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Modelling the impact of radiation damage effects in in-flight and on-ground irradiated Gaia CCDs

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ABSTRACT: The European Space Agency's Gaia spacecraft was launched in 2013 and has been in operation ever since. It has a focal plane of 106 Charge-Coupled Devices (CCDs) which are of the CCD91-72 variant, custom designed by Teledyne e2v. The detectors have been making measurements of parallaxes, positions, velocities, and other physical properties of over one billion stars and other astronomical objects in the Milky Way. Whilst operating in space, CCDs undergo non-ionizing displacement damage from incoming radiation. This causes radiation induced trap defects to form in the silicon lattice which can trap electrons during readout and increase the charge transfer inefficiency (CTI) of the devices significantly. From analysis of in-flight charge calibration data, Gaia's CTI values have been measured to be lower than what was expected based on the on-ground pre-flight tests. In this study, the CTI and trap landscape in both in-flight and irradiated on-ground devices are modelled to fit the new datasets. This was done thanks to the help of a detector simulation toolkit called Pyxel which implemented a version of a CTI model developed for Gaia called the Charge Distortion Model (CDM). These results provide more insights into the nature of radiation damage and the resulting trap landscapes, both in space and from on-ground irradiations.

KEYWORDS: Data analysis; Detectors for UV, visible and IR photons; Particle detectors; Space instrumentation

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1 Introduction

The Gaia spacecraft is a European Space Agency (ESA) observatory that utilises a focal plane of 106 charge-coupled devices (CCDs) to map out the Milky Way [1]. CCDs in space suffer from performance degradation over time due to radiation damage. Interstellar radiation leads to the formation of trap defects in the silicon; these capture electrons from signals and release them on probabilistic timescales causing charge loss and forming charge tails. This is known as Charge Transfer Inefficiency (CTI). The CTI degradation on-board Gaia has been measured to be lower than what was predicted given pre-flight laboratory tests. By performing simulations that forward model the CCD data, properties of the trap defects causing CTI in the devices can be better understood [2, 3].

2 Pyxel

Pyxel is a detector simulation framework, developed to promote reusability, reliability, and knowledge transfer in instrumentation research. It hosts a suite of different algorithms that can be used to simulate a variety of detectors effects, such as CTI. It also has several different running modes including a calibration mode that optimizes model and detector parameters to fit a user-defined target dataset [4]. In this work, Pyxel's calibration mode was used with an implementation of a CTI model called the Charge Distortion Model (CDM) to find the best parameters that would describe the CTI behaviour in the Gaia data [5].

Figure 1 details the charge tails of a single trap species, as simulated by CDM and by a more physically realistic but computationally expensive model called C3TM [6]. A single trap can be fitted with a single exponential fit in CDM but requires multiple fits when using C3TM. While CDM is reliable at finding parameters that best fit the data, these may not necessarily be physically accurate as it does not simulate all the physical effects, such as charge recapture [6].

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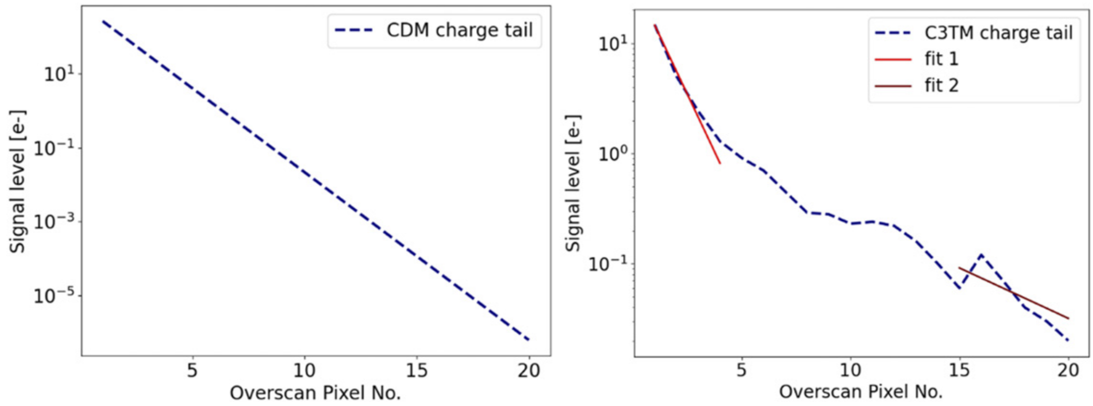

Figure 1. Charge tails produced from a single trap species as simulated by CDM on the left and C3TM on the right. Fits are also made at different points in the C3TM charge tail, illustrating non-linear behaviour.

3 In-flight and on-ground CTI comparison

3.1 Data

In-flight charge calibration data is routinely obtained from Gaia to track the in-flight CTI over time. Analysis of this data has revealed that the in-flight CTI after more than five years in orbit was measured to be lower than the expected CTI level from Gaia's pre-flight tests [3]. This suggests that the on-ground irradiations and subsequent radiation damage during the pre-flight tests were not reflective of radiation damage in space. For the case of Gaia, the on-ground irradiations were performed at room-temperature which are known to produce different trap landscapes as compared to cryogenic irradiations that are more reflective of in-flight conditions [7]. In order to compare the CTI measurements and the irradiation effects between in-flight and on-ground conditions, a new set of on-ground charge calibration data was obtained in the same format as the in-flight data, using a Gaia CCD91-72 flight-spare in the laboratory.

The on-ground charge calibration data was taken from a room-temperature irradiated device, before and after it was irradiated. The room temperature irradiations were performed at the predicted fluence levels during Gaia's pre-flight testing phase. The in-flight charge calibration data was taken from May 2014 and December 2019 to represent more than five years of irradiation in space. Pyxel was used on the in-flight and on-ground datasets respectively to measure the differences in the radiation-induced trap defect landscapes resulting from these different conditions.

3.2 Simulation results

Pyxel's calibration mode was used to find the best CDM parameters that would describe the CTI behaviour in the in-flight and on-ground datasets; these are highlighted in tables 1 and 2. The fitted CDM parameters represent the emission time constant and densities of the trap defects.

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Table 1. Best fit trap parameters for the on-ground charge calibration data.

Trap No.	τ_e(s)	Trap density (traps/cm^3)
1	5.0×10^{-4}	8.0×10^{8}
2	3.7×10^{-3}	3.6×10^{8}
3	3.1×10^{-2}	1.2×10^{9}

Table 2. Best fit trap parameters for the in-flight charge calibration data.

Trap No.	τ_e(s)	Trap density (traps/cm^3)
1	4.7×10^{-4}	6.9×10^{8}
2	3.6×10^{-3}	2.5×10^{8}
3	2.3×10^{-2}	4.2×10^{8}

4 Discussion

When comparing the three fitted emission time constants between the results for the in-flight and the on-ground data, it is noted that while the orders of magnitude are the same between the two datasets, the fitted values are not. Furthermore, the emission time constants in tables 1 and 2 do not match values of any real, physical traps when comparing the results with trap landscapes from other studies [7].

As discussed previously, CDM does not simulate all the physical effects and the fitted traps are the best fits from a collection of multiple physical trap defects producing non-linear effects. This would indicate that the fitted trap densities are not physically realistic as well but a combination of several effects. Given previous results, the 'divacancy', the 'unknown' and the 'continuum' are the likely trap defects to be acting in this region [6, 7]. The CDM calibration results are able to reproduce the charge calibration data very accurately. To get the most likely trap defect landscapes however, the results will need to be compared with C3TM simulations.

5 Conclusion

Simulations were performed on charge data to find the best trap defect parameters that describe the CTI in in-flight and on-ground Gaia data. While similar results were obtained between the two datasets, likely indicating the presence of similar defects, the emission time constant results did not match any physical values due to the limitations of the CDM. More investigations need to be done with more physically realistic models in conjunction with Pyxel and CDM to obtain a greater understanding of the trap defect landscape in irradiated Gaia CCDs.

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