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Radioactivity in HgCdTe devices: potential source of "snowballs"

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ABSTRACT

We hypothesize that the "snowballs" observed in HgCdTe infrared detectors are caused by natural radioactivity in the devices themselves. As characterized by Hilbert (2009) in the WFC3 flight IR array (FPA165), "snowballs" are transient events that instantaneously saturate a few pixels and deposit a few hundred thousand electrons over a ~5-pixel (~100-um) diameter region. In 2008, prior to flight of detector FPA165, Hilbert (2009) detected 21 snowballs during thermal vaccum test three (TV3) and inferred a rate of ~1100 ± 200 snowballs per year per cm^2 of the HgCdTe detector. Alpha particles emitted from either (or both) naturally radioactive thorium and/or uranium, at ~1 ppm concentrations within the device, can explain the observed characteristics of the "snowballs." If thorium is present, up to four distinctly observable snowballs should appear at the same location on the pixel array over the course of many years. While the indium in the bump bonds is almost entirely the radioactive isotope In-115, and 12% of the cadmium is naturally radioactive Cd-113, both of those emit only betas, which are too penetrating and not energetic enough to match the observed characteristics of "snowballs." Also, the Cd-113 emission rate is much less than that of the observed snowballs.

Introduction

This paper addresses the possibility that natural radioactivity[1] in the HgCdTe device itself may be responsible for the snowballs observed with the WFC3 IR array (FPA165). There are many pieces of circumstantial evidence for this. We address them in turn below: 1) earlier observations of a "hot" H2RG device by Finger et al. (2008); 2) Cadmium has a common, naturally occurring, long-lived radioactive isotope, Cd-113, but which appears to produce too little energy and too small a rate of decay; 3) Indium bump bonds are composed primarily of the common, naturally occurring radioactive isotope In-115 and its beta decays exceed the snowballs' event rate but apparently not their energy; and 4) alpha particles emitted from uranium and/or thorium impurities in the HgCdTe layer each or both could be responsible for the snowballs. In the latter case (4) of thorium, but not cases (2) or (3) or (4) with uranium, we may expect snowballs could repeat at the same location in the array.

Fingering radioactivity

Finger et al. (2008) noted a H2RG device (HAWK-I #88) that exhibited events that saturated the central pixel with more than 100,000 electrons, left charge over ~7x7 pixels and had an integrated charge of ~700,000 electrons, i.e. characteristics similar to the events in FPA165 that Hilbert cataloged and are called "snowballs." Finger et al. attributed the events to radioactivity in the BCS (balanced composite structure) to which the HgCdTe is epoxied. The event rate for device #88 was 1 event per 75 s over the 4 Mpixel array, i.e. 31000 events per cm^2 per year, or ~30 times the snowball rate observed in TV3 for FPA165. Other H2RG arrays Finger et al. identify device #88 alone as exhibiting anomalously large event rates. We notice in Finger et al.'s measurements of dark current from T = 110 K to 150 K, the dark current of device #88 increases from 1 e/s/pixel to 1000 e/s/pixel, and at each temperature is ~5 times greater than the three other devices tested. We speculate that the radioactivity in device #88 may also be responsible for the 5x greater dark current in that device at T> 110K, perhaps by damaging the surface of the HgCdTe. (At T< 100 K, all four devices, including device #88, have

[1] Nuclear reaction data is available from many sources. We used the interactive periodic table of the elements at http://environmentalchemistry.com/yogi/periodic/ and Argonne National Laboratory's "EVS Human Health Fact Sheet," dated August 2005, titled "Natural Decay Series: Uranium, Radium, and Thorium" which has clear diagrams of the complete uranium and thorium decay chains. GSFC has exensive radiation testing for space applications (http://radhome.gsfc.nasa.gov/top.htm).

similar and less-temperature-dependent dark currents.) The possibility of radioactive damage to pixels will be discussed again later.

The WFC3 IR array, a H1RG similar to the H2RG arrays except for the number of pixels (H1RG = $(1k)^2$ pixels; H2RG = $(2k)^2$ pixels), is composed of a HgCdTe detector layer mechanically supported with epoxy and electrically contacted with indium bump bonds to a silicon multiplexer. Naturally occuring isotopes of Hg are stable. All but one of the naturally occuring Te isotopes are either stable or have half-lives greater than 1E20 years; the one, Te-123 has a a half-life greater than 6E14 years (Alessandrello et al. 1996), but it decays by electron capture to stable Sb-123, so there's no particle emitted, and anyway the 0.05 MeV reaction energy is much too low to explain the snowballs. This leaves cadmium, indium, or unknown impurities as possible sources, which we address in turn.

Theoretically, 3.9 eV of kinetic energy is required to impact ionize an electron-hole pair in CdTe and 3.6 eV for Si (Alig, Bloom, Struck 1980), so a similar energy W would be required to produce a count in an array by impact ionization. For a HgCdTe detector with a long-wavelenth cutoff, λ_c, the energy W is ~3 times the energy of the cutoff, or ~ 3 $(\lambda_c / 1.2\ \mathrm{um})^{-1}$ eV. Fox et al. (2009) measured W = 2.6 eV per e-h pair in the WFC3 device (FPA165), so we use that conversion factor.

Betas

The penetration length of a beta is short, but long compared to an alpha, discussed in the next section. Groom (2004) explains worm-like transients visible as wandering, ~300 um long trails in a 300-um thick silicon CCD as caused by electrons with energies 1 MeV < E < 100 MeV generated by Compton scattering of environmental gamma rays. The energy loss rate for those electron energies is ~1 MeV per column of 1 g/cm^2 (i.e. 0.43 cm of Si, or a linear energy transfer, LET = 250 eV/micron), which for his CCD corresponds to ~2.1E4 e-h pairs per 300 um path length, or a linear charge transfer, LCT = 70 e-h/micron). Assuming the stopping power of HgCdTe is of the same order as Si, and using a LCT ~100 e-h/micron, we expect that betas with sufficient energy to be potential snowball sources (i.e. E ~ 1 MeV) generally will pass though the 10-micron-thick HgCdTe layer with limited probability for large-angle scattering and will produce only ~1000 e-h pairs, generally within one pixel or (after difffusion) a very few pixels, i.e. a similar morphology of a typical cosmic ray hit. Compared to a beta of the same energy, due to an alpha's much greater mass and double the charge, the alpha has more than a hundred times greater impulse than a beta of the same energy, so the alpha ionizes more and deposits its kinetic energy in a much smaller distance. For example, it takes only 45 microns of water to stop a 5 MeV alpha.[2] Also, for both betas and alphas, as their speeds drop, their impulse increases, so their efficiency (LET) rises. While it appears

[2] http://www.fas.harvard.edu/~scdiroff/lds/QuantumRelativity/PenetrationandShielding/PenetrationandShielding.html

already that betas cannot account for the snowballs' morphology and the total electron count per snowball, for completeness, we examine two beta emitters inherent to HgCdTe devices.

The decay of Cd-113 produces a 0.3 MeV beta, which is too low for snowballs since we'd expect no more than ~100,000 electrons detected per beta, if the HgCdTe layer was thick enough to stop the beta (which we estimated earlier it is not). The natural abundance fraction of Cd-113 is 0.12, and it would be hard to separate it from the Cd used in the manufacture of the device, so we may assume that is also the fraction in any IR device. However, we estimate that the activity of Cd-113 in events per cm^2 in the HgCdTe device is much lower than the observed snowball event rate (1100±200 snowballs per year per cm^2). To make an approximate estimate, we assume a volume of HgCdTe of 10 um x 1 cm x 1 cm, or 1E-3 cm^3. Using the density of HgCdTe = 8.0 g/cm^3 (Capper 1994) and a mean molecular weight of 142 amu for $Hg_{1-x}Cd_xTe$ with a fraction x~0.5 of those containing Cd atoms, we estimate our volume contains 1.7E19 Cd atoms of which the natural fraction 0.12 are Cd-113. So our volume contains 2.0E18 Cd-113 atoms, that are decaying with a half-life of 8E15 years (Dawson 2009), hence 2.0E18 ln(2) / 8E15 = 175 Cd-113 beta decays per year per cm^2 in a 10-micron thick layer of HgCdTe. (In a 800-micron thick substrate of CdZnTe, the Cd-113 activity would be proportionally greater, i.e. ~80 times more, but the betas would be absorbed within the substrate and could only affect the HgCdTe layer by photoluminescence, which would produce a much more diffuse feature than the snowballs.) Cd-113 beta decays into stable In-113, so there are no daughter radionuclides. We conclude that Cd-113 beta decays are too infrequent and not energetic enough to be the sole source of the snowballs.

Another possibility could be the indium bump bonds. In-115 has a natural abundance fraction of 95.7%, and beta decays with 0.5 MeV and a half-life of 4.4E14 years to stable Sn-115. As an approximate upper limit of the number of In-115 atoms in close proximity to the HgCdTe detector, we assume the volume of each indium bump bond is not larger than the volume of the HgCdTe pixel to which it is connected.[3] In that case, the 1 cm^2 reference area of HgCdTe discussed before is in close proximity to no more than ~3.8E19 In-115 atoms (rho = 7.3 g/cm^3; mu = 115 amu), and hence exposed to not more than 3.8E19 ln(2) / 4.4E14 = 60,000 In-115 beta decays per year per cm^2. Thus, the In-115 decay rate is at most ~50 times greater than required to explain the snowball rate, although the bump bond mass could easily be many times smaller than we have assumed. However, the 0.5 MeV per beta (~200,000 e-h pairs produced if the beta is stopped in the HgCdTe, a similar number if it is stopped in the indium, neither of which seems plausible) seems too low to explain most of the snowballs. Also, we don't know how the effects of a beta generated in the In-115 bump bond will compare to the effects of one generated in the HgCdTe. In favor of In-115 being a source of snowballs is the

[3] Broennimann et al. 2006 describe 20-micron diameter indium bump bonds for 100-um pixels.

inevitability of In-115 decaying with approximately the prescribed rate: we know (approximately) the mass of In-115 in the detector, and we know precisely both its half-life and the energy of the beta released. Perhaps In-115, plus a smaller contribution of Cd-113, is responsible for a population of low energy, non-repeating, "mini-snowballs" that would appear morphologically no-different than typical cosmic ray hits. However, something else is responsible for the snowballs (and the snowball repeaters) characterized by Hilbert (2009). We believe the culprit is alpha particles.

Alphas

The penetration length of an alpha is very short, tens of microns, so it is very likely to be absorbed in the HgCdTe layer in which we hypothesize it originates, and it will deposit nearly all of its kinetic energy therein. Again using the 2.6 eV per e-h pair produced by impact ionization, we predict that each 4 MeV alpha will produce ~1.5E6 electron-hole pairs, which is approximately three times the median integrated counts in a snowball, and 60% larger than the maximum reported by Hilbert (2009). Because the center ~4 pixels of each snowball tend to be saturated, the ~0.5E6 electron median value and the ~0.9E6 electron maximum value for snowballs may both be lower limits to the charge produced, because in saturated pixels, the charge produced but not collected will not spill over and be collected in adjacent pixels, as commonly occurs in a CCD. Whereas betas are emitted with a broad range of energies, energies of alphas have relatively little variation about ~4 MeV.[4] By conservation of momentum, the recoiling parent has ~2% (the ratio of masses, e.g. 4/230), or ~80 keV of the energy of the alpha. One final general comment about alpha decay: Te-106 is the lightest element that alpha decays, so if alphas cause "snowballs," we may limit our search of possible emitters to Te and heavier elements. Also, by mathematics not physics, the maximum number of generations of alphas from a single parent, could be ~33, i.e. (~238-106)/4, although no chain accomplishes that. The U and Th chains discussed below produce no more than 8 alphas.

In this section we discuss two decays chains. Table 1 contains some additional details of the two chains. The **U-238 decay chain** is as follows: U-238 → Th-234 + 4.3 MeV alpha (4.5E9 years); Th-234 → Pa-234 + 0.3 MeV beta (0.09 years); Pa-234 → U-234 + 2. MeV beta (2.3E-6 years); U-234 → Th-230 + 4.9 MeV alpha (0.24E6 years); Th-230 → Ra-226 + 4.8 MeV alpha (77,000 years) … at which point the chain is essentially dead for our purposes, frozen by the 77,000 year half-life of the latter reaction. The **Th-232 decay chain** is as follows: Th-232 → Ra-228 + 4.1 Mev alpha (1.4E10 years); Ra-228 → Ac-228 + 0.05 MeV beta (5.8 years); Ac-228 → Th-228 + 2.1 MeV beta (0.7E-3 years);

[4] This is known as the Geiger-Nuttall law, a result of the probabilistic nature of tunneling from the nucleus first estimated by Gamow (1928). An illustration of U-238's alphas is here: http://www.wise-uranium.org/img/adeu8s.gif

Th-228 → Ra-224 + 5.5 MeV alpha (1.9 years); the Ra-224 decays to Ra-220 with a 3.7-day half-life followed in rapid succession by 4 more alpha decays on the route to stable Pb-208 (two of which have half-lives less than 1 minute and hence are unlikely to be distinguishable as separate events in a sequence of IR array exposures).

The abundance of U-238 and Th-232 in the earth's crust are ~3 ppm, and in various common materials, Groom (2004) has measured U-238 and Th-232 concentrations of 5 ppm for a Sn/In alloy, 1 ppm for cement and a CCD mounting socket, 0.1 ppm for three mounted CCDs, and 0.01 ppm for epoxy. As a reference value, we use 1 ppm U-238 and/or Th-232 in the following estimates, either in similar concentration would give similar effects[5]: both U-238 and Th-232 produce 4 MeV alphas as the first decay in their chains. (Alternatively, if the indium bump bonds have a 5 ppm U-238 or Th-232 impurity concentration, i.e. the same as Groom measured in his Sn/In alloy, and the bump bonds have ~1/5 the volume of the HgCdTe layer, that would be approximately equivalent to 1 ppm in the HgCdTe layer). In our reference case, the volume discussed above (a 10-micron thick, 1 cm^2 area slab of HgCdTe) would contain 3.8E12 U-238 atoms, or 12 million U-238 atoms per pixel (10 um by 18 um by 18 um). The rate of 4 MeV alpha decays from U-238 → Th-234 with a half-life of 4.5E9 years is then 580 events per year per cm^2, which is aproximately half the observed snowball rate. (The other half could easily be from alpha decays of U-234, Th-232, or Th-228.)

In secular equilibrium, each of the daughter products in a reaction chain produces decays at the same rate as any of the others, i.e. there is a constant ratio of each daughter's abundance divided by its half-life. Even if the U-238 and Th-232 chains are approximately in secular equilibrium in the earth's crust, after extraction, purification, and deposition to produce the HgCdTe detector, who do not know the concentrations of the parents, or even the relative concentrations of parents and various daughter elements. We will assume that chemical fractionation is small and secular equilibrium applies to the isotope ratio(s) of any specific element in a chain. Then, we can estimate the number densities of various isotopes of particular radioactive impurities in the HgCdTe. For the U-238 chain, this would imply that alpha decays from U-238 and U-234 may occur at the same rate within a given volume, effectively doubling the rate of alpha decays from U. Analogously, the alpha decay rates of Th-232 and Th-228 will be equal, per unit volume.

Snowball repeaters and unstable pixels

If the spatial correlation discovered by Hilbert (2009) between unstable pixels and snowballs is causal rather than statistically coincidental, then we can make some predictions accordingly. In what follows, we will accept as a working hypothesis that the same radioactivity that creates snowballs also damages one or more of the adjacent pixels

[5] U-235 would require enrichment above its natural abundance to produce similar activity as U-238.

and makes them unstable. There are two logical possibilities: 1) the observed snowball precedes the pixel's unstable behavior, or 2) the converse, the pixel's unstable behavior precedes the snowball. Because FA165 was manufactured in 2006, the calibrations from which Hilbert identified unstable pixels were in spring 2008, the DCL snowballs were observed in spring 2007, and the TV3 snowballs were observed in spring 2008, we expect a greater percentage of TV3 snowballs to be of type 2 than the DCL snowballs. Indeed Hilbert measures an enhancement of the correlation between unstable pixels identified in TV3 and snowballs observed in TV3 relative to snowballs observed in DCL. As discussed later, the Th-232 decay chain might explain the enhancement of this spatial coincidence over the years since FPA165's manufacture.

In the first case, the snowball can come from any radioactive element located within the array since its manufacture. In the second case, the snowball must come from the decay of a daughter created *in situ* within the array. In this scenario, the daughter's parent (or grand-parent, …) earlier created the damage that made the pixel unstable. In that (second case), the half-life of the decay(s) responsible for the observed snowball is bounded to be longer than a few days because the snowball typically is observed long after the calibration from which the unstable pixels are identified, and it must be shorter than a few years, because the number of potential parents created *in situ* within the HgCdTe array after its manufacture will be only a few thousand. With only a few thousand daughters, their half-life has to be relatively short (a few years or less) for us to have a significant probability of observing snowballs from them.

The great majority of the time between the array's manufacture and the calibration that identifies unstable pixels, the array is not operational. Thus, even if all unstable pixels were created only by the very same mechanism that creates snowballs, we can expect far more unstable pixels than observed snowballs, simply because we have not been observing with WFC3 IR more than a small fraction of the elapsed time.

Inspection of the U-238 and Th-232 decay chains shows either could be a candidate for a snowball repeater, but the Th-232 chain seems more suitable. A possible source of snowball-repeaters could be Th-228 formed *in situ* in the array by Th-232 present since the device's manufacture. Soon after Th-228 alpha decays, there will be at least two distinctly observable snowball events possible in the next few days from the same site, and then no more from stable Pb-208. In summary, the scenario is this: the Th-232 damages the pixel while forming Ra-228 and emitting a snowball, months or years pass to form Th-228 via two beta decays, and months to years after that, a cascade of three distinctly observable snowballs will result within a few days, but thereafter the pixel will no longer be any more likely to throw another snowball than any other pixel.

The only mechanism for a snowball-repeater associated with U-238 is the first alpha in the chain damaging the pixel, then a few weeks later a 2.3 MeV beta could produce a "mini-snowball" at the site of the damaged pixel. But thereafter the pixel will no longer be any more likely to produce another snowball than any other pixel, because of the

0.24E6 year half-life of U-234. Also, an equal number of alphas will be produced by U-238 and U-234 that had been in the alloy since manufacture, and only the U-238 decay sites are possible snowball-repeaters; the U-234 alpha-decay product (Th-230) has too long a half-life to produce a second generation energetic particle that we might observe.

Another observable characteristic of a snowball repeater would be temporal correlation. Although parent decays with very long half-lives will be nearly Poissonian, subsequent daughter generations that decay rapidly may reveal themselves by temporal correlation (e.g. after Th-228 decays, 4 additional alpha decays occur over ~4 days, two of which occur within a fraction of a second). If the radioactive parent is inside the detector, the spatial correlation will be much more revealing than a temporal one, but if the radioactivity originates outside the detector (e.g. in the radiation shield[6]), there would be a temporal correlation but no spatial correlation. Given the low event rate of snowballs, if two were observed at different locations in the same readout, a causal connection is very likely, such as two radionuclides decaying in rapid succession.

Additional investigations

While our identification of natural radioactivity in the device itself seems plausible, the specific isotopes that we propose are much less secure: the radionuclide responsible for the snowballs could be something that we have not considered. A radioassay may be useful in determining the abundances of radionuclides in HgCdTe arrays. To motivate such a study, we note that in principle the consequences of not identifying the radionuclide could be bad, e.g. for JWST: if the parent isotope is abundant and has a very long half-life, but daughters in the decay chain have half-lives of a few years, then ground testing performed prior to much build up of daughters would exhibit a low rate of snowballs, but then the device will become "hotter" with time, potentially becoming unpleasantly so many years later during its operation in space. The Th-232 chain is a mild example of such a build up (see Table 1). By inspection of Table 1, the snowball rate will increase over ten years by a factor of ~2 if the common isotopes of U-238 and Th-232 are present in equal concentrations, with secular-equilibrium concentrations for the relatively short-lived isotopes U-234 and Th-228. If the only impurity at the time of manufacture was Th-232, i.e. zero Th-228, then the snowball rate would increase by a factor of ~4 in ten years, as the chain approaches secular equilibrium. The thorium chain (or one like it) could explain Hilbert's observation of greater correlation of unstable pixels with snowballs observed in TV3 than snowballs observed a year earlier at DCL.

This work does not address induced radioactivity, which will be different in space than on Earth, due to the different flux, energy, and type of particles in space. Pickel et al.

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[6] The "radiation shield" is intended to shield the detector from infrared radiation (photons) emitted by the relatively warmer walls of the detector housing. If it were radioactive, i.e. emitted alphas or betas, that would be unintentional irony.

(2002) and Labury (2002) discuss additional modes of ionization in HgCdTe detectors. Also, Groom (2004) reports that stainless steel plates that were exposed to two round trips across the USA on a stratospheric airplane exhibited cosmogenic isotopes that were not present prior to the trip. Combined, they produced 0.15 decays per minute per kg, although the heaviest of the reported isotopes was Co-60, so no alpha decays would result. Even if the cosmic rays passing through HST do not induce radioactivity directly, perhaps their secondaries do.

At this time, we are not aware of the quantitative characteristics of "snowball-like" events in NICMOS and JWST devices, or the WFC3 FPA165 on orbit. We hope to address those in a future report. NICMOS's three arrays and years of in-flight exposure may be helpful, although all three of the NICMOS3 arrays have substrates, whereas WFC3's FPA165 and all of the JWST devices have their substrates removed. A potential consequence of the latter, if a detector's radiation shield were to be radioactive (or to become radioactive on orbit), would be that alpha particles emitted from the shield would be stopped by a substrate before they could reach the detector, whereas in substrate removed devices (WFC3 and JWST) there would be a clear path from the first few microns of the shield to the detector. The average count rate would be similar to having an equivalent material in contact with the HgCdTe layer, although spatial and temporal correlations would be diluted by the distance from the shield to the detector.

In orbit, even when WFC3 IR is the prime instrument, the duty cycle of observation never is 100% and often is much less. A snowball, like over-exposed stars and cosmic rays, creates persistent after-images that power-law decay with time and can be detected an hour after the snowball's creation (McCullough et al. ISR WFC3-2008-33). This suggests that the persistent after-images of snowballs may provide an additional method of detection in circumstances in which the duty cycle of observation is less than 100%. Indeed, if WFC3 IR obtained one 700-sec SPARS50-15 ramp each 96-minute HST orbit, then that may be sufficient to provide gapless monitoring of snowballs via their persistent afterglows. However, automated identification of snowball after-glows will be much more challenging than the saturated signature of a snowball observed directly. On the other hand, careful inspection of exposures (or segments of ramps) immediately prior to the appearance of a snowball might reveal the afterglow of an earlier snowball: such an analysis may be useful for proving that snowball repeaters exist, if they do.

Conclusions

We conclude that the observed characteristics of snowballs (rate of events per unit area, morphology and size in pixels, electrons detected, spatial coincidence of snowballs with unstable pixels[7]) can be explained by natural radioactivity of impurities U-238, Th-

[7] The spatial coincidence with unstable pixels is still under investigation and has not yet been definitely proven.

232 and/or unknown radionuclides inside the HgCdTe detector material or the indium bump bonds, in abundances of ~1 ppm, typical of many common materials. The rate may be consistent with In-115 beta decays from the bump bonds, but not the other characteristics (morphology, size, electrons detected, and coincidence with unstable pixels). The radioactivity hypothesis also neatly explains the lack of snowball events in CCDs, either because silicon's impurity levels are exceptionally low (ppb, not ppm) due to its large market in the semiconductor industry, or because CCDs lack indium bump bonds. An important implication of the hypothesis of natural radioactivity within the HgCdTe device itself for the source of the snowballs is that the rate of snowballs will be not much different in low Earth orbit (HST) or at L2 (JWST) than measured prior to flight on Earth. If U-238 and/or U-234 decays exclusively create snowballs, then the snowball event rate will be constant with time. If Th-232 and/or Th-228 decays create snowballs, then the snowball event rate will grow with time by a factor of 2 to 4 in ten years.

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References

Alessandrello, A. et al. 1996, Evidence for Naturally Occuring Electron Capture of 123-Te, Phys. Rev. Letters, 77, 3319

Broennimann et al. 2006, Development of an Indium Bump Bond Process for Silicon Pixel Detectors at PSI, arXiv:physics/0510021v2 [physics.ins-det]

Capper, P. 1994, Properties of Narrow Gap Cadmium-Based Compounds (E M I S Datareviews Series) ISBN: 978-0852968802

Dawson J. V. et al. 2009, An Investigation into the 113Cd Beta Decay Spectrum using a CdZnTe Array, arXiv:0901.0996v1 [nucl-ex])

Finger, G., Dorn, R. J., Eschbaumer, S., Hall, D. N. B., Mehrgan, L., Meyer, M., & Stegmeier, J. 2008, Performance evaluation, readout modes and calibration techniques of HgCdTe HAWAII-2RG mosaic arrays, Proc. SPIE, 7021

Fox, O. D., et al. 2009, The 55Fe X-ray energy response of mercury cadmium telluride neari-infrared detector arrays, arXiv:0906.0579v1 [astro-ph.IM]

Gamow, G. 1928, Zeitschrift fur Physik , 51, 204

Groom, D. 2004, Cosmic Rays and Other Nonsense in Astronomical CCD Imagers, in Scientific Detectors for Astronomy, Springer, Amico, P., Beletic, J. M., and Beletic, J.E., eds.; see also snap.lbl.gov/ccdweb/ccdrad_talk_spie02.pdf

Hilbert, B. 2009, "Snowballs" in the WFC3-IR Channel: Characterization. WFC3 ISR 2009-43. http://www.stsci.edu/hst/wfc3/documents/ISRs/WFC3-2009-43.pdf Dec 2009.

Ladbury, et al. 2002, HST's Radiation Environment Inferred from Charge-Collection Modeling of NICMOS Darkframes, Presentation at NSREC in Phoenix, AZ July 16, 2002

McCullough, P. 2008, *in press*. WFC3 ISR 2008-33. http://www.stsci.edu/hst/wfc3/documents/ISRs/WFC3-2008-33.pdf Dec 2009.

Pickel, J.C., Reed, R.A., Ladbury, R., Rauscher, B., Marshall, P.W., Jordan, T.M., Fodness, B., and Gee, G., 2002, Radiation-induced charge collection in infrared detector arrays, IEEE Transactions on Nuclear Science, Volume 49, Issue 6, 2822

◇	A	B	C	D	E	F	G	H	I	J	K
1	Time	U-238	Th-234	Pa-234	U-234	U-234	Th-230	Ra-226			
2	(years)	4.50E+09	0.09057	2.3E-06	240000	240000	77000	1600			
3	MeV	4.27	0.27	2.27	4.86	4.86	4.77	4.87			
4	type	alpha	beta	beta	alpha	alpha	alpha	alpha			
5	0	3.80E+12	0	0	0	2.03E+08	0	0			
6	1	3.80E+12	583	582	582	2.03E+08	583	0			
7	2	3.80E+12	583	583	1165	2.03E+08	1165	0			
8	3	3.80E+12	583	583	1748	2.03E+08	1748	0			
9	4	3.80E+12	583	583	2330	2.03E+08	2331	0			
10	5	3.80E+12	583	583	2913	2.03E+08	2913	0			
11	6	3.80E+12	583	583	3496	2.03E+08	3496	0			
12	7	3.80E+12	583	583	4078	2.03E+08	4078	0			
13	8	3.80E+12	583	583	4661	2.03E+08	4661	0			
14	9	3.80E+12	583	583	5244	2.03E+08	5244	0			
15	10	3.80E+12	583	583	5826	2.03E+08	5826	0			
16											
17	Time	Th-232	Ra-228	Ac-228	Th-228	Th-228	Ra-224	Ra-220	Po-216	Pb-212	Bi-212
18	(years)	1.40E+10	5.8	0.0007	1.9	1.9	0.01014	1.8E-06	4.8E-09	0.00126	0.00012
19	MeV	4.08	0.05	2.13	5.52	5.52	5.79	6.41	6.91	0.57	
20	type	alpha	beta	beta	alpha	alpha	alpha	alpha	alpha	beta	alpha(2)
21	0	3.80E+12	0	0	0	516	0	0	0	0	0
22	1	3.80E+12	187	21	21	537	163	163	163	163	163
23	2	3.80E+12	354	40	54	428	130	130	130	130	130
24	3	3.80E+12	501	56	94	391	119	119	119	119	119
25	4	3.80E+12	632	71	136	408	124	124	124	124	124
26	5	3.80E+12	749	84	179	463	141	141	141	141	141
27	6	3.80E+12	852	96	220	542	165	165	165	165	165
28	7	3.80E+12	944	106	259	635	194	194	194	194	194
29	8	3.80E+12	1025	115	295	737	224	224	224	224	224
30	9	3.80E+12	1097	123	328	841	256	256	256	256	256
31	10	3.80E+12	1162	130	359	943	287	287	287	287	287

Table 1: Spreadsheet of U-238 (rows 1-15) and Th-232 (rows 17-31) decay chains. The U-238 chain is truncated at Ra-226; the Th-232 chain is truncated at Bi-212. Column A is the time in years since manufacture of the array. The row below the element names is the half-life in years. The next rows are the energy of the particle in MeV followed by the type of particle (alpha or beta). The numbers of U-238 and Th-232 nuclei at the time of manufacture of the device (cells B5 and B21 respectively) correspond to 1 ppm each in a 10 um thick layer of HgCdTe of 1 cm^2 area. The numbers of U-234 and Th-228 at the time of manufacture (cells F5 and F21) are the secular equilibrium values, i.e. scaled from the values in B5 and B21 according to the respective half-life ratios). Column E in each case shows the accumulation of U-234 and Th-228 created *in situ* within the array. For nuclei with half-lives much shorter than 1 year, e.g. Th-234, Pa-234, Ac-228, Ra-224, etc) each cell simply represents the number of nuclei created and destroyed in that year. The two purposes of this simplistic spreadsheet are to illustrate 1) the constant rate of decays associated with Uranium, and 2) the initially decreasing and then secularly increasing rate of decays of Th-228 to Ra-224 (cells G21-G31), caused by its two sources of Th-228: a) its initial number (cell F21) which decays exponentially, and 2) its *in situ* production which increases with time (E21-E31).