

SCIENTIA

Undergraduate Journal of Scientific Research
University of Notre Dame



A LETTER FROM DEAN CRAWFORD



Credit: Matt Cashore

Notre Dame takes pride in educating the next generation of scientists, and learning in the classrooms and laboratories is only part of the educational experience. Our undergraduates also need to learn the methods of scientific writing, peer review, and editing. Through this publication undergraduates are sharing their own new knowledge while honing their scientific communication skills.

Our undergraduate researchers inspire us with their rigor and drive. They are committed to moving beyond received wisdom, to expanding our understanding along with their own. They are also committed to helping each other and collaborating together as a community of scientists.

At Notre Dame, we do not make our students wait to enter the global scientific community. Indeed, we cannot afford to make them wait. The gaps in our understanding of the universe are endless, as are our tasks and problems here on Earth. It is only by a worldwide collaboration that ideas become solutions, and while research is always a means to an end, complete knowledge is beyond the grasp of any individual. We need each other. And we need to join the conversation as early as possible in order to make the best use of our time.

Go Irish!

Yours in Notre Dame,

Gregory P. Crawford, Ph.D.,
William K. Warren II Foundation Dean of the College of Science

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FROM THE EDITORS

April 16, 2012

We are pleased to present the third edition of *Scientia*, the journal of undergraduate science research at the University of Notre Dame. This year's edition carries on our proud legacy of presenting top research completed by undergraduates, reported by undergraduates, and reviewed by their undergraduate peers.

The very name of this journal, *Scientia*, is derived from the work of St. Augustine who claims that *scientia*, knowledge of the natural world, is the true and proper partner of *sapientia*, or wisdom. Within the College of Science, we are committed to the pursuit and partagement of our most advanced knowledge of the natural world, not only in the upper echelons of academia, but within the lives of our undergraduates. Therefore, in the pages of this journal you will discover articles on earthworms and maple trees, on nanosheets and hadron colliders. Even so, these articles only touch on the vast variety of research done by undergraduates across campus.

Beyond the publication of our print journal, we also celebrate this year the continued success of our monthly meetings of scholars and scientists. These public forums provide a rare opportunity for Notre Dame students from across the College of Science to come together to learn and listen, discuss and debate, with their peers and faculty mentors. Now in their second year, these meetings have been a great success with growing attendance and enthusiasm. Whether you are considering doctoral study, medicine, the professional world, or any other calling, we hope you will join us for our meetings and enjoy the lively community of thinkers who fill this University.

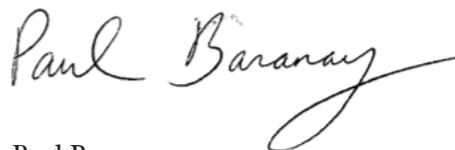
As we prepare to graduate from Notre Dame, we look back on our involvement in *Scientia* with great fondness. Though we must say goodbye, we have made every effort to ensure *Scientia*'s continued success for years to come. In particular, we are excited to announce Rachel Cotton and Rebecca Marton as *Scientia*'s next editors-in-chief. Rachel and Rebecca both joined *Scientia* as freshmen, during which time they took on the daunting task of leading the layout of the journal. This year, as junior editors, they have done phenomenal work coordinating many aspects of the *Scientia*, including not only the journal itself but also our meetings. We are confident they will do a superb job as editors-in-chief.

In closing, we thank all of the people whose generosity and support help make *Scientia* so successful. In particular, we would like to recognize Dr. Gregory Crawford, Dean of the College of Science; the staff of the Dean's Office; and Dr. Dominic Chaloner, our faculty advisor. We gratefully acknowledge all the students who submitted papers for review, as well as their mentors. Finally, we thank our editors, reviewers, and layout team for all of their fantastic work throughout the year, without which none of this would be possible.

In Notre Dame,



Nancy Paul
Scientia Co-Editors-in-Chief

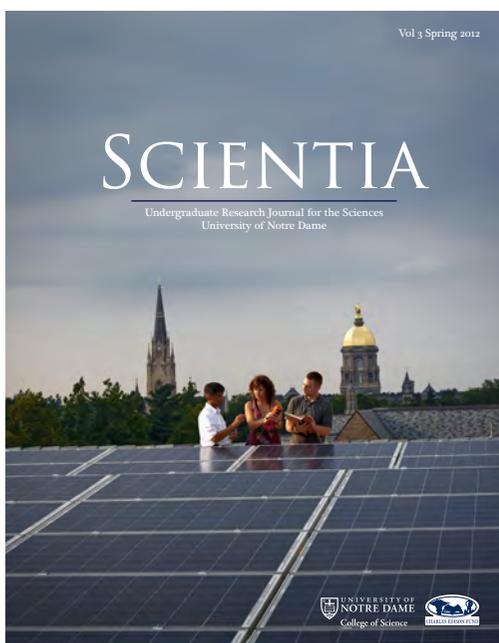


Paul Baranay

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◀ ON THE COVER

Professor Prashant Kamat, left, works with graduate students on the solar panels on the roof of Stinson-Remick Hall of Engineering.

Credit: Matt Cashore

Exploring “The Accelerating Universe” with Nobel Prize winner Brian Schmidt

Yuko Gruber

A lot of nerve and even more physics is required to contradict Albert Einstein. However, Nobel Prize winners Brian Schmidt, Adam Riess, Saul Perlmutter, and their respective research teams, accomplished precisely that with the discovery of the accelerating expansion of the universe. This conclusion resurrected the cosmological constant that Einstein rescinded as his “biggest blunder,” and, in the process, Schmidt’s team restructured existing conceptualizations about the fundamental fabric of the universe.

Hubble used Schmidt’s observation of the redshift of galaxies to calculate the Hubble Constant, a factor that describes the expansion of the universe. The Hubble Constant was then used to determine the age of the universe, estimated at about 14 billion years.

However, Schmidt qualified that 14 billion years is a slightly idealized estimate. The estimate is based on calculations of a universe without matter, but our universe possesses enough matter that physicists expected the gravity generated by such

matter to pull on the universe and slow or stop its expansion over time. The data collected by Schmidt, Riess, Perlmutter, and their teams however, showed a different pattern in the observed behavior of the universe.

Schmidt and his team collaborated to measure the brightness of Type Ia supernovae. “We can look into the past by looking at objects further and further away from Earth,” Schmidt said. The supernovae were located far enough from Earth and possessed light that took long enough to reach earthly telescopes that the researchers were allowed such a

window into the past.

The supernovae also have relatively standard luminosities which allowed accurate distance estimates and, combined with the redward shifts in their spectra, could be used to determine the size of the universe at the time the supernovae exploded relative to the size of the universe today. The teams then plotted these data to determine the behavior of the expansion of the universe, and found that rather than slowing down, the expansion seemed to be accelerating.



Brian Schmidt lectures on “The Accelerating Universe”

Credit: Matt Cashore

Schmidt lectured about “The Accelerating Universe” to members of the Notre Dame community in late February, describing the research leading to his team’s characterization of the expansion of the universe. Schmidt’s team, which included Notre Dame physics professor Peter Garnavich, made their conclusions through observation of distant supernovae. The distance and velocity of these supernovae, Schmidt explained, were estimated by measuring the brightness of the explosions and detecting shifts in their spectra caused by the Doppler Effect.

Since the beginning of the twentieth century, astronomers have relied on the Doppler Effect to recognize that other galaxies in the universe appear to be moving away from Earth. Vesto Slipher, an astronomer Schmidt proclaimed “almost no one in the audience will know,” was the first to acknowledge the “redward stretch” or redshift of the spectra from galaxies that indicated this motion. Alexander Friedmann further explained this phenomenon using Einstein’s equations to show that galaxies are not moving away from Earth, but rather that the space itself between Earth and distant galaxies is expanding. In 1929 Edwin Hubble confirmed Friedmann’s predictions by observing that the farther galaxies were positioned from Earth, the faster these galaxies appeared to be moving.



Schmidt and Riess at the Nobel Ceremony

Credit: Peter Garnavich

“If we can judge what the universe is doing over time,” Schmidt said, “we can judge its ultimate fate.” Thus, the revelation about the acceleration of the universe is significant in elucidating the trajectory upon which the universe is traveling. A universe with a rapidly decelerating expansion would eventually re-collapse, and one with modest deceleration would expand forever, slowing into eternity. But an accelerating expansion means every galaxy gets farther from every other galaxy, faster and faster.

So what is the thing that causes the universe to expand so quickly, and how does it act against gravity? What Einstein called his “cosmological constant” Schmidt and his colleagues have redefined as “dark energy”, an energy that seems tied to space itself. Dark energy imposes a negative pressure upon gravity – making gravity “push” matter apart rather than “pull” matter together. Schmidt said that the universe was decelerat-

ing billions of years ago, but since the density of matter in the universe decreases during expansion while the density of dark energy in the universe stays constant, there reaches a point in history at which the balance of dark energy and gravity shifted in favor of dark energy. This caused the expansion of the universe to begin accelerating. What is even more astonishing is that dark energy currently makes up 73 percent of the universe and this fraction is constantly increasing. This means that the Nobel prizewinners discovered 73 percent of the current composition of our universe.

Schmidt emphasized that while the discovery of dark energy is an exciting and informative piece in the puzzle of understanding the universe, the characterization of dark energy remains an open-ended and developing area of physics today. “Until we better understand what is accelerating the cosmos,” he said, “anything is possible.”

Rare Transit of Venus to Be Observed with the Napoleon Telescope

Sarah Owens

This summer, the historic Napoleon Telescope will provide faculty and students with the uncommon opportunity to view the transit of Venus. On June 5, 2012, the silhouette of Venus will move across the face of the Sun for only the eighth time since the invention of telescopes in 1610. The planet will be only barely visible to the naked eye, approximately 1/32 of the Sun’s total diameter, but the Napoleon Telescope will allow the Notre Dame community to clearly witness an event almost as historic as the acquisition of the telescope itself.

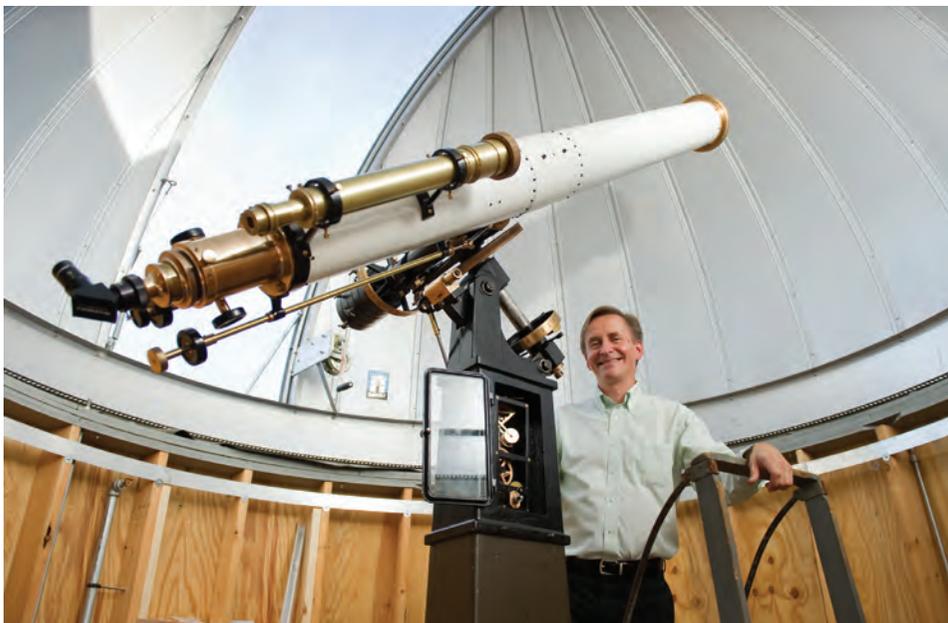
This spring heralds the 145th anniversary of the telescope’s arrival at Notre Dame. Emperor Napoleon III, a personal friend of Father Sorin, presented the telescope to the University in 1865, where it has since experienced a myriad of housings and acquired a colorful history.

The telescope was first placed in an observatory in the garden in front of the original Main Building, until the fire of 1879 forced the telescope’s relocation. Twelve years later, the telescope was refurbished and re-mounted in “Badin Observatory,” where it was cared for by the then-official Astronomy Department.

The construction of Hurley Hall forced another move for the telescope, this time to storage. The telescope remained unused until 1955, when some ambitious and slightly mischievous students skipped class to reassemble the telescope on the roof of Nieuwland Science Hall for their personal academic endeavors. One of these students, James Shilts, went on to become a priest and an

astronomy professor. He later obtained official permission and adequate funding to refurbish the weather-damaged telescope. The telescope was housed in a shed on the roof of Nieuwland until 2010, when a new dome was built, and the telescope mechanisms were once again fixed and polished by the Physics Department.

According to Prof. Peter Garnavich of the Physics Department, the Notre Dame community will gather in this new setting in June to watch Venus cross the face of the Sun for the last time until 2117. Despite all of the alterations made to the telescope housing and mechanisms, the telescope retains the original lens. Viewers will be able to witness the transit of Venus through 145 years of Notre Dame history.



Garnavich with the Napoleon telescope

Credit: Matt Cashore

Tackling Global Health Disparities

Orrin Belden

Despite available cures for tuberculosis (TB), there were 8.8 million new cases of TB in 2010 and 1.4 million deaths caused by the disease. In an effort to address global health disparities that contribute to the spread of curable diseases like TB, the University of Notre Dame and the Eck Institute for Global Health introduced a new one-year Master of Science in Global Health (MSGH) program this past year.

There are 14 MSGH students in the inaugural class, and the program is expected to grow in its second and third years. The global health curriculum, spearheaded by the Eck Institute for Global Health, includes courses in Global Health Challenges, Epidemiology, Global Health Methods, Bioethics, a weekly Colloquium, and a master's project. The new masters degree in global health differs from a degree in public health by addressing health disparities on a global scale. The global health program expands to not only include preventative health care but also curative care. Students are taught to examine the scope of a health problem without division by geographic location. With this inherent complexity, the curriculum naturally draws on interdisciplinary studies, both science and non-science based.

Fieldwork experience is also an integral aspect of the program. Many of the students will complete their field experiences over the summer, allowing flexibility for elective courses during the academic year. This year, some of the field experience sites will include Tanzania, Uganda, Haiti, Puerto Rico, and India. The field experience is the culmination of the pro-



Master of Science in Global Health students

Credit: Steve Toepp



gram when students apply the knowledge learned in the classroom to identify and address health disparities.

A 2011 Notre Dame alumna and current graduate student in the Global Health Program, Gabriela Moriel, will be conducting her field experience in Tena, Ecuador. She is collaborating with the non-governmental organization Timmy Global Health to design a Community Health Worker Program modeled after some of the successful programs implemented by the organization Partners In Health. When asked why she chose this particular location she explained, "Tena and its surrounding rural communities are often isolated from the benefits of modern medicine that are normally accessible in the urban hospitals. Our hope is to train individuals in the communities who will essentially act as local nurses who are qualified to perform a variety of basic medical practices, educate the communities in their medical knowledge, and send patients with emergency cases in the right direction of care." Gabriela will be headed to Tena with fellow masters student, Molly Elston, whose project focuses on gathering data to develop a health census for the Napo province and supplement the data reported by Ecuador's Ministry of Health.

The Master of Science in Global Health program is the embodiment of the mission of the University of Notre Dame to empower students to address the needs of the poor and the vulnerable. Although Gabriela will not be conducting her field experience until the summer, she remarked, "This program has already helped open up my eyes to many global health disparities that I may have never been exposed to otherwise."

Miguel Morales joins Biological Sciences Faculty

Claire Brady

You probably have not heard of *Leishmania*, the pathogenic protozoan parasite that assistant biology professor Miguel Morales has devoted his career to studying. Neither had Morales, in fact, until taking a parasitology course his senior year of college. However, his work with *Leishmaniasis*, the neglected tropical disease the parasite causes, was what brought him to join the Notre Dame faculty for his first professorship this past fall. "The mission of the University to help the world had a lot to do with coming here," Morales said. "The focus on global

health is very important, and that emphasis really makes [Notre Dame] a unique place."

Originally from Spain, Morales completed his Ph.D. in Molecular Biology and Biochemistry at the Complutense University of Madrid, with postdoctoral work at New York University and the Pasteur Institute in Paris. Most formative to his career path in parasitology was the time he spent in Rio de Janeiro and India, endemic areas for a variety of pathogenic parasites, during his years as a Ph.D. student.



Leishmania major parasites

“Parasitology is very related to poor countries, not like cancer, cardiology, and the stuff you see in the Western world,” Morales said. “It’s an underdeveloped area, and we need more researchers in that area.” The decision to specialize in *Leishmania* stemmed from witnessing the debilitating symptoms that ensue when people contract the parasite through a fly bite, including persistent sores on the skin and the infection of visceral organs. “I could see with my own eyes that patients were suffering from the parasite *Leishmania*,” Morales said. “I saw

little kids, so many people suffering, and I decided if I could I wanted to research that particular parasite.”

At Notre Dame, Morales will be working with the Center for Rare and Neglected Diseases as well as the Eck Institute for Global Health in effort to promote research in new treatments for Leishmaniasis and other neglected diseases, which drug companies do not deem profitable enough to invest in. Morales’ studies of the parasite’s MAP kinase enzymes hope to pinpoint a target for potential treatments, making the drug companies jobs easier.

“The current treatment for Leishmania is an old drug that is highly toxic,” Morales said. “Our research is important because we can take the data, go to companies, give them 20 to 30 percent of the work done, and let them take over.”

Morales emphasizes the urgency of learning about neglected diseases so that they might obtain more attention and exposure. To that end, he will be teaching an undergraduate course next fall, Molecular Medical Parasitology in addition to Topics in Infectious Diseases, the graduate-level course he teaches now. In the meantime, Morales is excited to be a part of Notre Dame’s expansion of its science programs and emphasis on research. “It’s a great place to be right now,” he says.

Notre Dame Professors Travel to Vatican for Adult Stem Cell Conference

Stephanie McKay

Last November, David Hyde, professor in the Department of Biological Sciences, and Phillip Sloan, professor emeritus in the Program of Liberal Studies, joined a number of scientists, physicians, theologians, and philosophers in the Vatican to discuss research with adult stem cells. Hyde and Sloan are both involved in the Notre Dame Adult Stem Cell Initiative (<http://adultstemcell.nd.edu/>), and with others from the Colleges of Law and Engineering are working to develop an active research group that will bring a broadly interdisciplinary approach to questions related to developmental biology.

The conference, Adult Stem Cells: The Science and Future of Men and Culture, was held November 9-11, 2011 and focused on the great strides as well as the future of regenerative medicine. It was jointly organized by the Pontifical Council for Culture and NEOSTEM foundation, and was closed with an audience and blessing from Pope Benedict XVI.

Hyde, who attended as a representative of the University of Notre Dame Department of Biological Sciences, found that the conference was a worthy platform to present not only the advances that have been made with adult stem cell research, but also discuss the ethical and legal implications of such work. “Successes they talked about are remarkable,” Hyde said. “There was a person who had approximately 34 stents put in. [He had] several bypass operations... and his heart capacity had fallen to about 15 percent. After the adult stem cell therapy, his heart capacity is now 55percent... It was remarkable how much his health and quality of life had improved.”

The conference exemplified how adult stem cells also have



David Hyde

Credit: Matt Cashore

the capacity to treat autoimmune diseases, forms of leukemia, and other maladies, as well as can be used to regenerate cartilage. The ethical and philosophical questions raised by stem cell research were also addressed through several papers and discussions. Sloan, who has been coordinating the Arts and Letters component of this project, delivered a lecture titled “Should the Hippocratic Oath Be Extended to Life Sciences?” which discussed the necessity of creating a set of ethical standards for the biological science research community to deal with such issues as stem cell research. This would recognize the deep ethical and social responsibility of life scientists in the coming decades as their work extends into work in human development.

Both Sloan and Hyde believe that interdisciplinary dialogue is very important and will continue to develop this in the coming period with seminars and lectures related to these

topics. “We want to create an environment where the scientists and the engineers can see and think about the ethical and legal implications of what they are doing,” Hyde says, “where at the same time the philosophers, ethicists and legal scholars can learn about the science and the engineering, instead of just reading about it.” All ethical questions aside, Hyde still believes that adult stem cells will play a large role in the future. “I really believe that regenerative medicine will be the way that a large number of diseases will be treated in the future,” he said.



Phillip Sloan

Credit: Matt Cashore

GoLIMS Cloud-Based Notebooks

Wendy Liu

For the last six years, Notre Dame has been experimenting with electronic laboratory notebooks in an initiative headed by Greg Crawford to make Notre Dame more environmentally friendly. As of the fall of 2011, several classes in the Notre Dame College of Science have been beta-testing cloud-based laboratory notebooks developed by GoLIMS, a software company located at nearby Innovation Park.

the data are protected and difficult to lose. Moreover, since the data are saved through a web account, data can be accessed from any device with a wireless internet connection.

Beginning in fall 2011, GoLIMS laboratory notebooks were introduced in the Organic Reactions and Applications Laboratory course. Currently, GoLIMS classroom use has expanded to include the Organic Reactions and Structure Laboratory and the Chemistry Across the Periodic Table Laboratory, as well as the Fundamentals of Genetics Laboratory, taught by Prof. Michelle Whaley.

In addition to allowing students to save, organize, and share data, GoLIMS generates presentations from stored laboratory notebook data, helps with research project management, fosters cooperation by allowing users to comment on collaborators' works, and includes a sample inventory to keep track of where sample and equipment locations and users.

Prof. Steve Wietstock of the Department of Chemistry and Biochemistry is currently implementing the GoLIMS cloud-based notebooks in several of his laboratory classes. He commented that he likes using the GoLIMS because he can work with the company to tailor the notebooks specifically for Notre Dame students. If he ever encounters an issue, he can immediately contact the developers to work out a solution. GoLIMS CEO Gregory echoed the benefits of the partnership between Notre Dame and GoLIMS: “Working with Notre Dame professors Steve Wietstock and Michelle Whaley, as well as their teaching assistants and students, has helped us refine our course application, which provides a paperless undergraduate laboratory experience. The positive reception by Notre Dame has encouraged us to expand our second application into additional universities.”

Wietstock finds that he likes how his teaching assistants can comment on and grade student reports online without messy paperwork and especially enjoys how GoLIMS notebooks allow him to view not only students' completed notebook entries but also those in progress so that he may detect problems before they occur. When asked if he believed Notre Dame would continue using GoLIMS laboratory notebooks, Wietstock replied, “I would hope so; I'm pleased with how things are going and I can see how it can be a great benefit to my colleagues and classes.”



Teaching assistant Grace Park uses GoLIMS

Credit: Chad Gregory

GoLIMS has developed software to help scientists organize their research in new and innovative ways. “Research today requires that data be accessible from anywhere, searchable, secure, and collaborative. We have developed our platform to meet and even exceed those needs, freeing researchers to focus more on discovery,” says GoLIMS founder and CEO, Chad Gregory.

GoLIMS is designed for entire teams of scientists, and offers data sharing solutions that help laboratory classes share data electronically. Data are also saved on multiple servers so

Notre Dame Research Group Presents New Analysis of Aging Pediatric Bruising

Katrina Magno

In 2010, the National Child Abuse and Neglect Data System reported an overall rate of 2.07 deaths per 100,000 children due to abuse or neglect. Approximately 40 percent of these fatalities were caused by maltreatment. The age of bruises can provide vital evidence in child abuse cases; however, the current methods being used by physicians across the country do not provide enough detail to confidently ascertain the age of pediatric bruises.

In light of this problem, Prof. Mark Alber, along with Prof. Greg Crawford, postdoctoral research associate Oleg Kim, and physics graduate student Collin Lines are working to develop a new method of acquiring evidence and time of injury. Crawford believes that the project “will enable doctors to determine the age of bruises in their assessment of child abuse if they suspect it may be taking place.” Their research, funded by the Gerber Foundation, combines data acquired from reflectance spectrometry with a stochastic photon transport model to produce an accurate age estimate. The improvement is based on the utilization of a detailed seven-layer approximation, as opposed to the more general one-to three-layer skin approximations.

Crawford, Alber, Kim, and Lines have combined numerical modeling based on Monte Carlo methods, a technique previously used on normal skin, and complex seven-layer approximations to determine concentrations of oxyhemoglobin, deoxyhemoglobin, and their metabolic intermediaries. These chromophores are key indicators of contusion age and give a

strong basis for accurately and quantitatively assessing the contusion.

The HR2000 spectrometer is a high-resolution device capable of identifying individual wavelengths spanning 340nm to 1030nm and analyzing sharp peaks in transmission or reflectance. The team combined the spectrometer with a broad spectrum source, enabling them to gather data from each layer of skin. The layers are scored on multiple parameters, including thickness, absorption and scattering properties, refractive index, and scattering anisotropy factors. After normalizing the spectrum data obtained from bruised skin over a period of time with normal skin, the resulting spectrum is plotted with photographs to assess aging.

Clinical trials are being conducted at the Hasbro Children’s Hospital in Providence, Rhode Island, where reflectance spectrum data is collected from accidental contusion cases in adults and children. Crawford emphasizes, “this will enable us to test our device and model in humans. We hope that this trial will move us closer to the practical use of this device in the hospital for child abuse cases.” As conventional methods of evaluating the cause of pediatric bruises, abusive or accidental, are significantly based in qualitative assessment, the development of a method combining qualitative and quantitative assessments provides a bright future for identifying and characterizing incidences of child abuse.



Crawford and Lines demonstrate spectroscopic bruise dating

Credit: Matt Cashore

Sharon Stack joins Notre Dame as Science Director of the Harper Cancer Research Institute

Rachel Cotton

Sharon Stack is the Ann F. Dunne and Elizabeth Riley Science Director of the Mike and Josie Harper Cancer Research Institute and Professor of Chemistry and Biochemistry. *Scientia* recently had the opportunity to sit down with Dr. Stack and discuss her vision for the Harper Cancer Research Institute, bridging the gap between the laboratory and the clinic, and even about some of her recent research in integrin and β -catenin signaling in ovarian cancer metastasis.

Mike and Josie Harper Cancer Research Institute

The Mike and Josie Harper Cancer Research Institute is a joint venture of the University of Notre Dame and Indiana University School of Medicine-South Bend (IUSM-SB). The institute is housed in the recently completed Harper Hall, which was built with a private donation from Charles M. 'Mike' Harper, and a matching \$10 million from the State of Indiana. The Harper Cancer REsearch Institute is the newest step in the growing collaboration between Notre Dame, IUSM-SB, and the local medical community.

Evidence of collaborative effort in the institute is apparent, looking at the internal organization of the institute alone. Sharon Stack is the Science Director of the Harper Cancer Research Institute and Professor of Chemistry and Biochemistry, while Rudolf Navari is the Clinical Director of the Institute and Professor of Medicine and Assistant Dean at IUSM-SB. Institute members include Notre Dame and IUSM-SB faculty from chemical and biomolecular engineering, physics, applied and computational math and statistics, chemistry and biochemistry, and biological sciences. The broad scale of research allows the problem of cancer to be attacked from multiple directions, from tumor cell biology to new drug therapies to earlier detection of cancer, and at all levels from basic discovery to clinical trials.

Upon the announcement of Stack's appointment as science director of the institute last winter, Dean Crawford said he was "very enthusiastic about Prof. Stack's vision for our future collaborative cancer efforts on campus, crossing college boundaries and institutions, and working with our local medical oncology community." In just her first six months here at Notre Dame, Stack has made considerable progress on all of these fronts.

Stack is most proud of establishing the Biosample Repository, already in operation, on site at the Harper Cancer Research Institute. The Biosample Repository is the result of collaboration with the South Bend Medical Foundation and dedicated community physicians, and this will allow basic scientists at



Notre Dame and IUSM-South Bend ready access to human tumor tissue for research. One application of the new access to human tissue through the tumor tissue bank is the production of tissue microarrays, which allow scientists to quickly and more economically assay tumor tissue from dozens of patients for a particular marker of interest. The Biosample Repository laboratory has an apparatus that can produce these microarray slides in house.

Stack is particularly excited about the chance to bring basic scientists from across the disciplines of engineering, physics, chemistry, mathematics, and biology together with clinicians through the Harper Institute. One of the things that was attractive to Stack about Notre Dame was the strength in basic science, but she recognized that our scientists had "no one to play with," with regard to the doctors and patients who see the real-world applications of laboratory research on a daily basis. She



Sharon Stack and Mike Harper at the Harper Hall dedication

Credit: Matt Cashore

envisions a "working group" program structure to get scientists and physicians who work on the same disease, "in the same room" through "mini-symposia" to discuss needs and observations on both fronts, the lab bench and the operating table.

Stack is insistent on "using every unrestricted penny for

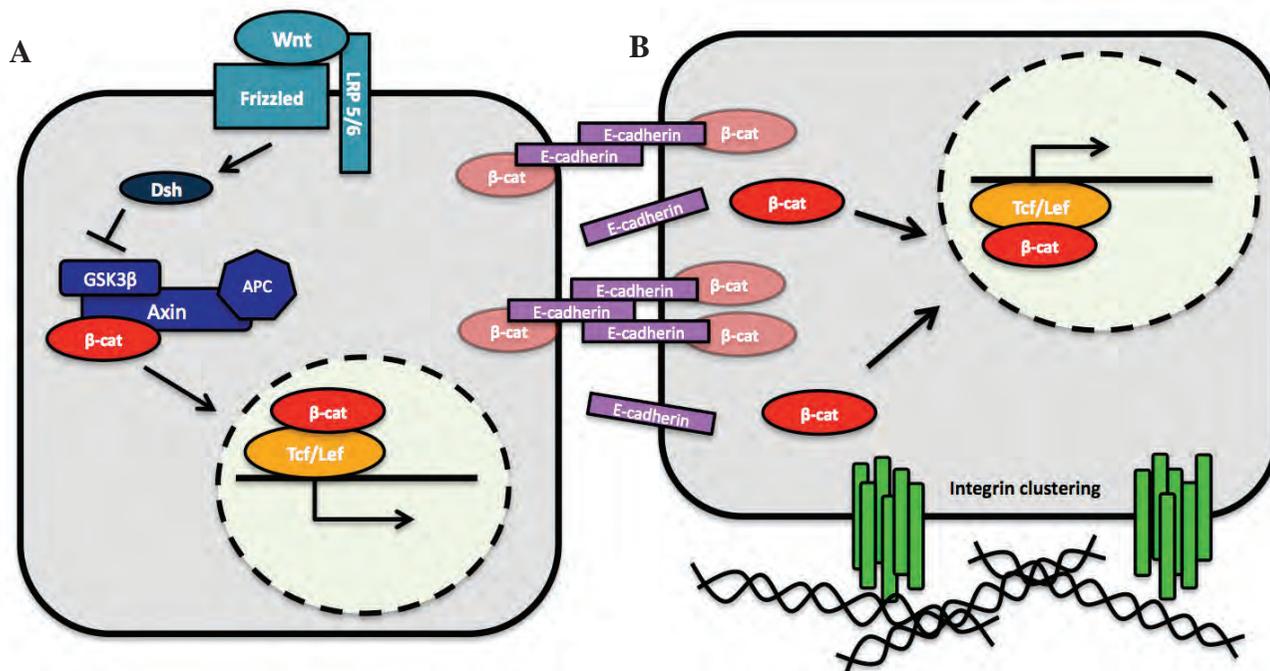


Figure 1A-B. β-catenin activates Wnt target genes in ovarian cancer. In the canonical Wnt pathway (A), Wnt ligands bind to surface receptors Frizzled and LRP 5/6, which then activate Dishevelled (Dsh) leading to the dissociation of β-catenin from Axin and GSK3β. β-catenin then translocates to the nucleus and binds to the transcription factor Tcf/Lef to ‘turn on’ target genes. (B) Clustering of collagen binding integrins destabilizes E-cadherin junctions between cells. β-catenin is intracellularly associated with E-cadherin such that when these junctions are disrupted, β-catenin is liberated and translocates to the nucleus to activate target genes, independent of Wnt ligands. In both cases, the genes that are activated include degradative enzymes that facilitate ovarian cancer cell invasion. Figure adapted from Barbolina *et al.*³

new ideas.” These funds will be distributed to researchers in the form of pilot grants to help get projects off the ground. Pilot grants would encourage collaborative efforts across disciplines. Furthermore these mini-grants would foster the pursuit of lines of inquiry that may not have enough data or foundation yet for a multi-year NIH grant, but nonetheless have exceptional potential.

Molecular Mechanisms of Metastasis: New Insights into Familiar Pathways

Stack’s own research interests lie in the molecular mechanisms of cancer metastasis; her laboratory studies ovarian and oral cancers. Stack described that her research aims to answer the question, “ovarian cancer metastatic cells float as multicellular clumps, so what tells them to start sticking?” Ovarian cancer is greater than 90 percent curable when caught before metastasis, but 75 percent of women diagnosed are already presenting with advanced disease, with established metastasis throughout the abdominal cavity.¹ These women have much poorer prognoses, with survival rates under 25 percent. Understanding how metastasis occurs is of great importance for making progress on the ovarian cancer front.

As tumor cells become adherent, they induce cells to expose an underlying extracellular collagen matrix, where they can further degrade the matrix and anchor themselves to the mesothelium, so the process by which tumor cells trigger the degradation and invasive activity is of particular interest.

A recent paper from the Stack laboratory described a novel mechanism by which cell matrix engagement can lead to

increased invasive activity of metastatic ovarian cancer cells. Specifically, the study showed that the clustering of collagen-binding integrins, receptors that mediate cell attachment, led to the expression of genes linked to increased cell proliferation, metastasis, adhesion, and invasion. These include degradative enzymes like matrix metalloproteinases and contributors to proliferation and adhesion like connective tissue growth factor, all of which are implicated in ovarian cancer metastasis.² What was particularly surprising was that the altered expression was mediated by β-catenin, despite the rarity of Wnt/β-catenin pathway mutations in epithelial ovarian carcinoma.

In the Wnt/β-catenin pathway, proteins called Wnt ligands engage specific cell surface receptors, liberating intracellular β-catenin, which then activates the transcription factor Tcf/Lef to control the expression of target genes (Figure 1A); many of these target genes have been well characterized and include proteins involved in cell proliferation and matrix degradation. In ovarian cancer however, β-catenin mobilization and activation of Wnt/β-catenin target genes occurred independently of Wnt ligands. Rather, integrin clustering mobilized β-catenin through an alternate mechanism, the internalization of E-cadherin. E-cadherin is associated with β-catenin and found particularly at cell-cell junctions, so the functional integrity of these cell-cell junctions is especially disrupted when β-catenin is liberated, triggering the downstream expression of proteolytic enzymes (Figure 1B).

This is an important observation in elucidating the molecular mechanisms of adhesion and invasion of epithelial ovarian carcinoma, and continued investigations include studying the

Wnt/ β -catenin pathway in ovarian cancer cells in response to engagement by 3D collagen matrices. In addition to the adhesion-based signaling studies discussed above, ongoing projects in the Stack laboratory include elucidating other mechanisms of proteinase regulation, using cDNA microarrays to survey gene expression in tumor cells, and using microRNAs as potential combatants to oral cancers.

Saturday Night Wrestling to South Bend Concession Stands

Since spending a year in Germany as a Fulbright Scholar and doing her graduate work at the University of Louisville, Stack has held positions at Duke, Northwestern, and the University of Missouri. When asked what in particular led her to accept a position at Notre Dame and the Harper Cancer Research Institute, Stack cited the draw of the challenge of heading a basic science institute from the start, and that there are not many opportunities to do that. She also added that she has been pleasantly surprised by how she has had an easier time getting MDs and PhDs together here at Notre Dame than at large medical centers.

Stack knew she made the right decision when Mike Harper, the founding donor and namesake of the Harper Institute, talked about his job in youth selling hot dogs at the concession stand at Notre Dame football games. Tubular meat is something the two have in common. Stack's first job in high school was selling corn dogs at Saturday night wrestling.

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Learning Through Experience: Notre Dame Undergraduates in the Harper Cancer Research Institute

Kirsten Adam

Notre Dame students wanting to get involved in off-campus research do not have to go far to seek such opportunities: the new Mike and Josie Harper Cancer Research Institute sits just outside of campus, at the corner of Angela Boulevard and Notre Dame Avenue.

The Harper Cancer Research Institute, dedicated in March 2011, represents a new and exciting partnership between Notre Dame and the Indiana University School of Medicine in South Bend. It houses a team of researchers from a variety of scientific disciplines who investigate many types of cancer and drug therapies from a variety of research perspectives.

This year, Notre Dame undergraduates were some of the first to work as research assistants in the new laboratories. "Right now, I am in Richard Dahl's lab," says Hoang Ho-Pham, a sophomore biochemistry major. "The lab has a focus on gene expression and leukemia, and I have had the opportunity to work on an independent research project."

For many students, working in a research laboratory is a rewarding way to apply knowledge outside of class. "I'm really interested in cancer research, especially cells and how they function," says K.C. Conley, a sophomore chemistry major. Conley works in Sharon Stack's lab, investigating tumor invasion and mechanisms of metastasis. "Research is different from lab classes," she says, "It's a lot more independent and I learn through experience."

Mary Clare Houlihan, a sophomore Biochemistry major, agrees. "We're actually getting to apply things

we learned in class," she says. "It's one thing to learn what microRNA is and another to say, okay, so this is what microRNA actually does in these cancer cells." Houlihan works in Karen Cowden-Dahl's ovarian cancer lab, examining the effects of chemotherapy drug dosages.

Ho-Pham, Conley, and Houlihan all plan to continue their research at the Harper Institute in their future years at Notre Dame. "I'm really glad I got involved," says Ho-Pham, "It was as easy as visiting websites, looking at professors, seeing what they were interested in, and emailing them about their research."



Harper Hall

Credit: Matt Cashore

Doctors Within Borders: Reflections on Doctor-Patient Interaction in Cuzco, Peru and Bloomington, IL

Casey Kraft

Advisor: Maria Coloma

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Abstract

All doctors have their own styles of interaction with patients and unique methods of practice. Yet how do these methods vary based on the types of cases and patient population the physician sees regularly? How does the familiar American patient-doctor interaction differ from that of a poor clinic in rural Peru? How do cultural and educational differences affect the visit of a patient from an impoverished rural community who is perhaps too embarrassed to answer questions truthfully or who misunderstands questions and medical advice?

This research project compares how socioeconomic and cultural factors impact doctor-patient interactions, particularly through communication style and effectiveness. This was done through a detailed, small sample size case study of doctors in rural clinics in Cuzco, Peru through a ProWorld Corps medical internship, as well as in the state of Illinois, following doctors as they examined patients of varying age groups and genders. Patient-doctor interaction was compared based on specific behavioral attributes of the doctor including tone, eye contact, time spent with patient, and word choice. Peruvian physicians were found to be more forceful and blunt in patient examination, whereas American physicians were more conversational and education-focused. These results may be attributed to the poor socioeconomic condition, lower level of education, and cultural biases of Peruvians as compared to Americans.

Introduction

Knowledge of cultural expectations of physicians can be a valuable tool for doctors working in foreign countries, or with patients of a different cultural background. Previous studies have shown that, between Japanese and United States physicians, U.S. physicians spent relatively more time on treatment and follow-up social talk; whereas the Japanese had longer physical examinations and diagnosis or consideration talk.¹ Doctors who are unaware of cultural differences such as these may experience barriers in treating patients. An in-depth understanding of society and culture is crucial in successful foreign aid work, or multicultural work in the United States. Another study asserts that more effective communication could be established through doctors' awareness of the contextual communicative differences.² This is based on physician interactions

with patients of lower socioeconomic status, a category which most fall under in the developing world. Knowing societal limitations, customs, or taboos in various cultures allows one to work around and eventually overcome these physician-patient barriers, rather than having their assistance be futile due to a lack of understanding, education, or other factors.

How can one successfully help in foreign countries? How can outside assistance jump this hurdle and make a difference? Cultural understanding is an imperative aspect of this task. Effective studies are necessary to gain a clear understanding of cultural contexts in medicine, and to facilitate effective practice both abroad and in the United States. The goal of this project is to help traveling physicians achieve this understanding. By analyzing the similarities and differences in communication styles between Peruvian and U.S. doctors, one can pinpoint specific differences in medical communication techniques that might be attributable to these cultural differences. These differences can enlighten doctors to more effective approaches of assistance and can improve coordination and communication among families and patients. In this study, clear differences were observed in communication styles with patients, specifically in terms of question choice, word choice, and how information is presented to the patient, based on what is culturally considered pertinent information. Results show that the patient execution of follow-up medications and therapies are affected by the doctor's delivery of information to the patient.



Figure 1. The Centro de Salud Buena Vista near Cuzco, Peru, one of the two health facilities investigated in this study.⁶

Methods

Observations were collected from two drastically different environments. First, doctor-patient interactions were studied in Peru through a six-week medical internship under the auspices of ProWorld Corps, shadowing local doctors in rural clinics and observing patient interactions.³ This was followed by another 4-6 weeks shadowing doctors in Bloomington, Illinois, noting typical patient interactions, and comparing and contrasting them to the typical Peruvian patient interaction. Through the ProWorld Peru medical internship, the research was conducted in an impoverished clinic on the edge of Cuzco, "Centro do Salud Buena Vista" (Figure 1). In the United States, this study

was done at “OSF Promptcare” in Bloomington, Illinois.⁴

Several American patient interactions were noted and compared to the observed Peruvian patient interactions. In Peru, physician-patient interactions were observed while working with staff on routine tasks, such as giving immunizations and taking patient histories, and shadowing doctors in a Spanish-speaking environment. It was possible to observe conversations they had with various patients, more specifically patient interview techniques, and time spent with patients. While listening to these conversations behaviors such as body language, language nuances, and word selection were noted. Certain cultural influences may have played a large part in the observed discrepancies between the U.S. and Peruvian physicians. These differences, as discussed below, represent the respective culture’s emphasis on health education.

Upon returning to the United States, an acute care physician in Illinois was studied. This allowed for similar notation of physician interactions with patients. Taking notice of the same implicit features of these interactions, such as body language and word nuances was critical to an effective comparison between the two interaction styles. Body language and word choice were also analyzed to take note of their challenges and successes with the patient in regards to pertinent information obtained.

In an effort to control for the effects of age and gender differences, the study attempted to be representative of both aspects while using a small-n sampling technique. Twelve participants, six in Peru and six in the United States, were selected for having walk-in appointments, in which the doctor has no prior knowledge of the condition. Participants were grouped into three categories with regard to age: young (18-30), middle age (31-60), and old (61+), with two participants in each category, one male and one female. Applicants were not recruited for the study but asked to participate without incentive or punishment for denial. Competence of the patients’ understanding was judged based on their response to the information.

Patient background also was attempted to be controlled along with the other factors, but legal issues in the United States limited shadowing opportunities to only one specific physician, and choice of clinic location was not an option. Therefore, the patient backgrounds were different between the Peruvian and United States clinics, but the results found are believed to be representative of the cultures as a whole because of the variety of participants observed. The number of patients observed in each age group was limited to one participant of each gender per age group because of uneven patient populations the clinics tended to serve. Maintaining consistent numbers in each age group limited the population to one participant per gender group for each age group.

Results

A strong difference between Peruvian patient-physician conversations and American ones was found with regards to the type or style of questions asked. Both in Peru and the United States, physicians began conversations by asking what was wrong, followed by direct questions to explain the issue until a diagnosis could be made. However, the style of asking questions was notably different between the two countries. For example, questions would begin with “So what happened?” in Peru as opposed to “So what seems to be the problem?” in the

United States, and created an air of informality with United States patients, versus a more blunt and to-the-point conversation in Peru. However, part of the informality of the meeting was added in a different way, which could not be replicated in the United States because of language differences. For example, Peruvian physicians used the informal “tu” (as opposed to the more formal “usted”) to address their patients, even the elderly. However, Peruvian physicians still spoke in a very condescending and direct tone, which would likely not be tolerated in the United States.

It was also noted that U.S. doctors spent less time with the patient than doctors do in Peru. It should be noted, however, that this time difference was largely due to Peruvian doctors spending time filling out paperwork in front of the patient. In the United States, certain tasks such as taking blood pressure are performed by nurses. In Peru, such tasks were completed by the doctor. These differences in clinic structure account for the time difference observed. Peruvian physicians often gave stern warnings to patients, and instructed them on how to avoid the problem in the future, while U.S. doctors focused more on prevention and education. This educational focus was not as prevalent in Peru. Peruvian physicians used forceful commands when communicating with their patients about recovery and avoiding complications, creating a much more paternalistic atmosphere than in the United States. U.S. physicians worked to help their patients in a more conversational manner, relying on confidence and trust in the physician, as opposed to Peruvian patients being instructed to obey by those more highly educated.

Discussion

The differences observed between doctor-patient interactions in Peru and the United States are likely due to the environment of the country and the varying cultures of health care. The difference in time spent with patients seemed to be linked to the structure of the clinics, and how efficiently they operated. Most of the Peruvian doctors would fill out insurance information, clinic records, and edit the patient’s history in front of them; while the patient sat quietly and waited for the doctor to finish before leaving. This was necessary because of the patient’s paperwork and identification cards that needed to be used for the records. Photocopies could not be made because of a lack of access to such equipment. In the United States, most of these documents for paperwork are copied and held in the patient’s file for such usage. Also, it is rarely the doctor doing the paperwork, which allows the U.S. doctor to spend more quality time with patients and less time filling out paperwork. The time spent with patients in the United States is focused wholly on the patient, whereas Peruvian patients often have a great deal of “empty” time with the doctor.

According to conversations with the medical personnel at the clinic, overall health awareness and education is also poor in Peru, so patients do not understand disease and are unprepared to ask questions compared to American patients. This would explain the focus on explanation and education in the U.S., but mostly on prevention in Peru. Most of the patients had minimal medical knowledge, and therefore would not easily understand intricate explanations from the physicians. The Peruvian doctors limited themselves to conveying what needed to be understood forcefully and quickly, so the patient would hopefully listen and take it seriously. The patients followed in

the United States came to the physician having researched their symptoms, and were much more informed about possibilities for diagnosis and treatment. The physician's job, then, was to either validate or correct the patient's assumptions, and then often times educate the patient to a more detailed level about what is happening and how to treat their problem. The lack of a strong educational infrastructure in Peru prevented the majority of patients from having this type of education-detailed interaction.

Another issue which contributes to the difficulty of working with patients in Peru is the cultural importance of health care. Previous studies have shown that lower income populations in Peru seek health care less in order to utilize their time in more productive manners. They tend to self-care for non-severe illnesses.⁵ The majority of the population served by the clinic in Cuzco consisted of low-income laborers; the complaint was often made that working is significantly more important than a doctor's appointment. Patients only visited the doctor when their health began impeding their ability to work. This undoubtedly contributed to the Peruvian physician's need to be forceful and blunt, without focusing on education since the patient had almost no interest in it. The lack of a cultural emphasis on good health practices certainly poses a challenge for Peruvian doctors who wish to advise their patients.

Conclusion

Clear differences were found between the United States and Peru in communication styles with patients and how information is presented to the patient, not in word choice, but rather in the forcefulness of the response, and the focus of the conversation. While the hypothesized distinctions between question choices used by doctors was not as dramatic as expected, word choice was clearly different, but for an unexpected reason. Word choice, such as the use of the informal "tu" form by the Peruvian physicians, created an entirely different patient-physician atmosphere. Further studies could indicate if this is a phenomenon of Cuzco alone, or Peru as a whole. In addition, further studies should be done with more similar participant populations in each country to eliminate confounding variables such as socioeconomic factors. However, this study provides valuable insight into trans-cultural interactions in the health sector, particularly with respect to how physicians address their patients in the examination room. Knowledge of cultural differences through communication can lead to more effective education and treatment both in the United States and abroad. More research is necessary for a complete understanding of cultural impact on health care, but this study can be an integral first step in that process.

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About the Author

Casey Kraft was born in Bloomington, Ill., and is a senior Science Pre-Professional major with a minor in the Glynn Family Honors Program. He has been working with his advisor, Maria Coloma, on this project for almost a year. Casey became interested in this type of research after taking Coloma's Spanish for the Medical Profession course last year, as well as working with the nonprofit "She's the First" for the past two years. He will be attending medical school next year, and hopes to continue similar international research there as well.

The Effects of Invasive Earthworms on Maple (*Acer*) Seedling Germination and Growth

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Abstract

All earthworms in the Upper Great Lakes region are invasive and have detrimental effects on area forests. *Acer saccharum* (sugar maple) forests are particularly affected, with sapling abundance and growth hindered by earthworms. However, little work has been done on *Acer rubrum* (red maple), which is becoming an increasingly important component of northern forests. *A. rubrum* seeds were grown in the presence of *Aporrectodea caliginosa*, *Lumbricus terrestris*, or *Lumbricus rubellus* and compared to seedlings grown in the absence of earthworms. A survey of the University of Notre Dame Environmental Research property was also performed to see if the negative correlation between maple abundance, height, and earthworm density reported in past studies in the Great Lakes region is seen on the property. The results show a significant difference in total biomass of seedlings, with the *A. caliginosa* treatment having a higher biomass than both control and *L. terrestris* treatments. No significant difference was found between the germination rates of different treatments, and no significant relationships were found between earthworm densities and the growth or height of maple saplings on property. The maple saplings on property are more likely affected by deer over-browsing than earthworms. This study indicates that red maples may not be hindered by earthworms in the same manner as sugar maples, which has future implications as earthworms continue to invade the Upper Great Lakes region.

Introduction

The last ice age extirpated native earthworms from the Great Lakes region.¹ However, non-native earthworm populations now occupy the majority of the Great Lakes forests mainly through human introduction, specifically by anglers and horticulture practices.¹ These introduced earthworms alter soil characteristics, affecting forest community dynamics developed since the last ice age in their absence.²

Earthworms have been found to have significant effects on soil structure and nutrient cycling in forest ecosystems, mixing soil layers and reducing organic matter.³ The invasion of non-native earthworm populations also increases nutrient leaching, causing a net loss in nitrogen over time.^{1,4,5,6} Earthworms have also been shown to cause a decrease in soil carbon storage.^{1,2} High earthworm densities significantly decrease leaf litter thickness and mass in areas where they are present, which hinders the regeneration and growth of plants adapted to germinate and grow in those conditions.⁷

In sugar maple dominated forests, earthworms cause a loss of plant diversity and cover as well as a reduction in the abundance of tree seedlings.⁶ Plant species richness in these forests also decreases as earthworm densities increase.⁸ Notably, *Acer saccharum* (sugar maple) seedling density and earthworm density have been shown to be negatively correlated.^{8,9} When *A. saccharum* is grown in mesocosms, earthworm presence decreases biomass and increases mortality of seedlings.¹⁰ Whereas previous studies have focused specifically on *A. saccharum*, none have studied any other maple species.^{8,9,10} *Acer rubrum* (red maple), a generalist maple species, is becoming increasingly more abundant in Great Lakes forests.¹¹ Therefore studying earthworm effects on this species' growth will be able to give us an important insight into how forest dynamics may change as earthworms continue to affect *A. saccharum* populations.

Based on results found from another study stating earthworms decrease sugar maple seedling biomass, it was hypothesized that earthworms would negatively affect total biomass of *A. rubrum* seedlings.¹¹ Also predicted was that germination rates would be lower when earthworms were present. The relationship between sapling abundance and earthworm density using an understory plant survey in a Great Lakes forest was also examined. This examination helped determine the generality of the negative relationship between sapling abundance and earthworm density. It was hypothesized that there would be the same pattern on property between earthworm densities for both sugar and red maple saplings.

Methods

This study was conducted at the University of Notre Dame Environmental Research Center (UNDERC), which is located on the border of Vilas County, Wisc., and Gogebic County, Mich. The habitat is mostly composed of northern mesic forest.¹² The worms used in this study were *Lumbricus terrestris* (night crawlers), *Aporrectodea caliginosa* (grey worms), and *Lumbricus rubellus* (red worms) which are three common species of non-native earthworms on property.⁴

Growth Experiment

Acer rubrum grows rapidly in a variety of conditions with germination times of approximately 10-15 days, making it ideal for a short term study.¹³ *Acer rubrum* seedlings were grown from seed in 15.4 cm diameter pots filled with standard potting soil for 42 days. Each pot was watered with 25 ml DI water and rotated daily to mitigate any local effects due to the placement of grow lights. Grow lights were on for 16 hours a day to mimic summer sunlight amounts in this region.¹⁰ If more than one plant grew in a single pot, one was randomly selected and removed as soon as it was discovered to limit competitive effects.

Each pot contained either an individual species of earthworm or no earthworms. *Lumbricus terrestris*, *A. caliginosa*, and *L. rubellus* were chosen as the three treatments. Each treatment had ten replicates. Only mature earthworms were used in this study, since it is nearly impossible to distinguish *L. rubellus* and *L. terrestris* as juveniles. Earthworms were collected on property after rainfall emergence or purchased from local dealers. All worms were identified to species using Schwert's

dichotomous key.¹⁴ The control pots contained no earthworms.

All treatments contained a high density of earthworms (242 g/m² fresh mass, 4.4 g/pot fresh mass). High density was defined by the observational findings of Wironen and Moore, which described high densities of earthworms as being >200 g/m².⁷ In order to standardize biomass among all treatments, each *L. terrestris* pot contained a single worm, the *L. rubellus* pots contained four worms, and the *A. caliginosa* pots contained five worms each.

To prevent earthworms from escaping, all of the pots were placed in a larger bin (Figure 1), and both the inside edges of the individual pots and the interior of the larger bin were coated with Teflon lubricant.¹⁵ After 42 days, the plants were removed, oven dried at 60°C, and weighed to compare biomass among the various treatments.¹⁶



Figure 1. The set up of the *A. rubrum* growth experiment showing how the 10 individual pots were placed within a larger bin to prevent the earthworms from escaping.

Germination Experiment

To test germination rates between various earthworm treatments, four pots were planted with 200 maple seeds each. Three pots contained an earthworm species treatment, and one had no earthworms as a control. *L. terrestris*, *A. caliginosa*, and *L. rubellus* earthworms were used. Each pot contained an equal biomass of earthworms, consistent with the biomass for the growth treatment. After 19 days, the seeds were dug up and the number of germinated seeds, determined by the presence of the radicle, was counted.¹⁷

Earthworm Density and Sapling Abundance Survey

Twenty areas of UNDERC dominated by maple forest were identified and three random locations within each forest were sampled. At each location, a 25 cm x 25 cm (0.0625 m²) metal square was placed on the ground and red and sugar maple saplings within the square were counted, and their height (in cm) was measured.³

Earthworm density at each site was estimated by liquid extraction.³ For each plot, 40 g of yellow mustard powder was mixed with 3.8 L of water. The yellow mustard solution irritates earthworm's epidermis and causes them to move above ground. After the mixture is poured over the area, all earthworms that surfaced within five minutes were collected. Earthworms were identified to species then placed in 95 percent ethanol to be preserved. Since many juveniles were collected and *L. rubellus* and *L. terrestris* are difficult to distinguish as juveniles, all *Lumbricus* sp. worms were grouped together. The earthworms were dried at 60°C and ashed at 500°C to obtain the ash free dry mass (AFDM) (following methodology described in NRRI

2006).¹⁸

Statistics

The growth biomass data, sapling abundance and height data, and earthworm density data were tested for normality using Shapiro-Wilk's test, and data found not to be normal was transformed accordingly. To analyze the results of the growth experiment, a one-way analysis of variance (ANOVA) compared total biomass across the different treatments. A Fisher's LSD post-hoc test was performed to determine which groups differ significantly. A chi-squared test compared the proportion of germinated seeds in the different treatments. Four correlations between both total AFDM and *Lumbricus* sp. AFDM at the forest sites, and both the abundance and height of *Acer* seedlings were run to see if earthworms significantly affect the growth and abundance of the maple species at UNDERC.

Results

Total biomass between treatments in the growth study was found to be significant ($F_{3,36}=3.28$, $p=0.032$, Figure 2). The mean for the control was 0.008 +/- standard error of 0.001. The mean for the *A. caliginosa* was 0.013 +/- standard error of 0.002. For the *L. rubellus* treatment, the mean was 0.012 +/- standard error of 0.003, and for the *L. terrestris* treatment, the mean was 0.007 +/- standard error of 0.001. A Fisher's LSD test revealed significant differences between the *A. caliginosa* and *L. terrestris* treatments ($p=0.034$) and the *A. caliginosa* and control treatments ($p=0.019$). All other groups did not differ significantly.

The germination rates did not differ significantly ($p=0.745$). Out of the 200 seeds placed in the individual pots, 3 seeds in the control pot, 5 seeds in the *A. caliginosa* pot, 6 seeds in the *L. terrestris* pot, and 6 seeds in the *L. rubellus* pot germinated.

The correlation between the transformed data for earthworm density and sapling abundance was not significant ($p=0.730$, $r^2=0.007$, Figure 3A). A correlation of total earthworm density and sapling height was also not significant ($p=0.519$, $r^2=0.023$, Figure 3B). Correlations between the densities of *Lumbricus* sp. and both sapling abundance ($p=0.754$, $r^2=0.006$, Figure 4A) and sapling height ($p=0.491$, $r^2=0.027$, Figure 4B) were non-significant as well.

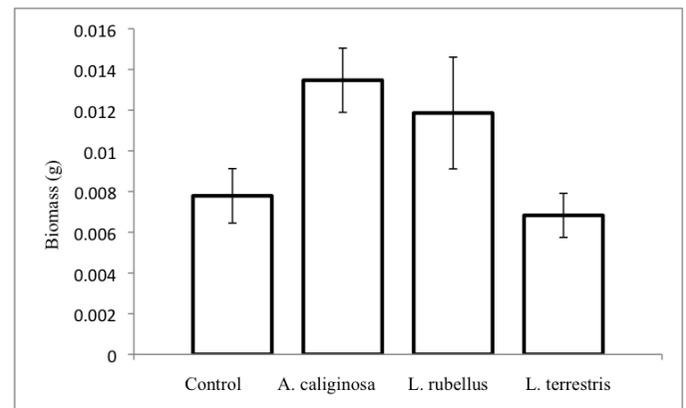


Figure 2. Averages of total biomass (g) and the standard errors for the *A. rubrum* growth experiment for each earthworm treatment.

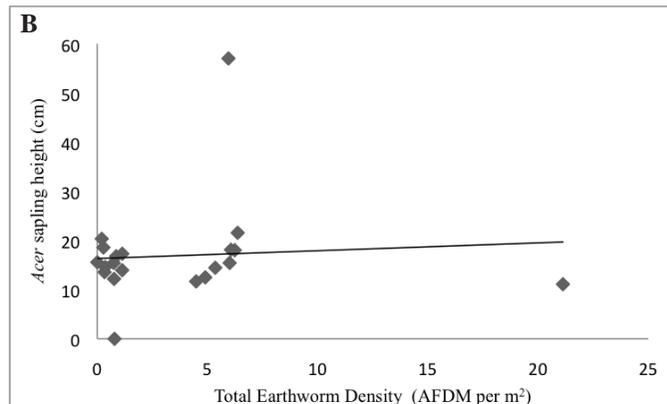
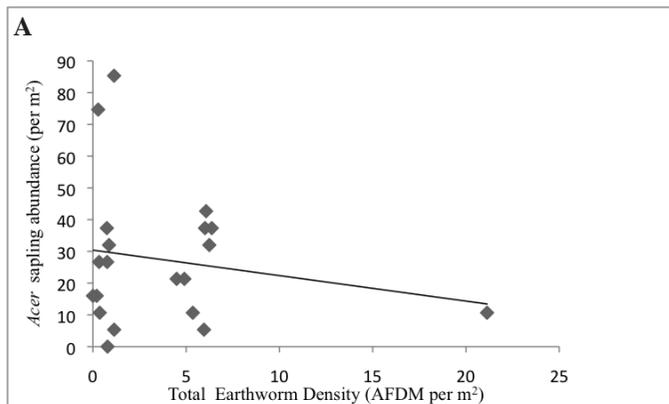


Figure 3A-B. The correlation between abundance (A) and height (B) of *Acer* saplings (per m²) and total earthworm *Lumbricus* sp. density (AFDM per m²).

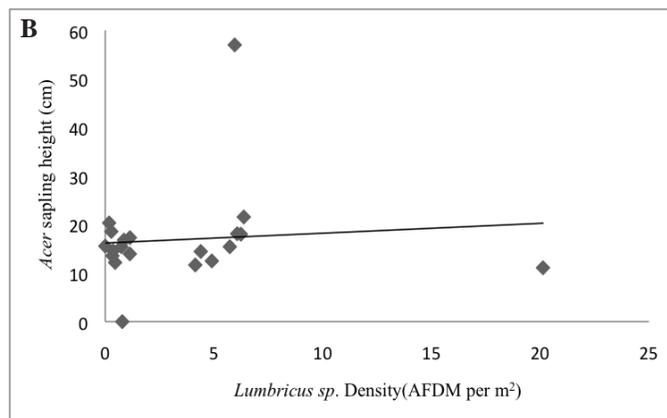
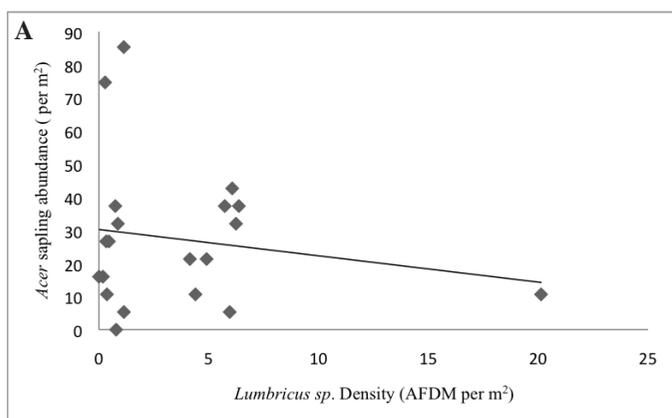


Figure 4A-B. The correlation between abundance (A) and height (B) of *Acer* saplings (per m²) and total *Lumbricus* sp. density (AFDM per m²).

Discussion

The proposed hypothesis that there would be a negative influence from the earthworms compared to the control on the growth of *A. rubrum* was not supported. The differences found were that *A. caliginosa* treatments had a higher total biomass compared to both the control and the *L. terrestris* treatments. *Lumbricus terrestris* also tended to have a lower biomass than the control; however, this trend was not statistically significant (Figure 2). These results suggest that areas dominated by *A. caliginosa* may possibly help *A. rubrum* seedling growth compared to areas more highly dominated by *L. terrestris*, or those forests that do not have any earthworms. This positive influence found by the presence of *A. caliginosa* and the lack of any significant negative influences of earthworm presence when compared to controls deviates largely from the drastic negative effects of earthworms on *A. saccharum* growth and biomass.¹⁰ *Acer rubrum* may be able to coexist well with these earthworms, and the data suggest that *A. rubrum* is either not affected, or is helped by the presence of earthworms. This observation has implications for forest management and community structure. If earthworms continue to increase in density and their invasion in the area, *A. rubrum* might begin to outcompete *A. saccharum* in forested areas invaded by earthworms.

If plants were grown over months or years, long-term ef-

fects of earthworms might be observed. Additionally, due to the varying effects seen between *A. caliginosa* and *L. terrestris* it would be advantageous to grow plants within mixed earthworm species treatments to test the combined effects. For instance, the presence of both *A. caliginosa* and *L. terrestris* could cancel their effects out or one species could have a greater influence.

Because the seedlings in this study were planted in homogenous potting soil, this study focused on the effects of earthworms on topsoil, and their mixing effects of various soil layers was not a factor. However, as seedlings are rooted in the very top layer of soil and this study was simply looking at the overall effect of biomass change with the presence of earthworms, the results still show an important trend.¹⁹ Future studies should be done in more natural environments to confirm the findings of this study.

The germination experiment yielded no significant results. Germination did not change between the various treatments. This is opposite of other studies that demonstrated a decrease in germination when earthworms were present.¹⁷ This result suggests that *A. rubrum* is likely to not be as affected by worm invasions as *A. saccharum*. However, this study was only able to run for 19 days and had poor replication. Even though the reported germination rate of red maples is 10-15 days, the ger-

mination observed in the growth pots suggested that normal germination time for the seeds being used was closer to 20-25 days.¹³ However, the germination rate of the growth experiment was not recorded. If the germination experiment ran for a longer period of time, and with more replicates, the data might have detected a difference. Also, some mortality was seen in the earthworm pots, specifically within the *L. terrestris* treatments. Even though dead individuals were replaced as soon as they were found, these deaths may have affected the results.

The relationship demonstrated in other studies comparing earthworm density and abundance and height of maple saplings was not demonstrated on the UNDERC property.^{8,9,10} The data showed no trends between height or abundance of maple saplings, and either the overall earthworm density or density of *Lumbricus* sp. This result is highly contradictory to other earthworm studies, but may be explained by confounding factors. For one, although all sites were occupied by earthworms, there was not enough variation in density of earthworms to detect any differences. If more plots were sampled with higher earthworm densities, a relationship may have been found. Also, like much of the Upper Great Lakes forest, the UNDERC property has been subject to over browsing by white tailed deer (*Odocoileus virginianus*) for decades, which negatively affects maple sapling and seedling growth.²⁰

Overall, this study suggests that earthworms do not negatively affect *Acer rubrum* seedlings, and seedlings may actually benefit from earthworm activity. Other studies investigating maple seedlings and earthworms have found negative relationships; however, all of these studies have focused on *Acer saccharum*. This study is the only one looking at the effects on *Acer rubrum*, and therefore its results open an avenue for future studies and research on why these differences occur. In addition these findings may affect forest management policies and the future composition of Great Lakes forests.

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About the Author

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The Ecology of the University of Notre Dame and Its Effects on Student Life

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Abstract

The University of Notre Dame is a unique urban environment which faces problems typical to urban environments as well as its own unique ones. This paper focuses on the five principles of urban ecology as described by Grimm et al., which are land use, biogeochemistry, climate, hydrosystems, and biodiversity.¹ This paper examines the unique challenges facing the University of Notre Dame in each one of these categories. Background information is provided for each challenge, as well as the University's response to these challenges. The consequences of these responses are examined and related to the lives of students at Notre Dame, focusing on the changes in ecosystem service availability due to the actions of the University over time. The goal is to increase student awareness of the fact that Notre Dame is not just a university; it is also an ecosystem, and that ecosystem impacts everyday activities. Therefore, the actions of the University with respect to its environment can indirectly impact student life. This paper raises awareness as well as providing a helpful framework for further study of the Notre Dame ecosystem.

Introduction

Urban environments are centers that drive large and small-scale environmental changes. The scientific study of these environments, which includes investigating factors that determine the distribution and abundance of organisms and their interactions with other organisms and the surrounding environment, is called urban ecology. Urban ecology is a relatively new area of study that was ignored for most of the 20th century. However, as urban centers continue to grow to unprecedented sizes, the importance of studying their effects on their own and surrounding ecosystems is increasing.¹ This paper is aimed at the undergraduate student body of Notre Dame and is intended to define and provide insights into the five major types of global environmental change resulting from urbanization in the context of urban ecology, and to relate these implications to the Notre Dame campus.

The five major types of global environmental change that result from increasing levels of urbanization include changes in land use, biogeochemical cycles, climate, hydrosystems, and biodiversity.¹ Global migrations to urban areas have resulted in large-scale changes in land use associated with satisfying the demanding needs of dense populations. Biogeochemical cycles, natural processes that cycle nutrients and other organic material

through the environment, have been severely altered by contaminated runoff associated with urban pollution and impervious ground covers, such as roads or parking lots. Urban areas can change local and global climate by absorbing increased levels of radiant heat energy that leads to heightened annual temperatures. In order to provide urban residents with a reliable source of water, natural hydrosystems have been heavily modified to provide services such as sewage disposal, irrigation, and drinking water. Finally, urban areas tend to cause an overall homogenization of biodiversity that can result in the increased prevalence of vector-borne diseases and destruction of natural food webs.

The study of urban ecology is relevant to the University of Notre Dame because of our proximity to urban centers such as South Bend, Gary, and Chicago. The natural systems on Notre Dame's campus provide its undergraduate students with multiple important services that enhance the life of the student body both on and off-campus, increasing the value of the tuition that is paid to attend this university. As great as these services are, there are many ecological impacts that students may not be aware of that are caused by the university and the surrounding urban environments. These ecological impacts directly affect the services available to each student, and are therefore pertinent to the everyday life of the student body.

Land Use

As a student at the University of Notre Dame, knowledge of anthropogenic changes in land use and land cover due to urbanization is important because of the implications that it has on the campus that you call home. Currently, over half of the world's population lives within an urban environment and this fraction is projected to exceed four-fifths by the year 2030.² This large migration of people to urban centers has occurred on less than three percent of the terrestrial surface area of Earth.¹ As these areas become increasingly urban, impervious surface cover comes to dominate land area at the expense of natural vegetation.¹ Due to the lack of productivity associated with impervious surfaces, fringe ecosystems surrounding urban cores have been heavily modified to support the urban population.³ These fringe communities support urban cores by providing resources such as food, energy, waste absorption, and building materials at the expense of their own ecosystems. This important interaction between urban centers and the surrounding ecosystems illustrates how urban areas can have a much larger ecological footprint outside their anthropologically defined borders.

Altering land in order to support changing lifestyles and growing populations is important because it is deeply embedded in the history of this school. The land that the Notre Dame campus currently occupies was once characterized by a vast wetland ecosystem. When the Erie Canal was built in 1825, greater access to the Midwest was made possible. Consequently, population of the area increased and a need for agricultural land came to the forefront of problems standing in the way of western expansion. With the invention of the steam dredge shortly thereafter, wetland conversion to agricultural fields became commonplace in the Midwestern States (Figure 1).⁴ During this period, the first members of the Congregation of the Holy Cross arrived in the to-be South Bend area but many of them perished at the hands of typhoid fever.⁶ At the time, there was a common



Figure 1. States with notable wetland loss in the time period between 1800 and 1860 due to the invention of the steam dredge.⁵

belief among the people of the area that the wetland setting they were living in was responsible for the incidence of the disease and the increased mortality of their population.⁶ Following suit with the rest of the Midwest and in an effort to provide a livable habitat for the University, the wetlands that occupied this area were drained. These drainage events and others across the states of Michigan, Illinois, and Ohio gave rise to the basic foundation that the current day landscape would be built upon.⁴

Wetland conversion is an example of anthropogenic alteration of land use and it has altered the ecology of the Midwestern United States in ways that are pertinent to the life of an undergraduate at this university. Wetlands have been proven to support high levels of biodiversity, help in flood abatement by considerably reducing free flowing water, and have also shown a high capacity to sequester atmospheric carbon, which helps reduce greenhouse gas levels in the air.⁷ Due to the widespread conversion of these ecosystems, the Midwest has surrendered these beneficial wetland traits and has undergone large-scale environmental changes.⁸ This surrendering of beneficial wetland traits in the Midwest as a whole also pertains to the Notre Dame campus. The University of Notre Dame supplies the campus with water from wells that connect to aquifers that are directly beneath the campus grounds. Consumption rates by members of the Notre Dame community are outpacing natural recharge rates of the campus aquifers.⁹ When this occurs, water volume in the aquifer declines, which allows underground contaminants to increase in concentration and thus could impact the water quality over time.⁹ This means that Notre Dame's water supply, while currently clean, could slowly lose its quality over time. Wetland ecosystems are excellent for water quality and purity improvement. A variety of studies have concluded that wetlands have a high capacity to remove sediments, nutrients and other contaminants from circulating water and because of this function, efforts to artificially construct wetland habitats have been performed to treat contaminated water supplies.⁷

For this reason, wetland restoration could propose a possible solution to the issue of water quality that Notre Dame will face in the future. Currently as precipitation falls on campus grounds, accumulating water comes into contact with potential contaminants. At this time, there is nothing in between this water and our underground aquifers, which could lead to con-

tamination of the University's water supply at some point in the future.¹⁰ Notre Dame could combat this issue with an ecological knowledge of the effects of wetlands on water quality. If artificial wetlands could be reconstructed in a fashion emulating the area's natural land use and placed in strategic locations based on campus drainage patterns, contaminated water would be intercepted and forced to circulate through them. This water would then utilize the purification capabilities of wetland ecosystems and ultimately wind up at its final destination with a lower concentration of pollutants.⁷ Even though a small amount of rainwater percolation actually reaches underground aquifers, its effect on water pollution is not negligible. Over time, this effect will compound itself, as will the effect of overconsumption, resulting in the degradation of on-campus aquifers to the point where they may no longer be usable. Without an attempt to improve campus water quality, Notre Dame will need to expend resources in an effort to look for alternative water sources in the next few generations to satisfy campus needs. With the affinity that Notre Dame graduates have for the campus and community of this school, it is important to recognize that alterations in land use due to urbanization have lasting negative implications on the ecology of the area and can influence future campus life.

Biogeochemistry

Biogeochemistry involves the study of chemical, physical, geological, and biological processes and relationships that compose ecosystems. This topic is important because it involves the cycles of important chemical elements such as carbon, nitrogen and phosphorus. In recent decades, human influence on biogeochemistry, especially as a result of urbanization, has grown in a negative way.¹ Issues associated with biogeochemistry in urban ecology include the overuse of macro-nutrients such as phosphorus (P), contaminated storm water runoff, and the previously mentioned effects that urban centers can have on areas outside their borders.

One important issue in biogeochemistry involves the planet's limited P supply.^{11,12} P is an essential macro-nutrient needed for plant growth and is added to croplands to increase yield. Although P is the 11th most common element in the world, it is only available in limited quantities for direct use by organisms, mainly primary producers.¹¹ This low availability of P found in soils functions to limit plant growth in natural ecosystems. In order to adapt to low P levels, plants have developed mechanisms to scavenge it from the soil.¹¹ When plants are removed from an area, so too is the P in their tissue.¹¹ In order to replace P and other nutrients such as nitrogen (N) and potassium (K), farmers and landscapers add chemical fertilizers. This method of returning nutrients to the soil allows farmers to increase the fertility of farmland in order to support the growing resource need of urban populations.¹² Despite these benefits, chemical fertilizers can be problematic as well. The main issue associated with chemical fertilizers rich in P is their general overuse and the resulting amount of waste that enters the environment.

The main way that P enters the natural environment is through runoff, which is the product of over-application and the resulting waste.¹¹ The current protocol for farmers and landscapers is to apply high levels of chemical fertilizers with the end goal of keeping N levels high. Unlike P and K, N is easily

evaporated and washed away.^{13,11} This leads to oversaturation of soil with P. P contaminated runoff contributes to aquatic eutrophication, algal blooms caused by nutrient overloading that suffocate bodies of water and cause them to appear stagnant and unhealthy (Figure 2).



Figure 2. Eutrophication is caused by an overabundance of limiting nutrients in a water system and can lead to spectacular but ecologically devastating algal blooms.¹⁴

A solution to the over saturation of P in ecosystems is to better manage the timing and placement of the fertilizer and to reduce P use.¹¹ Recycling P can also reduce chemical fertilizer waste. Currently, 11 million tons of recyclable P is lost per year in the form of animal, human, and food waste.^{15,12} Much of this waste enters waterways, where it contributes to eutrophication or ends up trapped in landfills.¹¹ Recycling plans are numerous and varied but the current lack of P regulations, and the high start-up costs associated with them, prevent their successful implementation. If Notre Dame undergraduates initiated campus-wide or individual dorm composting programs, they could reduce the need for chemical fertilizers and the money the university spends on them while limiting the campus's global P output in wasted food and other organic goods.

Another major biogeochemical issue is rain runoff that washes nutrients and chemicals into water systems resulting in eutrophication and ecosystem damage. A single, strong storm event in an urban area like the Notre Dame/South Bend area has the potential to shock a receiving water way with contaminants on a scale that is comparable to and sometimes greater than those caused by sewage treatment plants.¹⁶ These urban contaminants are a result of litter, fertilizer use, and fluids associated with automobiles. When such contaminants combine with high surface water flow induced by impermeable concrete surfaces, they can accelerate erosion of river banks, devastate

river habitats, increase eutrophication rates in lakes, and decline overall water quality.¹⁶ Due to these negative effects and the proximity of the campus lakes to an urban area, they are at risk of damage.

As water enters our lakes through runoff, contaminates can accumulate over time and irreversibly damage these water systems.¹⁶ Current monitoring has shown that nitrate and phosphate levels in both St. Mary's and St. Joseph's Lakes are lower than they have been in 35 years.¹⁷ These lower levels are a product of reduced agricultural land surrounding campus and better regulations regarding the use of chemical fertilizers.¹⁷ As long as the lower levels of contaminants in the lakes can be maintained, they will continue to remain beautiful for generations to come.

The final component of biogeochemistry is that it can be far reaching. This means that what we do at Notre Dame can have a direct effect on surrounding areas and as previously mentioned, what happens in seemingly far off places, like Chicago and Gary, can also affect the environment on campus. An example of this phenomenon from a biogeochemical perspective can be seen in ozone concentrations surrounding urban centers. In a study by Gregg et al. it was shown that ozone, an atmospheric pollutant when located close to the ground, was at higher levels surrounding the New York City area than it was in the actual city.¹⁸ This is because urban centers produce ozone precursors that are then carried downwind and form ozone after being exposed to light energy for a period of time.¹⁸ These higher levels of ozone have a negative effect on plant growth and can have serious effects on ecosystems.¹⁸ This idea that outside areas can influence our campus is troubling but also provides an opportunity for Notre Dame undergraduates to interact with the surrounding areas in a positive way by potentially developing informed solutions to these problems.

Climate

Another implication of the increasing level of urbanization in the modern world is its connection with climate change. The most well documented example of urban-induced climate modification is called the urban heat island effect, which states that cities tend to have higher air and surface temperatures than the less urbanized areas that surround them.¹ This climatic effect of urban environments has a direct tie to the changes in land-use that accompany urbanization. As an area becomes increasingly urban, impervious surface covers dominate land area at the expense of natural vegetation.¹ These surfaces, such as roads, parking lots and footpaths, are excellent absorbers of solar radiation and maintain radiant heat energy due to their high specific heat capacities.¹⁹ Concrete buildings must also be considered as they increase the surface area for absorbing solar energy in the same fashion as impervious cover.¹ The summation of energy trapped by these structures functions to increase an urban area's ability to maintain heat which results in an overall increase in temperatures.¹ The effect that impervious surfaces have on climate is further exacerbated by the loss of natural vegetation that is caused by the construction of these surfaces. Studies have shown that an increased level of vegetation in an environment functions to absorb heat energy for the creation of biomass through photosynthesis, and consequently decreases mean surface temperatures in proximal areas.²⁰ The principle of

the urban heat island effect displays how an increase in impervious surfaces and decrease in vegetation levels work in combination to raise urban temperatures.

The principle of the urban heat island is pertinent to the life of a Notre Dame student because it can be applied to the local climate on campus. The economic resources that the school has to landscape are important from a climatic perspective. As Jenrette et al. described as the “luxury effect hypothesis,” well-financed landscaping correlates with high levels of fertilizer and moisture, which increase the cooling effect that vegetation has on local climate.²⁰ Although the cooling effect from well kept landscaping is beneficial, the incidence of impervious surfaces on campus grounds is steadily increasing as new buildings that need parking lots and footpath entrances spring up across campus. On-campus construction patterns follow the general trend of land-use change stated by Grimm et al. as the grounds on which new structures are built are often converted from areas of vegetation to areas of impervious cover. This increases the capacity of campus to absorb and maintain heat, and consequently increases campus temperatures.¹

Increased mean temperatures from the urban heat island effect are important from a practical perspective because they have direct and indirect effects on human health. Direct effects of climate change on human health are displayed by physiological responses of human populations to prolonged exposure to increased temperature. The stress that is placed on the human body from exposure to heat most often results in cardiovascular and respiratory ailments such as asthma and heatstroke.²¹ Persistent warm and humid conditions during the summer and fall, a weather pattern that is often characteristic of the Midwest, leads to the highest rate of mortality among humans from such ailments.²¹ In July 1995, Chicago alone recorded 556 heat-related deaths, and analyses of climate change scenarios show a significant rise in heat related mortality in the next several decades.²¹ An indirect effect of increased temperatures on the ecology of an environment is that warm climates influence the population dynamics of intermediate disease-transferring organisms called vectors. Vectors are associated with diseases such as Malaria, West Nile Virus, Dengue and Yellow Fever, and act as a mechanism to transfer diseases to humans. Common vectors carry the capacity of disease-causing pathogens and adapt to a wide-range of ecosystem settings.²¹ Aquatic habitats that contain high levels of nutrients and are stagnant for long periods of time are hotspots for rapid increases in vector populations.¹⁰ When the population of a vector grows in size, human populations in the surrounding area are consequently at risk to an increased exposure to disease.²²

The importance of the effect of climate change due to urbanization on the ecology of insect borne viruses to undergraduates should not be discounted. St. Mary’s and St. Joseph’s Lakes are two aesthetically pleasing features of this campus but also represent two possible breeding grounds for insect vectors. Due to the drainage patterns of the campus, the lakes reflect the character of their respective landscapes. Extensive landscaping and fertilizer use on campus can overload the lakes with nutrients and cause issues such as eutrophication. If these nutrient loaded ecosystems are combined with prolonged periods of increased temperatures, the lakes would become prime locations for insect vectors, putting thousands of students at risk. The

ecological consequences of allowing the lakes to overload with nutrients can be avoided with good management of these ecosystems. By using suggestions made in the biogeochemical portion of this paper, nutrient loading of the lakes can be decreased to reduce threat of the lakes and other standing bodies of water developing into hotspots for insect populations.²¹

The Notre Dame campus is by no means equivalent to the concrete metropolis of the city of Chicago, but the climatic effects of the urban heat island can be seen on a small scale. As every year passes, the incidence of impervious cover on campus seems to increase at the expense of vegetation, resulting in increased air temperatures. Prolonged increases in air temperatures can have large consequences in areas that many students would not consider, such as population dynamics of insects that could represent vectors for diseases that could effect campus wide health. As an undergraduate at the University of Notre Dame, an understanding of the ecological impacts of climate change due to urbanization, no matter how subtle they may seem, is important considering their far reaching effects on campus life.

Hydrosystems

Hydrosystems are both important to and inextricably altered by urban ecology. Urban areas require readily available water in order to function properly. As such, the location of urban areas is commonly related to the accessibility of water and the ability of these hydrosystems to provide other services like sewage disposal, irrigation, and drinking water.¹ Notre Dame is no different from most major urban areas in its choice of location in that it is built in an area where water is abundant. This section will discuss the services provided by Notre Dame’s hydrosystems and how human-related activities alter these important systems.

University of Notre Dame would not be the same without its beautiful lakes. These lakes provide a surprising amount of desirable services to the Notre Dame student body. Some of the services provided by the surface and groundwater in and around the Notre Dame campus include swimming, fishing, boating, drinking water, water hazards on the Warren Golf Course, and power generation. The ability of hydrosystems to fully provide these desirable services is affected by human-driven factors like runoff, power plant discharge, pollution, and restorative efforts. These factors are linked to the changes in land use and biogeochemical cycles, like wetland removal and over-fertilization.

A case study on how restoration and mitigation of urban effects can increase ecosystem services is found in Juday Creek, which flows just north of campus through the Warren Golf Course. Historic land use has been focused on farming, which channelized the stream and made it prone to extreme fluctuations and vulnerable to pollution.²³ The altered biogeochemical cycles due to contaminated runoff rendered the creek useless. Eventually, land-use patterns shifted, and the creek was restored in the early 1990s during the construction of the Warren Golf Course. The restoration effort focused on changing the area’s land use back to a more natural state. This was accomplished by re-creating stream meanders, restoring the riparian zone, and by reversing years of unnatural erosion.²⁴ Gravel, boulders, and trees were also placed in the river to enhance fish growth, survival, and reproduction. The restoration efforts increased desir-

able fish populations, reduced silt load, and returned the riparian zone to a native composition of plants.²⁴ While the positive effects have diminished over time, the stream is healthier and more of an asset than before. Multiple parks line the stream and the cold clear water provides a refuge for economically important cold water fish like salmon, steelhead, and brown trout.²⁴ These fish are a part of a \$4 billion sport fishing-based economy, and this service shows how even a small, seemingly insignificant creek is connected to the wider world.²⁵ It is this interconnectedness that makes urban ecology both incredibly important and difficult to understand and manage. The far-reaching impacts of decisions regarding Juday Creek become much more important when viewed in the light of the wider ecosystem it affects. Finally the creek also provides the water hazards on the Warren Golf Course. Therefore, the stream provides three important services to the Notre Dame community: beauty, fishing, and recreation, while still maintaining its special status as a cold, clean spring creek, that is a rarity at this latitude.

Another example of human-induced change to urban hydro-systems is wetland draining. As previously described, wetland conversion has major impacts on services provided by groundwater, especially the supply of drinking water for the Notre Dame community. Without the important services provided by wetland ecosystems, polluted rain and contaminated runoff are constantly being integrated into the campus supply of drinking water. The changes responsible for the potential degradation of water quality, and overall alteration of the Notre Dame hydro-system are a result of changes made to accommodate increasing urbanization. Urban induced changes to the environment thus negatively impact students, and are functioning to prevent hydro-systems from providing adequate services to Notre Dame.

The lakes on Notre Dame's campus provide multiple services like swimming, boating, fishing, sailing, power, and general beauty. Runoff, power plant discharge, and pollution are the main factors influencing the lakes. Runoff from campus carries fertilizer and other pollutants to the lakes, contributing to eutrophication. This can make the lakes unpleasant due to scum buildup, decreasing the beauty and recreational value of the lakes.^{26,27} The effect of eutrophication can be magnified by changes in climate. The second factor influencing the lakes is the power plant. Contrary to popular belief, the power plant water discharge is actually very clean, and the lakes have the lowest concentrations of macronutrients of the past 35 years.¹⁷ However, the power plant is still a source of heat pollution. Past studies have shown that temperature in St. Joseph's Lake is different than St. Mary's Lake with the one explanation being power plant operations.^{28,17} Even small changes in temperature regimes can influence aquatic ecosystems.²⁹ The power plant discharge prevents St. Joseph's Lake from freezing or stratifying and this could contribute to poor fish condition in the future.^{28,30} If this were to happen, the ecosystem services provided by the lake would be reduced. The power plant also releases pollutants into the air. Airborne pollutants can, through the process of bioaccumulation, be incorporated into aquatic food webs and result in toxic mercury and persistent organic pollutant concentrations in the flesh of adult fish, making them unsuitable for human consumption.³¹ The power plant is perhaps the strongest factor influencing the lakes, and it greatly affects their ecology, which in turn affects their value to the larger Notre Dame com-

munity. Certainly, its effects warrant further study.

Biodiversity

Biodiversity is influenced by all other aspects of urban ecology. Biogeochemical cycles, climate, land use, and changes to hydro-systems all alter habitats, and thereby alter the types of animal and plant life that can inhabit urban areas. Changes in all of the urban ecological factors drive the general trend towards higher animal numbers, but lower overall species richness, which is defined as the total amount of species in a certain area.¹ Urban areas tend to have lowered biodiversity and Notre Dame is no exception.³² The changes that have been made to the campus ecosystem are taking their toll on species richness, and this has negative effects on student happiness and health. However, affluent suburban and semi-urban areas can change land use patterns and create the previously mentioned "luxury effect".²⁰ Biodiversity increases in these "luxury" areas because money is spent to introduce many exotic species to the already present native species. This creates new habitat niches, or living conditions, while providing for beautification of the landscape. Both of these factors, urbanization and the luxury effect, are at play on Notre Dame's campus, and can influence the services provided by biodiversity to students. The main service provided by enhanced biodiversity is campus beautification. Biodiversity also affects disease transmission, and therefore the health of students on campus.

Biodiversity is impacted by human-mediated changes to land use, biogeochemical cycles, and climate, which can create habitats favoring homogenous species assemblages and short-circuit food webs. We influence biogeochemical cycles to serve one species: humans. The outcome of this is the reduction of biodiversity to species assemblages that can live within favorable human parameters. Species homogenization plays a major role in disease transmission and zoonosis, or the transmission of disease between different animal species. Homogenization also simplifies food webs, and can remove decomposition and nutrient-recycling steps as ecosystems instead rely on unnatural nutrient inputs. This creates a negative feedback loop that can contribute to even more homogenization. Homogenization is the main force governing the ecosystem services provided by biodiversity.

The first service provided by biodiversity is beautification of Notre Dame's campus. Notre Dame has a reputation for having a beautiful campus through both its architecture and natural spaces. There are thousands of trees on campus with hundreds of different species from all over the world, from native beech to Japanese ginkgo. Notre Dame has committed to increasing the number of trees and shrubs on campus by planting hundreds of trees over the past few years.³³ The well-manicured lawns, impervious surfaces, and different tree species on campus are made possible by land-use changes like wetland draining and shifts in the biogeochemical cycles via fertilization. Many of the trees produce nuts and fruits that support birds and squirrels, which in turn support hawks. This simple food chain provides an opportunity to watch nature in action. A hawk eating a squirrel on God Quad tends to draw crowds of fascinated onlookers. Additionally, the high diversity of trees on campus makes for beautiful fall color and cooling shade on a warm spring day. Therefore, biodiversity contributes to the beauty and atmo-

sphere of campus. This beautification can have an influence on the decision to apply to the school, or the decision of whether or not to teach and live here as a professor. In this way biodiversity can positively impact the quality of an academic institution.

However, biodiversity on campus has been lowered by high resource availability and human presence, which has increased negative effects like increased disease transmission. The aforementioned landscaping has created a high density of food items on campus. This combined with animal feeding has increased bird and squirrel densities and contributed to homogenization.^{34,35,36} Semi-urban areas like Notre Dame with homogeneous, high concentrations of birds such as the Northern Cardinal have been shown to be hotspots for West Nile Virus transmission.²² Squirrels and other animals like chipmunks, ducks, swans, skunks, raccoons, and possums also make Notre Dame's campus home. All of these animals are vectors for disease like rabies, the bubonic plague, and others.^{22,37,38} This problem is exacerbated by the fact that these animals are accustomed to and unafraid of human contact, which makes disease transmission easier.³⁸ The animals on campus have become semi-domesticated because they are consistently fed by students and visitors, creating a dangerous association of food with humans.³⁸ These animals pose both the immediate threat of attack, and the secondary threat of disease transmission due to close contact with people.

Homogenization of species assemblages to favor disease-carrying, human-tolerant species on campus is therefore an important factor when it comes to student health and welfare. The long-term strategy to mitigate this threat is to work toward increased biodiversity. Creating and maintaining wildlife refuges and connecting these habitat patches are key principles that have been shown to increase biodiversity.³⁶ This can be accomplished on Notre Dame's campus by protecting and restoring the remaining woodlots. Notre Dame could also buy surrounding land and return its state to a natural temperate forest. These patches of forest could be opened as parks, increasing the amount of recreational space for the enjoyment of students, while increasing biodiversity. The next step in the fight against low biodiversity is to reduce human-animal interactions. Reducing handout feeding by intentionally providing animals with foul-tasting food items will break the human-food association and keep harmful interactions to a minimum.³⁹ Education could also help reduce handout feeding, and thereby decrease dangerous human-animal interactions. By increasing biodiversity through the processes described above along with mitigating the effects of homogenization, positive ecosystem services like natural beauty, enjoyment, and better academics will increase while at the same time decreasing undesirable effects of low biodiversity such as disease.

Conclusion and Moving Forward

The University of Notre Dame is not just a school; it is an ecosystem that has both negative and positive effects on the daily life of undergraduate students. By understanding the principles of urban ecology, we can develop a greater appreciation for our surroundings and gain insight into the processes that govern the ecosystem of this school. The land use changes implemented prior to the inception of the University created a

wetland-free area to allow the founders to clear the land and build a school. As the wetlands disappeared, the area was landscaped and fertilized for agricultural use. This fundamentally altered biogeochemical cycles in the immediate area, damaging natural ecosystem variability and processes, and causing negative effects like eutrophication and lower drinking water quality. Students can help by engaging themselves in a discussion about the possible restoration of wetlands. This may seem complex and hard to accomplish, but complex restoration projects like these have been successfully completed on campus in the past, as exemplified by the Juday Creek restoration. As this campus continues to expand with the construction of new buildings, pavement of new parking lots, and increased power plant production, the campus warms up both from local processes such as the urban heat island effect and global climate change. These changes to climate and biogeochemical cycles have an impact on Notre Dame's hydrosystems, typified by the lakes. A warming trend, increased heat pollution from the power plant, and fertilizer runoff can turn our lakes green and hurt fish health, reducing the lakes' aesthetic and recreational value. Students can help by reducing electricity use, which would reduce the amount of heat pollution produced by the power plant. Undergraduates and influential student groups like GreeND can also push the administration for reduced chemical fertilizer use. These two simple, easy to accomplish actions can keep our lakes clear and healthy. Finally, all of the alterations to the urban ecosystem affect natural habitats for the variety of animals that call this campus home. As populations homogenize and biodiversity decreases, animal-borne diseases increase, impacting student health and welfare. Students on campus can help combat this trend by refraining from feeding the animals. This will reduce animal-human interactions and keep disease to a minimum. Moving forward, greater awareness and education about urban ecology and its effects on the student body can help the University and undergraduate students ensure that the surrounding ecosystem provides positive ecosystem services while mitigating any negative effects associated with surrounding urban centers. It is through both human intervention and awareness that we will be able to fully enjoy and take advantage of Notre Dame's ecosystem.

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About the Authors

Kevin Kershnik is a junior Environmental Science major from Highlands Ranch, Colo., who is interested in natural resource management and associated environmental issues. Specifically, he is interested in oil and gas law in the United States and abroad and hopes to pursue a law degree after his time at Notre Dame. Last semester, Kevin worked under Dr. Dominic Chaloner in an ecology course in conjunction with the other authors in order to produce this piece on urban ecology and its importance to the campus life of Notre Dame students.

Nick Anderson is from Merrill, Wisc., and is currently a sophomore Biological Sciences major at Notre Dame. Last summer he worked in Dr. Jennifer Tank's lab as an undergraduate lab technician and research assistant to Ph.D candidate AJ Resinger. This coming summer Nick will attend the University of Notre Dame Environmental Research Center with the intent of continuing to develop his skills as a researcher. After graduation, he would like to pursue a Ph.D with a concentration in community and population ecology or conservation biology.

Jack McLaren is a sophomore Environmental Science major from Denver, Colo. He has been in love with ecology, especially urban and aquatic ecology, since he was a kid. He first became interested in these topics through fishing and camping in Colorado, especially in and around his Denver neighborhood. Jack hopes to work as a fish and wildlife biologist for a state government or the Federal government and is also interested in environmental policy. He will be heading to UNDERC this summer where he plans to research the region's native fishes. After Notre Dame, he plans to continue his research at the graduate school level.

Synthesis of CdSe Nanosheets

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Abstract

The synthesis and characterization of high quality CdSe nanosheets (NS) are described. A solution-based approach is used to synthesize the NSs by first mixing precursors with an organic fatty acid and a non-coordinating solvent at low temperatures. Subsequent injection of a cadmium acetate and selenium solution into the reaction vessel induces two dimensional (2D) NS growth. This leverages advances in the development of high quality colloidal quantum dots (QDs) with those of producing 1D nanowires (NWs) in order to create large-scale synthetic procedures for 2D NSs. Resulting rectangular CdSe NSs are approximately 30 nm in width, 90 nm in length, and 2 nm thick. Intra-sheet width variations are very small, although sheets exhibit both straight and curved edges along their widths. High resolution transmission electron microscopy (TEM) images reveal that the sheets are crystalline. In addition, quantum confinement effects are observed in the UV-visible absorption spectra of the CdSe NSs. Synthetic approaches used to vary the lateral dimensions of CdSe NSs are reported. This facile synthesis affords more opportunities for further investigations of the optical and electrical properties of 2D nanomaterials. The decoration of CdSe sheets with gold nanoparticles, for use in photochemical hydrogen generation, will be explored in future experiments. Overall, this investigation presents simple synthetic routes to the size control of 2D CdSe NSs which have potential uses in photovoltaics, nanodevices, optoelectronics, functional materials, and solar hydrogen generation.

Introduction

The prefix “nano” describes physical lengths that are on the order of a billionth of a meter (10^{-9} m). Nanoscale materials therefore lie in a physical size regime between bulk materials and single molecules and atoms. Although nanoscience is a relatively new field of research, it is a valuable research area because nanoscience explores why substances differ on the macro and microscopic scale. A bulk material has constant physical properties, while nanoparticles have size-dependent properties. For example, optical absorption and melting point of materials differ depending on the size of the material. One important difference between bulk and nanomaterials is the fact that nanomaterials have an increased surface-to-volume ratio compared to bulk, and this can be a valuable property for photovoltaic devices.

Nanostructure synthesis has been the subject of much research for several years. Namely, the synthesis of two dimensional (2D) semiconductor NSs [also referred to as quantum wells (QWs) or nanoplatelets (NPLs)], follows the advances in one dimensional (1D) semiconductor nanowires and zero

dimensional (0D) quantum dots [also referred to as nanocrystals (NCs)]. For several years researchers have studied QDs in order to better understand their unique size-, shape- and dimensionality-dependent optical and electrical properties. QDs are spherical clusters of molecules with charge carriers that are quantum mechanically confined in all three dimensions, and this gives QDs properties which are different from both bulk materials and individual atoms. Semiconductor NWs are nanostructures with a diameter of up to 100 nm and variable length. Here, charge carriers are quantum mechanically confined in two dimensions and occupy energy levels that are different from bulk energy bands. Quantum confinement effects are especially evident when the diameter of the NW approaches the Bohr radius of the electron-hole pair. 2D NSs are potential wells with discrete energies caused by the planar confinement of the charge carriers. Confinement effects are observed when NS thicknesses are similar to the de Broglie wavelengths of their charge carriers. Electron-hole pairs have no dimensional freedom in QDs, length freedom in NWs, and both length and width freedom in NSs.

This investigation, as does all synthetic work performed in the Kuno research group, uses a solution growth method. Although Molecular Beam Epitaxy (MBE), Vapor-Liquid-Solid (VLS), and Metalorganic Chemical Vapor Deposition (MOCVD) are some of the many methods for producing nanostructure morphologies, solution synthesis is a low cost/low temperature alternative.² Solution synthesis is not limited by substrate size, substrate uniformity or the need for expensive heating ovens, as are the above methods. Solution chemistry also enables the control of surface chemistry during reaction. By using organic ligands as surface coordinating or non-coordinating ligands the growth kinetics and morphologies of materials can be controlled, the resulting materials are protected from oxidation, and the nanostructures can be dispersed in common organic solvents for later characterizations.

The motivation for this study is to better understand nanostructure synthesis and develop strategies to control NS growth morphology. While excellent control has previously been demonstrated with solution syntheses producing QD sizes ranging from 2-6 nm in diameter, and NWs with diameters ranging from 5-40 nm, the controlled growth of nanosheets is not yet so developed. Hopefully, analogous strategies from QD and NW growth can be applied to synthesize high quality nanosheets. Since this is a very common research area, but currently suffers from lack of control over synthetic parameters, this experimental survey will seek to investigate nanosheet growth parameters such as temperature, time, reaction concentrations, and precursor sources in order to synthesize NSs with different shapes and sizes.

Experimental

Synthesis of CdSe nanosheets: The optimized synthesis of CdSe NSs (30 x 90 x 2nm) is described as follows, and the experimental setup is shown in Figure 1. Cadmium chloride (7.2 mg), myristic acid (11.4 mg), and octadecene (2.5 mL) were added to a three neck flask which was charged with a stirbar, connected to a Schlenk line and fitted with a thermocouple. Using a heating mantle and standard Schlenk line procedures, the reaction mixture was heated and degassed at 100°C for one-

hour. The temperature of the reaction mixture was then raised to 170°C under nitrogen; the solution color remained clear. At this temperature a solution of cadmium acetate (53.3 mg) in octadecene (1 mL) was injected and the reaction temperature was raised to 190°C - 200°C for 20 minutes in order to incorporate the injected solution. Finally, selenium powder (4.0 mg) in octadecene (0.5 mL) was injected and the reaction turned yellow. The product in solution was annealed between 170°C and 200°C for 30 minutes, and then the reaction was quenched to 80°C, whereupon tributylphosphine (1 mL) was added to coordinate any unreacted selenium. 10mL of ethanol was then added and the mixture was transferred to a centrifuge tube for centrifugation at 10,000 rpm for 10 minutes using a Sorvall ST 16R centrifuge. Supernatant was discarded and three subsequent washings were performed with 5 mL toluene and 5 mL ethanol. The NSs were suspended in fresh toluene for storage and characterization. Resulting NSs are shown in Figure 2 and Figure 3.

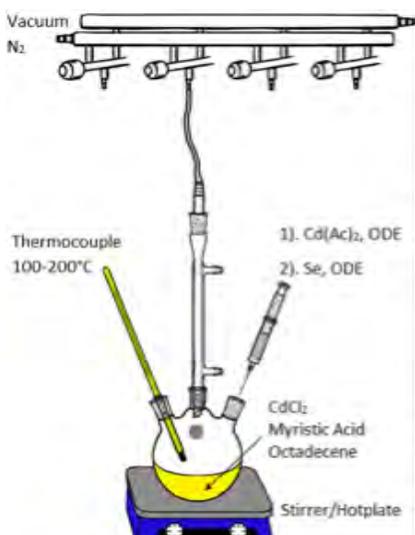


Figure 1. Cartoon schematic of the reaction apparatus used in the synthesis of solution phase semiconductor NSs. Chemicals and reaction conditions necessary for CdSe NSs are shown. Figure adapted from Kuno.²

Synthetic parameters investigated: Several experiments were conducted in order to optimize the synthesis. Briefly, many similar preparations were carried out with the following variations: a non staggered introduction of reactants with all components added initially, an increased Cd:Se molar ratio, annealing times of 1, 1.5, 2, and 3 hours, a 2x and 3x scaling up of all reactants, temperatures of 200, 230 and 240 °C, changing solvent volume, no to moderate degassing steps, changing myristic acid amounts, using octanoic acid rather than myristic acid, changing amounts of cadmium chloride and cadmium acetate or using only a single cadmium source. Preparations completely lacking any one of the reactants displayed inconsistent results, while altering the ratios of reactants produced different sized sheets. These different sized sheets are illustrated in Fig. 4 and Fig. 5. The NSs in Fig. 4 were prepared by including cadmium acetate and selenium in the initial reaction mixture in addition to injecting them at the end of the procedure as well. The NSs in Fig. 5 were synthesized as previously described but with a tellurium-doped final selenium injection.

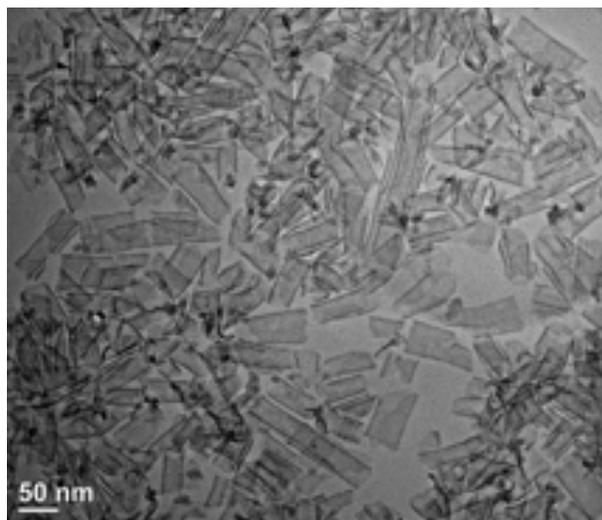


Figure 2. Low resolution TEM micrograph of optimized synthesis of CdSe NSs.

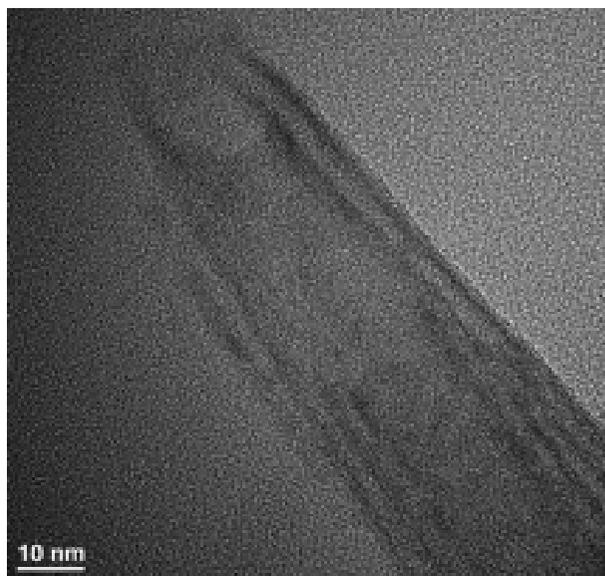


Figure 3. High resolution TEM micrograph image of stacking CdSe NSs with edges beginning to fold, visible by edge contrasts.

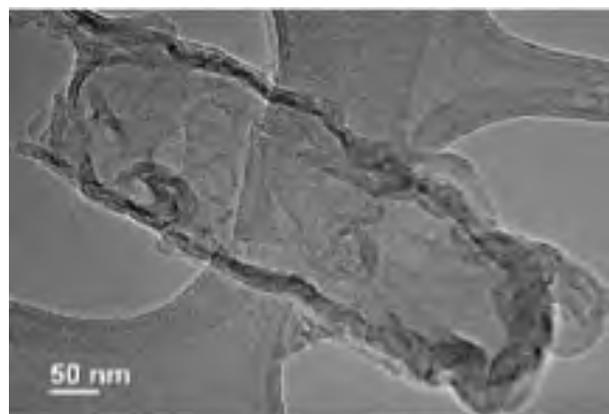


Figure 4. TEM micrograph image of enlarged CdSe NS due to changing reactant ratios.

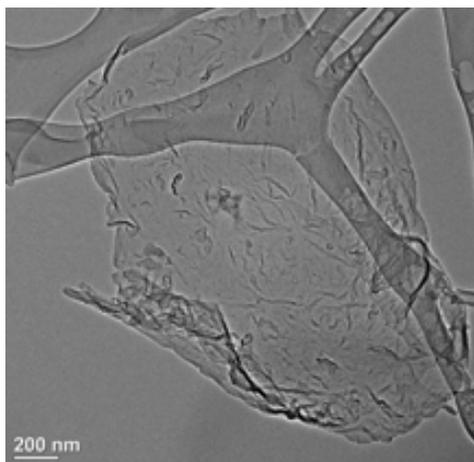


Figure 5. TEM Micrograph image of enlarged CdSe NS with Te doped Se injection.

Results and Discussion

Due to the ambiguity of proposed growth mechanisms in previous reports, this investigation used modified Peng and Dubertret preparations. This study produced very large sized sheets of several hundred nanometers, whereas previous reports outlined syntheses of square and rectangular platelets below 100nm. While the NSs synthesized in this study possessed large lateral dimensions, their thickness was consistent and not tuned. Figure 6 illustrates a UV-visible absorption spectrum of the optimized NSs. While the CdSe NSs are blue shifted from their bulk band gap of 713 nm due to quantum confinement, this synthesis yields exclusively NSs with a thickness of approximately 2 nm. Further investigations are required in order to elucidate the causes for NS stacking and thickening.

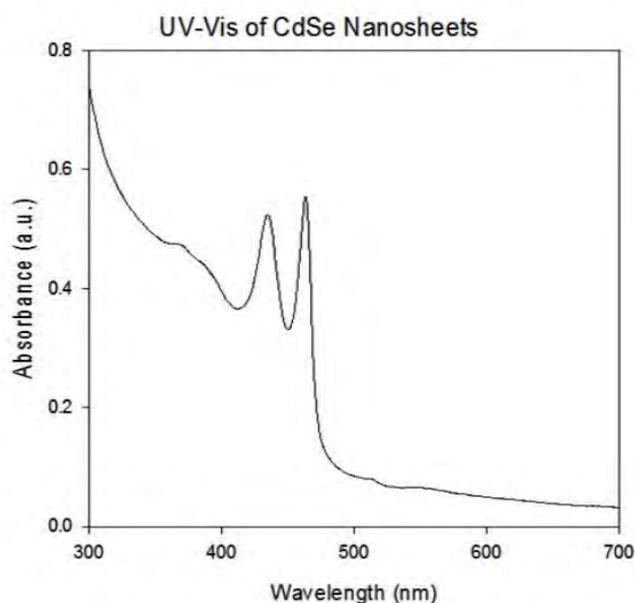


Figure 6. UV-Vis absorption spectrum of 2 nm thick CdSe NSs. Peaks at 465 nm and 436 nm.

The optimized synthesis yields well dispersed single NSs with rectangular shape and straight edges. As visible in the

TEM micrograph of Figure 2 there are many individual sheets rather than clumps. Figure 3 displays the occasional rolling or edge folding of the NSs; this is also seen in Figure 5 for the large sized NS. Figure 4 illustrates an enlarged sheet under the conditions of Cd and Se being added to the reaction vessel initially, and again during secondary injections. This different Cd:Se ratio led to larger NSs. Therefore, while the initial sheets grew using the precursors initially in the reaction mixture, this NS reflects preferential growth at the edges using the secondary injection of additional reactants. While adding more precursors can lead to creation of larger sheets, it must be noted that there seems to be a propensity for the reactants of the secondary injections to add to the NS edges rather than on the surface. Rolling of the edges moves the sheet's edge in space and may make the edge a preferential addition site for incoming reactant molecules. With regards to the ternary NS synthesis in Figure 5, it was found that larger NSs were synthesized due to changing the reactant ratio, but tellurium was not completely incorporated into the sheets, as EDX counts (signals) of Te were lower than in our group's previous CdTe NWs and NSs syntheses. This suggests tellurium was not completely incorporated but may still have had an effect on the formation of the nanosheets.

The thickness of the NSs is calculable using the UV-Vis spectrum and the particle in a box energy model. Due to quantum confinement the electron hole pair may only have certain discrete energies. These energies are measurable using UV-Visible absorption peaks, which can then be used to calculate the length of the box, in this case the thickness of a NS. The discrete energies of the particle within a NS are related to the thickness of the NS and can be isolated by solving for the energy levels of the Schrodinger equation, Equation 1. The energy, E , corresponds to the peak result in a UV-Visible measurement, $n = \{1, 2, 3, 4, \dots\}$, $h =$ Planck's constant, $m =$ mass of the particle (electron e^- or hole h^+), and $L =$ length (thickness of nanosheet).

$$E = \frac{n^2 h^2}{8mL^2} \quad \text{Equation 1}$$

The value E is solved from experimental measurement using the following equations, Equation 2 and Equation 3.

$$E = \frac{hc}{\lambda} \quad \text{Equation 2}$$

$$E = E_{hole} + E_{electron} + E_{bulk} \quad \text{Equation 3}$$

First, input Equation 2 as the left side of Equation 3, using $\lambda = 465$ nm from Figure 6. Next, input the E_{bulk} value of 713 nm for CdSe and subtract this from the total E , the left side. This leaves a total energy of 0.92 eV (1.48×10^{-19} J) comprised of the $E_{hole} + E_{electron}$ and can be solved using Equation 1. Manipulating Equation 1 for a hole, using an effective mass of $0.45m_e$ and manipulating Equation 1 for an electron, using an effective mass of $0.13m_e$, it is possible to arrive at an equation that is complete except for L . Previous results dictated the choice of CdSe electron, light hole, and heavy hole effective masses. Finally, inputting E_{hole} and $E_{electron}$ and arriving at L_2 it is possible to solve for $L = 2.00 \times 10^{-9}$ m or 2 nm.

This investigation surveyed many synthetic parameters, and these parameters are discussed below. Our synthesis proceeded with degassing and purging steps, and we have found that when

these are omitted, the resulting structures are low quality. Next, it was important to calculate the molar ratios of added Cd, Se, and myristic acid as it was found that reactions including more than 4:1 Cd:Se did not produce high quality NSs and also that preparations with too much, or too little myristic acid produced QDs. Scaling up reactions must be done with caution but can be a very valuable step. One must ensure that this is done methodically within proper temperature ranges, or else competing side reactions of QDs and NWs will dominate. Overall, positive results were found when properly scaling up reactant amounts, as this provided more precursors able to react in solution. Another factor which influences side reactions and poor NS growth is the temperature range. Higher temperatures such as 230 and 240 °C are believed to influence QD growth or destroy already formed NSs. Additionally, high temperatures are believed to deform NSs, as color changes from typical yellow colors to orange and dark brown were noticed with elevated temperatures. Subsequent analyses showed suppressed and shifted peaks in the absorption spectra, indicative of QD formation, and this was confirmed in TEM showing QDs and pieces of broken NSs. Trials using octanoic acid, rather than myristic acid, or using only a single cadmium source, produced QDs rather than NSs. Further investigation is required to determine the types of organic acids that can be used to influence NS growth.

Lastly, annealing time was an important factor in NS growth. For example, a previous report of nanobelt synthesis proceeded over 24 hours while some QD and NW syntheses occur in 30 seconds to 5 minutes. 30 minutes was determined to be an optimal time scale for NS growth in our study as annealing times of 1, 1.5, 2, and 3 hours lead to a depletion of precursor particles, which causes NSs to grow together in a curved fashion or clump together as unusable agglomerations. If the reactions were annealed for too long, already formed NSs began to grow together in an unorganized fashion and single NSs were no longer dispersed.

Conclusions

NSs were synthesized using an optimized procedure which investigated many different growth parameters and techniques. While a detailed mechanism of growth remains elusive, this study has shown that there are many factors which can influence sheet consistency, shape, and size. This study was most focused on producing NSs consistently in order that their characterization, optical properties, and electrical properties may be better understood through future research in our group. Additionally, this synthesis is reproducible and can accelerate NS overcoating and decorating investigations.

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About the Author

Rick Morasse is a member of the Notre Dame Class of 2012 from Port Colborne, Ontario, Canada. On campus, the Alumni Hall Dawghouse is his home. He is a Chemistry major and Theology minor. He has been an undergraduate researcher in the Kuno lab since 2010, including two summers. Rick has enjoyed working on projects focusing on the synthesis of straight and branched nanowires, and most recently nanosheets. Following graduation, he plans to attend graduate school to pursue a Ph.D. in Chemistry.

Analysis of $q \bar{q} \rightarrow W^{\pm} \gamma \gamma$ Event Production at the Tevatron

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University of Notre Dame, Department of Physics

Abstract

Radiative W boson production at hadron colliders is an important testing ground for the Standard Model of particle physics, which describes the interactions of the fundamental particles that make up the Universe. The DØ detector at Fermilab in Batavia, IL has collected and processed data regarding these kinds of processes from Run II of the Tevatron accelerator, which began in March 2001 and ended in September 2011. A crucial part of this analysis is to determine the rate of $q \bar{q} \rightarrow W^{\pm} \gamma \gamma$ event production at the Tevatron since this experimental data is a good way to check the accuracy of the Standard Model. This is a process where quark-anti-quark ($q \bar{q}$) annihilation produces a W boson (W^{\pm}) and two photons ($\gamma \gamma$). A measurement of the production rate for this process could reveal if the Standard Model requires revision or perhaps, in the extreme case, an entirely new theory relating our understanding of matter. The substance of this analysis involves measuring the transverse momenta (P_T) and energy (E_T) distributions of the particles produced in these events. However, these distributions can be skewed by background events that may presumably appear similar to the events that we are trying to measure and analyze. Thus, cuts must be applied to the data set in order to eliminate the undesired noise that could mask the signal. The $q \bar{q} \rightarrow W^{\pm} \gamma \gamma$ has not yet been observed, but theoretical estimates put it in reach at the Tevatron, given its large data set.²

Introduction

To date, the Standard Model is the most widely accepted theory relating three of the four fundamental interactions governing the dynamics of subatomic particles. The Standard Model includes three generations of matter known as fermions

with half-integral spin ($\frac{1}{2} \hbar, \frac{3}{2} \hbar, \dots$) which by definition, obey Fermi-Dirac statistics. Quarks and leptons are fundamental particle constituents that are classified as fermions. Quarks exist in six flavours known as up (u), down (d), charm (c), strange (s), top (t), and bottom (b), and carry fractional charges of $+2/3 |e|$ and $(-)/1/3 |e|$. There are also six leptons: the electron (e), muon (μ), and tau (τ), and their three corresponding neutral sister particles called neutrinos. The particles that mediate the interactions between the above-mentioned fermions and hadrons such as protons – which are made up of two up quarks and a down quark (total charge: $+e$) – are known as gauge bosons, which act as force carriers. For this analysis, we are primarily concerned with the W boson whose mass is on the order of 80 times the proton mass. The W boson can be positively or negatively charged and gives rise to interactions of very short

range precisely because it is so massive. The weak interaction between all quarks and leptons is mediated by the W boson. The weak interaction is responsible for the radioactive decay of subatomic particles and initiates the process of fusion in stars, wherein two or more atomic nuclei join together, or “fuse” to form a single heavier nucleus.

The Tevatron collided beams of protons and antiprotons at a center of mass energy of 1.96 TeV, with each beam attaining an energy of roughly 980 GeV prior to collision. At these high energies and hence momenta, the resolution of the spatial particle ‘probe’ is high (as governed by the Uncertainty Principle) and allows us to break subatomic particles all the way down to their elemental constituents. When a proton and antiproton beam collide, a multitude of events could occur, but we are primarily concerned with the interaction of the quarks and anti-quarks that compose the protons and antiprotons themselves. In the process we are trying to study, when an up quark and a down anti-quark ($u + \bar{d}$) or a down quark and an up anti-quark ($d + \bar{u}$) collide, a real W boson and two photons are radiated in the process. The W boson does not have a long lifetime, and thus decays into less massive real particles. There also exist virtual particles, which are subatomic particles that form out of “nothing” (vacuum fields conceptually analogous to lines of force between magnetic poles) for extremely short periods of time and then disappear again. Such particles permeate space, mediate particle decay, and mediate the exchange of the fundamental forces (electromagnetic, weak, strong, gravitational forces). Virtual particles are real and have measurable effects, but the same uncertainty principle that allows them to come into existence dictates that they cannot be directly observed. Here we study real W decays to leptons such as electrons or muons. Essentially, the signature of the final state of this process should look like two real photons (produced at the vertex of the interaction) and a full leptonic decay of the W boson.¹ A Feynman diagram of the process is included below in Figure 1.

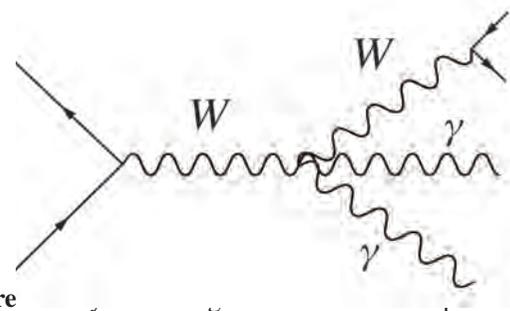


Figure adapted from Bozzi *et al.*²

Figure

The Detector

The DØ detector at the Tevatron has a central-tracking system consisting of a silicon microstrip tracker (SMT), and a central fiber tracker (CFT), both located within a 2T superconducting solenoidal magnet, with designs optimized for tracking and determining collision vertices. Central and forward preshower detectors are positioned just outside of the superconducting coil. A liquid-argon and uranium calorimeter has a central section (CC) covering pseudorapidities (a spatial orientation variable) $|\eta|$ up to ≈ 1.1 , and two end calorimeters (EC) that extend

coverage to $|\eta| \approx 4.2$, with all three housed in separate cryostats. An outer muon system, at $|\eta| < 2$, consists of a layer of tracking detectors and scintillation trigger counters in front of 1.8 T toroids, followed by two similar layers after the toroids. Luminosity is measured using plastic scintillator arrays placed in front of the EC cryostats. The trigger and data acquisition systems are designed to accommodate the high luminosities (a quantification of the intensities of the beams directly related to the number of events produced by the accelerator) of Run II. A side-view diagram with dimensions and the pseudorapidity is included below.

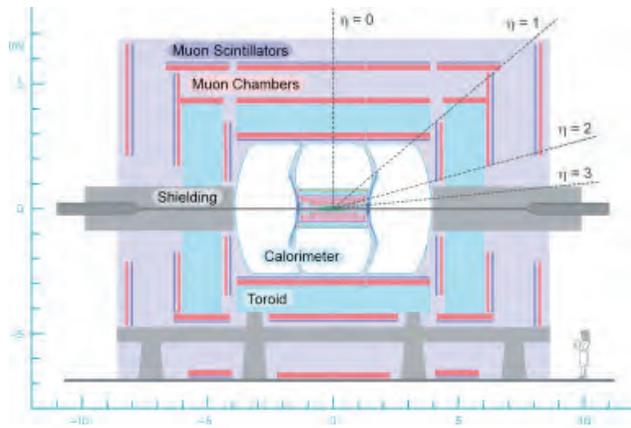


Figure 2. Side-view graphic of DØ detector with scaled dimensions.⁴

Reconstruction

Using energy and spatial orientations, we can reconstruct the events and processes that occur post-collision. The trouble with analyzing such a process and determining whether what one is seeing in the data is truly the event signature is the possibility of ‘imitators’. In essence, there exist quantum electrodynamical processes that may look like a $q \bar{q} \rightarrow W \pm \gamma \gamma$ process and could skew the measurements on these events. Thus, particle physicists must estimate the properties that such imitator events might contain which the $q \bar{q} \rightarrow W \pm \gamma \gamma$ events would not retain, and consequently devise methods to remove these background events as the data is processed. Certain cuts are applied to P_T , E_T , and spatial variables according to accepted identification criteria for the end state leptons and photons in order to narrow down the results. Unfortunately, this method cannot eliminate all the background events from the selection so an estimate of the ratio of background events to that of real $q \bar{q} \rightarrow W \pm \gamma \gamma$ events is necessary.

The main background that is believed to exist for the process we are considering is due to QCD (Quantum Chromo Dynamics) effects. When quark-antiquark pairs are produced, they materialize as ‘jets’ in the detector. A jet is a narrow cone or spray of hadrons and other particles produced by the hadronization of a quark or gluon. The occurrence of jets can be explained by a property of QCD known as confinement. Confinement postulates that as the separation distance between quarks increases, the force between them does not diminish. Consequently, it would take an infinite amount of energy to separate them. That is why they are forever bound inside protons and other hadrons.

The energy of the initial quark materializes as additional hadronic particles traveling in roughly the same direction as the primary quark. This hadronization process can fluctuate to the case where much of the energy is carried by a single neutral pion, which decays into two nearly-colinear photons. Because of this, it is entirely possible for a jet to be mistaken as a photon and since jets are copiously produced, this can be a large background for $q \bar{q} \rightarrow W \pm \gamma \gamma$ processes. The background event signature would look like a leptonic decay of the W radiating a muon, missing E_T , a photon, and a jet ($q \bar{q} \rightarrow W \pm \gamma \gamma$).

Event Selection

To carry out this analysis project, two data analysis programs known as CAFE and ROOT were used extensively. These are both based on the programming languages C/C++. The researcher had a large dataset of the DØ experiment available, and the researcher was able to use collision data and various simulated data sets to achieve a more complete understanding of the above mentioned background to the $W \gamma \gamma$ process. The final state of this event looks like a muon (from the leptonic decay of the W), two photons, and missing transverse energy (sign of a muon neutrino). The muon is required to be isolated in the tracker and calorimeter and to be associated with a central track with P_T greater than 20 GeV/c. The event is required to have missing E_T greater than 20 GeV and no additional tracks with $P_T > 15$ GeV/c or additional medium quality muons. The photons are required to be in the central or forward calorimeters ($|\eta| < 1.1$ or $1.5 < |\eta| < 2.5$) with $E_T > 7$ GeV. Each photon must be isolated in the calorimeter and tracker, have a shower shape consistent with an electromagnetic object, and have an associated pre-shower cluster. The electron signature closely resembles that of a photon in that its identification criteria are all the same, save for the pre-shower cluster. Instead, electrons are differentiated from photons by their associated central track. Similarly the key to identifying a jet versus a photon, is the significant fraction of calorimeter energy deposited in the electromagnetic layers. The photon and lepton are required to be separated in $\eta - \Phi$ space a distance of ΔR where:

$$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} > 0.7$$

and Φ is the azimuthal angle.³ This minimum cut on the spatial separation is required in order to distinguish the photon from the lepton and to guarantee that the particles are indeed separate entities, thereby reducing the final state radiated photons.

Techniques used to measure the rate for the faking of a photon (γ) were the primary focus, and they subsequently showed an event with a lepton, a photon, and a jet. Physicists Xuebing Bu et al. at Fermilab used a technique called ‘Reversing photon quality cuts’ in their analysis of $p \bar{p} \rightarrow W \pm \gamma$ processes.² True photons (goodEMs) are selected using the photon ID criteria defined above, and fake photons (badEMs) are selected by reversing photon track isolation variables or shower shape cuts. The ratio of goodEMs/badEMs is determined as a function of P_T and spatial orientation ($|\eta|$) in the detector by measuring and comparing the two samples. The ratio was then used as a weight for each $W \pm \gamma + \text{jet}$ event to determine an appropriate estimate for the background events.

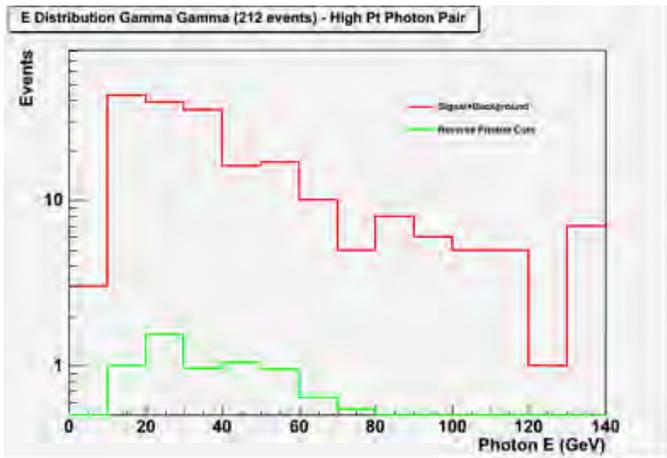


Figure 3. Number of di-photon events vs. E_T (photon with higher P_T is plotted)

Results

Initially, we 106 events were discovered in which the final state has a muon (from the leptonic decay of the W), two photons, and missing transverse energy (sign of a muon neutrino). These events are inclusive of background events. Luminosity determination techniques were employed to obtain an approximate integrated luminosity of 3.043 fb^{-1} for the datasets used. In the paper by G. Bozzi et al. on $W \pm \gamma\gamma$ production,¹ the Next to Leading Order cross section for this process at the Tevatron is on the order of 7.558 fb . Thus multiplying integrated luminosity with the cross-section provides a probability of roughly 22 events. Results indicate that there are far more such events than predicted. Therefore, there must be other background to account for the extra events observed, or the events are new physics! A plot of the transverse energy distribution of the photon with the higher transverse momentum of the photon pair is shown above in Figure 2 along with the cut from applying the background determination technique called “Reversing photon quality cuts” mentioned above.

Discussion

For the future, investigations into other possible sources of background will be necessary. One possible background could be due to the radiation of a W and Z immediately after the collision, where the Z boson decays into two electrons that are misidentified as photons. The cross section of this event, however, is very small. Another likely candidate for a background event is that a photon is radiated off one of the quarks pre-collision, but again the likeliness of such a process is also small. This begs the question, could there be other new physics that we are seeing?

The study of $W \pm \gamma\gamma$ production is relevant for the study of anomalous gauge interactions, which are interactions wherein the weak vector gauge bosons couple to themselves such that the $W \pm \gamma\gamma$ process is sensitive to the $WW\gamma$ and $WW\gamma\gamma$ vertices. This study also has a variety of applications beyond the Standard Model. For instance, a final state including two photons and missing transverse energy is seen in supersymmetry (SUSY) models with gauge-mediated breaking. More specifically, a hypothetical particle predicted by SUSY, the neutralino, is often the next-to-lightest supersymmetric particle. The

neutralino decays into a photon plus a gravitino, giving a signal of two photons and missing E_T . A further possible application is an estimate of backgrounds when searching for WH production, followed by Higgs decay to two photons.²

Acknowledgments

I wish to thank Professor Michael Hildreth for his guidance in this data analysis project. He has provided me an incredible opportunity to advance my knowledge of physics and develop my analysis skills through his sound counsel. I would also like to express my gratitude to the College of Science for providing a Summer Undergraduate Research Fellowship that enabled me to perform research during the summer of 2011.

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About the Author

Stanislava Sevova is a junior majoring in physics with a concentration in Advanced Physics. Although a native of Bulgaria, Stanislava has lived in Canada since age five and calls Mount Albert, Ontario, home. Her interest in particle physics was first picqued by an article she read describing the potential discovery power of the LHC in her junior year of high school. Stanislava became involved with physics research during the second semester of her sophomore year under the guidance of Prof. Michael Hildreth in the High Energy Physics department. She obtained a College of Science Summer Undergraduate Research Fellowship and continued to work for Prof. Hildreth during the summer of 2011, developing the analysis project described in this paper. Alongside her advisor, Stanislava has presented the research findings outlined above to the Electroweak Physics group at Fermilab. In the summer of 2012, Stanislava will be traveling to the University of Alberta in Edmonton, Canada, to work with the particle physics group there on blackhole detection using data from the LHC at CERN. After she graduates from Notre Dame, Stanislava plans to attend graduate school to pursue a Ph.D. in physics.

The Effect of a Sudden Southward Turning of the Interplanetary Magnetic Field (IMF) on the Ring Current after a Prolonged Dawn-Dusk IMF

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Abstract

Reconnection of the Earth's magnetic field lobes on the night side of the Earth results in the injection of plasma particles into the Earth's inner magnetosphere. These injections help form geomagnetic storms and substorms, with the composition of the latter being an important factor. The composition of these injections is determined by the composition of the solar wind and ionospheric outflow. Among other things, the orientation of the interplanetary magnetic field (IMF) affects the ionospheric outflow. For reconnection to occur on the night side, the IMF and magnetosphere must first merge on the dayside of the Earth. The frequency of this event is greatest when the IMF is southward. This work analyzes the effects of a sudden southward turning in the IMF after a prolonged dawn-dusk IMF on the magnitude of geomagnetic disturbances. OMNI data acquired from the CDAweb database is used to select events with the correct IMF orientations. No correlation between the orientation of the IMF prior to a southward turning, and the magnitude of geomagnetic disturbances was found.

Introduction to Magnetic Reconnection and Formation of Geomagnetic Storms

Solar wind is a supersonic plasma flow emitted by the Sun, comprised of electrons and ions. This solar wind has an embedded field of about 5 nT, averages a speed of 400 km s⁻¹ upon passing Earth, and has a density of about 5 electrons and ions per cubic centimeter.² The embedded magnetic field is called the interplanetary magnetic field (IMF) and spirals outward from the Sun, similar to the path of water being emitted from a sprinkler (Figure 1). Where the IMF meets the Earth's magnetosphere, the orientation of the IMF determines the amount and location of magnetic reconnection. Earth's magnetic field comes out of the south pole and enters the north pole. Therefore, the more the IMF points southward, the greater the amount of magnetic reconnection that occurs on the dayside, due to their antiparallel orientation.

In order to be more precise in describing the magnetic field orientations and their effects, the Geocentric Solar Magnetospheric (GSM) coordinate system is used in this work and the

origin of the system is within the Earth.³ The x-axis is defined as pointing from the Earth to the Sun. The y-axis is defined as perpendicular to the Earth's magnetic dipole such that the X-Z plane contains the Earth's magnetic dipole, making dusk the positive side of the axis. The z-axis is defined such that the X-Z plane always contains the Earth's magnetic dipole and as being positive towards the North Pole. Using GSM coordinates, the Earth's magnetic field is mainly in the positive Z direction and a southward IMF would be defined as having a negative Z component (negative IMF B_z).⁴

The IMF clock angle refers to the angle between the north magnetic pole of Earth, and transverse component of the IMF calculated using Equation 1. It can be calculated by using Equation 2. While dayside reconnection can occur for most IMF clock angles, the closer the IMF clock angle is to 180 degrees (southward IMF), the more antiparallel the IMF is to the Earth's magnetic field and the more dayside magnetic reconnection occurs. The more dayside magnetic reconnection occurs, the more probable the occurrence of a geomagnetic storm is.

$$B_T = \sqrt{B_y^2 + B_z^2} \quad \text{Equation 1}$$

$$\theta = \text{atan} \left(\frac{|B_y|}{B_z} \right) \quad \text{Equation 2}$$

Geomagnetic storms are comprised of three phases: sudden storm commencement, main phase, and recovery phase. The first occurs when the Earth's magnetic field is compressed due to increased pressure in the solar wind. Magnetic field compression is seen by ground magnetometers as a dramatic increase in the horizontal component of the Earth's magnetic field. After the sudden storm commencement, the horizontal component of the Earth's magnetic field decreases dramatically, an indication of the formation of a ring current in the inner magnetosphere. This is called the main phase. Both dayside and night side reconnection must occur to form the ring current during the main phase of the storm. The recovery phase is the final stage of a

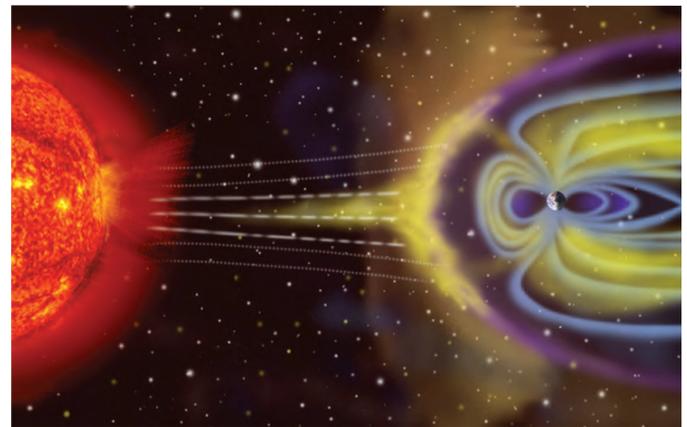


Figure 1. Artistic representation of the solar wind interacting with the Earth's magnetosphere.⁷

geomagnetic storm. Typically, there is minimal to no reconnection occurring during the recovery phase. During this phase the ring current returns to its quiet state, losing energy and particles through charge exchange.

Reconnection is not limited to storm times. Indeed, some form of reconnection is occurring most of the time; however, not all reconnection leads to particle injection into the inner magnetosphere. The reconnection cycle begins with the merging of the IMF and magnetic field of Earth, forming open field lines. The now open field lines allow charged particles to flow from the solar wind into the magnetosphere and from the ionosphere out into the solar wind. An extended magnetotail is created when the ends of the magnetic field lines in the solar wind drag the open field lines towards the night side of the Earth (Figure 2). The open field lines attached to the north (south) pole of the Earth are called the northern (southern) lobe. The two lobes have opposite polarities. Thus, as they are stretched out and compressed by the field lines coming after them, a thin sheet called a neutral sheet is formed. When the pressure increases to a certain extent, night side reconnection occurs, causing the release of energy to snap the now closed field line earthward, carrying the plasma with it. This forces plasma particles into the inner magnetosphere, forming a ring current. The latter is a torus of energetic charged particles, located 2-9 earth radii above the equator. Due to the shape of the magnetic field, the ions drift westward and the electrons drift eastward, forming a current that decreases the strength of the magnetic field earthward of its flow.¹ Ground-based magnetometers record magnetic disturbances and compile indices at high latitudes (auroral upper (AU) and lower (AL)), and mid-latitudes (sym-H).

When the IMF clock angle is close to 90 degrees (dawn-dusk IMF), dayside reconnection occurs and the open field lines are dragged nightward, allowing for ionospheric outflow to occur. This outflow adds oxygen ions to the composition of charged particles trapped on the field lines. Opposite from southward IMF, dawn-dusk IMF does not quickly reconnect on the night side of Earth. Thus, this work concentrates on determining whether the loading of oxygen ions during prolonged periods of dawn-dusk IMF preconditions the system, causing larger magnitude geomagnetic storms or substorms.

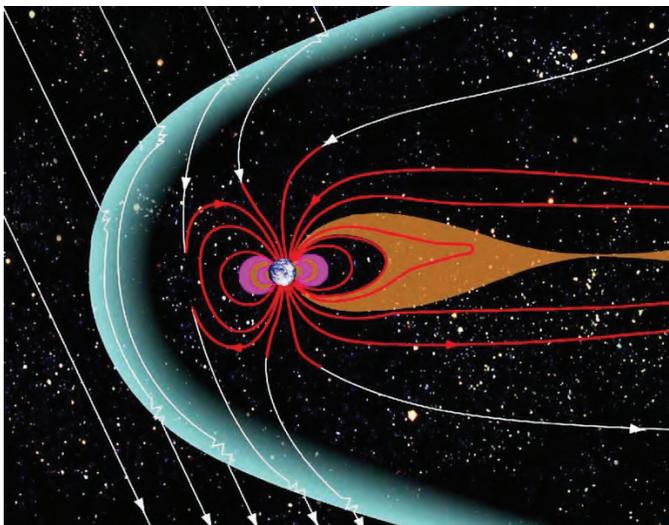


Figure 2. Diagram of Earth's magnetosphere.⁸

Motivation for Project

Magnetic disturbances may affect numerous components of the Earth, including electrical properties of the atmosphere,

temperature of the thermosphere, the surface temperature, meteorological conditions in the ionosphere, and abundance of ozone in the stratosphere. Changes in these variables can directly affect life on Earth. Disturbances in the Earth's magnetic field may damage costly satellites in the Earth's orbit, power lines on Earth, astronaut safety, radio communication, and environmental conditions. Figure 3 is a diagram of the Heliophysics System Observatory around the Earth, emphasizing the costly damage that may be caused by magnetic disturbances. Thus, necessary precautions must be taken through a better understanding of the workings of magnetic reconnection. This project looks for a relation between a southward turning of the interplanetary magnetic field after a prolonged dawn-dusk IMF, and the magnitude of the resulting magnetic disturbances.

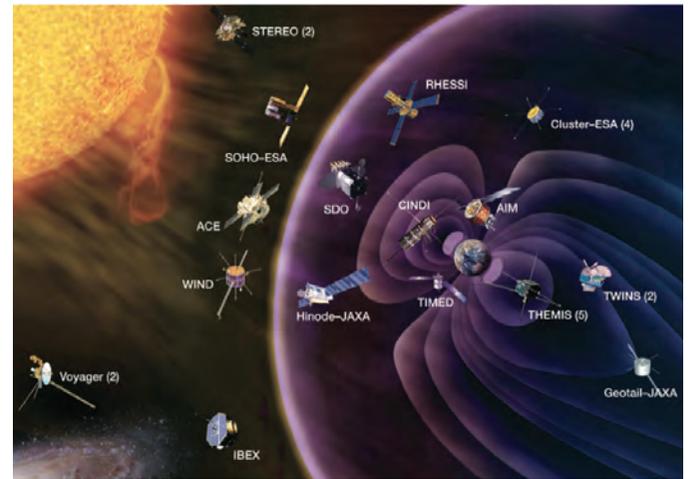


Figure 3. Heliophysics System Observatory.⁸

Methodology

OMNI satellite data from the CDAweb database from 1995 to 2009 was used to identify southward turnings.⁵ An AWK program was written to select events with absolute values of clock angles greater than 157.5 degrees, using Equation 2. A list of dates and times of the events was created and compared to another list containing the IMF B_z component and clock angles for each minute of the year. Events whose components one hour prior to the turning fit the parameters: $67.5 < |\theta| < 112.5$ or $|\theta| < 22.5$, were then graphed using the database. These restrictions identify a prolonged dawn-dusk IMF.

IMF B_y , IMF B_z , solar wind density, solar wind flow speed, AU, AL, sym-H, and θ were included in the graphs for each event. The IMF B_z and B_y components were then analyzed, placing more importance on the IMF B_z . An ideal case shows a decrease of more than 5 nT in B_z to the negative region and B_y returning to zero. From the events that fit the specified parameters, those with clock angles around ninety degrees prior to the southward turning, and those with angles closer to zero degrees were categorized. The zero degree cases acted as a control group, while the ninety degree cases provided the conditions to be examined. Two ideal ninety cases and two ideal zero cases were then chosen and submitted to the Community Coordinated Modeling Center at Goddard Space Flight Center using the BATS-R-US model in order to acquire a better view of the particle build up in the night side of the Earth before the magnetic storm.⁶

An IDL program was written to create graphs of each of the ninety and zero cases (Figure 4A-B). Afterwards, graphs with a significant response in the AL index were collected and used to create superposed epochs of the ninety cases and the zero cases by using their averages (Figure 5A-B). The positive and negative components of the ninety cases were then divided in order to avoid an average of zero. If prolonged dawn-dusk IMF allows a build-up of oxygen ions and preconditioning of the system, a larger response in the AL index is expected for the ninety degree cases than in the zero degree cases. A comparison of the responses in the AL index for each epoch was used to confirm or deny this. A zero and ninety case similar in magnetic field difference and proton density are chosen for further analysis, allowing a confirmation of the overall results.

Results

The four ideal cases chosen were the following:

- 1.08/02/2001 09:55-Zero Case
- 2.07/14/2008 13:55-Zero Case
- 3.09/04/2002 01:45-Ninety Case
- 4.01/26/2009 11:20-Ninety Case

The runs submitted to the CCMC revealed a significant increase in pressure due to the build up of charged particles around the night side of the Earth, indicating the beginnings of

a geomagnetic storm for all four cases. The superposed epochs for the ninety cases and zero cases showed no significant difference in the AL index. This result was also noted in the comparison between the ideal ninety case (01/26/2009 11:20) and zero case (04/16/2000 11:10). Based on the epochs, the average AL values for both types were around -250 nT, evidence of an initial substorm.

Figure 6 shows the build-up of inner magnetospheric pressure on the night side of the Earth for one of the ideal cases. Figure 6A shows the pressure during the prolonged dawn-dusk IMF period. Figures 6B-6D are after the southward turning, and clearly show that the inner magnetospheric pressure is building and reorganizing after the southward turning. These images fit with previously known patterns.

Conclusion

This project used filtered OMNI satellite data, selecting data that fit within the clock angle parameters, and separated them into two categories (0 and 90 degrees). Graphs of the IMF B_y , IMF B_z , solar wind density, solar wind flow speed, AU (auroral upper) index, AL (auroral lower) index, sym-H index, and θ were used to determine the effects of the two types of orientation. By analyzing the superposed epoch for the ninety cases and the zero cases, it can be determined that there is a lack of significant difference between the respective AL index values. Though there are slight variations between the two plots, they are not significant, as both cases have values that end in the -250 nT range. Thus, it can be deduced that a prolonged dawn-dusk IMF has no effect on the ring current. If there was an effect, the ninety cases, signifying the prolonged dawn-dusk IMF, would have presented larger AL index values than those of the zero cases.

Acknowledgments

I would like to thank my advisor, Elizabeth Mitchell, from NASA Goddard Space Flight Center, Heliophysics Division for aiding me through the editing process of this paper as well as being an excellent mentor. My research was conducted during my internship at NASA Goddard Space Flight Center over the summer of 2011.

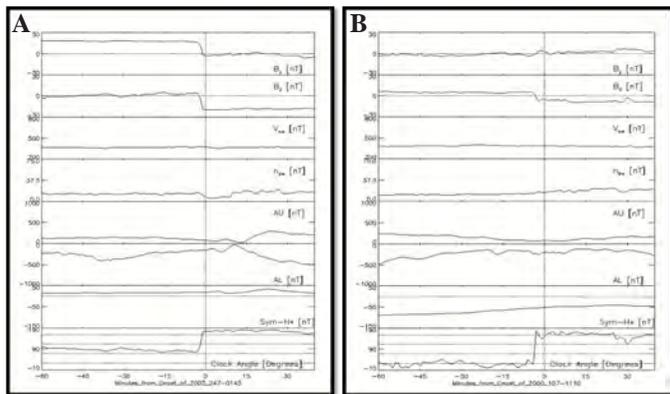


Figure 4A-B. Graphs of ideal ninety case (A- 09/04/2002 01:45) and ideal zero case (B- 04/16/2000 11:10)

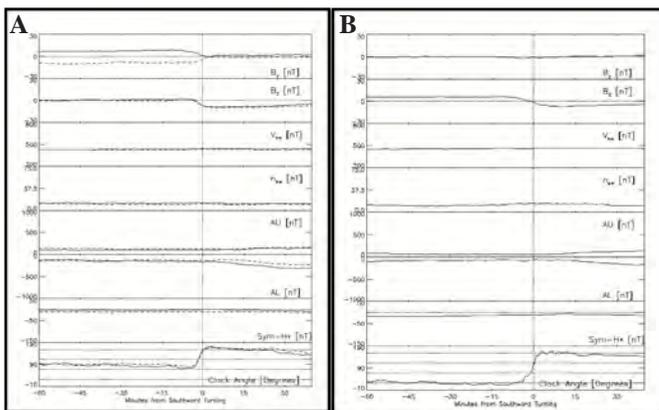
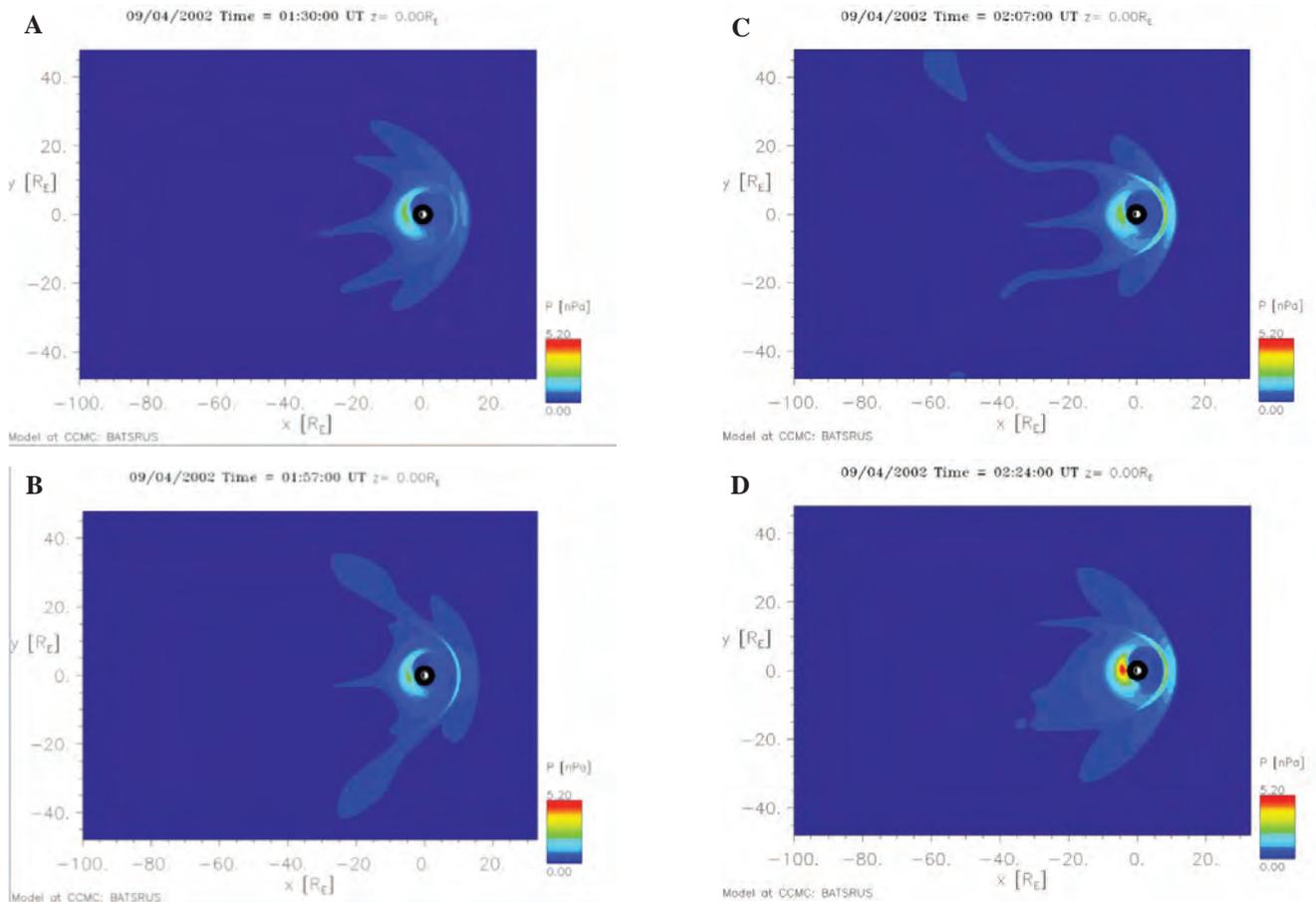


Figure 5A-B. Superposed epoch for ninety cases (A) and for zero cases (B).



Figures 6A-D. Four timesteps from the BATS-R-US model simulation for 09/04/2002 01:45. XY axis view of magnetosphere. Credit: Community Coordinated Modeling Center at Goddard Space Flight Center

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8. Photo credit: NASA/ Goddard/ Aaron Kaase

About the Author

Katrina Magno is a freshman physics major from Marlborough, Mass. During her sophomore year of high school Katrina became considerably interested in physics and began to look for research opportunities that would broaden her knowledge and experience. Thus, she applied for the NASA INSPIRE Program, an online community that enabled students to learn from NASA scientists and engineers. Fortunately, from this she was selected for an internship this past summer at NASA Goddard Space Flight Center. She conducted research in the Heliophysics Division under the excellent mentorship of Elizabeth J. Mitchell. With experiences such as walking down a single hallway and hearing five different languages at once, being inspired by the innovative minds of NASA scientists and engineers, and being exposed to state-of-the-art technology and the history of the human endeavor to better understand the universe, Katrina could not have had a more defining summer. This experience confirmed her passion for physics and broadened her understanding of the science and the world. Katrina has decided to pursue a concentration in astrophysics and is currently conducting research with Peter Garnavich of the Physics Department. In the future, she hopes to take part in more research experiences, including further NASA internships.

Atmospheric Corrections and Periodic Variations at Project GRAND

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Abstract

GRAND consists of 64 proportional wire chamber detector stations located near the University of Notre Dame and has been used to detect muons since 1995. First, single track muon data of GRAND are corrected for atmospheric effects using NOAA weather data to better understand the effects of pressure and temperature (mean muon creation height) on flux. This analysis yields a pressure correction coefficient (β_p) of -0.83 and for temperature, a creation height correction coefficient (β_h) of -0.71. Second, with these corrections a long term time series from July 2007 to January 2008 was analyzed to investigate the time dependence of the daily mean variation in cosmic ray flux over the course of a season. For this data set, signal processing techniques were used to identify the evolution of periodic trends, particularly at one and two cycles per day, indicating significant variations.

Introduction

Cosmic rays, energetic particles moving nearly isotropically through space at close to the speed of light, constantly collide with the earth's atmosphere. During the interaction of the highly energetic cosmic ray primary with air molecules, secondary particles are produced, which are mostly pions, very short lived mesons. Because of their short lifetime, the pions quickly decay into observable muons and unobservable neutrinos. These muons, second generation leptons with characteristics similar to electrons except with a much larger mass and a rest lifetime of 2.2 μ s, in turn interact with the atmosphere and ground, lose energy, and eventually decay.

Many physical processes both in the atmosphere and in space produce periodic phenomena in surface muon flux which can be detected through muon telescopes like Project GRAND at the University of Notre Dame. These periodic variations can be used to infer how cosmic rays and their secondary particles travel through the solar system and the Earth's atmosphere. One of the most notable of these periodic variations is attributed to Earth's relative motion in the Interplanetary Magnetic Field (IMF)³ which produces known short term variations at one and two cycles per day⁴ and longer period cycles corresponding to solar rotation and sun spot cycle.⁵ This analysis is largely concerned with detecting and observing variations in the one and two cycle per day Daily Mean Variation (DMV) through the use of signal processing techniques, particularly the short-time Fourier transform. In order to study this variation in long time series, the variations are first corrected for atmospheric effects like temperature and pressure.

Atmospheric pressure measured at the detector is inversely correlated with muon flux, as an increase in pressure or air mass means that the muons lose more energy as they interact with the denser air preventing the lower energy muons from reaching the detector. This phenomena can be corrected for via $N=N_0 \exp[\beta_p(P-P_0)/P_0]$ where N is the corrected rate, N_0 is the measured muon rate, β_p is the barometric pressure coefficient, P is the measured air pressure at that time, and P_0 is the mean pressure. This relationship can be approximated by a linear equation since $\beta_p(P-P_0)/P_0$ is sufficiently small.

The temperature is likewise inversely proportional to low energy muon flux since as the average temperature of the atmosphere increases, the atmosphere expands causing the cosmic ray primary to interact at a higher altitude. This forces the muon to travel a longer distance before reaching the detector resulting in a higher probability of it decaying in that time. To easily consider the effect of temperature on atmospheric expansion and to allow for easy temperature correction in the future, instead of looking directly at the temperature of different air layers and calculating an effective temperature, the mean altitude of pion creation for an atmospheric profile was found. This value is derived based upon the interaction cross-section of a typical primary decaying with the air. This is closely linked to the mean height of muon creation since pions have a very short lifetime, meaning that the distance a pion travels before decaying to a muon is small compared to the sample separation used in the atmospheric data.

Picture 7.png For this analysis low energy single track muon flux data from the top four performing detectors were collected in ten minute time periods, thus conservatively eliminating stations with non uniform response during this time period. For the atmospheric corrections, data from 2005 to 2012 were used while the periodic variations were primarily focused on a 171-day time series from 2007 corresponding to the longest continuous collection period.

Background

Project GRAND is an array of 64 detector stations located north of the University of Notre Dame at 41.7° N and 86.2° W at an altitude of 220 m above sea level. Two experiments are run simultaneously at the array: the tracking of low energy single muon events and the detection of high energy air showers. The single track muon experiment is increasingly sensitive to primary energies >10 GeV with a median value of 50 GeV for vertical tracks. Each station contains four pairs of proportional wire chamber (PWC) planes. These eight 1.29 m² PWC planes yield a total active area of 82 m². Each of the four pairs of chambers in a detector contain a horizontal plane of wires running north-south and another plane of wires running east-west. When a charged particle passes through the chamber, it leaves a trail of ions which accelerate toward the closest signal wire. As they gain energy, they collide with more gas molecules and release more charged particles in a process known as gas amplification, which further increases the charge collected on the signal wire, producing a small current. By identifying the closest wires in each plane and comparing the track position for each plane, the angle of the muon track can be reconstructed to within 0.5°, on average, in each of two projected planes: up/east and up/north. A 50 mm thick steel plate

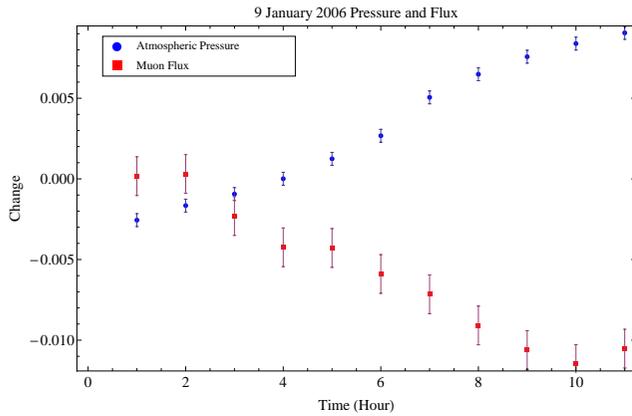


Figure 1. Percent change in atmospheric pressure and muon flux over 10 hours as a front moved through the area causing a large sudden change in pressure.

is situated above the bottom two PWC planes to discriminate between muon tracks which penetrate the steel and electron tracks which stop, shower, or are deflected by the steel. It is important to differentiate between muons and electrons because electrons are produced by higher energy cosmic rays and have a different response to atmospheric variations, including a weaker angular correlation compared to the muon. The array collects data at a rate of ~ 2000 identified muons per second. Added details are available at: <http://www.nd.edu/~grand>.

Climatic Effects

Pressure

In order to study the effect of barometric pressure on low energy muons, hourly pressure data from NOAA taken at the South Bend Airport⁶ were correlated with observed muon flux. Because the muon flux time series is not weakly stationary (the mean and variance are not constant), it is difficult to directly calculate the effect of atmospheric pressure over long periods of time. Therefore in this study only sudden changes in pressure corresponding to fronts passing through the area were used to

isolate the effect of pressure on flux. Sixty-four fronts were analyzed using simple regression analysis. These fronts were identified by looking for regions in the pressure data where the atmospheric pressure changed by at least 0.068 kPa per hour for at least ten consecutive hours with at most only one hour's pressure gradient less than this threshold; an example can be seen in Figure 1. A linear fit was then applied to the fractional change in pressure and flux values and the slope of this fit was taken to be the barometric correction factor. The fractional change in flux was calculated with respect to the windowed average of the 100 muon flux and pressure values surrounding the front event in order to decrease the effect of seasonal variations. In order for the fit to be used for the experiment, the correlation coefficient for pressure and flux data had to be less than -0.8 corresponding to a r-square value of 0.64. These fits reveal a wide range of possible barometric correction coefficients (β_p) ranging from -0.31 to -1.48 but averaged around $\beta_p = -0.83 \pm 0.23$ (Table available online). This wide range of pressure coefficients each with small fit errors indicates that the pressure correction coefficient for GRAND has some unidentified physical effects. Thus, using the mean values of -0.83 is a good place to start; however more work is needed to develop a more comprehensive correction method.

Temperature

Flux and temperature data were monitored for seven years to investigate seasonal variations due to temperature. Atmospheric datasets of temperature, pressure, and altitude were provided by NOAA via weather balloon flights every 12 hours.⁶ During each of these flights, the balloon's data recorder tracks the temperature and altitude at a preprogrammed set of barometric pressures. Five NOAA stations were selected in the region around Northern Indiana as seen in Table 1. For each atmospheric profile of a balloon flight, the mean pion creation altitude was found. This altitude was assessed for a 50 GeV proton which has an interaction cross-section of 278 millibarns (mb), so on average it will interact at a height with an air pressure of 8.52 kPa.² A simple linear interpolation between the two closest data points (7 kPa and 10 kPa) was used to isolate

Station	Latitude	Longitude	Weight
Davenport, IA	41.62	-90.58	0.18
Cincinnati, OH	39.42	-83.75	0.20
White Lake, MI	42.7	-83.47	0.26
Gaylord, MI	44.9	-84.72	0.17
Green Bay, WI	44.48	-88.13	0.19

Table 1. The five closest NOAA weather balloon stations to South Bend, IN. The weights correspond to normalized inverse distance to GRAND.

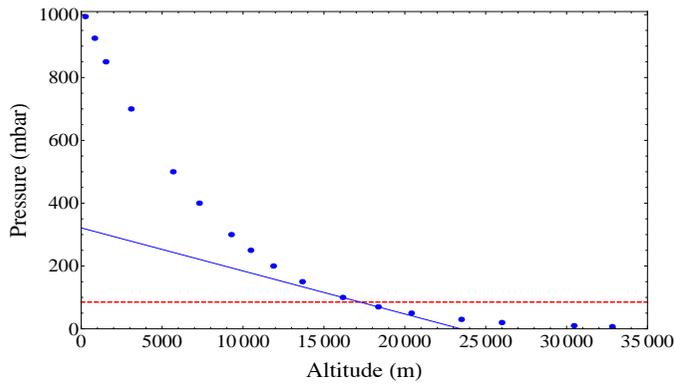


Figure 2. Sample model of pion creation height where the data points represent NOAA balloon altitude and pressure data, the dotted line indicates the pressure corresponding to pion creation, and where the fitted line intersects the dotted line is the mean creation altitude.

the target altitude; an example can be seen in Figure 2. The pion creation height at GRAND was then interpolated using the weighted average of the five stations based upon inverse distance for which at least three balloon stations had to contribute data at that hour. Because the number of uniformly active detectors for the first year of data was significantly lower than the other three years, these data were analyzed separately. By comparing this interpolated muon creation height with the muon flux data summed over ten days, a correlation coefficient of -0.87 was found. Comparing the percent change of altitude versus percent change of muon flux, a correction coefficient of $\beta = -0.71 \pm 0.03$ was calculated by fitting a linear trend line through the origin as can be seen in Figure 3.

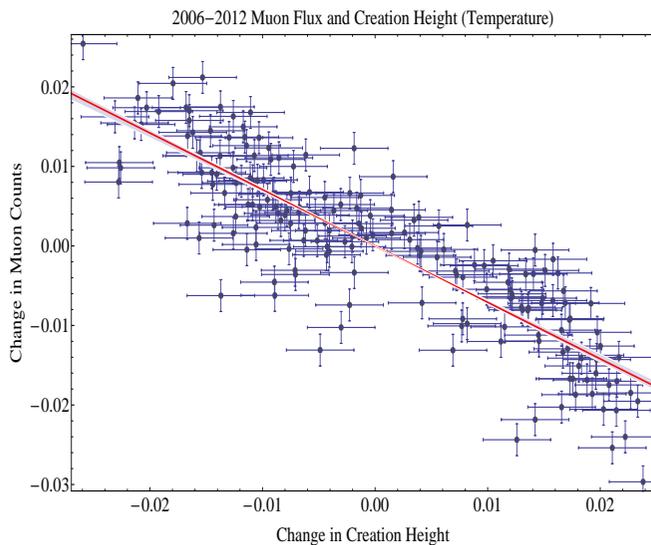


Figure 3. Correlation between muon flux and pion creation height in the atmosphere based upon fitted data from NOAA balloon flights. The line shown is the fit of the data corresponding to a correction value of -0.57 ± 0.04 .

Data

Data collected from July 21, 2007 until January 8, 2008 were analyzed with raw single track muon counts per hut being summed into ten minute bins. In order to improve data quality and correct for variations in detector sensitivity from both the number of huts active and the quality of those huts, data from only the top four performing huts were used for any given ten minute period. Using the top four huts eliminates many of the problems with hut quality because most of the failures which occur in the detectors or the hardware cause reductions in count rates, such as the presence of hot wires in the detector which are automatically ignored by the software, effectively reducing the detector's area. In order to eliminate major atmospheric effects the data were corrected for variations in temperature and pressure based upon the methods outlined above. The data can be seen in Figure 4. These corrections are important for investigating periodicity since atmospheric pressure also exhibits daily variations due to atmospheric tides which interfere with the two cycle per day variation in muon flux (Figure 5).

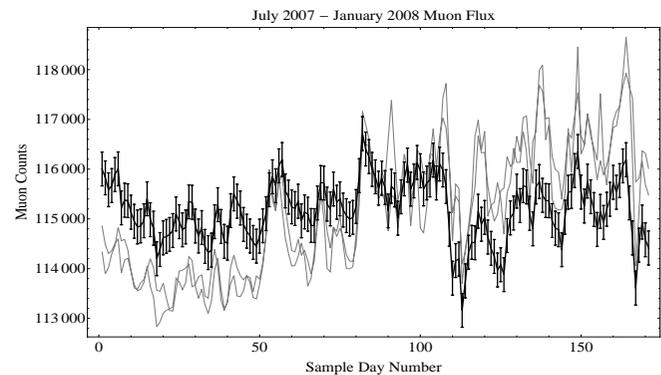


Figure 4. View of the smoothed data from the 171 day time period. The dark line is the temperature and pressure corrected time series while the light lines are the smoothed data before temperature and pressure correction.

Observed Periodicity

The periodic variations in muon flux can be identified by analyzing the Fourier transform of the pressure and temperature corrected muon flux time series. In Figure 6, the spectral data for four years of muon flux interpolated using nearest neighbor interpolation to ensure evenly spaced data points can be seen. In this power spectral density (PSD plot) there is an obvious one cycle per day variation along with higher order harmonics known as the Daily Mean Variation (DMV) or Diurnal Variation. The PSD also indicates that there are significant longer term variations to be found in the data however, the spectral resolution of the PSD at these frequencies along with the use of interpolation does not permit isolation of these features.

The finer structure of the DMV can be investigated using data folding to determine the shape of the DMV. In this method the flux data was summed into a histogram with 48 bins corresponding to 48 30-minute intervals over the course of a day (Figure 7). This method agrees with previous investigations of the DMV by GRAND.⁸

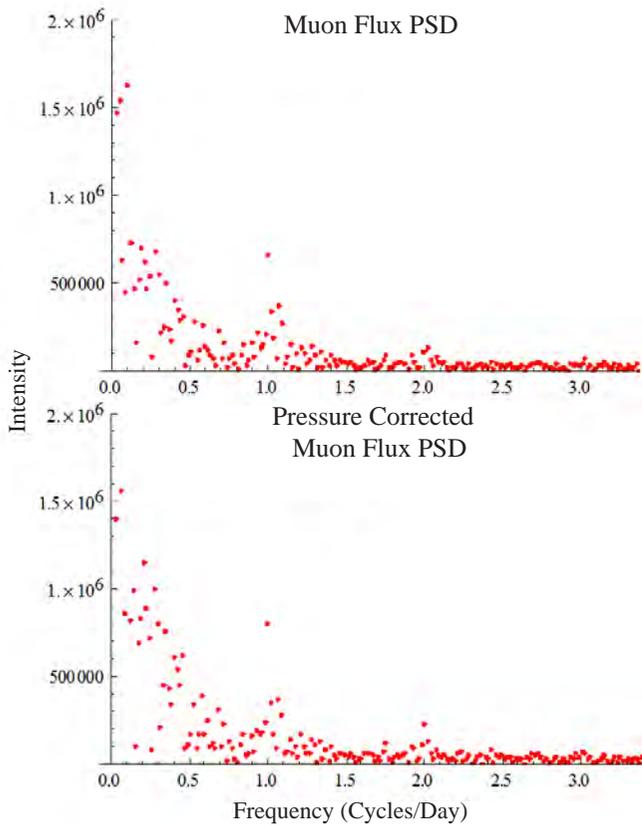


Figure 5. Comparison of the pressure corrected and the raw muon flux. Note the enhancement of the two cycle/day variation in the corrected data.

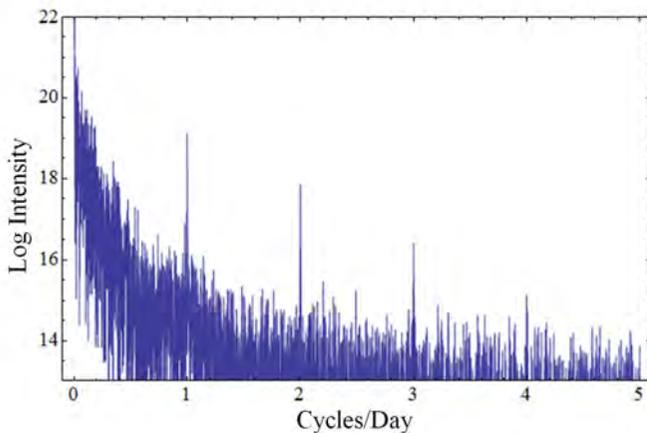


Figure 6. PSD of the 4 years of muon flux plotted on a log scale. Notice the significant peaks at 1, 2, 3, and 4 cycles per day and strong low frequency trends.

Evolution of Daily Variation

The dynamics of the DMV were then investigated by dividing the data set into 13 overlapping 56.9 day periods (8192 samples). Each of these 114 time series were then Fourier transformed so the amplitude and phase of the one and two cycle per day variation could be found effectively creating a short-time Fourier transform. This analysis reveals significant variations in the phase and relative amplitude of the two components indicating that the standard view of the DMV as constant is incomplete. Figures 8A and 8B show the evolution of the one cycle per day

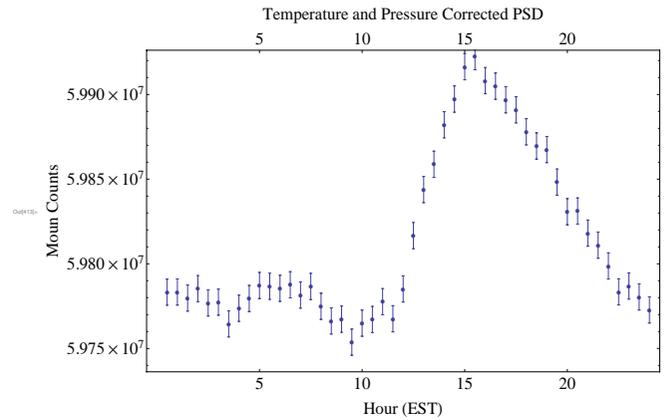


Figure 7. Histogram of muon counts separated into 30-minute bins for the 48 half hour periods in the day.

variation, which reaches an intensity plateau centered around November then decreases rapidly on the edges of this region in October and December, and a phase which reaches a maximum in late September and gradually trails off through the end of the year. Figures 8C and 8D show that the two cycle variation linearly increases throughout the year until late November, while the phase is uniform throughout most of the time series with the exception of the leading edge. Fitted one and two cycle per day curves can be seen in Figures 9A-E as the DMV evolves over the data set. The dates on these plots reflect the center date of the data series. When these variations are combined, very different phenomena can be observed as the DMV is almost entirely one cycle at the beginning of the time series, and then evolves to have a very strong two cycle component. It is also important to note that the temperature and pressure corrections play a significant role in the one cycle per day data, but only the pressure correction seems to be relevant for the two cycle per day trends.

Conclusion

This analysis has examined the record of GRAND data dating back to 2005 in order to investigate the relationship between pressure, temperature, and muon flux, and to establish correction coefficients and then use these corrections to analyze periodic effects. The analysis of sudden variations in atmospheric pressure reveals an average correction factor of $\beta_p = -0.83$ however, there was significant variation throughout the experiment. The effect of temperature was investigated by estimating the altitude of pion creation using NOAA weather balloon flights. By relating the mean pion creation altitude with flux summed over 10 days, a correction coefficient of $\beta_T = -0.71$ was found.

A total of 171 days of data from July 2007 – January 2008 were then analyzed using these corrections to investigate periodic trends in flux on a variety of timescales. Traditional Fourier analysis revealed significant one and two cycle per day trends, which have been well established in the literature and also lower frequency trends, which still need to be quantified due to the limited low frequency sensitivity of the analysis. The data were also investigated using less traditional techniques that can reveal interesting phenomena. For example, the time series was divided into smaller pieces so the dynamics of the one and two cycle variations could be in-

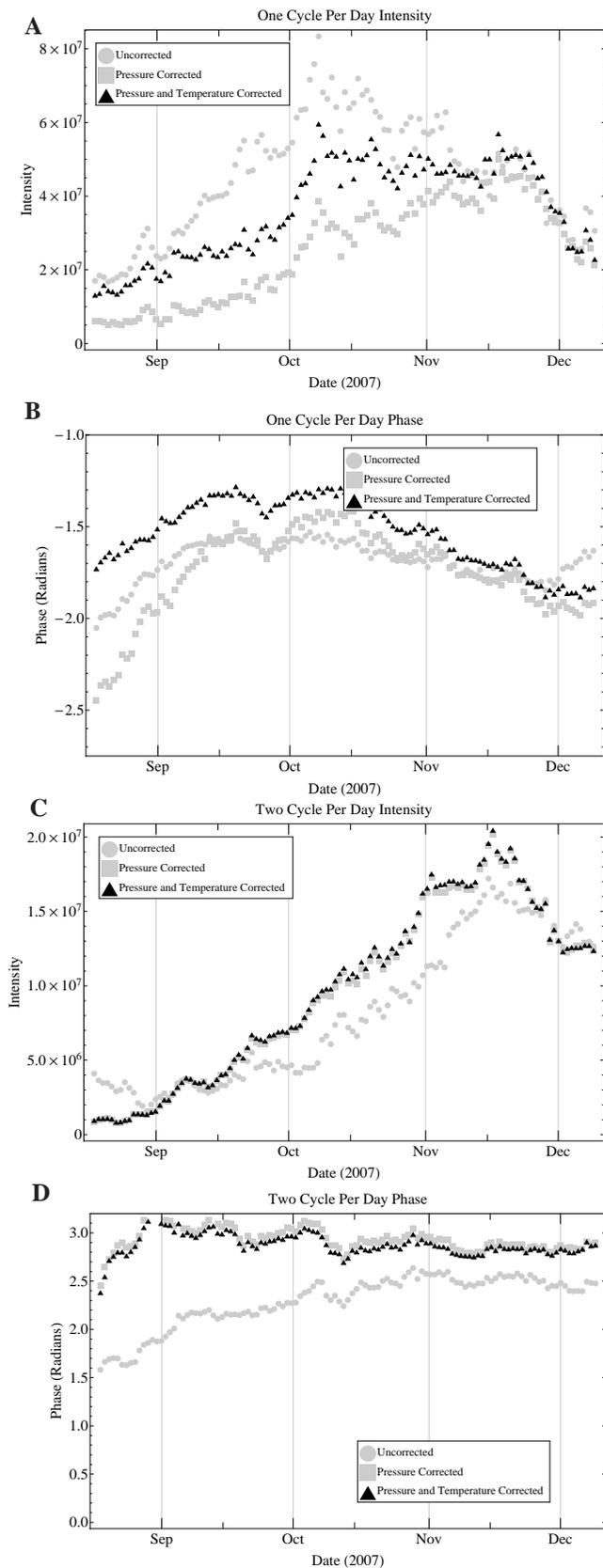


Figure 8A-D. One cycleday intensity variation (A), One cycle/day phase variation (B), Two cycle/day intensity variation (C), and two cycle/day phase variation (D). The different symbols represent different levels of data correction.

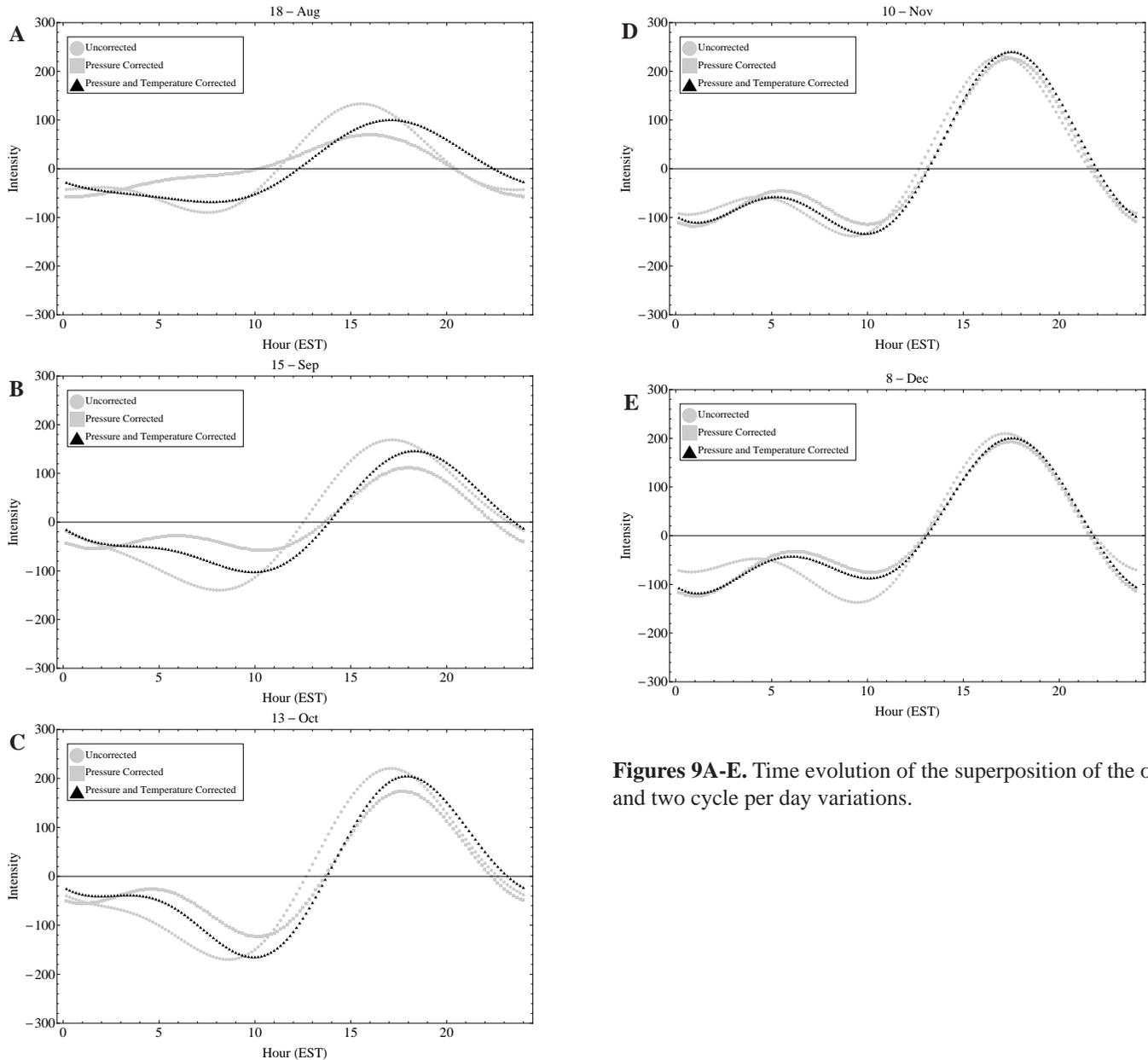
vestigated revealing significant changes in both the phase and the intensity of the trends over time. These variations are probably due to slight changes in the IMF over time, but further analysis must be done to relate these two quantities and to better quantify these variations in intensity and phase.

Acknowledgements

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Figures 9A-E. Time evolution of the superposition of the one and two cycle per day variations.

About the Author

Thomas A. Catanach is a senior physics major who grew up in Allen, Texas, and currently lives in Dillon Hall. His research interests span many disciplines from particle astrophysics to network systems. For four years he has been doing research at Notre Dame with Project GRAND under Prof. John Poirier along with three other summer research internships at SNO Lab, the SETI Institute, and the Santa Fe Institute. Next year he will be studying Applied and Computational Mathematics at the California Institute of Technology with a focus in stochastic modeling.

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