RESEARCH

Development of a Navigator and Imaging Techniques for Cryogenic Dark Matter Search Detectors

Christopher D. Wilen[1]

[1]*Carleton College*

Correspondence to: chriswilen@gmail.com

ABSTRACT

This project develops an imaging/navigational tool to assist in detecting flaws in the germanium detectors for the Cryogenic Dark Matter Search (CDMS) experiment. After imaging the detector surface with a precise imaging and measuring device, software was developed to stitch the resulting images together, applying any necessary rotations, offsets, and averaging to produce a smooth image of the whole detector. These images are tiled appropriately for the Google Maps API to use as a navigation tool, allowing inspectors to smoothly zoom and pan across the detector surface and detect flaws on the surface of the detector. Automated defect identification can then be implemented, increasing the scalability of the germanium detector fabrication. Increasing the ability to efficiently identify flaws in detectors takes the CDMS experiment closer to the objective of detecting dark matter directly.

INTRODUCTION

The effects of dark matter have been observed throughout the last century on astrophysical scales. Fritz Zwicky (1933) was the first to discover evidence of dark matter when he observed the Coma cluster of galaxies in the early 1930s. By looking at the overall brightness of the cluster, and counting the galaxies, he estimated how much mass appeared to be contained in the cluster. Observing the outer galaxies, however, Zwicky found that their rotation speed as predicted by Kepler's laws of motion was inconsistent with his mass estimates for the Coma cluster. The difference between the expected and actual estimates of galactic mass was almost 400 times. This observation was the first indication of the existence of some unseen mass exerting its effect on the motion of galaxies.

Since Zwicky's first observations, various hypotheses have attempted to explain anomalies based on conventional measures of visible mass. One such theory is referred to as Modified Newtonian Dynamics (MOND), and relies on altering classic Newtonian laws to explain the unexpected velocities of stars in galaxies (Milgrom, 1983). The theory that has gained most traction suggests that astrophysical structures such as the Coma Cluster, which show unexpected star velocities, are filled with something massive but invisible to our detection methods, namely dark matter. Numerous experiments searching for dark matter have been performed by considering the movement of galaxies, including some that examine our own spiral galaxy. Around the same time as Zwicky's observations, Oort (1932) measured the rotation curve of the Milky Way Galaxy by looking at the maximum redshift at different angles, finding that it levels out instead of dropping off as would be expected from the visible matter (Figure 1). Oort's findings have since been duplicated by others studying more distant galaxies (Rubin, 1983). Gravitational lensing also provides strong evidence for the existence of this invisible dark matter when light is bent more than it would be from visible matter alone (Walsh et al., 1979).

Other observations indicate that dark matter apparently clusters around and throughout galaxies and other visible but uncharged matter, and thus interacts with visible matter through gravity. Further evidence suggests that this interaction with dark matter does not go much further than gravity (Caroll & Ostlie, 2007). One of the strongest arguments supporting the dark matter theory comes from the recent analysis of the Bullet Cluster (Figure 2a). X-ray imaging shows two galaxy clusters colliding in the center, while gravitational lensing shows two concentrations of matter to either side, suggesting that the clumps of dark matter in each of the clusters went through each other with little interference (Figure 2b). This observation gives strong evidence against modified gravity theories, which cannot explain this effect (Clowe et al., 2006). Given dark matter's small cross section and the fact that it is unable to interact electromagnetically with photons, the limits of interaction can be narrowed to dark matter interacting with itself only through gravity and possibly the weak force.

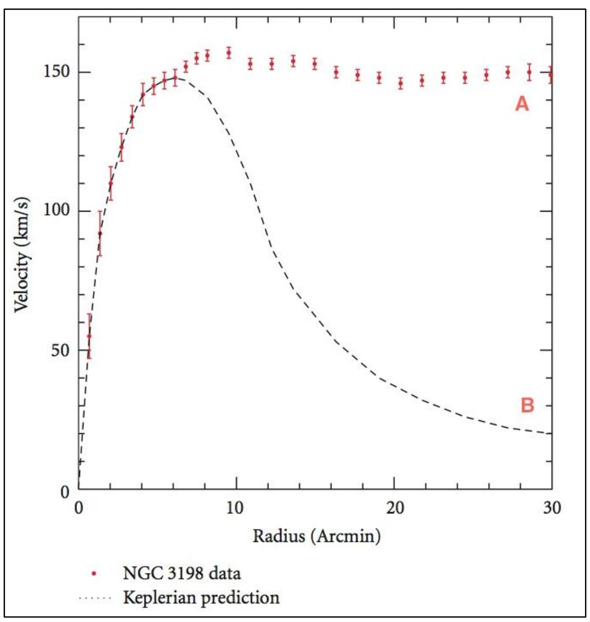


Figure 1. An illustration of the expected and measured rotation curves of the galaxy, showing the average velocity of matter as a function of distance in kpc (1 pc = 3.26 lightyears) from the center of the galaxy. Assuming Keplerian motion, and the fact that visible matter is concentrated at the center of the galaxy, we would expect rotational velocity to decrease with radius (curve B). The measured relationship (curve A) suggests that a large source of non-light-emitting matter exists in the galaxy or that Newtonian mechanics has flaws. Image courtesy of Begeman (1989).

Current estimates based on NASA and the Wilkinson Microwave Anisotropy Probe (WMAP) survey predict that the universe is made of roughly 5% atomic matter of the type experienced every day, 23% dark matter, and 72% dark energy (Filippini, 2008; Leman, 2006). Dark matter is thus significant, making up 85% of matter (as opposed to energy). But despite its significance, very little is known about the characteristics of dark matter.

A number of past as well as ongoing experiments involve detection of dark matter directly on a much smaller, single particle scale, instead of only looking at gravitational effects in large masses. The Cryogenic Dark Matter Search (CDMS) experiment is one of those experiments. Specifically, this experiment is looking for interactions between a type of (non-baryonic) dark matter called Weakly Interacting Massive Particles (WIMPS) and atomic matter, using germanium detectors. The type of direct detection being attempted by the CDMS experiment has not been previously successful, but direct detection will ultimately be

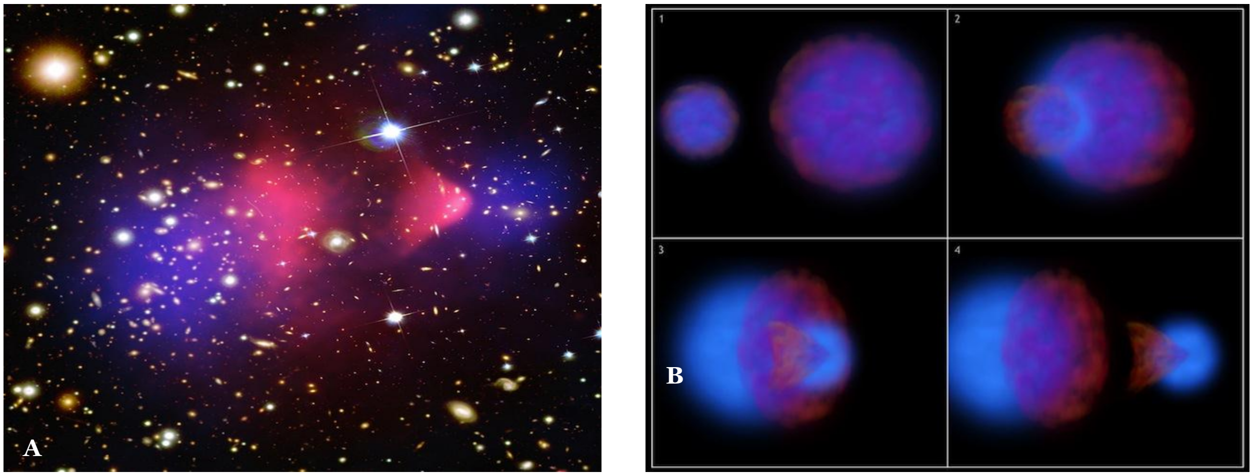


Figure 2. (A) An image of the bullet cluster taken with the Hubble telescope, with an overlay showing the calculated mass distribution in blue (The matter… 2008). (B) Computer simulations show that a model with weakly interacting dark matter closely match what we see (NASA 2006).

necessary to test current theories about dark matter, and to more fully understand its properties.

Because WIMPS are likely to be detected only rarely, it is important that detectors have a maximum chance of identifying them. The germanium detectors that are critical to the CDMS experiment are produced using photolithography. The photolithography used for patterning these sensors on the germanium crystals is much more expensive and error-prone than that used in similar processes for silicon. As a result, a method of examining the detectors in each stage of the patterning process, scanning them in detail, and finding flaws must be developed. The work reported here discusses an imaging/navigational tool developed to assist in the detection of flaws in germanium detectors. The tool images sections of the detector and then utilizes specialized software to stitch images together accurately, correcting for distortions. The images are tiled to utilize a Google Maps API to navigate across the composite image, enabling inspectors to scan the devices for flaws. Automatic flaw identification software can then be added, increasing the scalability of flaw identification when examining germanium detectors.

METHODS AND MATERIALS

Methods that attempt to directly measure dark matter do so by looking for evidence of WIMPS scattering off atomic nuclei. Because dark matter does not interact electromagnetically (Garrett & Duda, 2011), it is assumed to be constantly flowing through the matter around us, unnoticed by any current detectors. For a significant interaction to occur, the WIMPs have to hit the nucleus of atoms themselves, thereby transferring energy to the atom. Detectors in the CDMS experiment look for evidence of this transfer of energy. For the detector in the CDMS experiment, germanium was chosen over silicon and other more widely used options because of its high cross sectional area (greater surface area to interact with the dark matter and a higher density leads to a greater probability of detection). When a WIMP interacts with a germanium nucleus, some energy is transferred to the germanium from the dark matter particle through nuclear recoil. This energy propagates through the germanium in the form of phonons (lattice vibrations) until it reaches patterns of Transition Edge Sensors (TES), located on either side of the germanium crystal.

When phonons enter the aluminum in these sensors, they break apart some of the cooper pairs (the superconducting carriers), and the resulting quasiparticles are absorbed into a tungsten strip (Figure 3a,b). The whole detector is kept at a temperature of several milliKelvin, right on the edge of superconductivity for tungsten. As the resistivity of the tungsten changes due to the quasiparticles, a negative feedback loop reduces current through the tungsten to keep it at the same temperature. This change in current is measurable and recorded as a WIMP detection.

It is important to be able to distinguish dark matter detections from background radiation and decays of particles around the detector. When a charged particle or other ionizing radiation goes through the germanium, its electric field rips off electrons. By looking at the different signatures of charge build up on small electrodes patterned on surface of the detector, it is possible to eliminate detections that look like decays from atomic matter nearby or from background radiation, thereby separating noise from the desired signal indicating the presence of WIMPS.

This project developed a method for examining germanium detectors in order to identify production flaws that would interfere with accurate detection of WIMPS. A precise imaging and measuring device made by Optical Gauging Products (OGP) was used to help with the imaging process. Using several points on the detector, a coordinate system was established—corresponding with that of the detector—for the camera to move along. First, the z-value of three points was taken using adjustment of focus. With a plane representing the surface of the detector was created using these points, the x and y axis were then defined, zeroed around a point in the center, and aligned with the detector's vertical charge-detecting electrodes. Throughout the CDMS experiment, several detector patterns have been devised, so although the patterns being

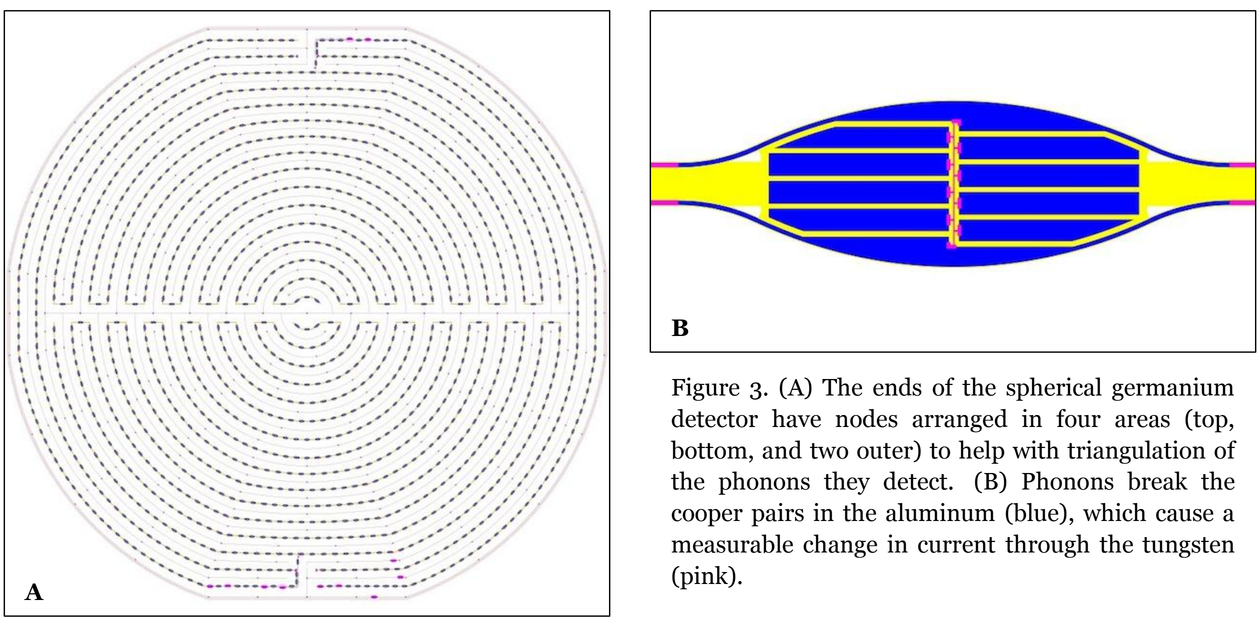
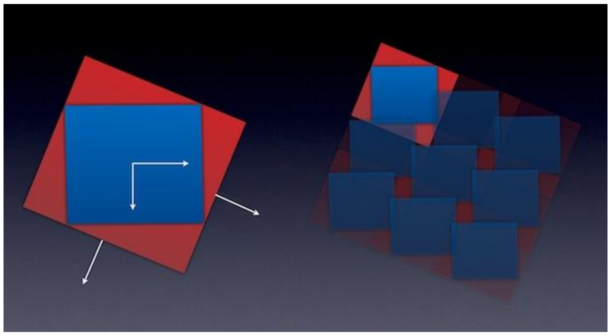


Figure 3. (A) The ends of the spherical germanium detector have nodes arranged in four areas (top, bottom, and two outer) to help with triangulation of the phonons they detect. (B) Phonons break the cooper pairs in the aluminum (blue), which cause a measurable change in current through the tungsten (pink).

imaged varied, this procedure of setting up axes generally worked. A series of images was then taken of the detector, each 640 pixels by 480 pixels, with a 20 pixel overlap. This resulted in roughly ten thousand images per detector.

Once the detector had been imaged, the images needed to be compiled into a larger composite image that could be browsed easily in order to detect flaws. During the process of creating the composite image (for which the Java programming language was used), it was possible to account for small corrections to the imaging process, such as offset, overlap, and rotation. This was important because the rotation of the camera was not necessarily aligned with the coordinate system of the detector. Compiling all the images into a single large image took significantly more memory than most computers have, so they were arranged together into larger tiles, each several thousand pixels wide. Any overlap between images was saved as an average of the overlapped areas. Instead of rotating the individual images and putting them together, the coordinate system was rotated and the images were kept in their own coordinate system to prevent loss of quality (Figure 4). Blank tiles were not written to save space and processing time.

Figure 4. Instead of rotating each image (blue) within the reference frame of the detector (red), we rotated the reference frame of the detector to prevent loss of quality.



The stitching together of the images utilized a technique known as flat field averaging, used to remove systematic variation in light intensity from a non-uniform light source. This procedure involves averaging several blank images (containing no features), and dividing every pixel by the average pixel value of the averaged image. This matrix can then be divided into all other images to remove systematic variations. When assembling color images like the ones worked with here, this flat field averaging must be done separately for each color channel.

After the large composite images were created, a navigator was created to view them for the purpose of finding hair-line fractures and other surface flaws. Ben Legler's image viewer was used as a navigator with the Google maps Application Programming Interface (API) as a foundation (Legler, Google). The Google API takes in many small image tiles and provides an interface through which the user can zoom, move, and measure distances. To make these small tiles, a program was written to take the composite images created in the previous step and translate and scale them into smaller output tiles labeled correctly (<zoom level>_<column>_<row>.<filetype>) along with the .txt file needed for the Google API.

Processing these images took a considerable amount of computer processing time, and thus multi-core threading was utilized to split the program between multiple computers or cores. This was done by splitting the rows being processed into different groups for the different processors. As input, the program was given the number of processes desired for the split, N, as well as which process was to be run by each call (thread number), n. The program then ran on the rows defined in the range given by

$$ceil(\frac{n}{N}\lambda) < row < floor(\frac{n+1}{N}\lambda)$$

where λ is the total number of rows of images produced. Empty tiles were deleted to save space and processing time.

RESULTS

In short, the methods and procedures for scanning the germanium detectors worked as intended, producing an accurate and flexible navigation tool. Each set of 8,000-9,000 images taken of the detector was stitched together with smooth looking interfaces that were barely noticeable. The stitched images were rotated and offset properly so lines and features going through the individual images matched to adjacent images with no breaks. On average, the process took one hour to complete on a modern processor, resulting in almost 15 images per tile, of which there are about 650. Figure 5 shows an example tile of stitched images.

The tiling program took these tiles and cut them into approximately 85,000 tiles that could be viewed and navigated with the Google API. The web interface to navigate and view the detectors was easy to use. The zoom and pan was smooth and loaded fast, and the additional tools such as the ruler worked as intended. The tile creation process took around ten to thirteen total run hours, which was split between two cores. A sample interface can be seen at

http://www.slac.stanford.edu/exp/cdms/CDMS_ImageNavigatorII/IZipG47_Side1_TES/.

The flat field averaging had a dramatic effect on the smoothness observed across the images. Figure 5 shows the difference between tiles where flat field averaging was implemented and where it was not. Because the brightness varied across each image, the lines where the images were stitched together can be clearly seen without flat field averaging. In the image where flat fielding is implemented, the systematic lighting differences were taken out and the

Figure 5. (A) These images of the detector were put together without flat field averaging. The seams where they were stitched together are visible because of the variation in lighting across the image. (B) Using flat fielding, these systematic variations can be removed, creating a much smoother looking image. Note: the difference in contrast is not caused by the flat fielding.

resulting composite image is smooth and seamless.

DISCUSSION AND CONCLUSIONS

Although the imaging and software programs developed in this project worked well for their purpose, the image sets are large and it took many hours to process them. Since the program has to be run after every imaging, improvements in speed would be exceptionally valuable. Future efforts should be devoted to improving the computational efficiency of the methods developed here. Ideally, the results from these programs can also be integrated with software for detecting flaws. For example, software could be written to compare the stitched images to the corresponding sections of the template using a threshold to match the colors. Any differences, where flaws are most likely to be, could then be highlighted and overlaid on the detector using the navigator so that an inspector can easily see where flaws and corrections are.

The tools and methods developed in this project are potentially crucial to the overall workings of the detector and to the success of the CDMS experiment. The detectors need to be as accurate and precise as possible to isolate dark matter detections from background. Identifying flaws in the detectors and making any possible repairs to these areas is thus an important part of the experiment. Currently the detectors need to be completely examined by hand after each step in the photolithography process. Using the methods developed in this project coupled with automated detection of flaws would allow inspectors to only examine the necessary small areas, resulting in an increase in production speed and scalability of detector fabrication. With 100 or more detectors to be fabricated, the ability to accurately scale up the flaw identification procedure could have a drastic effect on the timing of the experiment, bringing the scientific community closer to direct detection of dark matter.

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