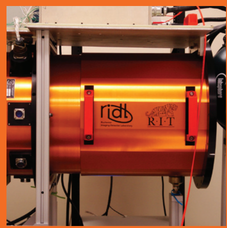
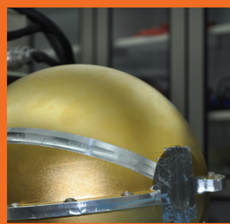
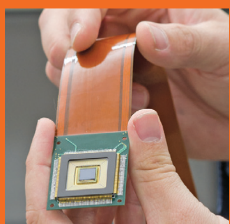
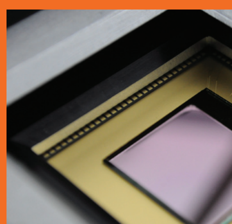
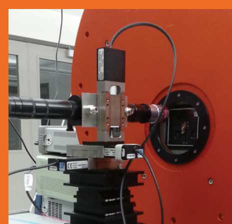
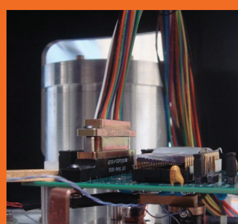


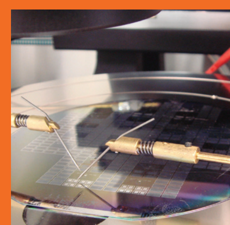

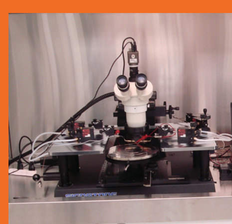

CENTER FOR DETECTORS

ANNUAL REPORT 2014

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Director's Comments

Welcome to the Center for Detectors (CfD), a cross-Institute Academic Research Center in the College of Science at the Rochester Institute of Technology. The CfD continues in its fifth year of operation. In the past year, the Center has increased its performance in terms of research projects, student experiences and outcomes, and external research funding.

Imaging detectors have been key enablers for cutting-edge space-based astronomy platforms, such as the Hubble Space Telescope and the Spitzer Space Telescope. Those missions were preceded by many years of infrared detector development and deployment on ground-based facilities. The CfD's role is to provide advanced technology with state-of-the-art facilities in order to develop these detectors. The Center is currently collaborating with Raytheon Vision Systems to develop larger and more advanced infrared detectors for both ground- and space-based astronomy missions. This work promises to break the current performance versus cost paradigm for IR detectors, and open a much larger volume of "discovery space" for future missions.

Student involvement in the CfD is key to all of our activities. Students perform original research at all levels, from early undergraduate to PhD. Their home departments are typically in the College of Engineering and the College of Science.

The following Annual Report describes the new and exciting activities of the Center of the past year. In it, you will find descriptions of CfD research, education, and outreach programs in this report.

I welcome your interest in the CfD and look forward to your support and feedback.

Dr. Donald Figer
Professor, RIT College of Science
Director, Center for Detectors

Highlights

Research

- Current projects are: Clumping in OB-Star Winds, New Visible/IR Detectors for NASA Missions, A Zero Read Noise Detector for the Thirty Meter Telescope (TMT), and Single Photon Counting Detectors for NASA Astronomy Missions.
- Projects completed this year are: A Photon-Counting Detector for Exoplanet Missions and The Mass Loss of Red Supergiants.

NASA Fellowship

- PhD student Kimberly Kolb continued her research of single photon counting imaging detectors through ongoing support from a NASA Earth and Space Science Fellowship (NESSF). Last year, her proposal was one of only nine out of 114 proposals in the NASA Astrophysics Division selected for funding.

Publications and Presentations

- Center for Detectors (CfD) team members published nine papers.
- Four talks and four posters were presented.

Executive Summary

This report summarizes activities in the Center for Detectors (CfD) over the past year, spanning July, 2013 through June, 2014. The purpose of the Center is to develop and implement advanced photon detectors to enable scientific discovery, national security, and better living. These objectives are met through leveraging multi-disciplinary and symbiotic relationships between its students, staff, faculty, and external partners, and by pursuing projects with personnel from multiple colleges, departments, companies, and national laboratories. The vision, mission, and goals are described in the Center Charter Document. The CfD was established in January, 2010. It is an Academic Research Center within the College of Science at the Rochester Institute of Technology.

Personnel

CfD members come from a diverse range of academic programs and professional occupations. During the 2013-2014 academic year, the staff included two Professors, three engineers, one student lab assistant, three PhD students, one MS student, and various other support staff.

Student Vignettes

Many of the Center's students do research in the Center's laboratories for their academic programs at RIT. CfD student, Kimberly Kolb is completing her PhD research. She won a prestigious NASA Earth and Space Science Fellowship in 2013 to research single-photon counting detectors for next-generation NASA imaging systems.

Publications

In the past year, CfD researchers published nine papers. Two of these papers were published in the Proceedings of the Scientific Detector Workshop, held in Italy. Other publication highlights include an article published in the Proceedings of the SPIE.

Grants, Contracts, and External Funding

The Center is grant-funded, and has been awarded more than $12 million in research funding. NASA, the Gordon and Betty Moore Foundation, and the NSF are the Center's primary supporters. In October, 2013, the Gordon and Betty Moore Foundation awarded a further $283,000 to the CfD for research to develop photon-counting imaging detectors.

Projects

Many CfD projects combine a variety of science areas, including various branches of engineering, physics, chemistry, and astronomy. Projects such as "The High Mass Initial Mass Function" use traditional techniques of observational astrophysics. Other projects, such as the NSF-funded New Infrared Detectors for Astrophysics, combine microelectronic engineers, astronomy experts, and various other professionals in the engineering fields.

Press & Presentations

Last October, as part of a NASA project, Kimberly Kolb presented test results for an array-based avalanche photodiode detector before and after irradiation, at a conference in Italy. The photon counting detector was developed with MIT Lincoln Laboratory with support from the Gordon and Betty Moore Foundation. Brandon Hanold also gave a presentation at the conference on the subject of an NSF project to develop new infrared detectors in collaboration with Raytheon Vision Systems.

Equipment and Facilities

The CfD is equipped with three cryogenic dewars, which were designed by the Center's lab engineers. The dewar systems have temperature controllers, readout controllers, motion stability optical tables, integrating spheres, and data acquisition and reduction computers. Last year, the CfD also purchased a gold integrating sphere, as well as new data acquisition electronics.

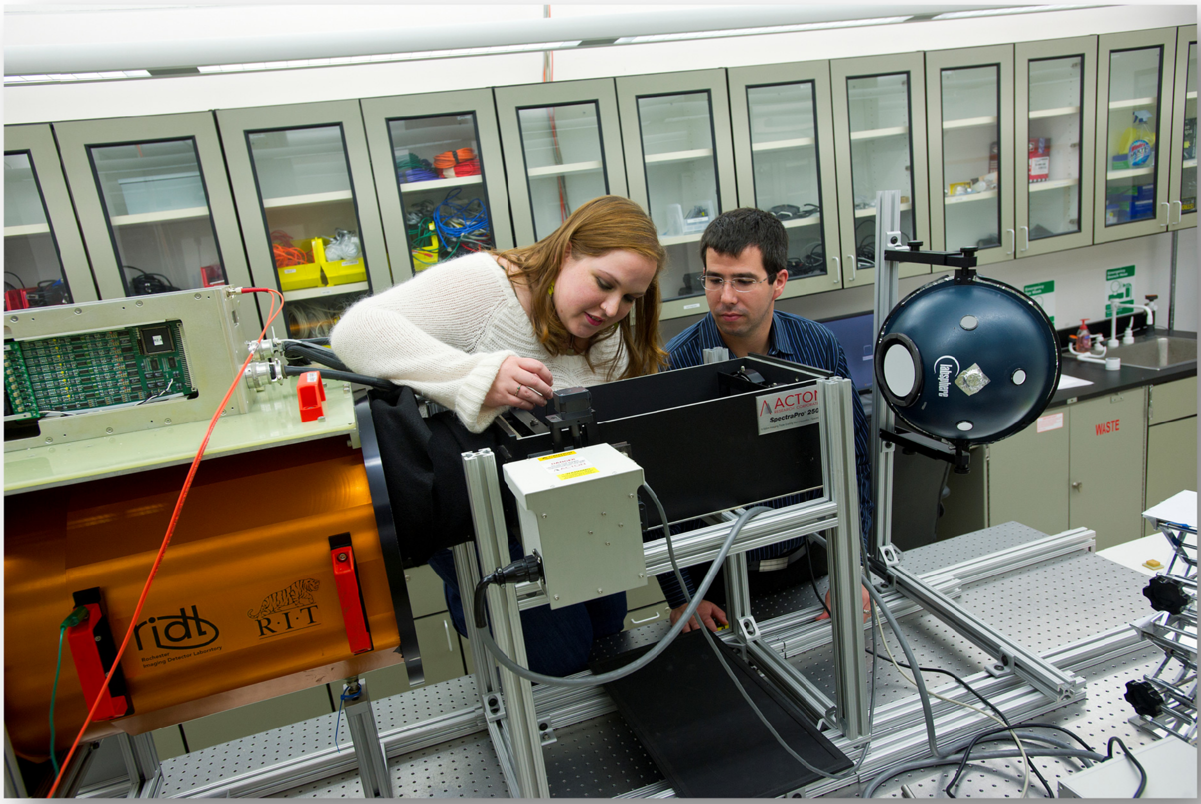
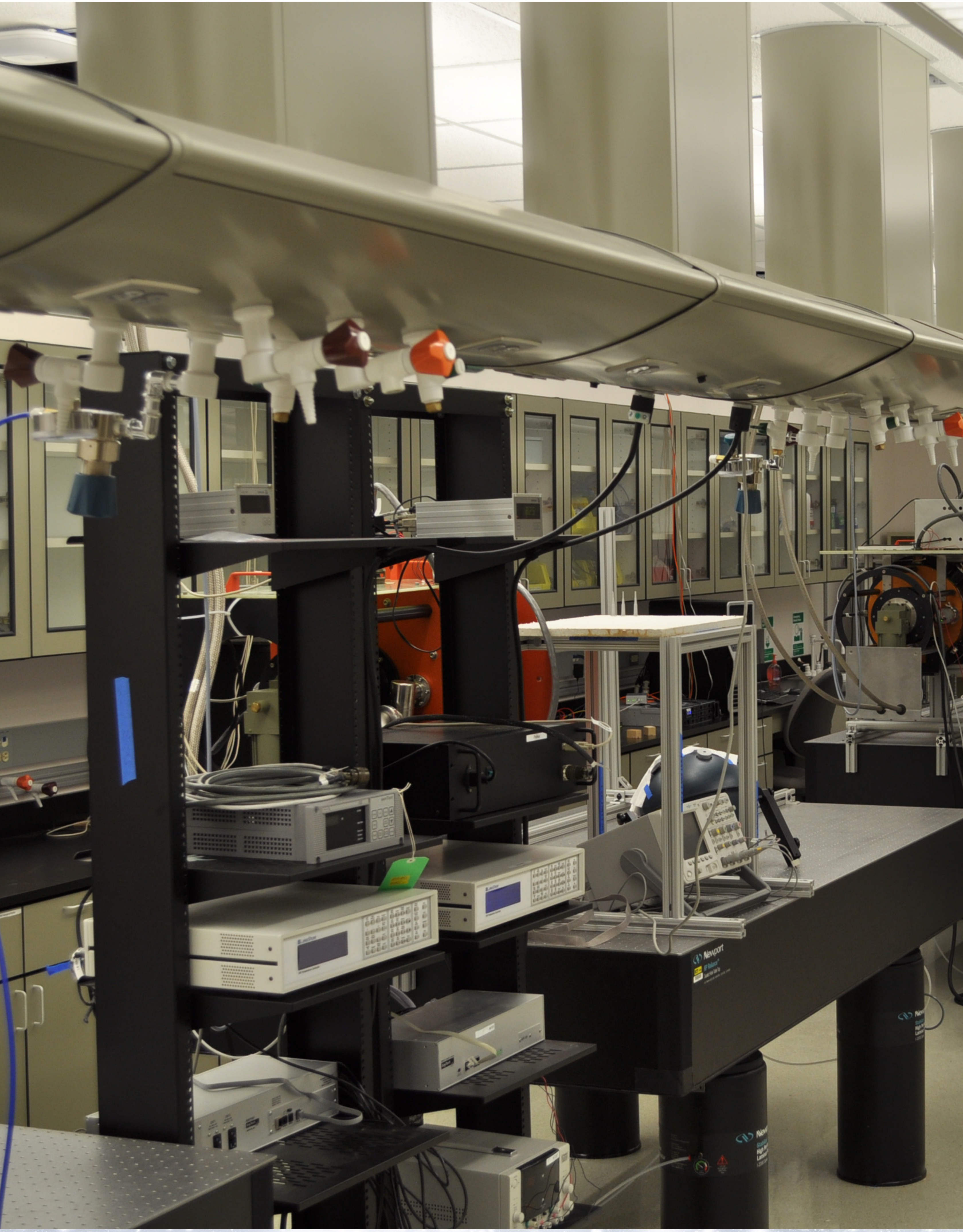


Photo courtesy of A. Sue Weisler/RIT

Research


Newport

New Visible/Infrared Detectors
NASA/Astrophysics Research and Analysis Program
NSF/Advanced Technologies and Instrumentation Program

This project seeks to develop a new generation of infrared detectors for both ground- and space-based astrophysics missions in collaboration with Raytheon Vision Systems. The new technology provides high sensitivity, broad wavelength coverage from the optical to infrared, low noise, low dark current, very low and characterizable interpixel capacitance (IPC), low cost, and scalability to very large format sizes. The technological advances that enable these benefits include new processing for depositing HgCdTe on silicon wafers. By maturing these processes, astronomers will have a powerful new tool for fabricating extremely large infrared focal planes up to 14K×14K pixels in size. The development includes the design and fabrication of test structures and hybridized focal planes in 1K×1K and 2K×2K pixel formats (Figure 1). All of these parts are being rigorously evaluated using test equipment and procedures that CfD personnel used in other successful detector development programs, *e.g.*, for the James Webb Space Telescope (JWST).

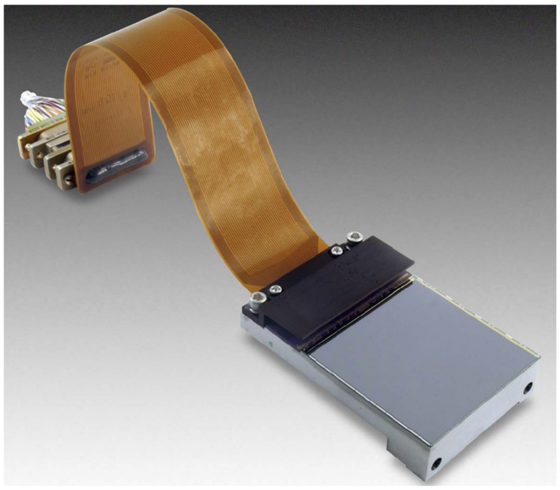


Figure 1. The picture shows a Raytheon VIRGO 2K×2K infrared detector, much like the ones that have been designed, fabricated, and tested in the current project.

These devices are ideal for missions that require large format infrared and optical detectors. NASA and NSF currently anticipate new missions that rely on the detectors like those developed in this project. These include the Thirty Meter Telescope, the Giant Magellan Telescope, the European Extremely Large Telescope, missions to study dark energy/matter, exoplanet missions, and general Astrophysics missions. One example of a future mission that is an ideal candidate for the new detectors is the Wide Field Infrared Survey Telescope (WFIRST), the highest rated space Astrophysics mission to develop in the next decade. The devices will also be very valuable for Earth Science and Planetary Science missions.

The project leverages a long heritage of device design, fabrication, and testing by the team. Particularly relevant experience lies in the ~15-year development of the process to deposit HgCdTe on silicon wafers that has been matured by Raytheon. Raytheon has a record of successfully delivering advanced detectors to a broad range of customers for a diverse set of space missions. The development uses a successfully deployed readout circuit that is being used for the Visible and Infrared Survey Telescope for Astronomy (VISTA) telescope project.

During the past year, the team fabricated and characterized seven devices to evaluate the material growth process. Material for two of the devices, VIRGO-9A and VIRGO-14, were grown from existing processes for depositing HgCdTe on CdZnTe and Si respectively. They were characterized as benchmarks for the improved HgCdTe:Si growth process. CfD received five 1K x 1K devices from the HgCdTe:Si fabrication run to date. These devices were fabricated with two different doping profiles to determine the best process for optimizing dark current and quantum efficiency.

The most interesting open question concerning this project relates to the dark current. Ideally, this "self-generated" signal would be zero. Despite over 20 years of development, the technology used in this project previously yielded detectors that had relatively high dark signal. Measurements obtained over the past year now confirm that the new process is much better and yields very low dark current that would be suitable for challenging astronomy applications (see Figure 2).

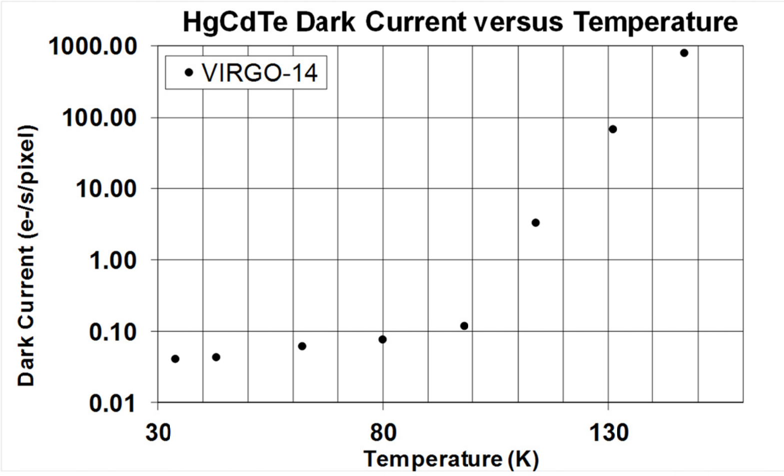


Figure 2. The graph demonstrates that the HgCdTe:Si technology used in this project yields very low dark current that is competitive with state-of-the-art devices.

Each of the data points in Figure 2 is computed by using many measurements of dark current for all of the pixels in the array. For example, a typical data point in this plot represents the median dark current signal for the four million pixels that make up a 2K×2K pixel detector. For each pixel, the dark current is estimated by fitting a slope to many reads throughout a single exposure. A more detailed look at the increasing signal during a single exposure is shown in Figure 3. Here, one can see the median signal for the whole detector as a function of time during a single integration. A line has been fit to the data. The slope is an estimate of dark current. In this example, the slope is 0.01 Analog-to-Digital Units, which is equal to 0.03 e^-/second/pixel. The temperature of the detector was 43 K during this experiment. Note that a line is not a very good fit to the data. In fact, at later times, the slope appears to be less than it is at early times in the exposure. The dark current at later times is 0.01 e^-/second/pixel.

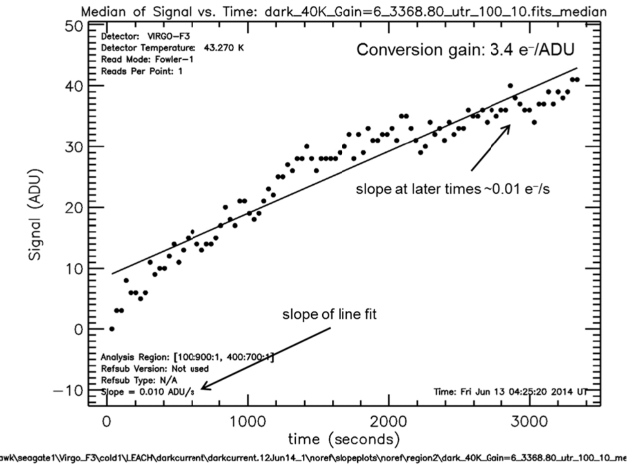


Figure 3. This plot shows the slowly-increasing signal generated by one of the detectors developed for this project. In this experiment, the device is shielded from all light. The signal should ideally be zero for the duration of this exposure, but in real cases, there is always some amount of dark current. The device that has been tested to make this plot has very low dark current, making it suitable for demanding astronomy applications.

The read noise for one of the delivered devices was measured to be 17 e^- in the correlated double-sampling read mode (Figure 3); that reading method is represented by "one" Fowler pair in the plot. This is relatively low as compared to the state of the art. As with most infrared detectors, this type of device can be read multiple times in order to obtain a better estimate of the signal. As the device is read with more samples, as shown in the plot, the effective read noise can be reduced at a rate of one over the square root of the number of reads.

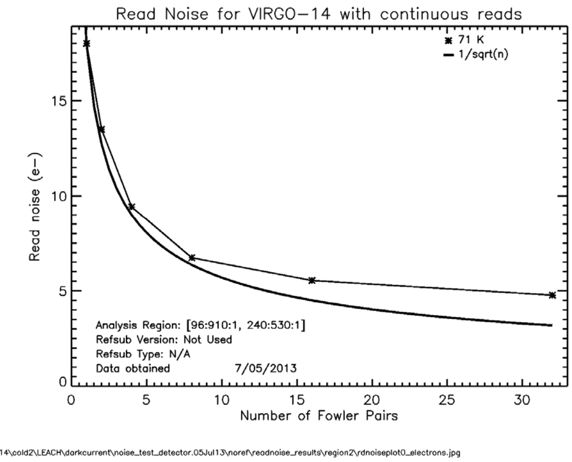


Figure 4. Above is a plot of read noise vs number of samples. About 17 e^- read noise was measured at 71 K.

Quantum efficiency (QE) represents the fraction of light that a detector translates into signal, or the number of electrons generated by each photon. Ideally, a device would generate a detectable signal for each photon that hits it, in other words the quantum efficiency (QE) would be one. In practice, QE is always less than one. A QE above 60% is very competitive with state-of-the-art devices. Figure 5 shows the measured QE as a function of wavelength for one of the new devices made for this project. The measurements were made using wide-band optical filters that are relevant for astronomy applications; therefore, the data points cover three discrete wavelength bands. In those bands, the QE is generally higher than 60%, showing that the new technology used in this project produces devices with excellent QE.

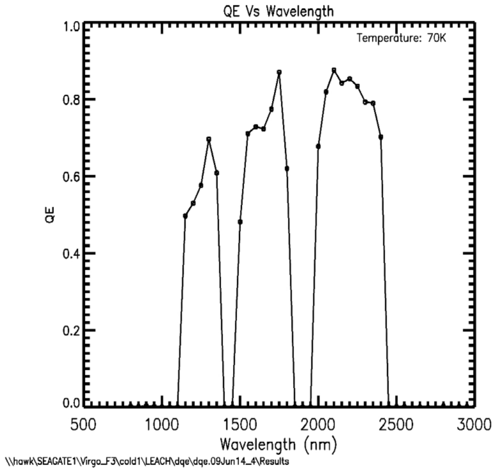


Figure 5. This plot shows quantum efficiency as a function of wavelength at 70 K for one of the devices fabricated using HgCdTe deposited on silicon. The QE is relatively high and competitive with the best devices currently available.

Figure 6 is a representative result from an experiment to measure pixel-to-pixel crosstalk. This is often described as a measurement of "interpixel capacitance," because the physical mechanism that produces the crosstalk is usually associated with mutual capacitance between pixels. The plot is produced by first identifying pixels that were hit by cosmic ray secondary particles that naturally occur in the laboratory. Once this is done, an algorithm is used to cull the sample of pixels so that only the ones that were centrally and normally hit remain. Once this is done, the signal of neighboring pixels is measured and compared to the signal in the central pixel. The results show that the tested devices have very low crosstalk. As a comparison, note that the detectors chosen to fly on the James Webb Space Telescope have at least two times greater crosstalk. The improved performance of our new devices will lead to sharper images, yielding more accurate measurements galaxy shape in dark matter projects, for example.

Detector Temperature (K): 61.4
Number of Images: 8
Number of Events: 82
Date: Fri Jun 06, 2014
Region: [0:1022,0:1022]
Crosstalk Results (%):

−0.23	0.38	−0.12
0.28	100.00	0.30
−0.24	0.37	−0.13

Figure 6. This table shows the response in a typical 3×3 pixel region of one of the new devices fabricated for this project. It shows that the nearest-neighbor pixels register a signal that is approximately 0.35% as strong as the central pixel which absorbed the incoming photon. This is at least a factor of two less than competitive technologies.

In addition to the results above, the CfD have obtained much more extensive results that will be published elsewhere. The schedule for next year includes characterization of 1K×1K devices after backside thinning. These results will be compared to the characterization results taken prior to thinning for analysis of the thinning process and its effect on the dark current and quantum efficiency. Raytheon will finish device fabrication of all remaining 1K×1K and 2K×2K HgCdTe:Si devices. After fabrication, the devices will be sent to CfD for characterization and comparison to previous measurements.

Device testing at a telescope is scheduled during the next year. Given recent developments at the national observatory, we will need to find an alternate telescope to use instead of the one proposed in the proposal. There are potential opportunities at such telescopes on Mauna Kea, in Hawaii, and on mountains in Chile.

Massive Stars in a Giant Molecular Cloud

Stars form when gas and dust collapse under the force of gravity in a molecular cloud. This process usually occurs in a cloud that is massive enough to produce many stars in a cluster. The size of the cloud determines the number of stars that are formed – bigger cloud means more stars. The most massive stars are formed in very massive clusters from giant molecular clouds.

The CfD has done pioneering research in massive star clusters, having instigated the creation of the field over the past 15 years by identifying the first massive young star clusters in the Galaxy; by "massive," astronomers mean having a total mass in stars that is greater than 10,000 times the mass of the Sun. This work continues, as researchers use infrared detector technology to peer more deeply through the interstellar dust in the disk of the Galaxy. In all, there are about a dozen young massive clusters identified in the Galaxy, with over half having been identified by CfD researchers.

One example of this research targets an area of sky that is northeast of the Galactic center by approximately 20 degrees in a star formation region known as W41. Former CfD Postdoctoral Scholar, and current collaborator, Maria Messineo has been leading a multi-wavelength research effort to assess the population of massive stars in this region. She has found a remarkable collection of multiple budding clusters that form a giant complex that is distributed throughout a giant molecular cloud. It appears that there has a been a string of ongoing star formation at this site over the past 20-30 million years, organized in sporadically-occurring massive bursts, each producing a massive star cluster. Some of the clusters are old enough that their most massive members have already exploded as supernovae, leaving behind the tell-tale high-energy signs that are indicative of such objects.

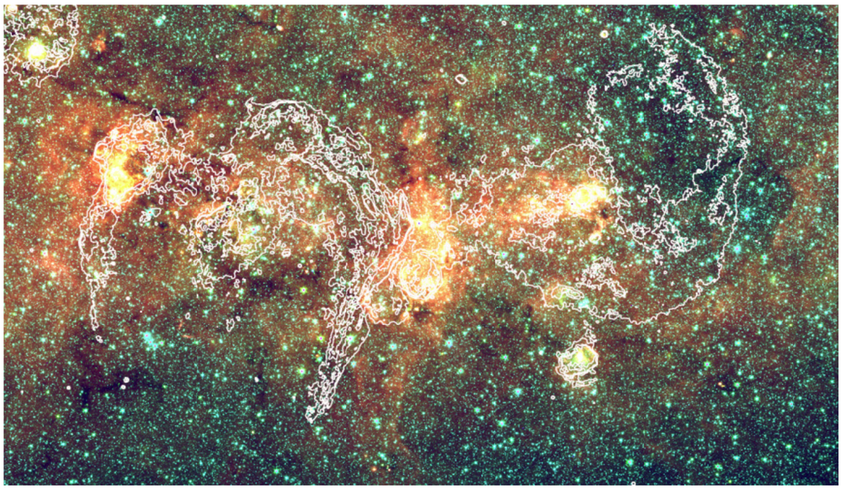


Figure 7.This figure shows a false-color composite image of the G23.3–0.3 molecular cloud complex. It was created with GLIMPSE data: 3.6 μm (blue),4.5 μm (green), and 8.0 μm (red). Contours of the 20 cm radio emission are super-imposed.

Single Photon Counting Detectors

Single photon counting detectors have the potential to deliver a big advancement for astronomy. The ability to detect single photons facilitates science goals that are impossible to achieve with current state-of-the-art detectors. The CfD is currently testing Geiger-mode avalanche photodiode (GM-APD) imaging detector arrays with zero read noise for a number of research projects. The performance of devices are also being compared to other single photon counting detectors, such as electron-multiplying charge-coupled devices (EMCCDs) and linear-mode avalanche photodiodes (LM-APDs). Over the past year, CfD research of the GM-APD-based devices occurred within the three projects described below.

A Zero Read Noise Detector for the Thirty Meter Telescope
Gordon and Betty Moore Foundation

The objective of this project is to develop a detector that will enable the most sensitive observations with the world's largest telescopes, i.e. the Thirty Meter Telescope (TMT). Having no read noise, the GM-APD detector would effectively quadruple the collecting power of the TMT, compared to detectors currently envisioned in TMT instrument studies, for the lowest light level observations. It will also be useful for space-based astrophysics, Earth and planetary remote sensing, exoplanet identification, consumer imaging applications, and homeland safety, among many others. The detector will be quantum-limited (zero read noise), be resilient against the harsh effects of radiation in space, consume low power, operate over an extremely high dynamic range, and be able to operate with exposure times over one million times faster than typical digital cameras. The CfD is teamed with MIT's Lincoln Laboratory to leverage their GM-APD technology for developing the imaging detector. In the past year, both visible-light (Si) and infrared (InGaAs) GM-APD arrays were fabricated.

A Photon Counting Detector for Exoplanet Missions
NASA/Technology Development for Exoplanet Missions (TDEM)

This project was completed in the past year. Its objective was to advance photon-counting detectors for NASA exoplanet missions. An "exoplanet" is a planet orbiting a star outside of our solar system. A photon-counting detector would provide zero read noise, ultra-high dynamic range, and ideal linearity over the relevant flux range of interest. This project leveraged the project funded by the Gordon and Betty Moore Foundation, by using the same device design, but in higher quantities than needed for that project. By using multiple detectors, it was possible to draw statistically significant conclusions about their performance and resilience in the presence of high energy radiation. This was important for predicting performance in a space mission. The TDEM project concluded in 2014 with a NASA review. The original plan was to test high-fill-factor (HFF) devices for the project, but these detectors had very high crosstalk and were not suitable for a majority of the testing. Low-fill-factor (LFF) detectors were used instead to test the device concept. Improvements to the HFF design are in progress. The success criteria for the TDEM project are shown in Table 1.

Table 1 – Success Criteria for the TDEM project are listed. ✓ status is successfully met.

	Success Criterion	Status
1	One or more GM-APD arrays will be fabricated with a high fill-factor with a 256×256 format and a pixel size of 25 microns.	✓
2	One GM-APD array described in criterion 1 will be tested to demonstrate a baseline photon detection sensitivity of 35% at 350 nm, 50% at 650 nm, and 15% at 1000 nm.	
3	Criteria 1 and 2 must be satisfied for one or more GM-APDs that demonstrate zero read noise.	✓
4	One GM-APD, having previously complied with criteria 1-3, will be exposed to high energy radiation and tested.	
5	The pre-radiation tests described in criterion 2 and the post-radiation tests described in criterion 4 shall be repeated three times without warming up the detector.	✓

Three of five success criteria were met. A HFF device was fabricated with a 256×256 format and a pixel size of 25 μm, meeting the first criterion. The second criterion was not met. The maximum photon detection efficiency (PDE) of the HFF device was ~15% near 650 nm, <1% at 1000 nm, and the device had a short-wavelength cutoff of ~450 nm. PDE will be improved in future designs by reducing crosstalk, which will allow the device to operate at higher overbiases. Both the LFF and HFF devices demonstrated zero read noise, meeting the third criterion. LFF devices were used to compare pre- and post-radiation results for the fourth criterion, but the HFF devices could not be fully characterized due to crosstalk. Finally, each experiment was completed three times without warming the detectors, thus meeting the final criterion.

CfD Engineer Joong Lee designed the radiation testing program, defining the relevant mission parameters, and simulating the expected on-orbit radiation dose. It was determined that the radiation dose at the L2 orbit is expected to be ~5 krad (Si) over 11 years. Three GM-APD devices were irradiated at Massachusetts General Hospital's Francis H. Burr Proton Therapy Laboratory with monoenergetic 60 MeV protons. They were exposed to a cumulative dose of 50 krad (Si) in geometrically spaced doses, simulating 10 solar cycles at an L2 orbit (assuming a 1 cm Al shield). The entire testing system was transported and set up at the proton beam facility so that the detectors could be tested between radiation doses in a vacuum- and temperature-controlled environment. The system was set up so that the detectors were in the path of the radiation beam inside the dewar, with the radiation passing through a thin metal cover, which kept the dewar completely dark. Figure 8 shows an image of the testing setup at the radiation facility, just before testing commenced.

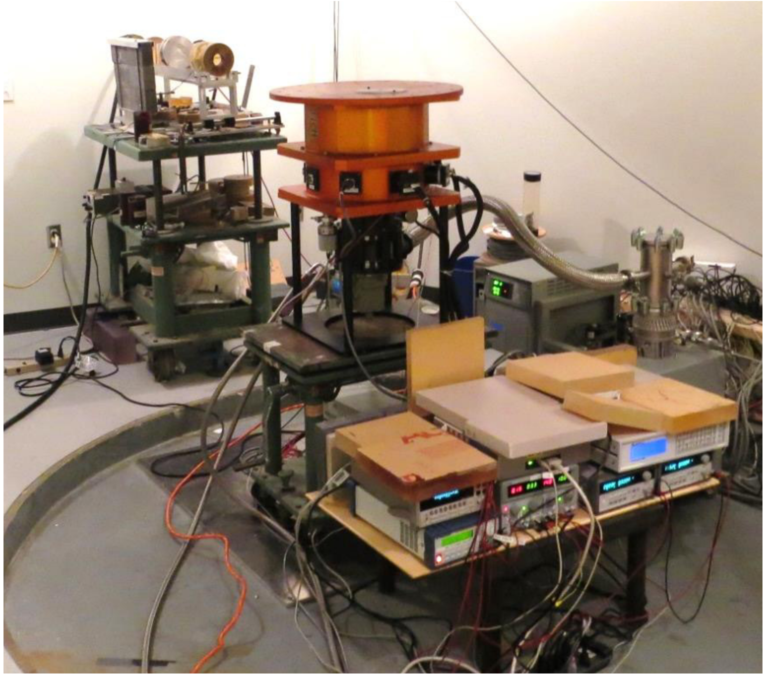


Figure 8. The radiation testing setup at Massachusetts General Hospital's Francis H. Burr Proton Therapy Laboratory is shown. In the image, the dewar (center, in orange) is under vacuum, cooled, and ready to be positioned into the radiation beam line. The control electronics (lower right) are shielded from radiation damage with lead bricks and high-density composite materials.

Figure 9 shows the in-situ results for the radiation testing of the devices. Data was taken for 20 minutes (wall time) per detector between radiation doses and overnight after the final radiation dose. The detectors were kept cold (~220 K) for the duration of the experiment. After the final dose, the control electronics suffered some failures, which were likely single-event upsets from secondary neutron scattering. The electronics were reset and reprogrammed before starting the final data set, leaving a short gap in the data.

The increase in steady-state dark count rate (DCR) is likely due to lattice damage caused by the proton radiation. Atoms that are dislodged from the lattice structure create intermediate energy states and become carrier generation sites.

There were no detector failures during in-situ radiation testing. However, despite being behind a shield of lead bricks, the electronics suffered a single-event upset that resulted in the failure of one readout channel on all the detectors. After resetting the electronics, they operated normally. The four FPGAs in the control electronics were re-programmed, as a precaution, before testing continued.

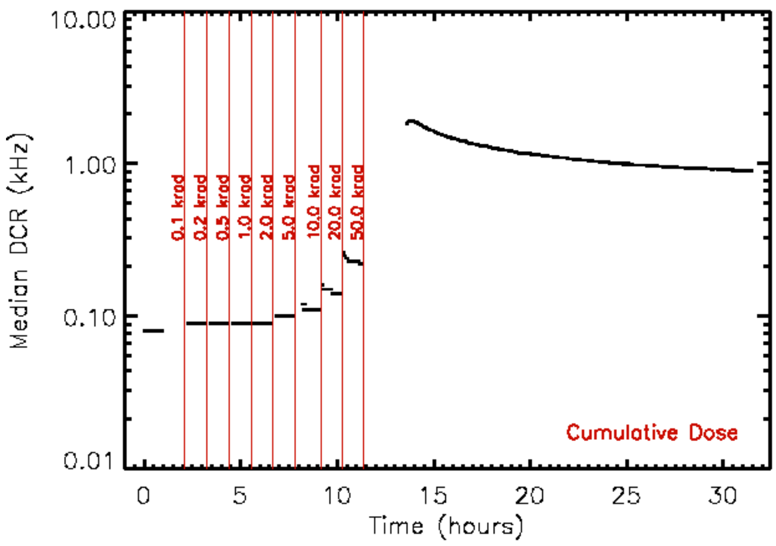


Figure 9. Median dark count rate vs time over incremental radiation doses is shown for a GM-APD device. The radiation dose is marked at the time when the radiation beam stopped for that dose.

Following the cold in-situ radiation testing, the detectors were warmed to 300 K and brought back to the CfD. Cold testing resumed when the DCR reached 99% of the settling point, calculated with an exponential decay function. Figure 10 shows warm data, taken with the same settings as when the detectors were cold.

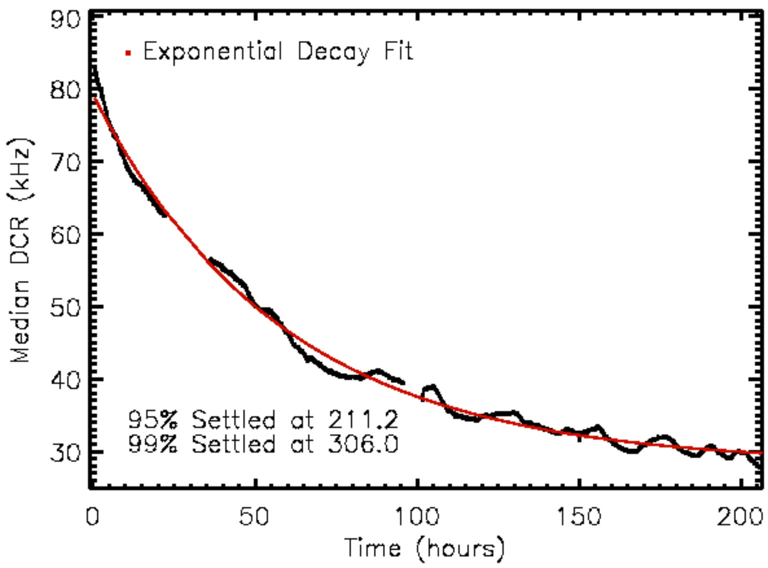


Figure 10. This figure shows median DCR vs time at room temperature for one of the GM-APD devices.

Unlike the decay in in-situ radiation data, the decay at room temperature was likely due to annealing, or self-healing, of the lattice using energy from the increased temperature. Over time, the DCR will approach a new steady-state value, which will be higher than pre-radiation levels because some lattice damage will not anneal at room temperature.

Once the DCR settled, the detectors were cooled. Over the course of three weeks, DCR data was taken at multiple temperatures in four separate experiments. Figure 11 shows the results from these four runs overlaid on the same plot. The mean percent standard deviation between the DCR data points at each temperature was ~1%. This consistency verified that the DCR had reached its new post-radiation steady-state level.

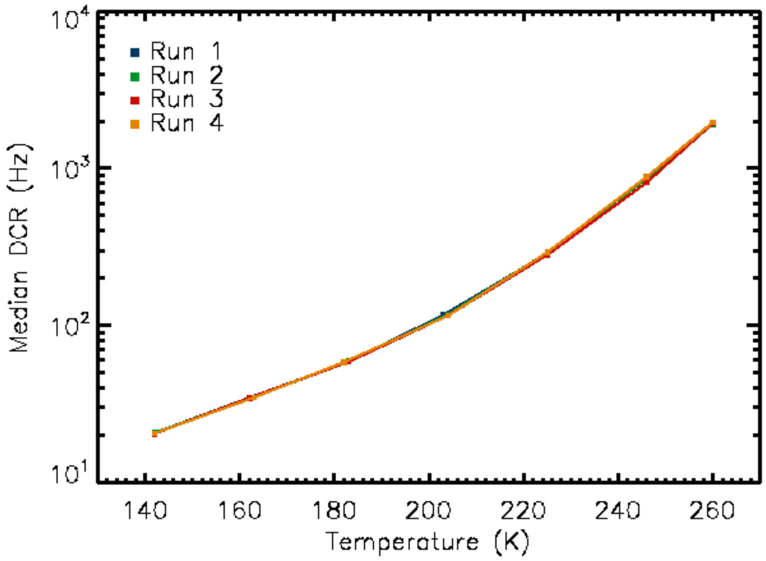


Figure 11. This figure shows median DCR vs temperature for a GM-APD detector. Each run is a separate experiment in a three week period.

Table 2 shows the pre- and post-radiation values of relevant performance characteristics for the GM-APD device.

Table 2 – SNR modeling characteristics for a GM-APD device at various radiation levels are shown.

Parameter	Pre-Radiation Value	1 solar cycle	10 solar cycles
DCR (Hz)	38	51	17
PDE (%)	0.3	0.3	0.2
Duty Cycle (%)	97	97	86
Optimum Operating Temperature (K)	160	160	140

The effective overbias for the post-radiation data after 10 solar cycles is 0.5 V, which is why the DCR is lower than for the other two radiation levels. For reference, at the same temperature and overbias, the pre-radiation DCR was 5.9 Hz, implying an increase of 11.5 Hz after 10 solar cycles of radiation at 140 K.

Figure 16 shows the expected SNR for pre- and post-radiation performance characteristics per Figure 12. The projected SNR of a detector at a specific fluence helps determine if the detector could be used for astronomical observations.

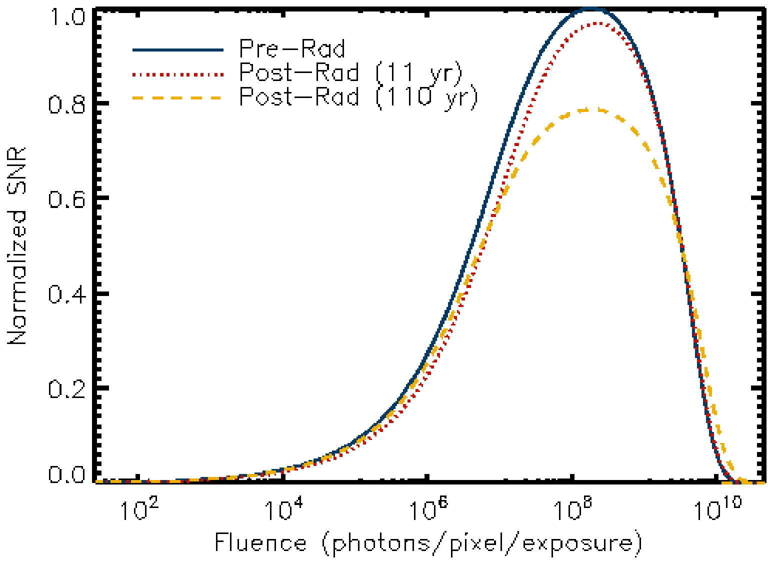


Figure 12. This plot shows the expected pre- and post-radiation SNR of the GM-APD devices.

Single Photon Counting Detectors for NASA Astronomy Missions
NASA/NASA Earth and Space Science Fellowship (NESSF)

In the next 20 years, many NASA missions requiring single photon counting will be proposed; but, which single photon counting detector implementations best suit the performance needs of NASA's astronomy programs? The goal of this project is to characterize (theoretically and physically) three unique implementations of single photon counting detectors, benchmark their operation over a range of performance characteristics, and provide comprehensive justification for the superiority of one of the implementations for each of these NASA astronomy applications: exoplanet detection, high-contrast imaging, adaptive optics, and array-based light detection and ranging (LIDAR).

This project includes the simulation, testing, and comparison of three different single photon counting implementations: GM-APDs, EMCCDs, and LM-APDs. The simulation phase includes evaluation of the material, electrical, and noise characteristics of the devices to estimate the signal-to-noise ratio (SNR) at different photon signal levels. The measured and simulated characteristics will be compared to those of other detectors, including state-of-the-art CCDs. The testing includes evaluation of read noise, DCR, afterpulsing, crosstalk, PDE, intra-pixel sensitivity (IPS), and overall SNR. A detector's susceptibility to radiation damage in space is another important characteristic. Radiation damage is physical damage to a detector caused by high-energy particles, and it causes increased dark current and afterpulsing. Studying the effects of radiation damage on the device is crucial to the project. A comparison of the devices will result in recommendations based on specific performance benchmarks for both ground- and space-based astronomy.

The research plan includes collaboration with Dr. Shouleh Nikzad (JPL), lead of the Advanced Detector Arrays and Imaging Systems group (which is currently investigating ultraviolet APDs and EMCCDs). The CfD has a long-standing, successful relationship with Dr. Nikzad, having collaborated with her on PIDDP and APRA projects.

SNR expressions for all three detector types were derived and matched to simulated Monte Carlo data in the case of LM-APDs and GM-APDs, and to published results in the case of EMCCDs. The SNR expression for an LM-APD is fairly straight-forward, since the device uses linear gain to estimate the signal. This proposal assumes that the LM-APD device is a HgCdTe detector, since HgCdTe has effectively zero noise in the avalanche gain – e.g., there is no excess noise factor in the gain process. The only consideration to take in addition to the standard charge-coupled device (CCD) SNR (aside from gain) is the un-multiplied leakage current that must be subtracted periodically to avoid saturation during an exposure. The resulting noise affects the estimation of the signal, since the gain is relatively low in these devices (10-100). Eq. 1 shows the full SNR equation.

$$SNR = \frac{S_p \cdot QE}{\sqrt{S_p \cdot QE + i_{dark} \cdot t_{int} + \frac{i_{leakage} \cdot t_{int}}{G^2} + \left(\frac{\sigma_{read}}{G}\right)^2}} \qquad \text{Eq. 1}$$

Figure 13 shows the theoretical SNR and Monte Carlo results according to Eq. 1 for the same LM-APD detector. The results are in good agreement.

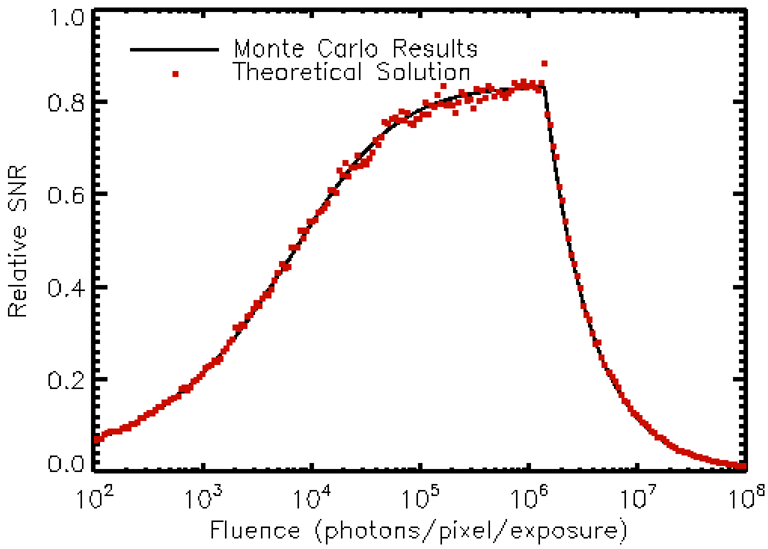


Figure 13. This plot shows Monte Carlo results (individual points) and the theoretical solution (solid line) for the relative SNR of an LM-APD detector.

Eq. 2 shows the full SNR equation for an EMCCD in photon counting mode.

$$SNR = \left[\frac{QE \cdot \lambda_p \cdot n_{gates}}{\sqrt{x(1-x)n_{gates}}}\right] \sum_{k=1}^{\infty} \frac{\Gamma\left(k, \frac{T}{G}\right) e^{-\lambda} \cdot \lambda^{k-1} \cdot (k-\lambda)}{k!\,(k-1)!}$$

Eq. 2

where $x = \frac{\#\, ones}{n_{gates}} = \sum_{k=1}^{\infty} \frac{\Gamma\left(k,\frac{T}{G}\right) e^{-\lambda} \cdot \lambda^{k}}{k!(k-1)!}$

$$\lambda = QE \cdot \lambda_p + \lambda_d + \lambda_{CIC}$$

The equation simplifies if a few assumptions about the operating conditions are made, such as the flux being <<1 photon/s/pixel, the threshold for detection at the output being set to at least three times the read noise (σ_r), and the signal being much higher than the T/σ_r threshold. Figure 14 shows the derived SNR for this research and the experimentally calculated SNR for identical detector characteristics. The derived results are in good agreement with the published experimental results, though there is a discrepancy in the saturation characteristic of the model used by the published source and the derived model presented here. The model used in the paper is very simplistic and does not take into account the noise due to thresholding, which adversely affects the SNR when the device begins to saturate. The derived model in this proposal matches the measured data at the beginning of saturation better than the model presented in the published source, though the difference in fit is small.

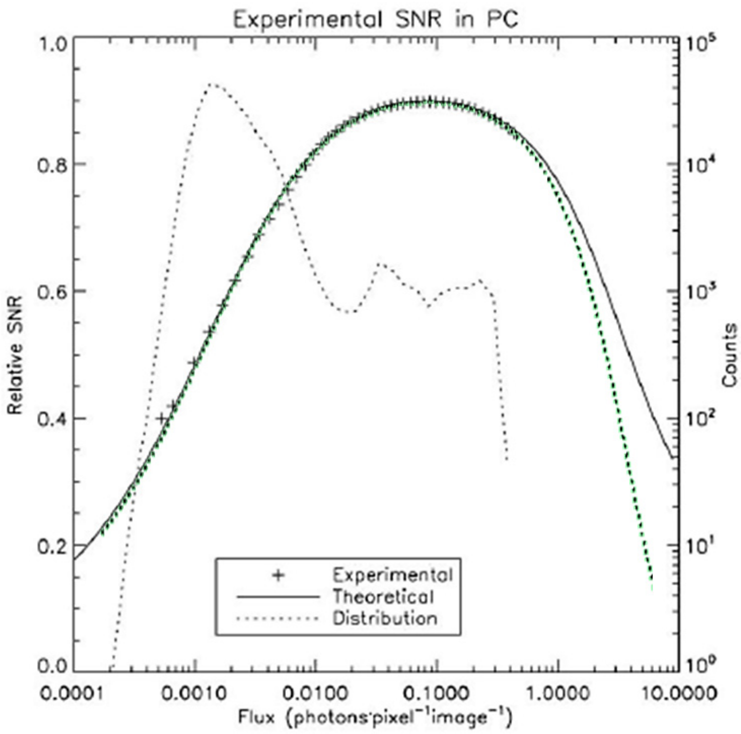


Figure 14. This plot shows derived results (green dotted line) and published experimental results (individual + signs) for an EMCCD in photon-counting mode with the same settings and noise values. The thin solid line is the SNR expression used in the reference. The derived results are overlaid on the published data figure with the same axis scaling. The only discrepancy is in the shape of the curve in saturation, but there is no experimental data to compare the theoretical curves. The derived results have a slightly better fit to the data points at the highest flux values.

It is important to note that, while the majority of GM-APD applications use arrival time-based measurements or analog avalanche totals to count photons, this GM-APD detector measures intensity by measuring the avalanche probability during a set window (usually on the order of microseconds). For this detector, the measurement is actually of the probability of an avalanche given a certain gate length, and all resolution of arrival time is lost.

The full derivation of the SNR of a GM-APD in photon-counting mode has been published in a peer-reviewed journal. The conclusion of the derivation and the comparison to Monte Carlo results are reproduced here for reference. The SNR expression, including afterpulsing, is shown in Eq. 3.

$$SNR = \frac{PDE \cdot \lambda_p \cdot n_{gates}}{\sqrt{P_1 P_0 \left(1 + 2\frac{p_{aft}e^{-\lambda}}{1 - p_{aft}e^{-\lambda}}\right)\left(\frac{1 - p_{aft}}{P_0(1 - p_{aft} \cdot P_1)}\right)^2 n_{gates}}}$$

where $$P_1 = \frac{1 - e^{-\lambda}}{1 - p_{aft}e^{-\lambda}}$$ Eq. 3

$$P_0 = \frac{e^{-\lambda}(1 - p_{aft})}{1 - p_{aft}e^{-\lambda}}$$

$$\lambda = PDE \cdot \lambda_p + \lambda_d$$

λ_p is the photon flux in photons/gate, λ_d is the dark count rate in electrons/gate, n_{gates} is the number of gates in the exposure, and p_{aft} is the afterpulsing probability. The equation simplifies significantly when $p_{aft} = 0$.

Figure 15 shows an overlay of Monte-Carlo simulation results and the theoretical solution according to Eq. 3 for the same detector. The simulation agreed with the theoretical data in both mean and standard deviation.

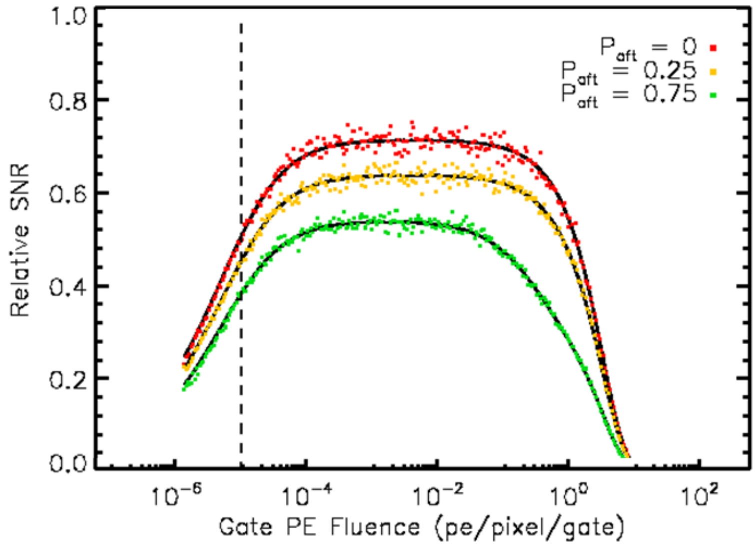


Figure 15. This plot shows Monte Carlo results (individual points) and analytical solutions (corresponding solid lines) for the relative SNR of a GM-APD in photon-counting mode vs gate fluence for multiple afterpulse probabilities. The dashed vertical line notes the fluence at which photo-generated signal and noise contributions are equal. Relative SNR is normalized to the ideal SNR, the shot-noise limited case where SNR = $\sqrt{Fluence}$.

The earlier onset of roll-off at high fluence for larger values of p_{aft} is due to an effective decrease in saturation level. Given the same fluence, the avalanche probability will increase with increasing afterpulse probability. The roll-off at low fluence is still due to DCR. While the relative SNR still has a maximum of $\sqrt{PDE}$ for the case of p_{aft} = 0, the maximum for cases where p_{aft} > 0 is lower.

New simulations have built on the simulations performed to determine the SNR for a variety of conditions and noise characteristics. The plot in Figure 16 shows the expected performance of a GM-APD device (after irradiation) at Kitt Peak National Observatory's 2.1 m telescope. For a single night of observing, the faintest object that could be imaged would have a magnitude of 21 in the V-band. The simulation accounts for plate scale, band-specific background, band transmission, and telescope diameter. The minimum settings in the bottom right corner of the figure are based on operational limits.

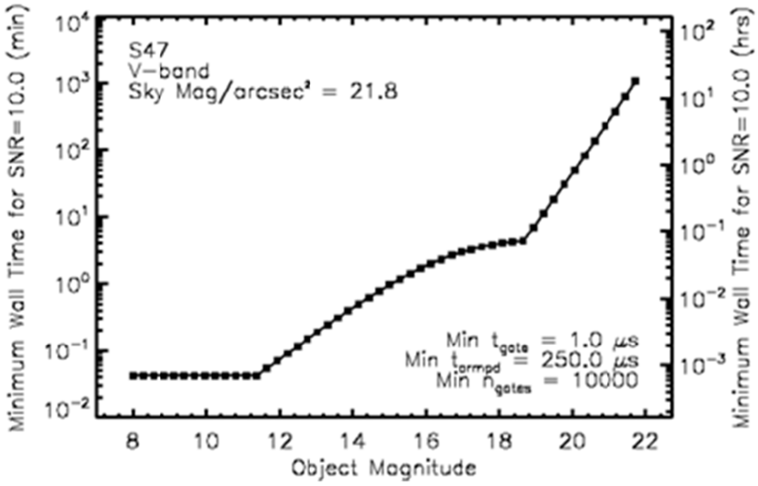


Figure 16. This plot shows the minimum wall time to reach an SNR of 10 vs object magnitude for a GM-APD.

In order to assess the performance of GM-APD array imagers for future applications, they must be compared to current state-of-the-art semiconductor-based technologies. Table 3 shows reasonable best-performance metrics for each established detector, and projected performance for a next-generation GM-APD.

Table 3 – This table shows state-of-the-art performance characteristics for fast exposures of 0.1 s (requiring pixel rates in the tens of MHz range for moderately-sized CCD- and CMOS-based imagers).

Parameter	Standard CCD	CMOS APS	L3CCD	EMCCD	GM-APD
Dark Current (e-/s/pix)	0.0002	0.02	0.0002	0.0002	0.027
CIC (e-/pix/frame)	0	0	0.0025	0.0025	0
Read Noise (e- rms)	10	10	<<1	<<1	0
QE	90%	90%	90%	90%	70%
Duty Cycle	90%	90%	90%	9%	100%
ADC Saturation (1000s e-)	72	100	1,000	1,000	N/A

The gate time for the GM-APD is assumed to be the minimum time required to read out the array for the fast (0.1 s) exposure, currently 210 μs. Under this assumption, the entire array can be read out during the next gate and the duty cycle can be 100% (assuming that there is no afterpulsing in most of the pixels). The projected DCR is a scaled version of state-of-the-art DCR based on the pre-radiation DCR trend. Figure 17 shows the expected SNR for each device in Table 3.

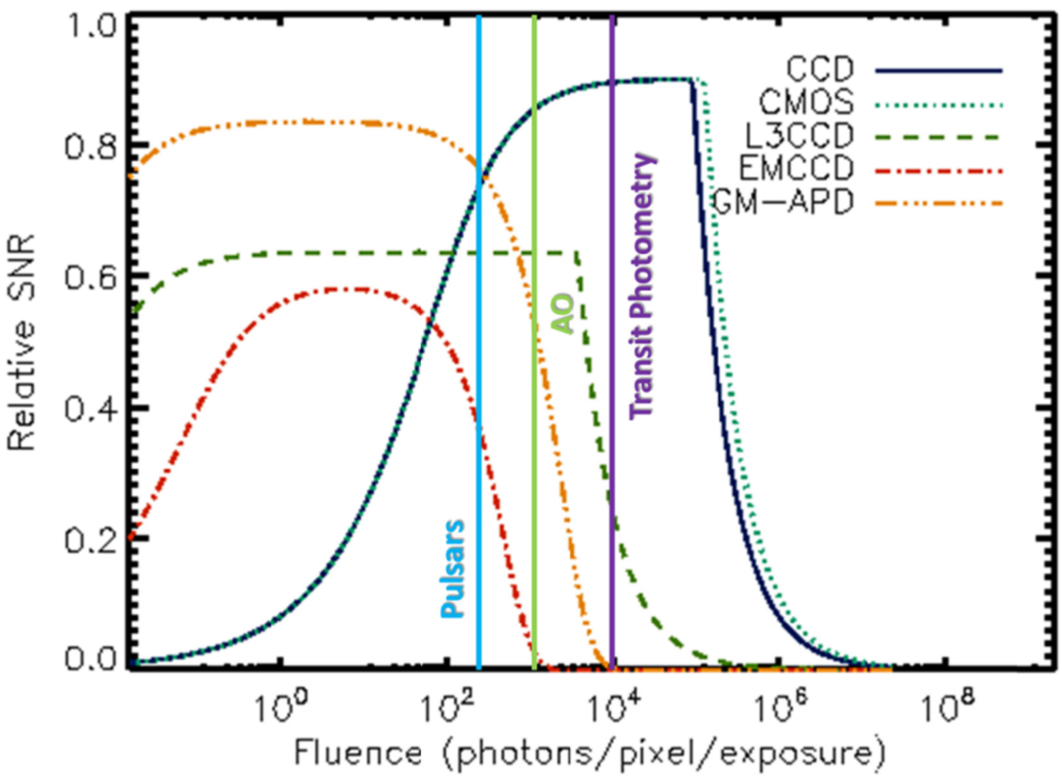


Figure 17. This plot shows the relative SNR for a variety of detector technologies in two imaging scenarios for a simulated exposure of 0.1 s wall time. The SNR for each device is normalized to the shot noise limit for each fluence value.

The CCD and complementary metal-oxide-semiconductor (CMOS) active pixel sensor (APS) detectors have nearly the same performance except for a small change in ADC saturation. Their poor performance at low fluence levels in the fast exposure scenario is due to the high read noise necessary to read out the array quickly. This disadvantage does not apply for long exposures where the read noise decreases significantly. The L3CCD (a commercially-available EMCCD, operated in analog mode for this simulations) is limited to 70% of the shot-noise-limited SNR because of the excess noise factor caused by uncertainty in the gain. It also saturates more quickly, even though its analog-to-digital converter (ADC) has a higher saturation level than the CCD or CMOS devices, because of the gain. The EMCCD suffers from very low duty cycle in the fast exposure scenario due to the maximum pixel readout rate (tens of MHz). Additionally, the clock-induced-charge (CIC), which introduces as much noise as an equivalent amount of dark current, is high when the pixel readout rate is as high as required here. In the fast exposure scenario, the GM-APD clearly dominates at fluence levels between 1 and 100 photons (corresponding to 10-1000 photons/s in this simulation). If t_{gate} were shorter (e.g., if the readout electronics were optimized for fast readout), the detector would saturate later and offer significant competition to the CCD and CMOS detectors at higher fluence levels. The absence of read noise for the GM-APD, even though the dark current is higher, makes it the best candidate for fast imaging if the projected performance levels can be met.

Table 4 – This table shows state-of-the-art performance characteristics for long exposures of 1000 s.

Parameter	Standard CCD	CMOS APS	L3CCD	EMCCD	GM-APD
Dark Current (e-/s/pix)	0.0002	0.02	0.0002	0.0002	0.027
CIC (e-/pix/frame)	0	0	0	0	0
Read Noise (e- rms)	2	3	<<1	<<1	0
QE	90%	90%	90%	90%	70%
Duty Cycle	100%	100%	100%	100%	100%
ADC Saturation (1000s e-)	72	100	1,000	1,000	N/A

A 1 ms gate time for GM-APD operation is assumed for the long exposure in order to maximize SNR at low fluence. Figure 18 shows the expected SNR for each device in Table 4.

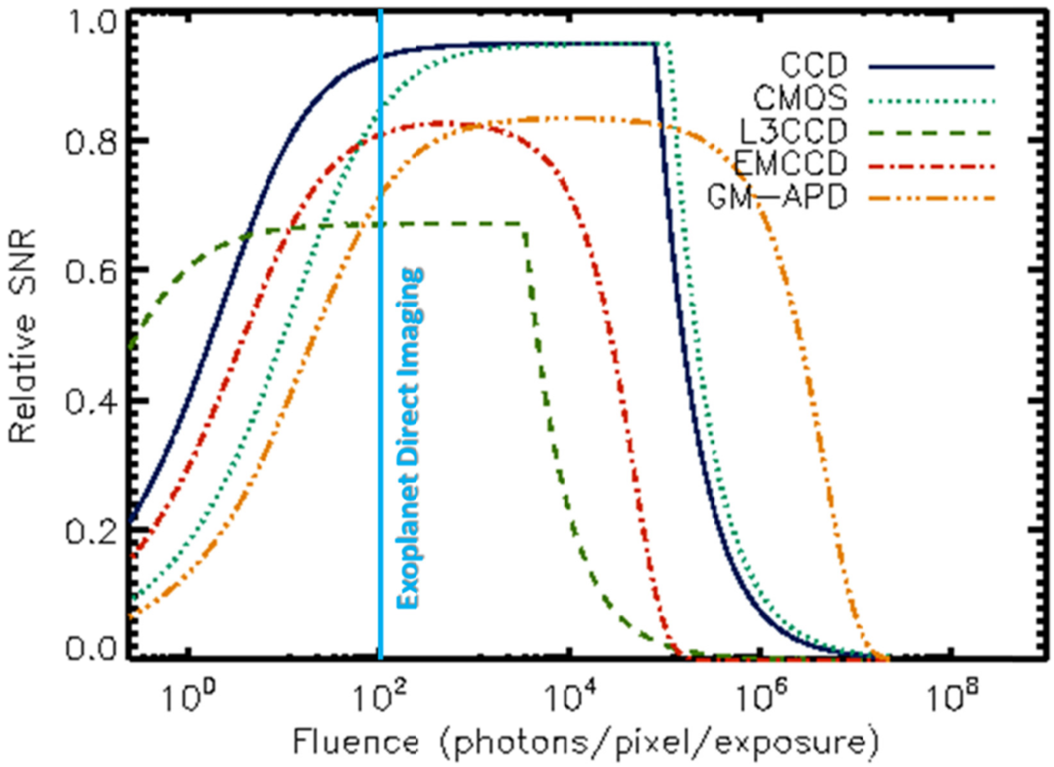


Figure 18. This plot shows the relative SNR for a variety of detector technologies in two imaging scenarios for a simulated exposure of 1000 s wall time. The SNR for each device is normalized to the shot noise limit for each fluence value.

For long exposures, the higher dark current of the GM-APD results poor performance below a total fluence of ~100 photons (0.1 photons/s), and it is out-performed by the CCD and CMOS devices between 1,000 and 100,000 photons (1-100 photons/s). However, if DCR were to improve to the levels of CCD and CMOS devices, the GM-APD would out-perform the EMCCD and the L3CCD at all fluence levels, and the CCD and CMOS devices below 10 photons (0.01 photons/s).

Mystery in the Center of the Galaxy Solved!

The precise natures of the five infrared stars for which the Galactic center's Quintuplet Cluster was named have long been a mystery. Not only do they suffer the same large interstellar extinction that obscures all objects in the Galactic center, but they are also each embedded within a warm and dusty cocoon. The pinwheel morphologies of dust around two of them suggest that they are Wolf-Rayet colliding wind binaries; however, their near-infrared spectra reveal only dust continua steeply rising to long wavelengths. Figure 19 shows an image of the Quintuplet cluster obtained by CfD Director, Don Figer, using the Hubble Space Telescope.

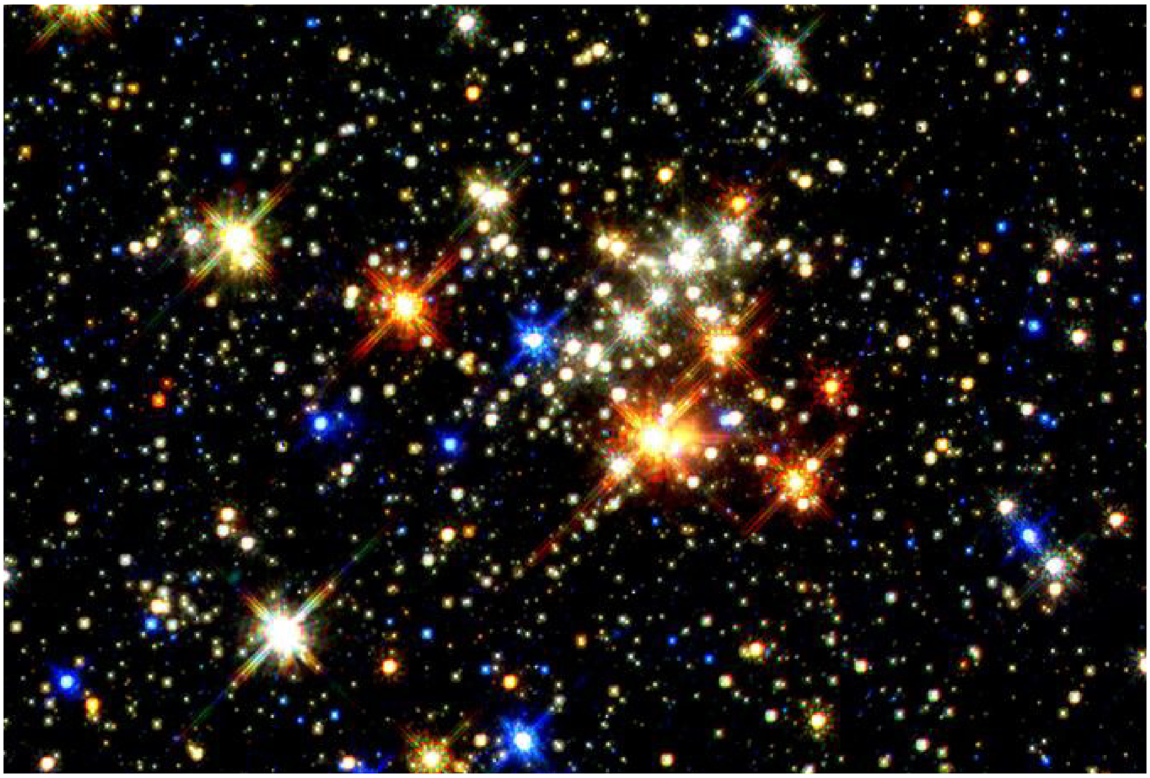


Figure 19. This is an image of the Quintuplet cluster, obtained with the Hubble Space Telescope by CfD Director Don Figer in 1997. It is one of the most massive stellar clusters in the Galaxy, containing more evolved massive stars than any other cluster. The total mass in the thousands of stars in the cluster is in excess of 10,000 times the mass of the Sun. The five very red stars are extraordinary for their very cool temperatures and dust shrouds that envelope them. Their precise natures have been a mystery since they were discovered in 1990. In 1999, CfD Director Don Figer proposed that they are dust-embedded Wolf-Rayet stars. New CfD research confirms this prediction.

If these objects are dust-embedded Wolf-Rayet stars, then one might expect to see characteristic broad emission lines from carbon and helium at shorter wavelengths where the thermal emission from circumstellar dust is less than at long wavelengths. The CfD identified just such emission lines in this objects. The work was done in collaboration with Paco Najarro and Diego de la Fuentes of CSIC and Tom Geballe of Gemini. We report the detection of a number of emission lines characteristic of hot and massive stars in 1.0-1.8 μm spectra of four of the Quintuplet stars. We confirm that the objects are dusty late-type carbon Wolf-Rayet stars.

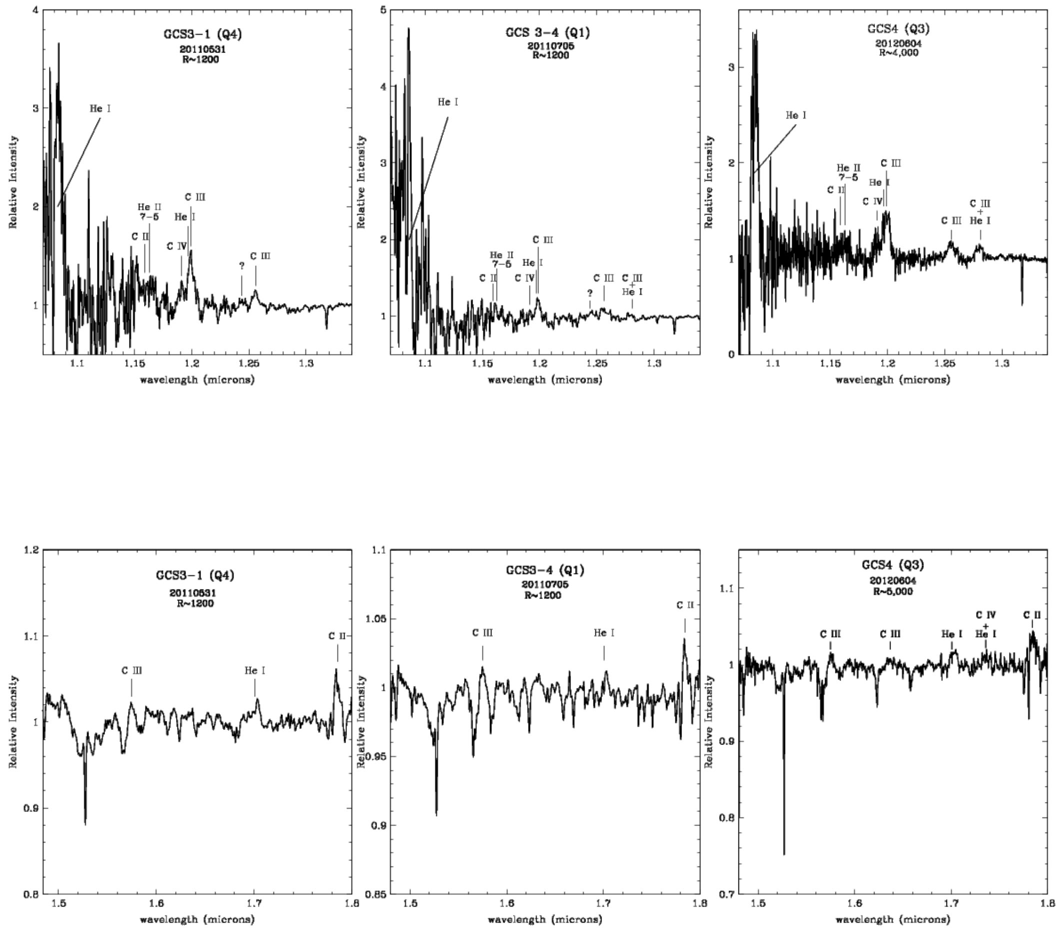


Figure 20. Infrared spectra of three of the Quintuplet stars. Wavelengths and identifications of clearly and marginally detected emission lines are shown.

Clumping in OB−Star Winds

NASA/Herschel

Massive stars have massive winds, streams of particles that the star emits into interstellar space. These winds are not smooth. Instead, they likely contain clumps of material that are important to understand in order to accurately estimate the rate of mass lost in these winds from observations made from Earth. The amount of “clumpiness” can be quantified in a “clumping factor.” It is possible to estimate this factor using advanced stellar wind models coupled with far-infrared observations. Commonly, the mass−loss rates of luminous OB stars are inferred from several types of measurements, the strengths of ultraviolet spectral lines, H−alpha emission and radio and far-infrared continuum emission. Only a consistent treatment of ALL possible diagnostics, scanning different parts of the winds, and analyzed by means of state of the art model atmospheres, will permit the determination of accurate mass−loss rates.

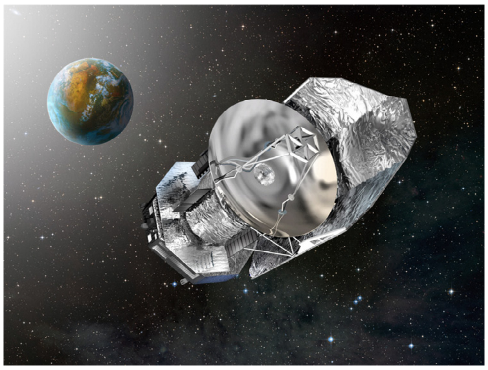


Figure 21. Artists’ rendition of the Herschel Space Observatory used in recent CfD research of massive stars.

To this end, CfD astronomers, in collaboration with researchers at the Spanish Consejo Superior de Investigaciones Científicas, used the European Space Agency Herschel Space Observatory to observe a sample of otherwise well known massive stars (Figure 21). We used the Photodetector Array Camera & Spectrometer (PACS) instrument to obtain far-infrared flux measurements from a sample of 29 massive stars.

The data obtained for this project have been excellent. Preliminary results demonstrate the power of the proposed method, showing the far-infrared flux measurements can provide for reliable measurements of wind clumping. Figure 22 demonstrates the method by using the new data. In the left panel, the Herschel/PACS data (red diamonds) for τ Scorpius can be fit with a new unclumped model. On the right, the data for ξ Persei, demonstrate that some amount of clumping is necessary to reproduce the observations.

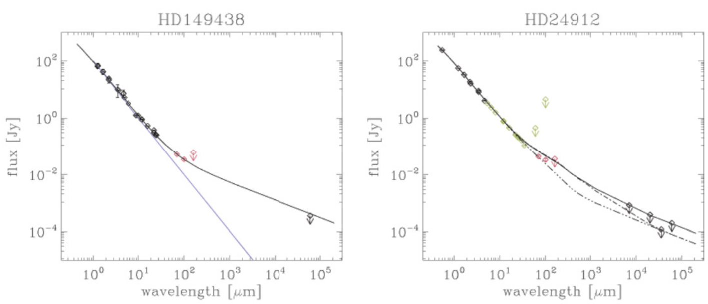


Figure 22. These plots show flux as functions of wavelength for two stars. The red data points represent measurements obtained in this project using Herschel-PACS observations. The lines represent model predictions which assume various levels of wind clumping.

Student Vignettes

Kimberly (Manser) Kolb

Kimberly (Manser) Kolb is a graduate student member of the Center for Detectors (CfD) who is pursuing a PhD in the Imaging Science program. She completed her MS degree in the same program during the summer of 2011. She completed a BS degree in Microelectronic Engineering in 2008. Her combination of degrees and experience is useful in the field of high-performance detectors, giving her a knowledge base that encompasses detector development through fabrication, characterization, and implementation. As an undergraduate student in 2007, Kimberly worked for the CfD to develop a fabrication process for the fabrication of silicon p-i-n diodes for hybridization. This work culminated in her capstone project for her BS degree.

After working for Fairchild Semiconductor (2008-2009), Kimberly returned to RIT and the CfD to pursue an MS in Imaging Science, funded by the BAE Systems Fellowship. This fellowship included a three-month co-op experience at BAE systems in Lexington, MA, working on infrared detector fabrication and process improvement. The topic of her MS thesis was the characterization of single-element, on-wafer Geiger-mode avalanche photodiode (GM-APD) devices. She tested structures to determine their noise characteristics and developed a new model for determining the contribution of optical self-retriggering to the dark count rate.

After completing her MS degree in 2011, Kimberly decided to stay with the CfD and complete a PhD. In 2013, she won a prestigious NASA Earth and Space Science Fellowship (NESSF) for her thesis proposal. The fellowship funding ensures continued training of a highly qualified workforce in disciplines needed to achieve NASA's scientific goals. Kimberly's proposal was one of only nine selected for funding out of 114 in the Astrophysics division that year. This fellowship will allow her to collaborate with leaders in the field, including Dr. Shouleh Nikzad of NASA's Jet Propulsion Laboratory. Kimberly's PhD thesis involves the testing and comparison of a variety of photon-counting devices, including GM-APDs, electron-multiplying charge-coupled devices (EMCCDs), and linear-mode APDs (LM-APDs), in array formats for imaging. Her research plan requires the full characterization of GM-APDs in the CfD, as well as the effects of radiation on the devices, and the testing of a UV-enhanced EMCCD at NASA's JPL. A theoretical model of LM-APDs for comparison to the other devices is based on the work of Dr. Don Hall at the University of Hawaii.

In the past year, Kimberly's NESSF has been renewed to provide funding through her expected graduation date of May 2015. She has published a portion of her thesis work in the Journal of Optical Engineering, detailing the derivation of the signal-to-noise ratio for the GM-APD array devices that she tested and the comparison of her theoretical model to a statistical Monte Carlo simulation (see Figure 23). Most of the GM-APD testing is complete as of this year, and Kimberly will travel to JPL in the fall of 2014 to test UV-enhanced EMCCDs and present her work on GM-APDs and comparisons to other technologies.

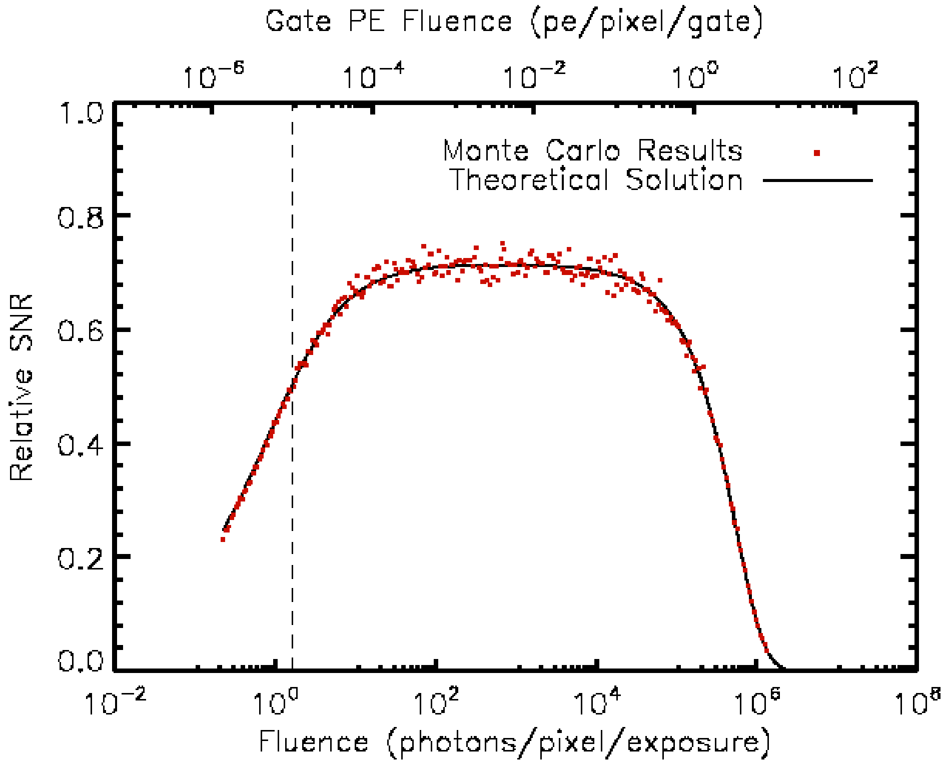


Figure 23. This plot shows Monte Carlo results vs. theoretical model for the relative signal-to-noise ratio (SNR) of a GM-APD in photon-counting mode over a range of fluence values. The dark count rate is 1 Hz. The dashed vertical line notes the fluence at which photo-generated signal and noise contributions are equal. Exposure time is 1 s, photon detection efficiency is 60%, and duty cycle is ~85%. Relative SNR is normalized to the ideal SNR, the shot-noise limited case where SNR = $\sqrt{Fluence}$.

Keith Leung

Keith Leung is a CfD student researcher pursuing a dual degree Bachelor/Master of Science in Electrical Engineering.

As an electrical engineering student at RIT, Keith has been involved with two clubs and his academics. He is a Dean's List student, past treasurer in the RIT Amateur Radio Club, and the current armorer in the RIT Fencing Club.

Keith began with the CfD in May, 2014. The focus of his work has been data analysis and hardware/software maintenance of the lab equipment. In particular, he has written data acquisition code, allowing newly gathered data to be automatically reduced. His work with the various hardware is very eclectic, especially involving the dewar systems. He has constructed simple cables, and has created SolidWorks drawings for new dewar parts (Figure 18).

Keith has also organized experiments involving test equipment, such as measuring transmission ratios of new infrared diffusers. Connected with his work on data acquisition/reduction code is his work with data analysis. His background allows him to analyze data on experimental detectors, seeing both the electronic properties and the electro-magnetic properties. He hopes to gain more knowledge and understanding of the electronics that drive modern and future astronomical technologies in his time with the CfD.

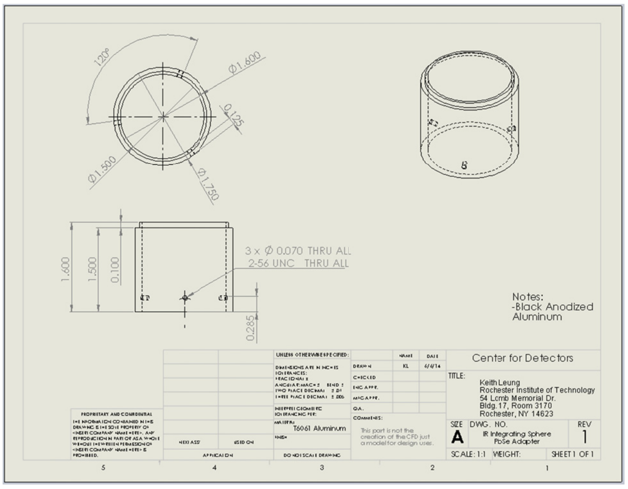


Figure 24. Keith Leung created this drawing of an infrared integrating sphere PbSe adapter. This drawing was used as a guideline for constructing the part. It is one of three drawings outlining the dimensions of an adapter designed for interfacing an integrating sphere with one of the dewar systems.

Dmitry Vorobiev

Dmitry Vorobiev received a Bachelor of Science in Astrophysics from the University of New Mexico and joined the CfD in the Fall of 2011. Before arriving at RIT, Dmitry worked with the Measurement Astrophysics (MAP) group at UNM on a NIST-funded project, developing extremely accurate techniques for ground-based photometry aimed at developing a catalog of photometric standard stars. Dmitry used real-time direct measurements of atmospheric transmission using an atmospheric LIDAR and demonstrated that these new techniques are an improvement to conventional methods, such as differential photometry.

Dmitry has been working with advisor Zoran Ninkov to develop polarization-sensitive focal plane arrays for use in a wide range of applications in astronomy, remote sensing and machine vision. This work is done in close collaboration with MOXTEK, Inc. – a world leader in the fabrication of optical components. Dmitry is involved with the characterization of microgrid polarizer arrays (MGPAs), fabrication of the polarization-sensitive FPAs and FDTD modeling of these systems.

External Funding and Collaborating Partners

Figure 25 shows funding per year since the inception of the Rochester Imaging Detector Laboratory in 2006, and continuing through the period after the Center for Detectors (CfD) was established. A breakdown of current individual grants and contracts is given in the following pages.

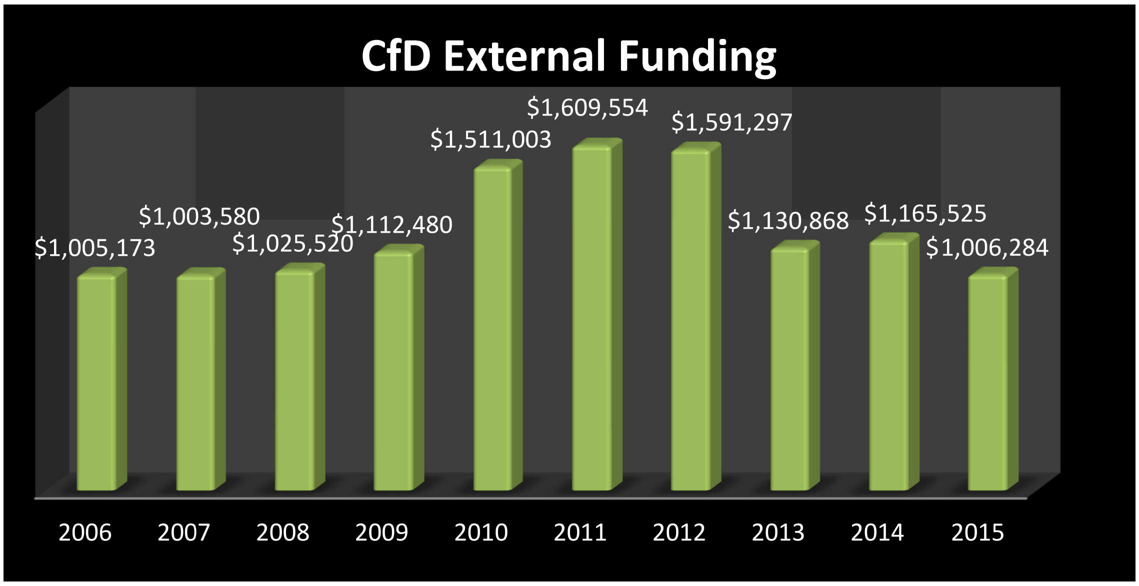


Figure 25. Since its inception in 2006, the CfD has been awarded over $12 million in research funding. The largest contributions are from the Moore Foundation and NASA. The Moore Foundation has awarded $3.1 million to support the development of a zero noise detector, while NASA awarded over $7 million in research grants. In 2012, NSF also became a major sponsor with a research grant of $1.2 million for the development and testing of infrared detectors grown on silicon wafers. In 2013, NASA granted $1.1 million to the Center to advance a new family of large format infrared detectors grown on silicon wafer substrates. In September of 2013, NASA granted graduate student Kimberly Kolb $30,000 fellowship funding.

Grants and Contracts- New

Title	Funding Source	Dates	Amount
The Development of Digital Micromirror Devices for use in Space	NASA/SAT	01/01/2014-12/31/2017	$749,281

Grants and Contracts - Ongoing

Title	Funding Source	Dates	Amount
A New VIS/IR Detector for NASA Missions	NASA	03/01/2013-02/29/2016	$1,115,107
New Infrared Detectors for Astrophysics	NSF	06/01/2012-05/31/2015	$1,246,799
Enhancing the UV/VUV Sensitivity of CMOS Image Sensors	Thermo Fisher Scientific NYSTAR UofR/CEIS	07/01/2010-06/30/2014	$134,550
THz Virtual Scene Generation and Microgrid Polarizer Development/THz Antenna Modeling	ITT Exelis NYSTAR UofR/CEIS	07/01/2012-06/30/2014	$178,500
Next Generation Imaging Detectors for Near- and Mid-IR Wavelength Telescopes	Gordon and Betty Moore Foundation	10/01/2008-09/30/2015	$3,122,191
Single Photon Counting Detectors	NASA/NESSF	09/01/2013-08/31/2016	$90,000

Grants and Contracts - Completed within the Past Year

Title	Funding Source	Dates	Amount
A Photon-Counting Detector for Exoplanet Missions	NASA/TDEM	02/19/10-02/18/14	$783,981
The Mass Loss of Red Supergiants	SOFIA	01/16/13 - 01/15/15	$8,000

Collaborating Partners

The CfD collaborates extensively with diverse types of external organizations including other academic institutions, government agencies, and industry leaders. Some examples are, the University of Rochester, NASA, ITT Exelis, and Raytheon Vision Systems. The vision of the CfD is to be a global leader in realizing and deploying ideal detectors and associated systems, which requires the support of brilliant engineers, passionate philanthropists, and truly inspired industrial partners. Our mission requires a team effort, distributed across several organizations, each with its own world-class expertise and often significant infrastructure developed over decades of past projects.

Because of our collaborative approach, and the centrality of student involvement in all of our projects, CfD students benefit from the exposure to a wide range of research and development environments. Another major goal of the CfD is to train students through deeply immersive work with authentic externally funded research that defines the cutting edge of what is possible. Some students have the opportunity to visit partner organizations for extended periods of time. This training and preparation in the CfD helps students launch their careers after graduation.

Universities

UCDAVIS
UCIRVINE | UNIVERSITY of CALIFORNIA
UNIVERSITY of ROCHESTER
THE UNIVERSITY of NEW MEXICO
NYSTAR
University of Hawaii Institute for Astronomy
Gordon and Betty MOORE FOUNDATION
R·I·T
LELAND STANFORD JUNIOR UNIVERSITY
UNIVERSITY OF PITTSBURGH

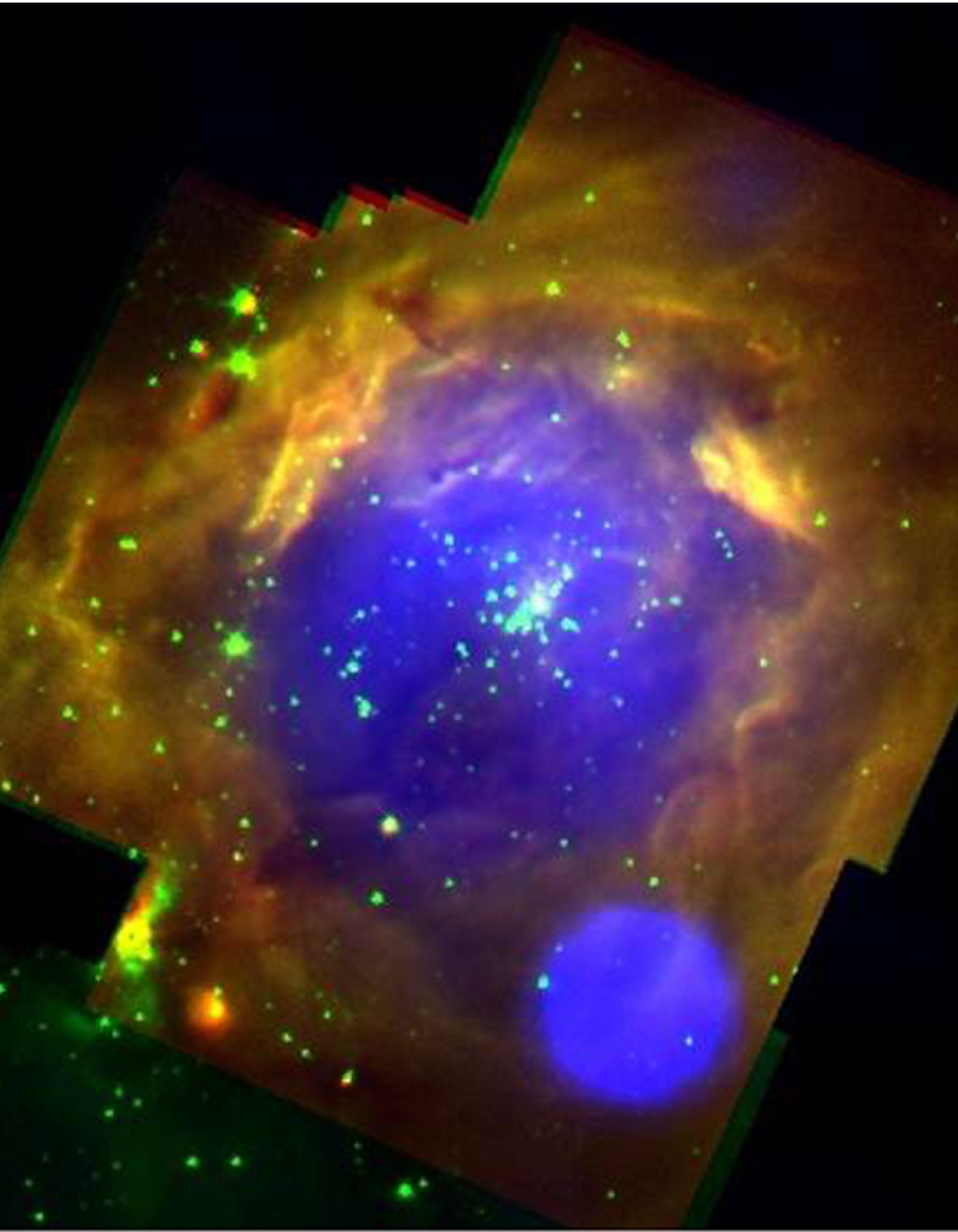
National Research Laboratories

MARSHALL SPACE FLIGHT CENTER
NSF
NASA
DEPARTMENT OF ENERGY UNITED STATES OF AMERICA
LSST
MIT Lincoln Laboratory
Office of Science U.S. DEPARTMENT OF ENERGY
National Optical Astronomy Observatory
CSIC
SLAC
JPL
SPITZER SPACE TELESCOPE
SNAP
Sandia National Laboratories
BERKELEY LAB
SPACE TELESCOPE SCIENCE INSTITUTE

Industry

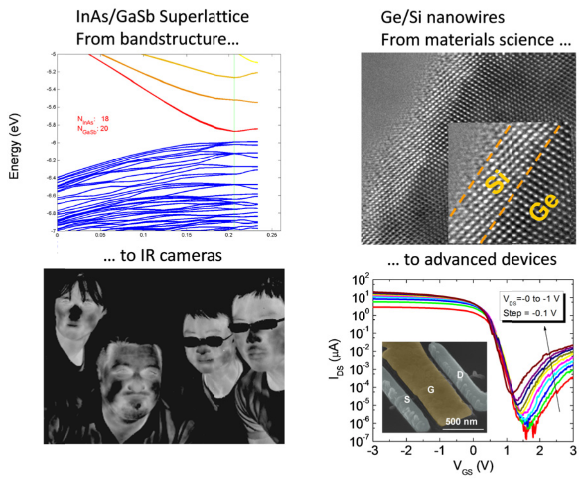
Rochester General Health System
Carestream HEALTH
BAE SYSTEMS
TELEDYNE SCIENTIFIC & IMAGING, LLC A Teledyne Technologies Company
INFOTONICS technology center inc
Raytheon
Thermo SCIENTIFIC
Ball
ITT Engineered for life
Kodak

Communication



Distinguished Speaker Series

Nanoscale Semiconductor Hybrids: Fundamental Physics and Advanced Devices – Dr. Binh-Minh Nguyen



Abstract

Artificial low dimensional systems such as quantum dots, quantum wires, and quantum wells have been significantly broadening mankind's knowledge and experience on the quantum nano-world. However, in many cases, going toward low dimensionality requires to sacrifice a degree of freedom which is an intrinsic property of bulk 3D materials: interaction between sub-systems. Inspired by the way Nature put isolated atoms together to create more complex interacting systems, we are interested in constructing novel semiconductor heterostructures from low dimensional building blocks. Hybridizing these quantum structures are expected to enhance the control and manipulation of these systems in order to broaden their applications in advanced electronic/optoelectronic devices. In this presentation, I will give two examples of low dimensional hybridization: 1) one dimensional chain of multiple interacting quantum wells InAs/GaSb with the bandgap engineering capability for high performance infrared imaging and 2) concentric Ge/Si and Si/Ge heterostructured one dimensional nanowires for high performance, ultrashort channel length field effect transistors. The large flexibility in realizing and controlling nano-scale heterostructured semiconductors in one and two dimensions is the key stepping stone toward the goal of constructing and exploring low-dimensional hybrid systems, which will be discussed at the last part of the talk.

About the speaker

Binh-Minh Nguyen is a Director’s postdoctoral fellow at the Center for Integrated Nanotechnologies (CINT), Los Alamos National Laboratory. He received an engineer degree from Ecole Polytechnique, France and a doctoral degree in Electrical Engineering from Northwestern University, USA in 2005 and 2010 respectively. Nguyen’s research encompasses multi-disciplinary fields of materials science and applied physics and engineering, with a strong focus on device physics, material growth and nano-fabrication.

In the News

CfD Graduate Student Kimberly Kolb Studies Tiny Details of Vast Universe

In October of 2013, the Center for Detectors was featured in an RIT News release, "*CfD Graduate Student Kimberly Kolb Studies Tiny Details of Vast Universe*". The article was about Kimberly Kolb, a graduate student who has made outstanding progress in her research. Her work involves "imaging arrays of Geiger-mode avalanche photodiodes, or GM-APDS, which count each photon, or unit of light, carried in an 'avalanche,' or a flurry of electrons".

The article goes on to talk about how Kolb spent her summer testing and analyzing the devices in the CfD. Kolb, along with four of her colleagues, tested the detectors at the Massachusetts General Hospital Francis H. Burr Photon Therapy Center in order to simulate the effects space would have on the detectors. The process included irradiation, which is the process by which an object is exposed to radiation.

In the fall of 2013, Kolb won a fellowship from NASA's Earth and Space Science program to compare the new Geiger-mode avalanche photodiodes with two other single-photon detectors, linear-mode avalanche photodiodes and electron-multiplying charge-coupled devices.

Don Figer, CfD Director, was quoted in the article when he mentioned "Kim's research has the potential to dramatically transform our perception of the universe and also our ability to probe the human body. She has been more deeply embedded in the center's research than any other graduate student we have had, and she is now in a unique position in the world to do the most meaningful development of new photon-counting detectors."

CfD Shedding light on Earth-like planets

Photo courtesy of A. Sue Weisler/RIT

"*Shedding Light on Earth-like Planets,*" was an article written by Susan Gawlowicz of RIT's University News program in November of 2013. The story covers CfD work using the proton accelerator at the Francis H. Burr Proton Therapy Center. The accelerator produces high energy protons to kill cancer in patients at the Massachusetts General Hospital during the week and does double-duty on the weekends to simulate the harsh effects of space as a source of radiation for astronomical instruments.

The plan was to test three detectors that RIT, along with MIT, are developing for NASA exoplanet missions, otherwise known as the quest for Earth-like Planets beyond the Milky Way Galaxy.

The most important factor in detector technology is the ability to detect photons, or units of light. From the article, "Imaging detectors collect the packets of light and record the radiation in signals that scientists read like sheet music to gain new understanding of astronomical objects. The pressure is on for imaging technologies that can withstand the radiation in space and collect more photons with less interference. Future space missions depend on detectors to sharpen the focus and widen the view and to record the symphony of the early universe without static."

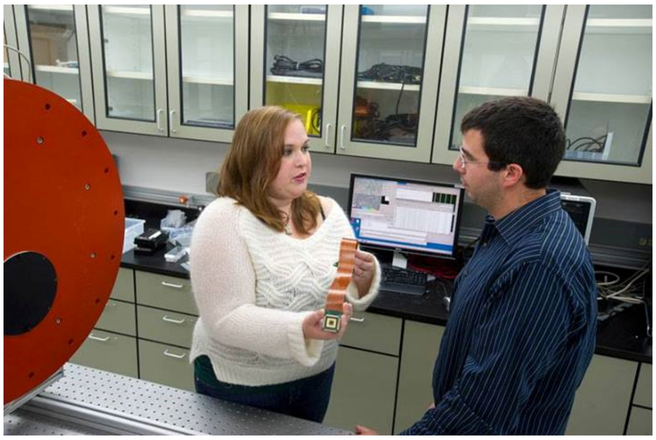
The light-sensitive detectors tested for this project are made of silicon. "Silicon has a sensitivity range very similar to the human eye, mostly in the visible spectrum," explains Kimberly Kolb a Microelectronic Engineer at the Center for Detectors. "Infrared detectors can "see" photons at lower energies than the human eye is capable of seeing because a longer wavelength equals lower energy. While going the other way on the spectrum, ultraviolet and X-ray detectors "see" photons that have energies too high for our eyes to see."

Better detectors for scientific exploration also provide for a broad range of societal benefits. This includes anything from new methods of biomedical imaging to remote sensing applications that monitor not only the health of the planet but also the safety of the nation. "Center for Detectors researchers are pushing the edge of what is possible in ways that will expand future discoveries," Don Figer says. "This radiation testing is another example of doing what it takes to advance technology."

Infrared Detector Technology at RIT's Center for Detectors

In February of 2014, the CfD was featured in an RIT University News article, written by Susan Gawlowicz. It discussed CfD's upcoming projects involving new infrared detector technology. CfD is collaborating with Raytheon Vision Systems in order to develop new kinds of detectors to be used for different applications. Raytheon is a global company focused on technology and innovation specializing in defense, security, and civil markets. They provide state of the art electronics, mission systems integration and other capabilities in the areas of sensing.

The goal of this project is to develop larger detectors. Currently, the detectors contain around 4 megapixels, which is already fairly large, but CfD is trying to bump that number up to the gigapixel level. The new detectors are highly sensitive and cover an immense field of view. They will have very low noise, allowing scientists the ability to see faint objects, such as galaxies. An advantage to this new wave of ultra-sensitive detectors is that "We could see other planets that are like earth – maybe that harbor extraterrestrial life", says Don Figer, Director of the CfD.



In order to achieve these standards, the most sensitive detectors are required. This is being obtained by CfD by running test and measuring the number of photons they observe. The number of photons a detector can detect answers many of science's difficult questions. Questions such as: Where is the exoplanet? Where is the ozone hole? Where is the cancer in a patient's body?

CfD is one of only a select few locations where testing of the highest precision can be performed. Because of this, CfD is sponsored by both NSF as well as NASA. "We're the lead organization, so that means we're going to set the end goals and the plan for how to reach these goals", states Don Figer. This is a similar role that the CfD Director played in the development of detectors for the James Webb Space Telescope. Two competing types of detectors were proposed for that space observatory. Based on measurements obtained by Figer, NASA chose the winning technology. The telescope is scheduled to be launched in late 2018 when it will perform a very delicate sequence of maneuvers to unfurl its segmented mirror in space. The operation will keep scientists and engineers on edge because the observatory cannot be fixed if this operation goes awry, given that the telescope will be about a million miles away from Earth and inaccessible by astronauts.

Education and Public Outreach

Promotional Videos

Over the past year, two promotional videos explaining the importance of the CfD's work were made. The first video, titled "Center for Detectors," was produced by RIT Production Services. It begins by showing a baby and explaining that seeing clearly is an important part of observing and understanding life. The CfD is developing technology to improve our ability to see clearly not only things that are far away in space but also within our own bodies. With funding from the Gordon and Betty Moore Foundation, and in collaboration with MIT's Lincoln Laboratory, the CfD is developing an imaging detector that will advance the power of telescopes as well as probes used to look inside the human body. This device could also be used to find other Earth-like planets as well as peer into the early universe. The Center's research has discovered large carbon-based molecules in the Milky Way Galaxy. If these contain amino acids, it may indicate how the building blocks of life got to Earth. Figure 26 shows what this might have looked like. In addition to research, the CfD is a key component to RIT's masters and doctoral programs in astrophysics, imaging science, and microsystems engineering. The video concludes by showing some students working on the research that will be used to advance science and industry.

Figure 26: Shown above is an artist's rendition of meteors containing carbon-based molecules entering Earth's atmosphere.

The second video, titled "Infrared Detector Technology at RIT's Center for Detectors," was filmed by David Wivell, the Multimedia Producer at RIT's University News Service, and describes CfD projects to develop infrared detectors with Raytheon and zero noise detectors with Lincoln Laboratory. The goal is to produce detectors that are larger than any currently in use that have a field of view in the scale of giga pixels. This greater sensitivity will allow scientists to detect more distant and faint galaxies with less noise, the salt and pepper pattern in Figure 27. This may also allow us to detect other Earth-like planets that harbor life. PhD candidate Kim Kolb, explains that it may seem as if counting photons is inconsequential to our lives however, this helps science answer many important questions not only for astronomical discoveries, but it also has applications in more immediate concerns such as finding holes in the Ozone Layer or finding cancer cells. The Center is a world leader in precision testing of these detectors.

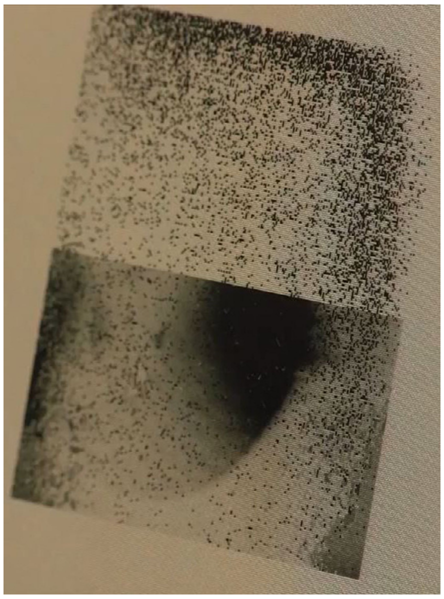


Figure 27: This is an image from a detector showing noise.

Both videos can be found on the home page of the Center's website, http://ridl.cfd.rit.edu, or on YouTube at:

https://www.youtube.com/watch?v=rRMiVk4sySY (Center for Detectors)

https://www.youtube.com/watch?v=VgPAaVymB2M (Infrared Detector Technology at RIT's Center for Detectors).

Publications

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Organization


17
IT Collaboratory
IT Collaboratory

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Charter

About the Center for Detectors

The CfD designs, develops, and implements new advanced sensor technologies through collaboration with academic researchers, industry engineers, government scientists, and students. The CfD enables scientific discovery, national security, better living, and commercial innovation through the design and development of advanced photon detectors and associated technology in a broad array of applications such as astrophysics, biomedical imaging, Earth system science, and inter-planetary travel.

Vision and Mission

Our Vision is to be a global leader in realizing and deploying ideal detectors and associated systems. Our Mission is to enable scientific discovery, national security, better living, and commercial innovation through the design and development of advanced photon detectors and associated technology by leveraging collaborations with students, scientists, engineers, and business partners, at academic, industrial, and national research institutions.

Goals

- Develop and implement detector technologies that enable breakthroughs in science, defense, and better living.
- Train the next generation of U.S. scientists and engineers in team-based, interdisciplinary, world-class research.
- Create opportunities for faculty, students, and international leaders to advance the field of detectors and its relevant application areas.
- Grow externally-supported research.
- Increase economic activity for local, regional, and national companies.

Focus Areas

The Center seeks to apply its technologies to many different scientific areas including Astrophysics, Biomedical Imaging, Defense, Earth Systems Science, Energy, Homeland Security, and Quantum Information. These focus areas are mainly what brings together the great variety of individuals from diverse areas of expertise.

Astrophysics – A zero read noise detector will enable the discovery of Earth-like planets around nearby stars, life on other planets, the nature of dark energy and dark matter, and the origins of stars and galaxies.

Biomedical Imaging – The Biophotonic Experiment Sensor Testbed will enable safe detection and monitoring of breast cancer and cognitive functioning with unprecedented sensitivity.

Defense – Space-based cameras will be equipped with the most sensitive detectors that provide rapid delivery of the most sensitive information.

Earth Systems Science – The Center's detectors will be exploited to address fundamental Earth system science questions, such as sensing of photosynthesis or the creation of atmospheric pollutants, detection of atmospheric or ocean temperature gradients, or the timely viewing of extreme events.

Energy – New high photon-efficiency solar cells will be developed to ensure sustainable energy generation for economic competitiveness and national security.

Homeland Security – Advanced imaging detectors will be able to reveal potential airborne biochemical hazards through high-resolution three-dimensional ranging, spectral discrimination, and motion pattern recognition.

Quantum Information – High-speed single photon receivers will be deployed to support future technologies in photonics, communication, quantum computing, and quantum cryptography.

Governance

The Center is supervised and operated by its founding Director, Dr. Donald Figer. A committee of experts, from RIT and elsewhere, advise the Director to ensure successful definition and execution of the Center's vision and goals. The committee meets once per year after the completion of the CfD Annual Report. Center members include academic researchers, industry engineers, government scientists, and university/college students.

Funding

Since its inception in 2006, the Center for Detectors has received $13 million in research funding. The largest contributions are from the Moore Foundation and NASA. The Moore Foundation has granted $2.8 million to support the development of a zero noise detector, while NASA awarded over $6 million in research grants. In 2012, NSF also became a major sponsor with a research grant of $1.2 million for the development and testing of infrared detectors grown on silicon wafers. In 2013, NASA granted $1.1 million to the Center for a related project to advance a new family of large format infrared detectors grown on silicon wafer substrates. In October, 2013, the Gordon and Betty Moore Foundation award $283,000 to the Center for Detectors.

Capabilities, Equipment, and Facilities

The Center for Detectors is located in the Engineering building (Building 17) at the Rochester Institute of Technology. It has 5,000 square feet of space for offices and labs, including offices for 17 people, and four research laboratories: the Rochester Imaging Detector Laboratory (see Figure 28), the Quantum Dot Detector Laboratory, the Imaging LIDAR laboratory, and the Wafer Probe Station laboratory. The laboratories contain special facilities and equipment dedicated to the development of detectors.

Figure 28. Above is the main CfD lab, the Rochester Imaging Detector Laboratory.

These facilities include a permanent clean room, ESD stations, vacuum pumping systems, optical benches, flow tables, light sources, UV-IR monochromators, thermal control systems, cryogenic motion control systems, power supplies, general lab electronics, and data reduction PCs. The equipment is capable of analyzing both analog and digital signals. Separate rooms in the CfD are devoted to electrical rework and laser experiments. In addition to these dedicated facilities, the CfD has access to facilities within the Semiconductor and Microsystems Fabrication Laboratory (SMFL) and other areas across the RIT campus.

The RIDL detector testing systems (Figure 29) use three cylindrical vacuum cryogenic dewars. Each individual system uses a cryo-cooler that has two cooling stages: one at ~60 K (10 W) and another at ~10 K (7 W). The cold temperatures yield lower detector dark current and read noise. The systems use Lakeshore Model 340 temperature controllers to sense temperatures at 10 locations within the dewars and control a heater in the detector thermal path. This thermal control system stabilizes the detector thermal block to 400 μK RMS over timescales greater than 24 hours. The detector readout systems include an Astronomical Research Camera controller having 32 digitizing channels with 1 MHz readout speed and 16-bit readout capability, two Teledyne SIDECAR ASICs having 36 channels and readout speeds up to 5 MHz at 12-bits and 500 kHz at 16-bits, and custom FPGA systems based on Altera and Xilinx parts. The controllers drive signals through cable harnesses that interface with Detector Customization Circuits (DCCs), which are designed in-house and consist of multi-layer cryogenic flex boards. The DCCs terminate in a single connecter, which then mates to the detector connector. Three-axis motorized stages provide automated lateral and piston target adjustment. Two of the dewars have a side-looking port that is useful for exposing detectors to high energy radiation beams. The lab also has a large integrating sphere that provides uniform and calibrated illumination from the ultraviolet to through the infrared, and it can be mounted to the dewars. The dewars are stationed on large optical tables that have vibration-isolation legs.

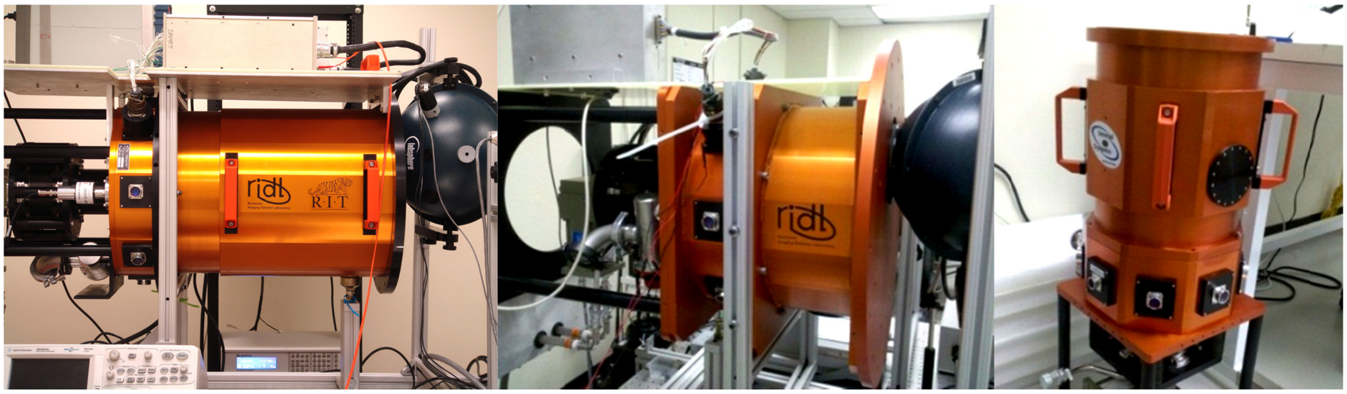

Figure 29. Detectors are evaluated in three custom dewar test systems.

The lab equipment also includes a Pico Quant laser for LIDAR system characterization and other testing that requires pulsed illumination. In addition, the lab has monochromators with light sources that are able to produce light ranging from the UV into the IR, with an approximate wavelength range of 250 nm – 2500 nm. NIST-traceable calibrated photodiodes (with a wavelength range of 300 nm – 1100 nm) provide for absolute flux measurements. CfD also has a spot projector to characterize the inter-pixel response of the detectors, including optical and electrical crosstalk. Figure 30 shows a laser spot projection system on a 3D motorized stage that produces a small (~few microns) point source for measurements of intrapixel sensitivity.

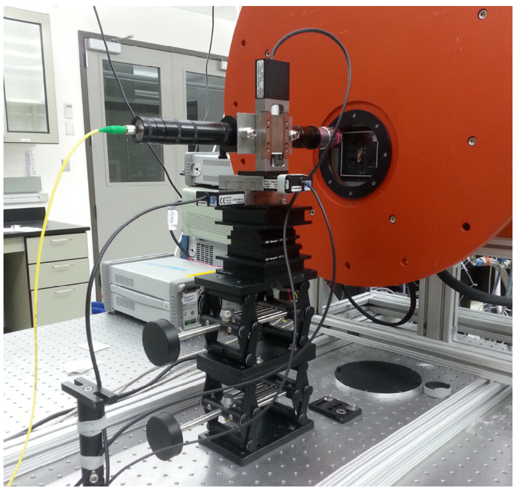

Figure 30. Shown here is a laser spot projector with three axis motion control system.

The lab contains eight data reduction PCs, each with eight processors and up to 16 GB of memory for data acquisition, reduction, analysis and simulations, and 25 TB of data storage. Custom software runs an automated detector test suite of experiments. The test suite accommodates a wide variety of testing parameters through the use of parameter files. A complete test suite takes a few weeks to execute and produces ~0.5 TB of data. The data reduction computers reduce and analyze the data using custom automated code, producing publication-quality plots in near-real time as the data are taken.

CfD has the capability to design system components needed for detector testing using CAD programs, *e.g.* SolidWorks. This thermal finite element analysis software is also used to simulate thermal cooling of system components and detectors. Eagle and PCB Express are used to design layouts for readout circuits that interface with the detectors. System-based software tasks also include data processing with IDL, C and C++, HDL programming on Xilinx and Altera chips, as well as the SIDECAR ASIC.

CfD has a dedicated class 1000 cleanroom (by FED Standard 209E), located in the SMFL. The SMFL has 10,000 ft^2 of additional cleanroom space in class 1000, 100, and 10. Using the SMFL's resources, the Center can fabricate detectors with custom process flows, and has the freedom to use multiple process variations.

The Center's cleanroom and probe stations offer wafer-level testing, even during the fabrication process, allowing mid-process design changes (Figure 31). The probe station accommodates electrical and circuit analysis of both wafers and packaged parts, including low current and radio frequency (RF) probing. Also available for CfD use are the Amray 1830 Scanning Electron Microscope (SEM; see Figure 32), used for high-magnification imaging of devices, and the WYKO white light interferometer, used for surface topography measurements. The SMFL also has other in-line fabrication metrology capabilities, including material layer thickness, refractive index, and wafer stress characterization tools.

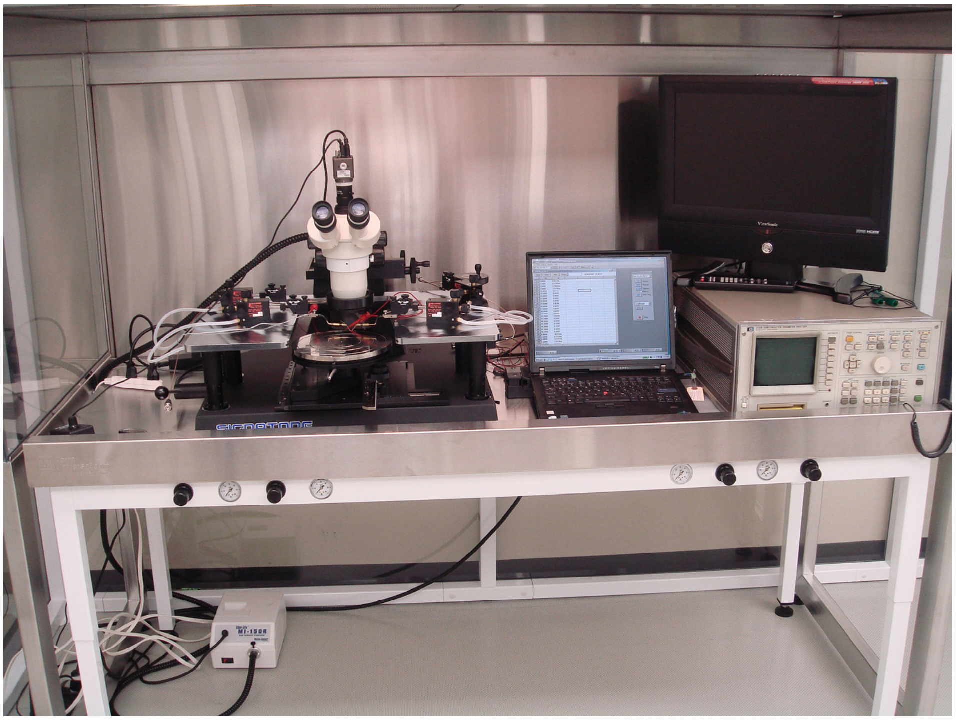

Figure 31. Device wafers are tested in the clean room lab probe station.

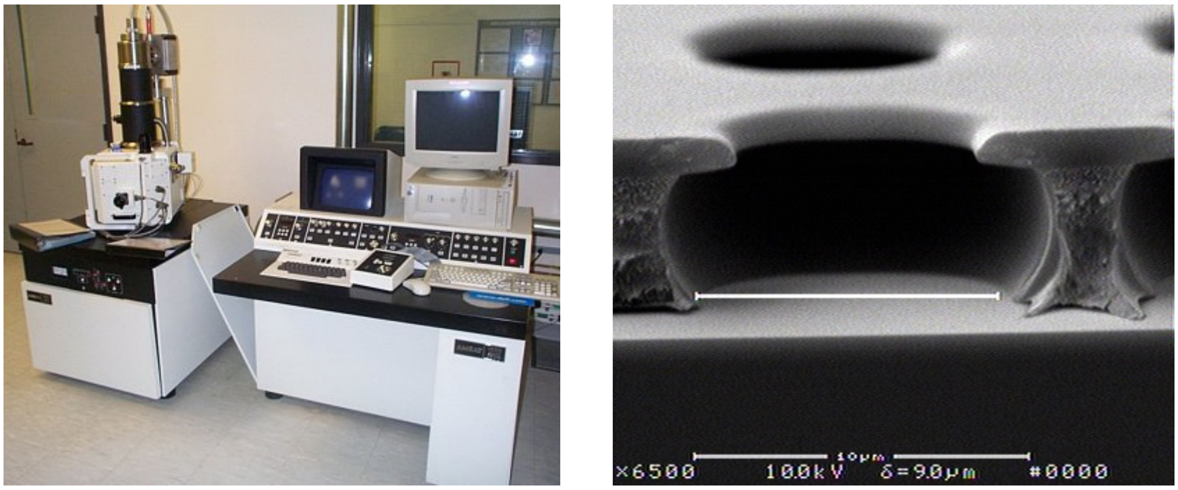

Figure 32. (left) The Amray 1830 Scanning Electron Microscope is used to image devices. (right) SEM image of a device that has been prepared for indium bump deposition.

Figure 33 shows a customized setup consisting of two voltage power supplies, an Agilent oscilloscope, an LCD screen for viewing devices through the microscope probe station, and a custom circuit board for specific device diagnostics. The dedicated lab computer also runs a specially-designed data acquisition program to collect and analyze data from the device.

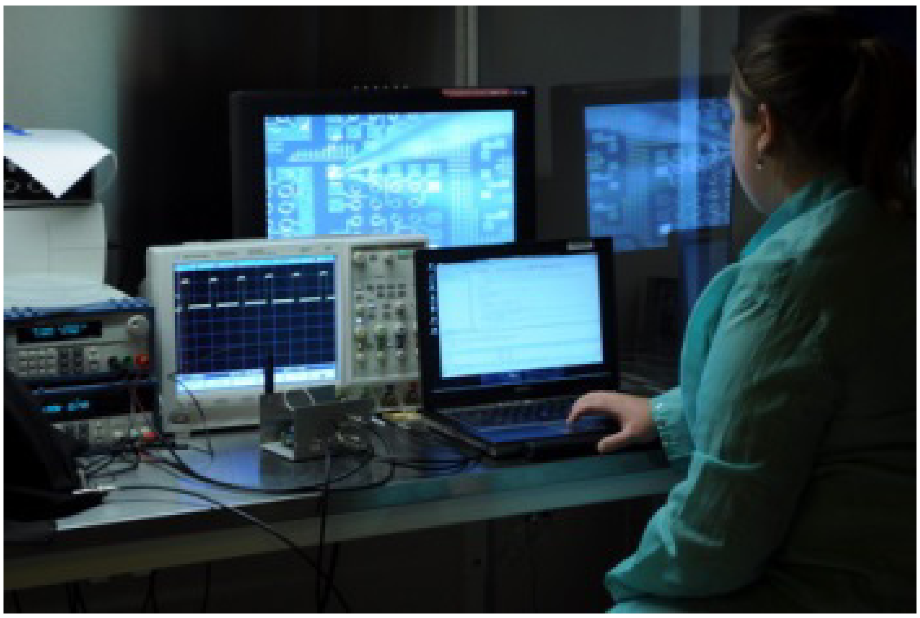

Figure 33. PhD student Kimberly Kolb conducts electrical experiments on one of the cutting edge devices being characterized at the Center for Detectors.

The entire probe station is covered so that no stray light enters the testing environment. These conditions provide the basis for valuable testing and data analysis. The probe tip is contacting a single test device via a metal pad with dimensions of only 70 microns by 70 microns (an area of 0.005 mm^2).

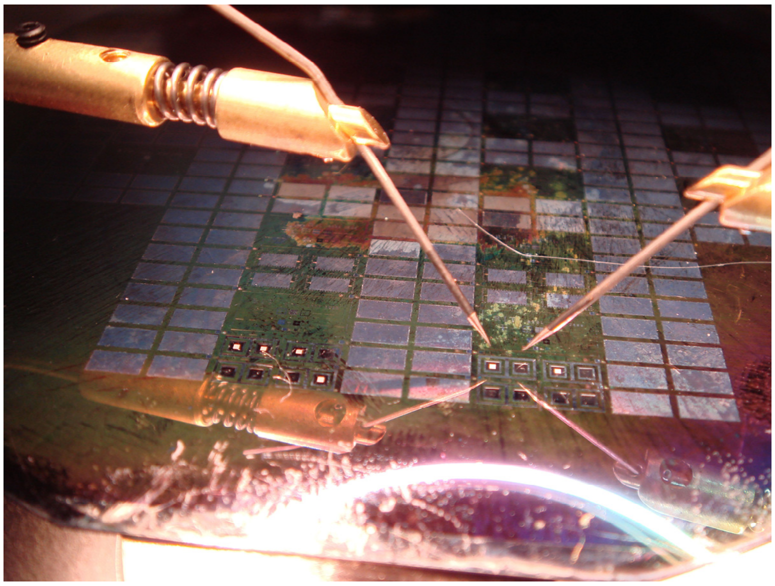

Figure 34. This image is a close-up of a device wafer being tested on the probe station.

In addition to fabrication and testing capabilities, the Center for Detectors has access to sophisticated simulation software to predict the performance of devices, from fabrication processes to performance of a completed device. Silvaco Athena and Atlas are powerful software engines that simulate the effects of processing on device substrates and the electrical characteristics of a fabricated device. Athena simulations can describe all of the processes available in the RIT SMFL, building a physics-based model in 3D space of a device from initial substrate to completed device.

The Center for Detectors uses many other RIT facilities, *e.g.*, the Brinkman Lab, a state-of-the-art facility for precision machining, and the Center for Electronics Manufacturing and Assembly (CEMA), a facility for electronics packaging (Figure 35).

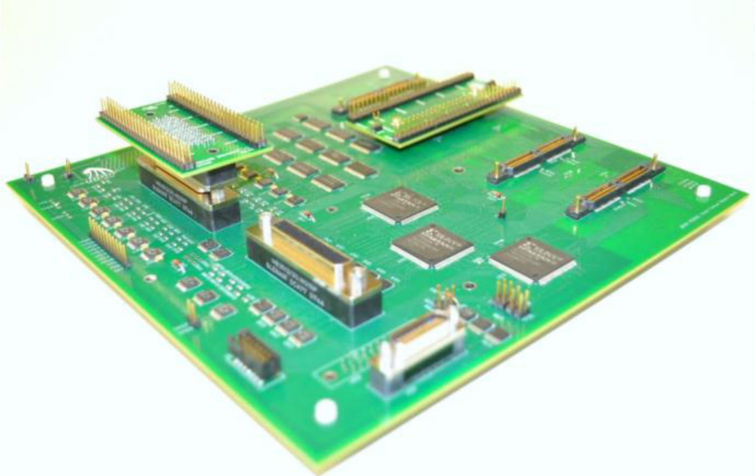

Figure 35. This image shows a cryogenic multi-layer circuit board designed in the CfD and populated in CEMA. All of the components on this board will be exposed to temperatures as low as 40 K, nanoTorr pressure levels, and high energy particle radiation.

Recently, the Center for Detectors has acquired a new piece of equipment, a Gold Integrating Sphere. The sphere allows researchers at the CfD to uniformly scatter and diffuse incident light, with entrance and exit ports. It also measures the diffuse reflectance of surfaces, providing an average over all angles of illumination and observation. The integrating sphere is currently being used to create a light source with apparent intensity uniform over all positions within its circular aperture. The finely deposited gold is used for infrared measurements (Figure 36).

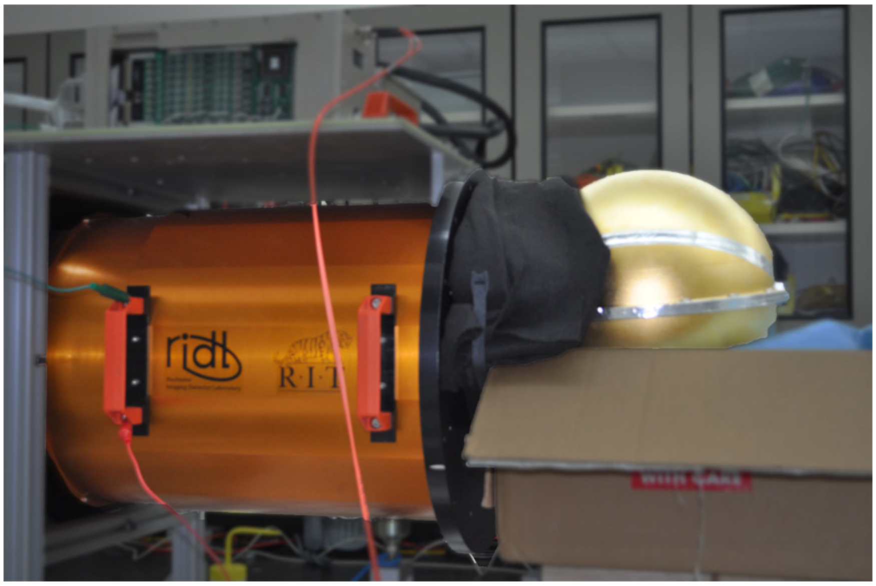

Figure 36. This image shows the Gold Integrating Sphere attached to one of the dewars.

In 2013, the CfD acquired the Leach System. Made up of many components such as video boards, power control boards, fiber optic timing boards and cables, and PCI interface boards, each part has been carefully designed to minimize the danger that it will damage sensitive and delicate IR imaging detectors. After assembling the many different parts into a propriety design, the Leach system aids in high-level dewar control (Figure 37).

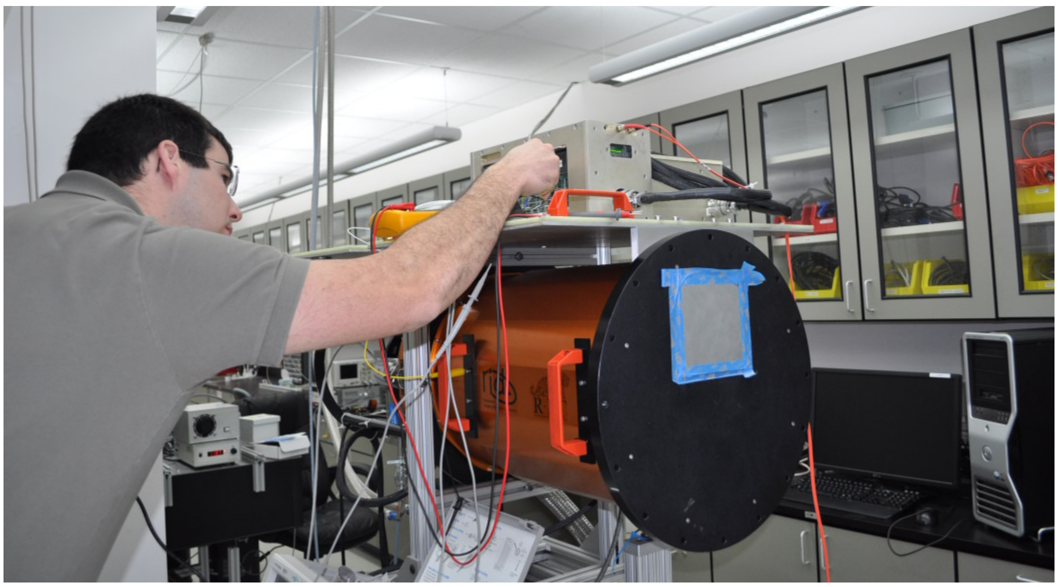

Figure 37. This image shows Brandon Hanold adjusting the readout electronics of a dewar system.

Center for Detectors