔雑誌論文〕　計11件（うち査読付論文　8件／うち国際共著　8件／うちオープンアクセス　4件）

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２．論文標題 Simulations of systematic effects arising from cosmic rays in the LiteBIRD space telescope, and effects on the measurements of CMB B-modes	５．発行年 2021年
３．雑誌名 Journal of Cosmology and Astroparticle Physics	６．最初と最後の頁 013～013
掲載論文のDOI（デジタルオブジェクト識別子） 10.1088/1475-7516/2021/09/013	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

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オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 －

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掲載論文のDOI（デジタルオブジェクト識別子） 10.1007/s10909-019-02329-w	査読の有無 無
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 －

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オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

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10.1007/s10909-020-02380-y	有
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10.1007/s10909-020-02359-9	有
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掲載論文のDOI（デジタルオブジェクト識別子）	査読の有無
10.1007/s10909-019-02302-7	有
オープンアクセス	国際共著
オープンアクセスではない、又はオープンアクセスが困難	該当する

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2．発表標題
Simulations of systematic effects arising from cosmic rays in the LiteBIRD space telescope, and effects on the measurements of CMB B-modes
3．学会等名
Japanese Physical Society summer meeting
4．発表年
2021年

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〔図書〕　計0件

〔産業財産権〕

〔その他〕

－

６．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

７．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

８．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関