183. Gaia CCDs, CTE, and solar activity

The detectors used across Gaia's astrometric, photometric (BP/RP), and radial velocity spectrometer (RVS) instruments are CCDs. And while CCDs are ubiquitous in consumer and professional imaging systems, and widely used in space, Gaia presented a number of new and demanding requirements, which in turn required an extensive development program pre-launch.

In 'normal' CCD imaging, data readout is performed *after* terminating an exposure. Then, all CCD rows are successively shifted down one row, with a pause after each shift as the latest row is 'clocked out' through a horizontal shift register and associated output amplifier.

In the 'time-delay integration' (TDI, or 'drift scanning') mode of operation, there are no discrete exposures: star images drift continuously across the focal plane of a telescope. The CCD rows are shifted to match the image drift rate as the exposure builds up. This type of scanning has been used, e.g. by Spacewatch between 1984–2011, and by the Sloan Digital Sky Survey Telescope since 1999. With Gaia, instead, the telescope scans the sky, and rows are shifted to match the spin rate.

There are 106 CCDS in Gaia's combined focal plane (including 4 for metrology). The TDI read-out rate is fixed, and the fields of view follow the pre-defined scanning law by continuous adjustment of the satellite's rotation using micro-Newton thrusters. This avoids the overheads of the usual 'point-and-stare' type operation, and results in a fixed exposure time (of 4.4 s per CCD).

A substantial challenge in implementing this observation mode for Gaia was in optimising the fraction of the full CCD that could be read out and sent to the ground. Reading out all CCD pixels (as is done for Gaia's 'sky mappers') would have demanded a much higher readout rate (and associated higher readout 'noise'), and a data volume (and resulting data rate) far too large to be telemetered from its L2 operational location.

The adopted solution is a complex 'windowing strategy', where only small sky regions surrounding each detected object image are read out and sent to the ground (others are flushed at high speed in the readout register).

A far bigger challenge was the stringent requirement on the accuracy of the estimation of the location of each stellar image in the along-scan direction. For example, a parallax accuracy of 30 μas for a 15 mag G2V star after 5 years requires a highly demanding location accuracy of 0.005 pixels at each observation epoch.

Accordingly, the pre-launch CCD development program addressed issues such as their metrology and thermal stability, optimisation of the readout noise, minimisation of amplifier cross-talk, and so on. But there were other highly critical issues that required specific developments of the CCD themselves.

Indeed, CCD91–72 was designed and manufactured specifically for Gaia by the UK company e2v (since 2017, Teledyne e2v), and they considered it their most complex to date. I will touch here only on a few key design features and properties, out of an enormous body of industrial specifications, laboratory tests, in-orbit measurements, and on-ground software calibration efforts.

The Gaia CCDs are 4-phase, back-illuminated devices, with 4500 × 1966 pixels, each $10 \times 30\,\mu\mathrm{m}^2$. The full-well capacity is ~190 000 electrons, the readout noise is 3–5 e^- rms, and the operational temperature of 163 K was selected as a compromise to minimise both dark current and the effects of radiation damage (Prusti et al., 2016; §3.3.2). While all used the identical architecture, different anti-reflection coatings and resistivities were used for the BP and RP instruments.

Charge overflow in the case of bright stars has been a well-known problem for CCDs since their first use in astronomy in the late 1970s. 'Anti-blooming' techniques were further developed for Gaia and, in particular, included the use of a dedicated anti-blooming 'drain'. This prevents excess charge bleeding down columns (i.e. along scan) from bright stars, thus allowing the simultaneous measurement of faint stars in their vicinity.

Observations of the brightest stars ($G \lesssim 13$) make use of 'gates' (at 4500, 2900, 2048… 16, 8, 4, and 2 TDI lines) to restrict integration times, according to the sky mapper magnitude estimates (not all are used in practice).

RADIATION DAMAGE is a phenomenon which has adversely affected satellites since the dawn of the space age. It was responsible for many problems and the ultimate demise of Hipparcos in 1993, stranded in its geostationary transfer orbit and passing through the Earth's Van Allen radiation belts twice per day. Today, satellites routinely make use of radiation-hardened electronics, radiation shielding, and redundant units.

In its operational L2 orbit, Gaia is exposed to Galactic cosmic rays, but it is the sub-atomic particles of the solar wind (electrons, neutrons, and in particular solar protons) that dominate the radiation environment, especially from coronal mass ejections or flares during periods of enhanced solar activity. With energies up to several MeV, early predictions of the effects for Gaia were based on data from the IMP and OGO spacecraft between 1963–91 (Feynman et al., 1993).

HIGH-ENERGY PARTICLES also have a potentially disastrous effect on the CCDs themselves. Here, non-ionising processes, quantified by the Non-Ionising Energy Loss (or NIEL), can result in long-term cumulative effects by creating 'displacement damage' due to the displacement of atoms in the CCD crystalline substrate. The physics is complex, with the effects of vacancies, diffusion, and both doping and impurity atoms contributing to the creation of bulk 'traps', of different energies. These traps lead to a decrease in the 'charge transfer efficiency' (CTE), or equivalently to an increase in charge transfer *inefficiency* (CTI), as the CCD is read out. Some early analyses were made, for example, in the case of the HST–WFPC2 (e.g. Holtzman et al., 1995).

The problem for Gaia is that the signal carriers (electrons) can be captured stochastically, then re-emitted at later times (on time-scales of μs to several seconds), resulting in distortion in the shape of the charge packet, with an associated positional bias and potentially significant loss of accuracy. Effects depend on the location and type of traps (which accumulate over time), on the charge packet size (i.e. star magnitude), and on the previous illumination history of that part of the CCD. Modelling efforts are founded on the Shockley–Read–Hall formalism (Shockley & Read, 1952; Hall, 1952).

The effect was considered to be potentially catastrophic for Gaia, and a substantial effort was devoted to its characterisation and mitigation.

THE LAUNCH of Gaia was originally planned for 2012, and eventually took place at the end of 2013. With solar cycle 24 expected to start in 2008–10, and with a predicted maximum expected in 2013, radiation effects on all satellite subsystems were taken very seriously. Unhelpfully, pre-2006 predictions varied between *'the smallest solar cycle in 100 years'*, and *'the most intense cycles since record-keeping began'*.

PROGRESS INVOLVED many studies and laboratory tests, numerous meetings with the CCD manufacturer e2v, radiation studies by the electro-optical company Sira UK (e.g. Hopkinson et al., 2010), and in-depth commitment by the industrial prime contractor EADS Astrium (now Airbus; e.g. Laborie et al., 2007).

One specific feature built into the Gaia CCDs was the inclusion of a 'supplementary buried channel', in addition to the standard 'buried channel' structure below the silicon surface (where the charges collect). This confines the charge packets to a smaller silicon volume, reducing the number of traps with which the signal interacts. The design goal was for a supplementary buried channel accommodating up to 3000 electrons, although the reality was considerably more complex (Kohley et al., 2009; Seabroke et al., 2010; Seabroke et al., 2013).

Radiation damage effects on the astrometric accuracies were eventually mitigated through a combination of extra spacecraft shielding; the periodic injection of 'sacrificial charges' to occupy traps and so avoid them capturing signal charges; and innovative treatment in the on-ground processing (Short et al., 2010; Prod'homme et al., 2011; Prod'homme et al., 2012; Holl et al., 2012; Short et al., 2013; Lindegren et al., 2021, §3.3).

BUT FORTUNE WAS ALSO on our side. Solar activity in cycle 24 was minimal until early 2010, reaching a maximum in April 2014 at a value substantially lower than other recent solar cycles, and *'unseen since cycles 12–15'* (1878–1923). Solar cycle 25 began in 2019, with early indications suggesting low activity comparable to cycle 24, together perhaps indicative of a possible 'modern Gleissberg minimum' (Upton & Hathaway, 2018).

As part of the detailed calibration of the astrometric solution (Lindegren et al., 2012), the degradation in charge transfer efficiency in the scan direction is evident (e.g. Lindegren et al., 2021, §6.2), but at an order of magnitude less than predicted pre-launch. The CTI in the serial register is still dominated by traps inherent in the manufacturing process, with radiation-induced degradation of only a few per cent after 3 years (Crowley et al., 2016). The situation had not degraded significantly further even after 6 years in orbit (Ahmed et al., 2022).

Incidentally, two 'prompt particle events' in Gaia's sky mappers have also been identified with astronomical sources: Cyg X–1, and the γ-ray burst GRB221009A (see Gaia's Image of the Week, 9 November 2022).

AFTER 10 years in orbit, all CCDs still continue to operate flawlessly (although with a failure of the AF1 VPU/PEM electronics on 15 May 2024). These industrial achievements are a tribute both to e2v (led by David Morris), and to the prime contractor EADS Astrium, where the focal plane development was led by Anouk Laborie, and the CCD development by Cyril Vetel.