Cosmic Rays and Other Nonsense in Astronomical CCD Imagers

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Abstract: Cosmic-ray muons make recognizable straight tracks in the new-generation CCD's with thick sensitive regions. Wandering tracks ("worms"), which we identify with multiply-scattered low-energy electrons, are readily recognized as different from the muon tracks. These appear to be mostly recoils from Compton-scattered gamma rays, although worms are also produced directly by beta emitters in dewar windows and field lenses. The gamma rays are mostly byproducts of ^{40}K decay and the U and Th decay chains. Trace amounts of these elements are nearly always present in concrete and other materials. The direct betas can be eliminated and the Compton recoils can be reduced significantly by the judicious choice of materials and shielding. The cosmic-ray muon rate is irreducible. Our conclusions are supported by tests at the Lawrence Berkeley National Laboratory low-level counting facilities in Berkeley and 180 m underground at Oroville, California.

Keywords: CCD, cosmic rays, high resistivity, fully depleted, back illuminated, Compton scattering, gamma ray

1. Introduction

The ability of ionizing radiation to generate electron-hole pairs in silicon is the bane of optical astronomy, where "cosmic rays" contribute confusion and loss of imaging pixels in CCD's. Multiple exposures and elaborate software are used to eliminate these artifacts.

Genuine cosmic rays near the bottom of the atmosphere consist almost exclusively of relativistic muons produced by secondary meson decay. These penetrate even meters of material without interaction or deflection. But other radiation artifacts usually dominate, and these are not irreducible. Most seem to be Compton recoil electrons from scattered ambient gamma rays, but in some situations, such as when a high-potassium glass like BK7 is present in the dewar, direct β rays produced near the surface of the glass can strike the CCD.

In thin CCD's a radiation event usually occupies 3 or so pixels, and in most cases it is distinctively sharp compared to a star. With the advent of thicker high-resistivity CCD's [1,2], the story is somewhat different. The straight cosmic-ray muon tracks are often quite long, and there are abundant wandering tracks which we call "worms." There are also localized events, usually with fewer counts than would be expected

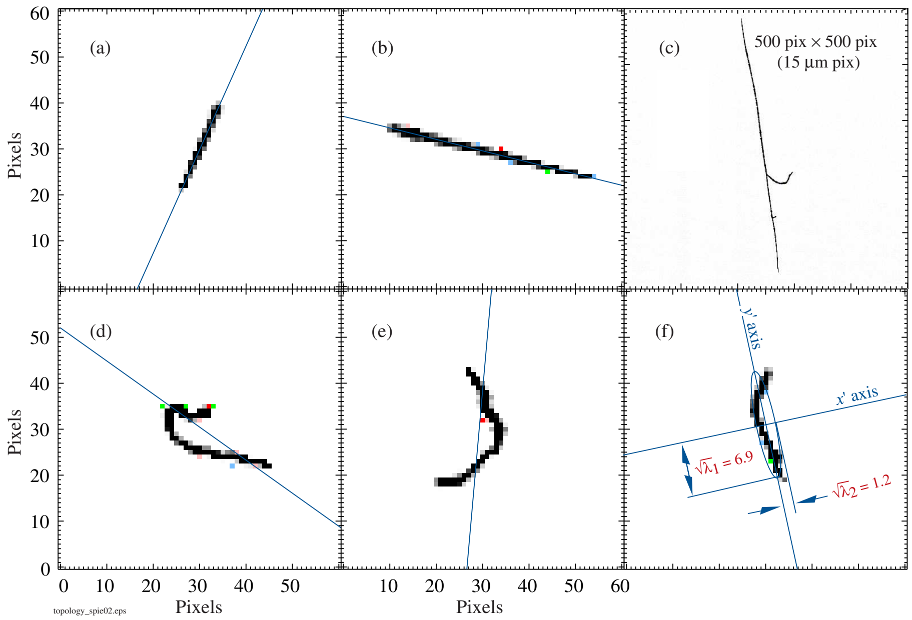

Figure 1. Examples of cosmic-ray muons (a–c) and worms (d–f) in a totally depleted 200-μm thick LBNL CCD. (c) shows one of the longest tracks found, and two δ rays (knock-on electrons) can be seen. (f) also indicates the the definition of λ_1 and λ_2, the principal moments of the distribution.

from cosmic-ray muons, which we call "spots." Muon tracks and worms are shown in Fig. 1. Those familiar with nuclear emulsion experiments readily recognize the worms as multiply-scattered low-energy electrons.

We have made a study of these events, in most (but not all) cases in totally depleted LBNL CCD's [1] 200–300 μm thick. Long dark images were obtained under different conditions at a variety of places: The UCO/Lick and NOAO CCD laboratories, in a low-background room at LBNL, deep underground at Oroville, CA, at Kitt Peak, Cerro Tololo, the Keck, and Lick Observatory. Here we explore the nature of the events and the use of lead shielding to reduce the number of spots and worms.

2. Cosmic rays

The vertical flux of cosmic rays in the atmosphere as a function of composition and height is shown in Fig. 23.3 of Ref. 3. At sea level 98% of cosmic rays are muons (mean energy $\approx$ 4 GeV); most the remainder is protons and neutrons. The muons are decay products of mesons produced in hadronic cascades initiated by primary cosmic rays, which are mostly protons. Maximum intensity occurs at an altitude of about

10 km, and for $E \geq 1$ GeV there is an approximately exponential decrease in intensity below 500 g/cm^2 ($\approx$ 6 km). At low energies the angular distribution is usually approximated as $\cos^\alpha \theta$, where θ is the zenith angle, and $\alpha \approx 2$ for $E \sim 3$ GeV. For $\alpha = 2$ the flux in a horizontal detector is $\pi/2$ times the vertical intensity. For a vertical detector the flux is half this, but the tracks are longer. The vertical intensity is uncertain because of the low energy threshold and low-energy flux uncertainties, but the flux in a horizontal detector is expected to be 0.84–0.94 $\mathrm{cm}^{-2}\,\mathrm{min}^{-1}$ at sea level. At an altitude of 2500 m (typical of many large observatories) it is 1.6 times greater, and on Mauna Kea it is 2.1 times greater. The proton/neutron flux is $\sim$2% at sea level, but on Mauna Kea it adds another $\sim$30% to the total flux.

Energy deposit by a muon is a highly stochastic process, and because large energy deposits are rare the most probable deposit depends strongly on thickness [4]. At $-100°$ C it is about 75 e-h pairs per μm for a 300 μm active region, 56/μm for a 20 μm thickness, and only 27/μm for the 13 μm thick SITe CCD's used in CTIO's MOSAIC.

3. Event characterization

A long dark exposure shows a zoo of muons (straight lines), worms, and spots. Software has been developed which is at least partly successful in distinguishing between them. The events are isolated using standard astronomical software: An event is defined as a group of connected pixels with counts above background, with at least one pixel having a significantly higher number of counts. The code generates a number of parameters for each object, including the second moments of the distribution about the centroid.

The number of counts (or e-h pairs) produced by a normally incident muon is expected to distribute about some most probable value, with tailing on the high side. It is thus convenient to scale the number of counts by the active region thickness divided by the track length as calculated from the projected length and the thickness. This number is almost proportional to the number of e-h pairs produced by a normally incident muon. For lack of a good name, we call it "perpendicular counts" or "perp counts." This reduction distorts the energy deposit information for other kinds of events, but we are mainly using it to help separate muons from the rest.

The distribution of this quantity for a series of long dark exposures under extremely clean conditions at the LBNL Low-level Background Facility (LBF) [5] is shown in Fig. 2(a). The vertical dashed line indicates the most probable number of counts. The vertical cuts above and below the peak are chosen conservatively to include essentially all of the muons.

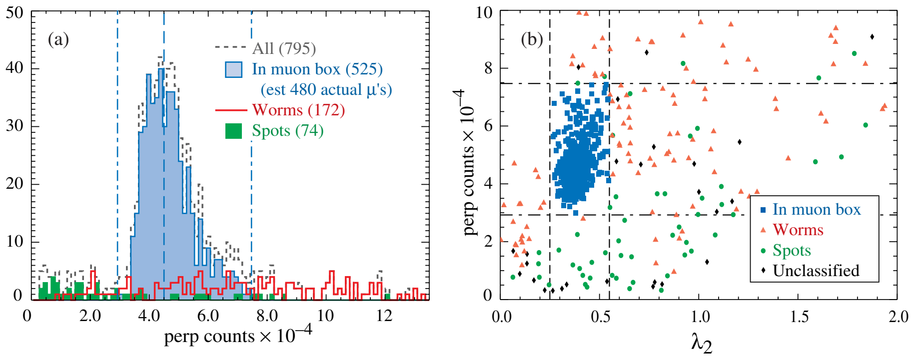

Figure 2. Total exposure of 4800 s at the LBNL Low Background Facility (LBNL LBF). (a) Distribution of the normal projection of the number of counts ("perp counts"). The cuts chosen for the "muon region" are shown by the dash-dotted lines. (b) Distribution of "perp counts" as a function of the smallest eigenvalue λ_2. The "perp counts" cut and the additional cut $0.25 < \lambda_2 < 0.55$ define the "muon box."

A muon track should be a straight line. A measure of "straightness" can be obtained from the second moments matrix. One can imagine rotating the coordinate system, as shown in Fig. 1(f), so that the matrix is diagonal. With the labels as shown, the $x'x'$ moment is minimal for a straight line (muon), while the $y'y'$moment can have any value. The $x'y'$ moment is zero, by the definition of the transformation. These moments are simply the eigenvalues of the original matrix, so the transformation does not need to be made explicitly. We define λ_1 (λ_2) as the maximum (minimum) eigenvalue of the second moments matrix, normalized by dividing by total number of counts in the event so that the result is independent of amplifier gain.

A plot of "perp counts" as a function of λ_2 for the muon-rich exposures at the LBF is shown in Fig. 2(b). In this case most cosmic-ray muons are in the interval $0.25 < \lambda_2 < 0.55$; in other situations limits are chosen differently because of different CCD bias, thickness, and other factors. Our "muon box" is defined by the cuts on "perp counts" and λ_2. Non-muon events similar to those outside the box also occur inside, although in this example the estimated contamination is less than 10%. Hand-scans of a muon-free run (discussed below) verify that non-muon events in this box are genuinely indistinguishable from muons. On the other hand, some muons escape from the box. Scanning shows these to be mostly unusual muon events with a small δ-ray track or other artifact superimposed on an obvious muon track. In even dirty situations, we usually observe "muon box" rates of 0.7–1.0 cm^{-2} min^{-1} in horizontal CCD's, consistent with the cosmic ray rates discussed in the last section. We observe roughly half this rate when the CCD is vertical.

4. The nature of cosmic rays, worms, and spots

Four sets of long dark exposures were obtained, using the same CCD, dewar, and controller configuration:

(a) In the basement UCO/Lick CCD laboratory in Santa Cruz. About a third of the events were muons (at the expected rate); the remainder were worms and spots.

(b) In the LBNL Low Background Facility [5], a room with 1.5 m thick concrete walls; the special concrete has very low radioisotope content. Most events were muons.

(c) Near the power plant of the Oroville (California) dam, 480 meters-water-equivalent underground, where cosmic rays are attenuated by 10^3. Worms and spots were observed, but no muons.

(d) Again at Oroville, this time in an ultraclean lead vault built for demanding low-level counting experiments. Almost nothing was observed—120 events in 7400 s. Surprisingly, 113 of the 119 events outside the muon box fell above the upper cut on muon energy deposit. This is also reflected in the high worm/spot ratio ($\approx$3) as compared with the ratio outside the vault ($\approx$1). Given other experience with the vault, these events are thought to originate in the dewar assembly itself.

These results are summarized in Table 1. The conclusions are simple: Events identified with cosmic ray muons are observed inside or outside a well-shielded room, but are not seen underground. Worm and spot rates are much reduced in an environment without the normal traces of U, Th, and K in the walls, and are essentially zero in an ultraclean environment.

Further evidence for the Compton electron nature of the worms and spots was provided by a series of measurements at the Lick Observatory 3-m Coudé spectrometer room. Fig. 3(a) shows the "perp counts" spectrum obtained with a CCD without (much) shielding. The muon rate was about as expected, but the rate outside the muon box was 1.6 $\mathrm{cm^{-2}\,min^{-1}}$. As layers of 0.16 mm Pb were wrapped around the dewar, the "outside the box" rate fell below the muon rate. (We consider this a reasonable goal for all instruments.)

We also obtained spectra with a cryogenic Ge gamma spectrometer, shown in Fig. 3(b).* Results are consistent with the typical potassium,

* If the spectrometer were exposed to a monochromatic gamma source, one would see a very sharp line representing complete containment of the event, a valley on the low-energy side, and a plateau at smaller energies due to partially contained events, mostly recoils from Compton scattering. The spectrum shown can be understood as

uranium, and thorium abundances found in ordinary concrete and rock. There is no evidence for ^{60}Co, an occasional contaminant of steel. The addition of 1 cm Pb around the detector reduced the rate by 80%, mostly at low energies ($\lesssim$ 500 keV) where the Compton scattering probability in the CCD is highest. We view this reduction as a function of energy consistent with the reduction in the rate outside the muon box when 1 cm of Pb shielding is used. There is an important corollary: Since most of the problem is with low-energy gamma rays with short interaction lengths, there is little point to using massive shielding. One centimeter of shielding seems to be sufficient.

Table 1. Evidence for Compton nature of worms and spots. There is usually contamination in the muon box, hence the apparently greater muon rate at UCO/Lick than at LBNL. Since some events could not be classified, the spot + worm rate is in general less than the "outside muon box" rate.

Experiment	Integration time (s)	Spots	Worms ($cm^{-2}min^{-1}$)	Muon box	Outside box
1. UCO/Lick (Santa Cruz)	1000	0.87±0.08	0.97±0.08	0.93±0.08	2.16±0.12
2. LBNL, shielded room	4800	0.10±0.01	0.22±0.02	0.71±0.03	0.37±0.02
3. Oroville, 180 m underground	7843	0.21±0.01	0.20±0.02	0.06±0.01	0.47±0.02
4. Same, inside lead vault	7400	0.02±0.00	0.07±0.01	0.00±0.00	0.10±0.01

Most of our observations are consistent with the worms and spots being the tracks of low-energy electrons, the recoils from elastic-scattering (Compton scattering) gamma and x rays in the few hundred keV range. There is an important exception: Our NOAO collaborators observed an increase of 2.8 $cm^{-2}\,min^{-1}$ over the normal background in the room when a BK7 field lens was inside the dewar, and no increase if it were immediately outside the dewar. This observation is consistent with beta rays from ^{40}K decay close enough to the suface of the glass that the particles can escape. Other groups have encountered the same problem with BK7 [6,7], which has a high potassium content.[†] (Except under

a superposition of many such monochromatic gamma spectra plus low-energy events due to a sea of low-energy gammas already degraded by Compton scattering.

[†] Potassium 40 is a two-bladed axe: 11% of the time it decays to ^{40}Ar with the production of a penetrating 1.46 MeV photon, perhaps the commonest source of worms, and 89% of the time to ^{40}Ca by β^- emission (1.33 MeV endpoint). The β's have ranges of $\lesssim$ 0.07 g cm−2, but those produced near the surface of glass inside the dewar can reach the CCD.

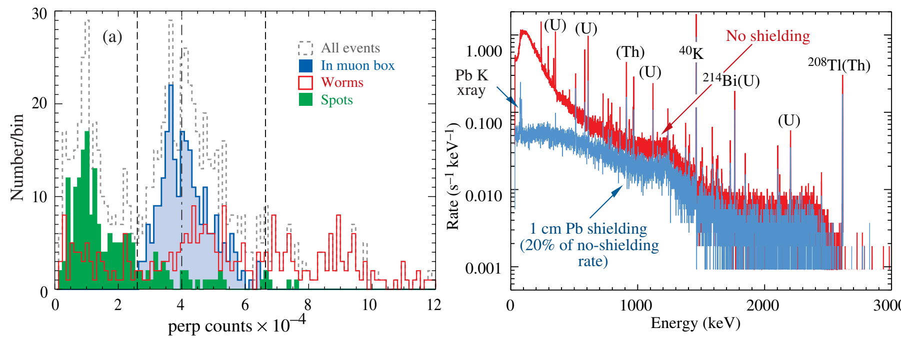

Figure 3. Lick 3-m Coudé spectrograph room: (a) Distribution of the normal projection of the number of counts ("perp counts") in two long darks with nearly no shielding. (b) Gamma spectra in the spectrometer room, without and with a 1-cm lead shield. Characteristic lines correspond to gamma rays produced in ^{40}K decay and in the U and Th decay chains.

bizarre circumstances, alpha particles are never a problem because of their very short range.)

5. Other observations

Long dark exposures were made at UCO/Lick with an LL/MIT CCD20, a deep-depletion device intended for the DEIMOS spectrometer at the Keck Observatory [2]. The sensitive thickness is estimated to be 40 μm. The distributions show the familiar peak in "perp counts" and a populated muon box with about the expected rate. The distributions were much broader than in our thick devices, and a clean muon/Compton separation was not possible. Rates outside the box were very much reduced by shielding with 5 cm of Pb. We estimate that the ratio of Compton rates for an unshielded LL/MIT thick CCD to that in the LBNL CCD is 0.65, with $\sim$ 10%–15% uncertainty. The thickness ratio is 0.15. The difference provides evidence that many of the Compton recoil electrons do not originate in the sensitive volume of the CCD. Sensitivity to Compton recoil electrons (and, obviously, direct β rays if potassium is present in the dewar) is not limited to thick CCD's.

Dark exposures were obtained at CTIO with MOSAIC (horizontal orientation), which consists of 8 SITe CCD's with $\approx$13 μm sensitive regions. In spite of the lack of useful pattern recognition, the distributions show peaks at the expected most probable number of e-h pairs. The rate was 4.3 cm^{-2} min^{-1}, as compared with an expected cosmic ray rate at that altitude of about 1.4 cm^{-2} min^{-1}.

An 800×1980 (15 μm)^2 LBNL fully-depleted CCD on the RC spectrograph at the KPNO 4-m telescope (60° from vertical) obtained a muon box rate of 0.66 cm^{-2} min^{-1}, and the rate outside the muon box was 0.51 cm^{-2} min^{-1}. The muon rate is consistent with the expected rate for this altitude and CCD orientation. The Compton rate is the lowest recorded in any of the observations without shielding. Perhaps the mechanical housing provides shielding. The same CCD in a vertical orientation at the NOAO laboratory in Tucson measured 0.60 cm^{-2} min^{-1} in the muon box (OK) and 2.00 cm^{-2} min^{-1} outside it (among the highest Compton rates we have ever observed in the absence of BK7 glass).

After the tests showing that 1 cm of lead reduced the Compton rate to an acceptable level in the Lick 3-m spectrometer room, a lead box was built to shield the dewar on the spectrometer. It seemed to have no effect. Measurements with the Ge gamma spectrometer are scheduled in an attempt to understand the situation.

Tests with the "standard" CCD setup used for the Oroville and other measurements were also made at the Keck I telescope—horizontal and vertical, on the floor and on the Nasmyth deck, inside and outside of a lead box built for the purpose. Controller problems prevented characterization of the events, but total rates of about 5 cm^{-2} min^{-1} were observed. The horizontal/vertical rate difference was consistent with expectation, but rates inside/outside the lead box were about the same. Long high-altitude exposure[‡] of the stainless steel alloy used in the dewar ruled out cosmogenic activation of the dewar on the flight to Hawaii as the source of the problem. It is still not understood.

6. Assay results

We have characterized the U, Th, and K content of most materials in the dewar which might act as radiation sources. The results are given in the upper section of Table 2. The "black socket" for our test CCD was a radiation source, as seems to be expected for materials with black dye. Indium is naturally radioactive, but the thin (∼500 Å) In/Sn coating we use as a rear window in our CCD's makes a negligible contribution.

We also characterized the concrete at the Lick 3-m telescope and the lava used as concrete aggregate at the Keck and other telescopes on Mauna Kea.[◇] These results are shown in Table 1. In both the Lick 3-m

[‡] The stainless steel was characterized underground at Oroville, sent on four overnight Federal Express delivery trips from LBNL to Harvard and back, and again characterized. Cosmogenic activation was observed, but at a totally insignificant level.

[◇] No lava was harmed in making these tests, and except for a few decayed atoms all of it has been returned to the Mauna Kea summit.

and UCO/Lick environments the Compton rate was 2.2 $\mathrm{cm^{-2}\,min^{-1}}$, in contrast to 0.8–0.9 $\mathrm{cm^{-2}\,min^{-1}}$ for cosmic rays. In rooms or on dome floors made from such concrete, enough shielding to achieve gamma-ray attenuation by a factor of three or more would be desirable.

Characterization results from an NOAO sample of BK7 optical glass are given at the end of the table. The potassium content is tentative pending chemical analysis.

Table 2. Radiological assay results for common materials found in CCD dewars and nearby concrete. Numbers in parentheses indicate the error in the last place, and "ND" indicates "none detected." The approximate conversion factors to decay rate are 0.66 (pCi/g)/ppm for chemically pure uranium, 0.11 (pCi/g)/ppm for thorium, and 8.5 (pCi/g)/percent for potassium.

Sample	U (ppm)	Th (ppm)	K (%)
CCD black socket	0.64(4)	1.38(6)	0.011(1)
Si wafers (3 in box)	0.025(6)	0.16(2)	ND
Aluminum nitride	0.010(2)	0.019(5)	ND
Aluminum sputter	ND	0.044(14)	ND
Circuit boards (Lick)	0.064(4)	2.07(8)	0.016(2)
Epoxy (Lick)	0.012(3)	0.010(3)	ND
INVAR, bar stock	ND	ND	ND
Molybdenum, bar stock	0.020(3)	0.020(3)	ND
Sn/In alloy	5.0(1)	4.6(1)	ND
Lick 3-m core	1.35	4.0	0.72
UCO/Lick lab core	1.2	1.2	1.23
Mauna Kea lava$^{\diamond}$	1.5	4.7	1.52
BK7 glass (NOAO)	0.10(5)	0.7(2)	3.5(1)

7. Observations and conclusions

We are not the first to find non-cosmic-ray events in CCD's, nor the first to recognize the distinctive energy deposit of a (normally incident) cosmic-ray muon. In his 1986 review [6], Mackay discusses the rate excess over that expected from cosmic rays, and in one case diagnoses much of the problem as radiation from the glass dewar window. He reports rates of 10 $\mathrm{cm^{-2}\,min^{-1}}$, more than 10 times the cosmic-ray rate. Florentin-Nielsen and Anderson [7] describe experiments in which the device was operated 37 m below ground level in a chalk mine, with a reduction to 33% of the surface rate, to 0.56 $\mathrm{cm^{-2}\,min^{-1}}$. In other experiments they identified a UBK-7 lens as producing very high rates because of its ^{40}K content. An old ESO report lists cosmic-ray rates in a dozen CCD's ranging from 6 $\mathrm{cm}^{-2}\,\mathrm{min}^{-1}$ in RCA SIC 501 CCD's to 1.4 $\mathrm{cm}^{-2}\,\mathrm{min}^{-1}$ in a GEC 8603 [8].

Deep-depletion CCD's have been used in x-ray astronomy for a long time. Walton et al. [9] describe a study in which signal size is used to discriminate against cosmic rays—the x-ray mirror response cutoff was at 10 keV, and only 10% of the cosmic-ray signals were this small.

There is anecdotal evidence of hotspots in a concrete telescope pier (Hugo Schwarz, reported on CCD-world), drywall (Roy Tucker, reported on CCD-world), radioactive dewar windows (BK7 seems notorious in this regard), and thorium-containing lenses. There is also continued worry about radioisotope tracers such as the ^{60}Co used in steel process control.

Our study is unique, however, in that the thicker CCD's have made it possible to do a moderately good job in isolating the muon and non-muon components. It again emphasizes the need for care and careful characterization for every material used in the vicinity of the CCD, especially inside the dewar. The gamma ray background from ubiquitous potassium, uranium, and thorium decay can be reduced to an acceptable level by careful shielding. But we are left with mysteries: Shielding usually worked as expected, but in some cases had no apparent effect. Work continues.

Acknowledgments

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