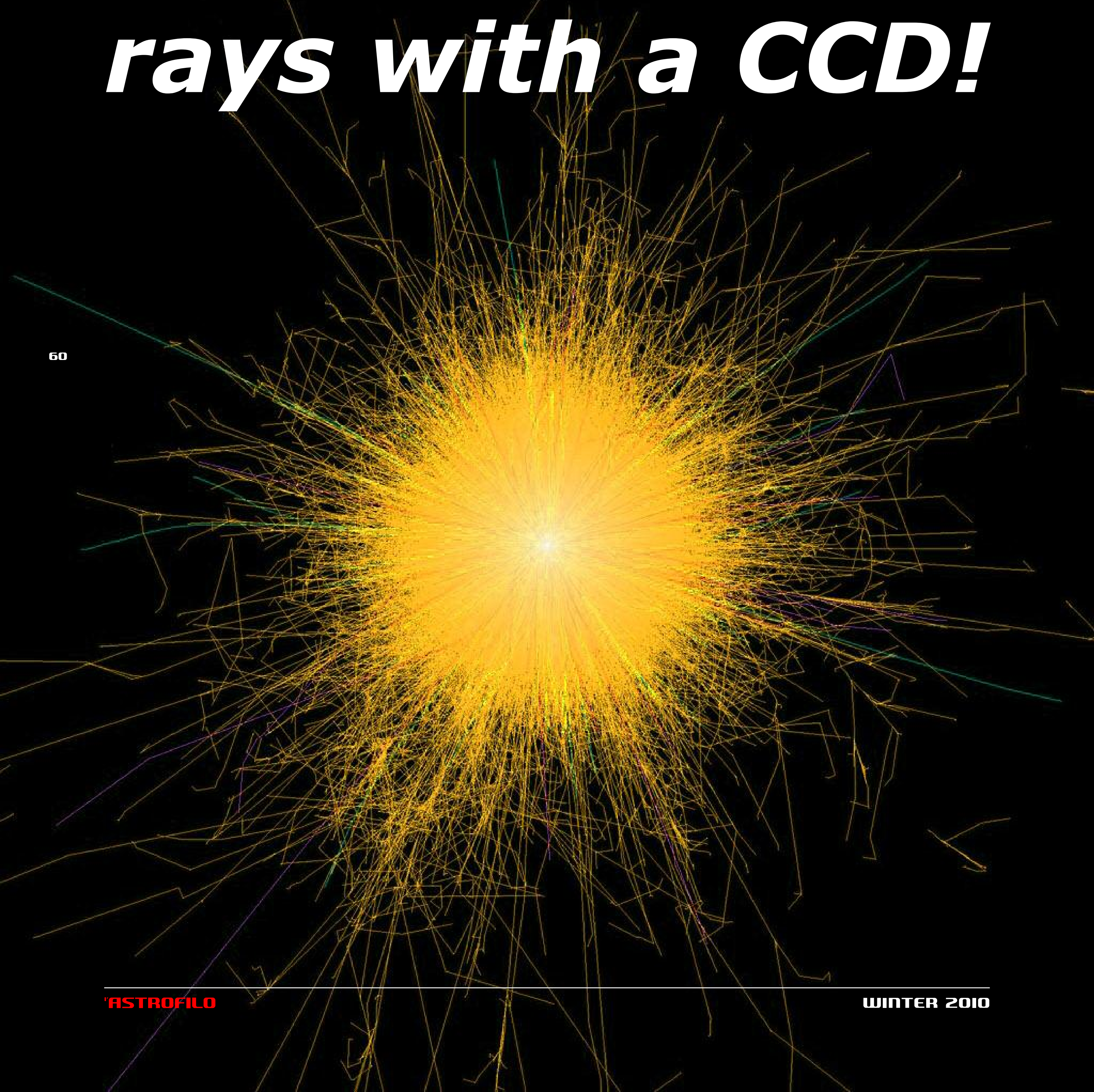
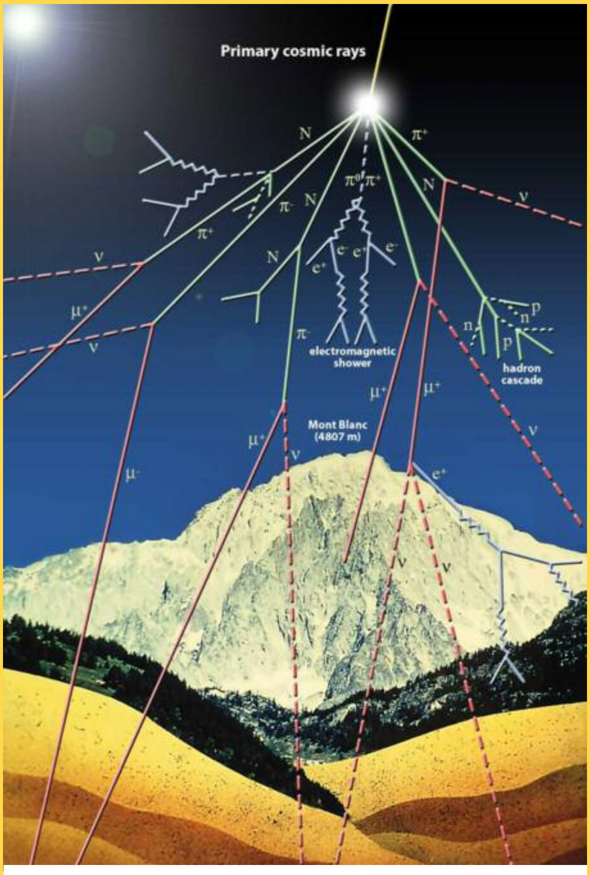
Catching cosmic rays with a CCD!



If the weather is bad or late nights in the open don't particularly appeal, then you might be interested to know that even a modest CCD can be used for astrophysical research 24 hours a day, without the least effort. Even while you sleep!



Schematic representation of the various particles produced when a cosmic ray enters the atmosphere.

Ever since I was a boy I have been passionate about astronomy, it's occupied my thoughts for years. Then, inevitably, as often happens, life takes you down roads that you didn't choose, and so one's passions can also subside. But we all know that you never forget your first love, and sometimes your passion can come and look for you. As part of my work I often examine dark frames produced by cooled CCD cameras. In fact, just by looking at dark frames it's possible to check many of the functions of an instrument. As a result, I often see the tracks left by cosmic rays when they impact on the CCD pixels.

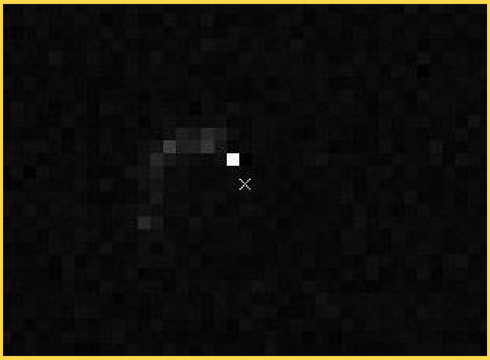
Not all CCD sensors behave in the same way. Some are much more sensitive than others, I'm not sure why, but it probably has something to do with the different doping used on the silicon. I've never managed to establish a link between the environment or an astronomical event but it has always fascinated me how some days they arrive with greater frequency.

Cosmic rays are energetic particles coming from outer space, to which the Earth, and all of us, are exposed.

The discovery (simultaneous but independent) of cosmic rays was by the Austrian Victor Franz Hess and the Italian Domenico Pacini, both with works published in 1912.

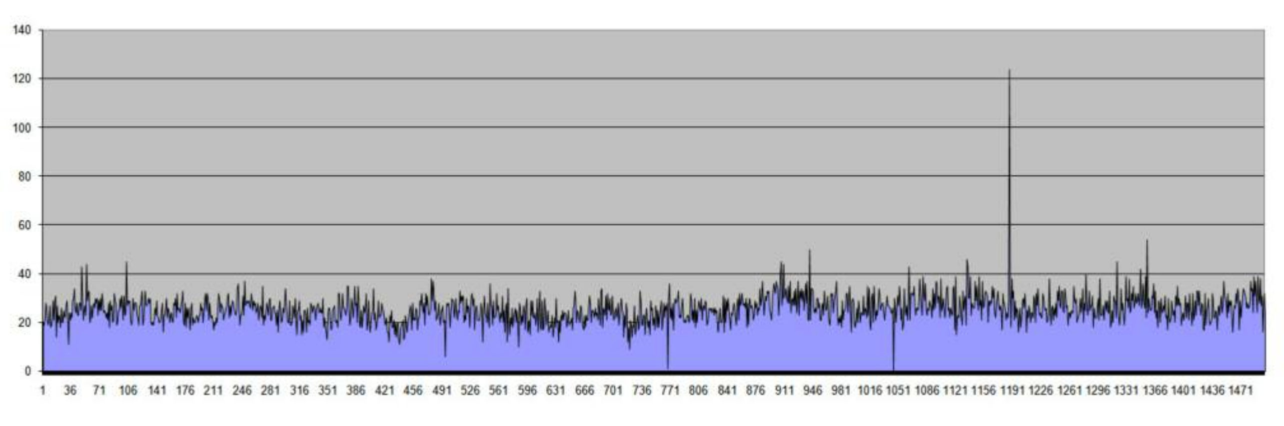
Before cosmic rays interact with the terrestrial atmosphere they are mostly protons (95%) and helium nuclei (5%); but also electrons, photons, neutrinos and a tiny fraction of anti-matter (positrons and anti-protons) make up the primary cosmic rays. When they reach the atmosphere, the particles interact with the nuclei of the atmospheric molecules, creating, in a cascade process,

Simulation of the impact of a cosmic ray with the atmosphere and the subsequent particle cascade.



Typical track left by a cosmic ray, with the impact pixel the most luminous, corresponding to the greatest energy release. Adjacent pixels that were traversed are less bright.

new particles that are propelled forward and that we call secondary cosmic rays. All over the world there are many laboratories that work on the detection of these cosmic rays, using a range of tech-niques. Having easy access to CCD sensors, however, I decided to use these. Therefore, about two years ago, having a cooled digital camera available, equipped with a FOS (Fiber Optic Scintillator) and beryllium window, I decided to start a series of observations. I decided that I would record events 24 hours a day for ten or so days, setting an exposure time of 20 seconds with 2x2 binning, at an operating temperature of 10°C. To reduce the noise caused by dark current it would have been useful to work at a much lower temperature, but the presence of the FOS stuck on the top meant that it would have been a risk to go below 0°C due to the different expansion coefficients of silicon+glue+glass. Anyway, despite the rather high working temperature, I always had excellent signal-to-noise ratios. I chose 2x2 binning in order to reduce the size of the images produced, without losing imaging area. Bear in mind that with these parameters more than 4000 images are produced in a day, about 2.1 GB/day! The time for the program to extract the events from the recorded images is also non-negligible, so this experimental configuration seemed a good compromise. The results of the project were very interesting, even if they pose more questions than they answer.



This graph shows the number of events recorded as a function of time over an 8 hour period.

An example of the recorded data is shown in the above graph, that shows the number of events as a function of time, over a period of about 8 hours. Only because the graph is rather compressed in time are the two modulations in the flux not very evident. One is rather rapid, the other much slower, and they repeat in the subsequent days.

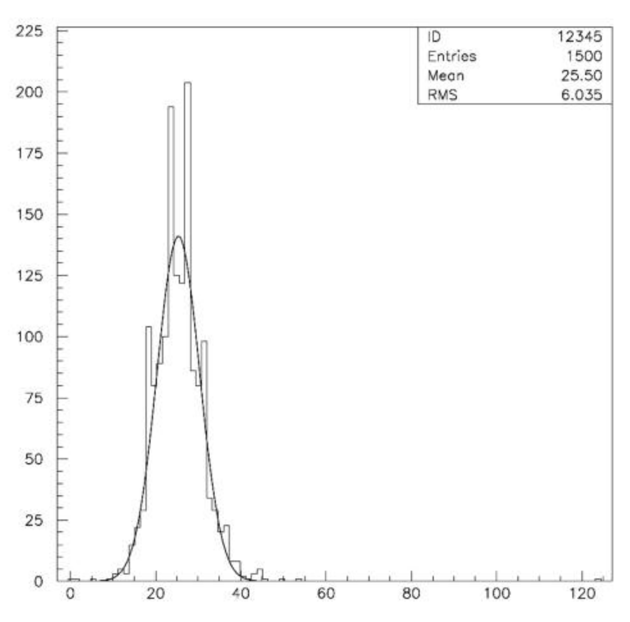
I didn't expect to find any kind of "information" but rather a chaotic behaviour. Therefore, after confirming my ignorance, in an attempt to understand what

The CCD used for the "observational" campaign. In the foreground is the beryllium window.

was in the recorded signal I sought the help of a number of researchers of the national laboratories that work on cosmic rays, getting a range of diverse answers. Here are some examples. Reply from a junior researcher: *"The cosmic ray flux is anti-correlated with the daily changes in atmospheric pressure, that in 24 hours (apart from long period variations due to weather systems) rises and falls almost sinusoidally and has two maxima and two minima. If you have a barometer you can measure the pressure and see the exact correlation between pressure and your counts. For the variations on shorter time scales there could be many causes: either an instrumental problem or something more physical... or the tram that passes by your house!"*.

Another researcher said, *"The muon rate varies between 100 and 200 per square metre (depends on the altitude: the more atmosphere they pass the higher the possibility of decay; in fact they are particles with a mean lifetime of order two microseconds, especially if they are not very energetic). We can be quite sure of this number. If you can, try to repeat the analysis increasing the threshold between an event and noise: try to see if the flux becomes uniform (at the moment it varies by about 20% on average)"*.

Another solution proposed was: *"The environmental background is due to interactions with low energy particles (alpha particles mainly, due to the presence of radon) or active metals and so forth. The only way to eliminate it is to connect two detectors one above the other separated by a fixed distance. In this way you detect all cosmic rays that pass (clearly you must take account of the range of angles for which this is true) while the detections of alpha particles are uncorrelated between the two (change room!)"*. The last researcher also sent me an analysis (see graph below) of the raw data that I sent, in



This graph shows the divergence of the counts from the main Gaussian. On the x-axis is the number of counts in a single frame, while the y-axis is the frequency of obtaining a given number of counts.

For the image analysis, in search of events, I wrote a little program in Javascript, that for each image does the following:
1) subtract from the image a mean dark frame
2) analyze the corrected image in blocks of 10 × 10 pixels
3) calculate the standard deviation of the block under study
4) calculate the centroid and the area of the event if the standard deviation exceeds a predefined value (if the area is greater than one pixel and there are no saturated pixels then count an event)
5) go to the next block and return to step 3.

Here is a few lines of output from the script.

```
Frame:   9, Event   15 @ X =  165.000, Y =  177.000, V =   266, A =   1
Frame:   9, Event   16 @ X =  440.000, Y =  206.718, V =   563, A =   2
Frame:   9, Event   17 @ X =  437.529, Y =  218.473, V =   217, A =   4
Frame:   9, Event   18 @ X =  439.000, Y =  223.000, V =   615, A =   1
Frame:   9, Event   19 @ X =  296.542, Y =  256.427, V =   252, A =   4
Frame:   9, Event   20 @ X =  352.000, Y =  284.000, V =   377, A =   1
Frame:   9, Event   21 @ X =  153.000, Y =  297.000, V =   690, A =   1
```

At the end the script generates a text file with the recorded counts and a graph.

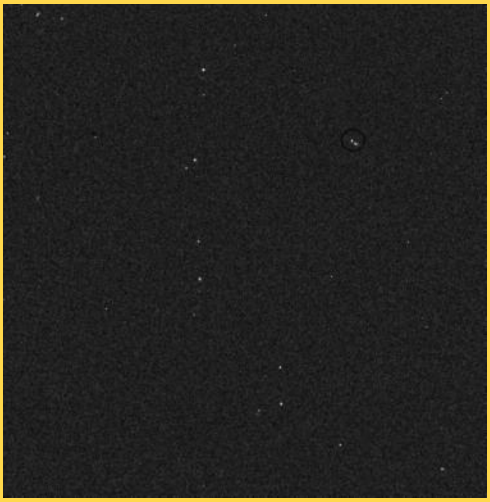
which the modulations were seen.

At that point I realize that a lot of time is going to be needed to investigate the problem and I draw up a plan of the subsequent measurements and checks to be carried out. Unfortunately though, two years have now passed since the first observations and it has all stayed "in the draw". May be it would be reasonable to conclude that I don't have (and can't afford to spend) enough free time for this study. As it is, the original study was done during holidays.

I would have liked to publish the results of this study with a few more certainties, but at this point it's better to share what I have. The hope, obviously, is that some amateur astronomer is motivated into following this particular type of astrophysical research.

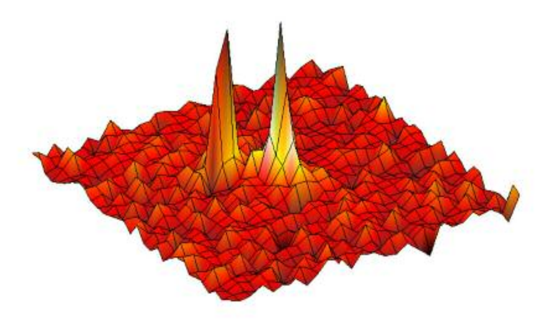
To sum up, as an observational activity it has various advantages: you can do it in your cellar, 24 hours a day, even with low grade sensors and normal cooled CCD cameras, even though these will preferentially interact with high energy particles. For the benefit of those who would like to have a go, I'll briefly describe how I set up the experiment.

I had a 16 bit cooled digital camera, with a 1024 x 1024 pixel sensor. The pixels were 24 microns, so my useful detection area was 24.5 × 24.5 mm. A FOS had been attached to the sensor. This type of camera was developed for low energy X-ray applications (8-40 keV), but it has proven useful also for my unusual application, given that the silicon interacts directly with the high energy particles while the scintillator converts into light those of lower energy, that would otherwise interact little with silicon.



In this typical image the detections of cosmic rays can be seen.

The FOS is made using a FOP (Fibre Optic Plate), essentially a bundle of optic fibres of a few microns, that simply transport the light generated by the scintillator directly onto the pixels of the CCD. There are various kinds of scintillators on sale, in my case I had some gadolinium sulphide (Gd_2O_2S), an inorganic crystal capable of producing photons at 550 nm when it interacts with a particle or highly energetic photon with an efficiency of over 10% in the energy transfer. The camera had a beryllium window, that is very transparent to particles but completely opaque to ambient light. You can also use a thin (0.1 mm) aluminium or plastic plate instead of the rather dangerous beryllium (it's carcinogenic). Installing a FOS on a CCD is an expensive operation and I strongly advise against trying to do it yourself, as you'll almost certainly damage the sensor, so it's best to work directly with a obscured CCD (sensors with big pixels are best).

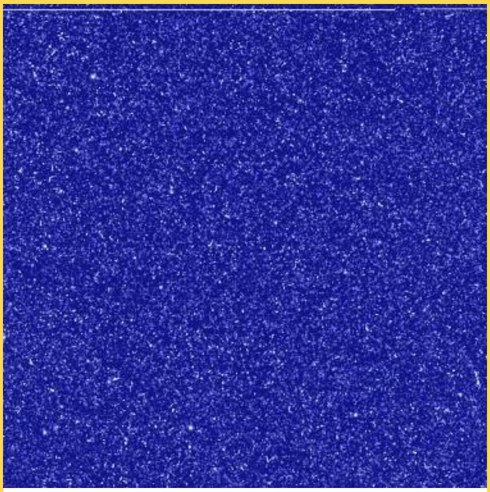


3D visualization (flux on the z-axis) of the event circled in the previous image.

Also a word about data reduction. It is necessary also to extract the number of counts from the images acquired. Just to give some kind of idea of what we are talking about (and above all to show the kind of image) we show in the figure on the previous page a typical 20 second exposure made with this equipment. Above, in 3D, we show in more detail one of the detections.

In the last image, instead, we can see what regions of the chip were struck most (in an 8 hour period), the proof that on short time scales bad luck exists!

In conclusion, the introduction of the CCD in astronomy has offered, also to the amateur, various possibilities for the exploration of the space that surrounds us. To be honest, I don't know how efficient this detection technique is compared to other methods, but if we already have a digital camera that we use for optical observations it can also easily be used as described here without any modifications. Who knows, may be we can detect the interaction between our sensor and the protons coming from a distant galaxy!



Total detections of cosmic rays on the surface of the detector in an 8 hour period.

Manuele Turini, born in Pisa in 1957, has been interested in astronomy and science since childhood. He has always thought that mathematics and physics were keys to reading the world that surrounds us. For over 30 years he has worked in the electronics industry, specializing in scientific instrumentation.