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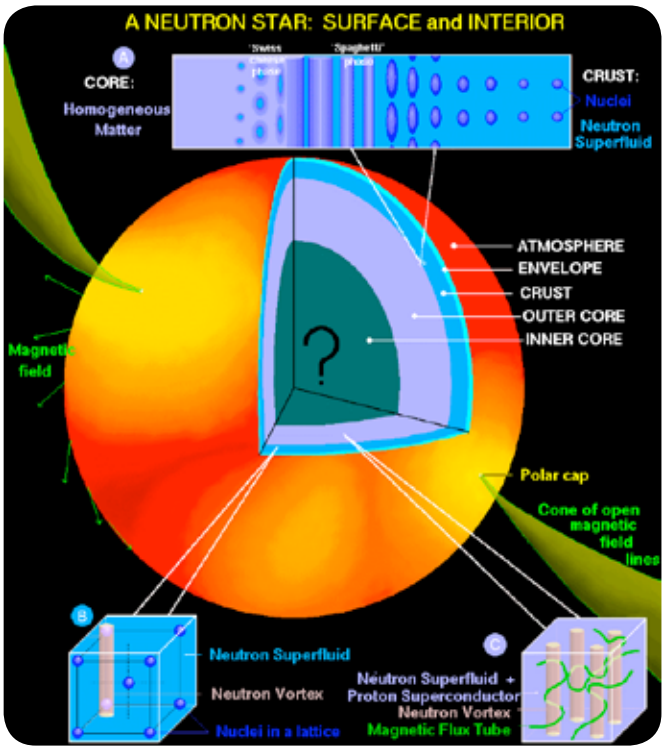
The Physics and Astrophysics of Neutron Stars

This article was prepared by Madappa Prakash who joined the faculty at Ohio University in September of 2005 as Professor. Please see the departmental website for more information.

Einstein's theory of General Relativity links space-time geometry with the internal properties of matter, specifically the relationship between the pressure and energy density which constitutes the equation of state of macroscopic objects. A marvelous example of this link is encountered both in the observation and observed properties of neutron stars. Almost every physical aspect of a neutron star tends to the extreme when compared to similar traits of other commonly observed objects in the universe. The term ``neutron star'' as generally used today refers to a star with matter containing on the order of 10^{57} baryons and with a mass in the range of 1-2 solar masses confined to a sphere of radius 10-12 km (recall that our sun's radius is $R_\odot = 6.96 \times 10^5$ km) representing one of the densest forms of matter in the observable universe. Depending on the equation of state of matter at the core of a neuton star, the central mass density could reach several times ρ_o, where $\rho_o = 2.65 \times 10^{14}$ g/cm^3 is the central mass density of heavy laboratory nuclei (compare this to the mean solar density $\rho_\odot = 1.4 \times 10^3$ g/cm^3).

Although neutrons dominate the nucleonic component, some protons (and enough electrons and muons to neutralize the matter) also exist in neutron stars. At supra-nuclear densities, exotica such as strangeness-bearing baryons, condensed mesons (pion or kaon), or even deconfined quarks may appear. Fermions, be they in the form of baryons or deconfined quarks, are likely to exhibit superfluidity and/or superconductivity. Observations of electromagnetic emissions from the surface imply surface magnetic fields in the range 10^9 - 10^{15} gauss to be compared with the highest magnetic fields of about 10^5 gauss currently achievable in the laboratory.

Neutron stars are made in the aftermath of type II supernova explosions which result from the gravitational core collapse of massive $\geq 8\ M_\odot$ stars. A back-of-the-envelope neutron star accounting is instructive. Based on the metals (in astronomical parlance, all elements heavier than helium are regarded as metals) observed around our galaxy, the historical supernova rate is inferred to be such that approximately 10^9 neutron stars have been produced in the history of the galaxy. To date, the number of neutron stars observationally discovered as radio pulsars is about 2000. The number observationally discovered as part of X-ray binaries is about 500. Those observed as isolated neutron stars amount to about 10.



The major regions and possible composition inside a normal matter neutron star. The top bar illustrates expected geometric transitions from homogenous matter at high densities in the core to nuclei at low densities in the crust. Superfluid aspects of the crust and outer core are shown in insets. Figure courtesy D. Page; adapted from Lattimer and Prakash, Science, 304, 536 (2004).

The confluence of theory and astronomical observations concerning neutron stars is truly remarkable. The entry of neutron stars in theorists' minds dates back to 1930s whereas their discovery had to wait until the 1960s. Since then, it has been realized that all known forces of nature, strong, weak, electromagnetic and gravitational, play key roles in the formation, evolution, and the composition of neutron stars. Research on the physics and astrophysics of neutron stars has been the forerunner in the study of extreme energy density physics, spurring other activities such as relativistic heavy-ion collisions in which high energy density is investigated at much higher temperatures than encountered in neutron stars.

Internal Structure and Composition--Combining theoretical and observational studies, a picture of the structure and composition of a neutron star from its birth to old age is beginning to emerge. In its fully formed stage, a neutron star has five major regions, the inner and outer cores, the crust, the envelope and

the atmosphere (see Figure). The atmosphere and envelope contain a negligible amount of mass, but the atmosphere plays an important role in shaping the emergent photon spectrum, and the envelope crucially influences the transport and release of thermal energy from the star's surface. The crust, extending about 1 to 2 km below the surface, primarily contains nuclei. The dominant nuclei in the crust vary with density, and range from ^{56}Fe for matter with densities less than about 10^6 g/cm^3 to neutron rich nuclei with atomic number A≈200. Such extremely neutron-rich nuclei are not observed in the laboratory, but rare-isotope accelerators hope to create some of them.

Within the crust, at densities above the neutron drip density 4 x 10^{11} g/cm^3 where the neutron chemical potential (the energy required to remove a neutron from the filled sea of degenerate fermions) is zero, neutrons leak out of nuclei. At the highest densities in the crust, more of the matter resides in the neutron fluid than in nuclei. At the core-crust interface, nuclei are so closely packed that they are almost touching. At somewhat lower densities, the nuclear lattice can turn inside-out and form a lattice of voids, which is eventually squeezed out at densities near ρ_o. If so, beginning at about 0.1 ρ_o, there could be a continuous change of the dimensionality of matter from 3-D nuclei (meatballs), to 2-D cylindrical nuclei (spaghetti), to 1-D slabs of nuclei interlaid with planar voids (lasagna), to 2-D cylindrical voids (ziti), to 3-D voids (ravioli, or Swiss cheese) before an eventual transition to uniform nucleonic matter (sauce). This series of transitions is known as the nuclear pasta.

The core comprises up to 99% of the mass of the star (see Figure). The outer core consists of a soup of nucleons, electrons and muons. The neutrons could form a $^3P_2$ superfluid and the protons a $^1S_0$ superconductor within the outer core. In the inner core exotic particles such as strangeness-bearing hyperons and/or Bose condensates (pions or kaons) may become abundant. It is possible that a transition to a mixed phase of hadronic and deconfined quark matter develops. Delineating the phase structure of dense cold quark matter has yielded novel states of matter including color-superconducting phases with and without condensed mesons.

Recent Observations and their Implications—Recently, several key observations of neutron stars have been made. The theoretical interpretation of these observations has been pursued vigorously around the world with important contributions from the team at Ohio University (Madappa Prakash and graduate student Sergey Postnikov, who is currently a post-doctoral research scientist at UNAM, Mexico) in collaboration with James M. Lattimer of Stony Brook (recipient of Ohio University's Glidden Visiting Professorship during 2008-2010), Dany Page of UNAM, Mexico (Glidden Visiting Professor during 2011-2012), and Andrew W. Steiner (currently a research assistant professor at the Institute for Nuclear Theory, Seattle, Washington). Two recent topics, in which Ohio University's investigators have been involved and have received a great deal of national and international attention, are highlighted below.

I. Neutron Star Masses--One of the most fascinating stories in astrophysics concerns the accumulation of precisely measured neutron star masses. The most accurate measurements of neutron star masses are for radio pulsars in bound binary systems. In these systems, five Keplerian parameters can be precisely measured by pulse-timing techniques, including the binary period P, the projection of the pulsar's semimajor axis on the line of sight a_p sin i (where i is the binary inclination angle), the eccentricity e, and the time and longitude of periastron (the point at which the two stars are closest together) T_0 and ω.

Fortunately, binary pulsars are compact systems and general relativistic effects can often be observed. These include the advance of the periastron of the orbit, the combined effect of variations in the transverse Doppler shift and gravitational redshift around an elliptical orbit, and the orbital period decay due to the emission of gravitational radiation. The inclination angle can be constrained by measurements of two or more of these effects. However, only in extremely compact systems is this precisely possible. Otherwise, additional effects, such as an eclipse or limits obtained from the lack of an eclipse, or Shapirotime delay (Phys. Rev. Lett. 26, 789 (1964)), which is caused by the propagation of the pulsar signal through the gravitational field of its companion, must be observed. The Shapiro delay δ_s is a periodic function of ϕ, the angular parameter defining the position of the pulsar in its orbit, the amplitude of which is large only for edge-on binaries, sin i ≈ 1 or those that have both large eccentricities and large magnitudes of sin ω. A measurement of the Shapiro delay is crucial to determine the companion mass. Only a fraction of pulsars in binaries have two or more sufficiently well-measured relativistic effects to enable precise measurements of the pulsar mass M_p. To date, the Shapiro delay measurements exist for only 10 of nearly 2000 known pulsars.

The important thing to note is that the measured five Keplerian parameters and the additional general relativistic effects are vastly different functions of the masses of the neutron star and its companion. This happenstance renders the system over determined in establishing the masses, the precision limited mainly by the precision to which Newton's gravitational constant G is known.

The recent determination of 1.97±0.04 $M_\odot$ for the mass of PSR J1614-2230 by Demorest et al. (Nature, **467,** 1081 (2010)) was made possible by the measurement of the Shapiro time delay (peak-of-cusp to bottom-of-delay amplitude being 48.29 μs) to establish the inclination angle. This 3.15 ms pulsar is in an 8.7 d nearly circular orbit about a 0.5 $M_\odot$ companion, with a_p sin i=11.3 light-second and sin i=0.99989, i.e., it is almost edge on.

In a recent book article *What a Two Solar Mass Neutron Star Really Means* written for Gerry Brown's Festschrift (From Nuclei to Stars, Ed. Sabine Lee, World Scientific (2011); pp: 275-304), Lattimer and Prakash have highlighted the implications of this mass determination on the structure and composition of a neutron star. In general relativity, the maximum mass of a neutron star is directly governed by the functional relationship between the pressure and energy density, or the equation of state, of matter. In order to support a 2 $M_\odot$ star, the pressure must vary relatively rapidly above nuclear densities. When the interior of the star is comprised of nucleons only, several proposed equations of state are able to support a 2 $M_\odot$ star whereas several others cannot. The latter proposals are thus ruled out.

The density at which exotica (hyperons, Bose condensates, quarks) appear is uncertain and depends sensitively on the nature of strong interactions at high densities. In most cases, however, the equation of state with exotica is softer than that without. Consequently, the maximum mass that a star with exotica can support is often smaller (with few exceptions) than that of a pure nucleonic star. In view of the observation of a 1.97 $M_\odot$ star, the natural question to ask is whether or not exotica are even

permitted within such stars. A survey of current equations of state with exotic matter indicated that stars containing significant proportions of exotica would be almost impossible.

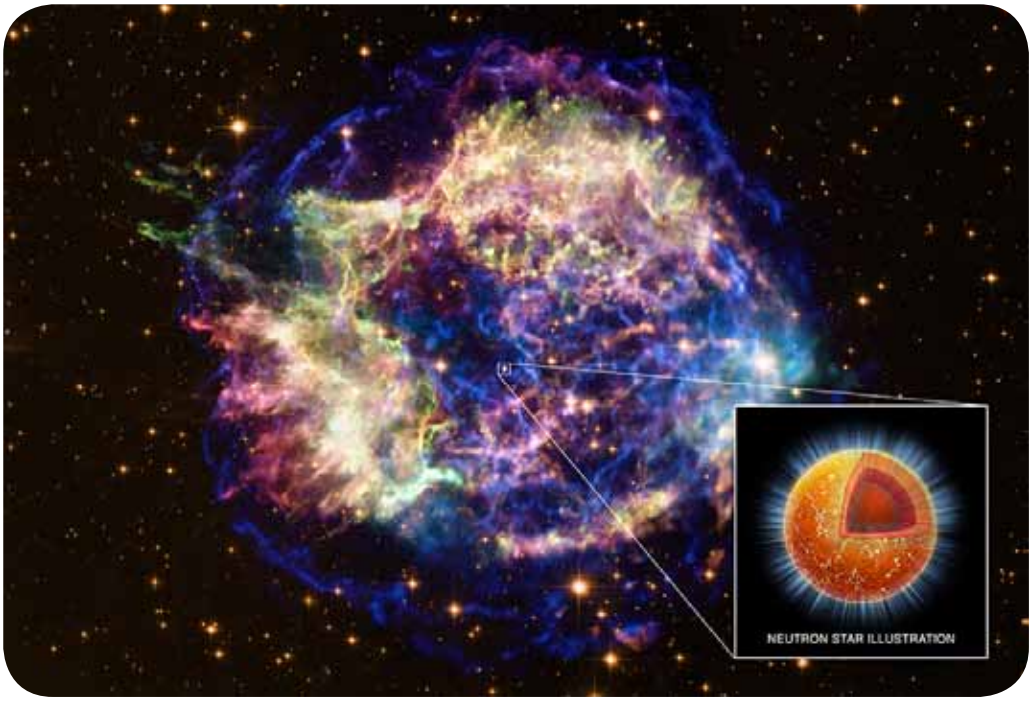
II. Evidence for Superfluidity from the Rapid Cooling of the Neutron Star in Cassiopeia A—The neutron star in Cassiopeia A (Cas A hereafter), discovered in 1999 in the Chandra first-light observation targeting the supernova remnant, is one of the youngest known in the Milky Way. The observed thermal soft X-ray spectrum of Cas A implies a surface temperature $\cong 2 \times 10^6$ K and an emitting radius ~ 8 – 17 km. These results raise Cas A to the rank of one of the very few isolated neutron stars with a well determined age and a reliable surface temperature, thus allowing for a detailed modeling of its thermal evolution and the determination of its interior properties.

Analyzing 10 years (from 2000 to 2009) of archival data, Heinke and Ho (Astrophys. J. Lett. **719,** L167 (2010) recently reported that Cas A's surface temperature has rapidly decreased from 2.12×10^6 K to 2.04×10^6 K. This rate of cooling is significantly larger than expected from the standard neutrino emitting processes expected to occur in the core of a neutron star. Although many possibilities for rapid cooling exist, the rapidity with which cooling has occurred in Cas A at such an early stage of its life sheds light on the most likely process. A successful accounting of the observed data involves superfluidity of neutrons and superconductivity of protons in the core of Cas A. As the star is cooling down due to neutrino emission processes, a stage is encountered when the temperature falls below the critical temperature for neutron and proton pairing phase transitions leading to the phenomena of superfluidity and superconductivity. At temperatures just below the critical temperature of a pairing transition, the continuous breaking and formation of pairs results in enhanced neutrino emission. Numerical calculations and analytical analysis performed by Page, Prakash, Lattimer and Steiner (Phys. Rev. Lett. **106,** 081101 (2011)) have indicated a critical temperature $\cong 0.5 \times 10^9$ K for the triplet neutron superfluidity. The observed rapidity of the cooling implies that protons were already in a superconducting state with a larger critical temperature.

The cooling rate of Cas A is the first direct evidence that superfluidity and superconductivity occur at supra-nuclear densities in the cores of neutron stars. Two days after the work of Page et al. was submitted for publication, Shternin et al., (Mon. Not. R. Astron. Soc., **412**, L108-L112 (2011)) arrived at similar conclusions in an independent work. The prediction of Page et al. that this cooling will continue for several decades at the present rate can be tested by continuous monitoring of this neutron star, which is being pursued vigorously by observers.

Future Prospects--In addition to the examples highlighted above, ongoing observational and theoretical research on neutron stars includes studies to determine their radii, moments of inertia, limits to rotational periods, surface temperatures and crustal cooling times. Transient phenomena involving X-ray bursts from accreting neutron stars and giant flares in soft-gamma repeaters have opened up the possibility to conduct seismological studies. Phenomena associated with intense magnetic fields as large as 10^{15} gauss, found in many neutron stars (termed ``magnetars''), continue to be intriguing. Observation of neutrinos emitted in core-collapse supernova explosions and of gravitational radiation from isolated and merging neutron stars are exciting future possibilities.

These astrophysical investigations are being complemented by concomitant accelerator experiments, including high-resolution studies of the neutron skin thickness by parity-violating electron scattering on ^{208}Pb and other heavy nuclei. Studies of extremely neutron-rich nuclei with rare isotope accelerators will probe conditions intermediate between laboratory nuclei and neutron star matter. Intermediate energy heavy-ion experiments could establish in-medium properties of pions and kaons that are crucial for delimiting the extent of Bose condensation in dense matter. Hyper-nucleus experiments will shed light on strangeness-bearing hyperons likely to occur in dense matter. Such a strong connection between laboratory experiments and astrophysical observations bodes well to delineate the properties of neutron stars in which the ultimate energy density of observable cold matter is found.



The neutron star in Cassiopeia A (termed Cas A) is a remnant of a core collapse supernova explosion that occurred in 1680 which gives it an age of 330 years. Discovered in 1947 and located at a distance of 3.4 kpc, it is the strongest radio source outside the solar system. An X-ray source was detected in 1965 and an X-ray point source was detected by the Chandra observatory in 1999. Since then, x-ray emission from Cas A's surface has been monitored each year. Image courtesy X-ray: NASA/CXC; Optical: NASA/STSci; Illustration: NASA/CXC/M. Weiss.

A Note from the Chairs

David Ingram and Joe Shields

Greetings to friends and alumni of the Department of Physics and Astronomy at Ohio University. Our department continues as an active and vital environment as we help students realize their potential and advance the frontiers of science. Our alumni are testimony to the past success of our program and an inspiration as we look to the future. We're happy to share some updates from our program with this newsletter. Several developments have affected the composition of our faculty in the past year. As reported elsewhere in this newsletter, we were saddened by the loss of two of our emeritus faculty, **Charles Chen** and **Roger Finlay**. Among our current faculty, **Tom Statler** continued as a temporary Program Officer in the Division of Astronomical Sciences at the National Science Foundation in Washington, D.C., and has committed to remain there for a third year during 2011-2012. **Ido Braslavsky** is on leave while working at the Hebrew University of Jerusalem. **Steve Weppner** (Ohio University Ph.D. 1997) returned to the department on sabbatical from Eckerd College, and taught a class for us, with outstanding results. **Joe Shields** was selected as Interim Vice President for Research & Creative Activity and Dean of the Graduate College effective July 1, and **David Ingram** is now standing in as Interim Chair of Physics & Astronomy. **Saw Hla** has accepted a position as Group Leader for Electronic & Magnetic Materials & Devices in the Center for Nanoscale Materials at Argonne National Lab, but will be continuing his association with Ohio University as a part-time member of our faculty. **Steve Grimes** and **Louis Wright** concluded their formal "early retirement" phase but we are happy that both remain engaged members of the department and have agreed to teach a course for us in the next year. We are also pleased that **Violet Mager** is continuing as a Visiting Assistant Professor to help us meet our teaching needs amongst these changes.

Our faculty have received several notable recent recognitions. **Doug Clowe** and **Nancy Sandler** were promoted to Associate Professor with tenure, and **Saw Hla** was promoted to Professor, recognizing their excellent performance in teaching, research, and service. **Carl Brune** was named a Fellow of the American Physical Society, an honor bestowed on less than 0.5% of the APS membership annually in recognition of outstanding contributions to physics. **Ken Hicks** received the College of Arts & Sciences Grasselli Brown Faculty Teaching Award, and five members of our department were recognized by the university as "Transformative Faculty": **Markus Boettcher, David Drabold, Saw Hla, Mark Lucas,** and **Art Smith**.

The support we receive from our friends and alumni remain an invaluable element in helping our department in the pursuit of its mission. We always appreciate visits by our alumni (see separate news stories), as a means to educate our students about possible career paths and to help our department remain connected to a larger community. We also express our sincere thanks to those who have contributed financially to our program, as listed elsewhere in this newsletter. In particular we would like to call out the generosity of Emeritus Professor **Folden (Burt) Stumpf** and **Margaret Stumpf** who signed an agreement earlier this year to establish an endowed scholarship in the department as a gift from their estate. Burt remains an active and valued member of our department, and in establishing this forward-looking gift, he and Margaret have ensured that their influence will benefit generations of students to come.

A Note from the Editor

Louis E. Wright

During problematic financial times, the members of the Department of Physics and Astronomy continue to perform at a very high level. In addition to invited talks, publications, service on professional society committees, their accomplishments are recognized by success in obtaining resources for supporting the research efforts of students, staff and faculty. Fiscal year 2011 (July 1, 2010 through June 30, 2011) was another record breaking year for the department. Competitive research grants to members of the department in fiscal year 2011 totaled $5.850 million—a significant increase over last year's total of $4.738 million. Many of the grants in these totals are funded under the auspices of various institutes that members of the faculty are associated with. In fiscal year 2011, the Institute of Nuclear and Particle Physics (INPP) had funding of $3.085 million, the interdisciplinary Nanoscale and Quantum Physics Institute (NQPI) had funding of $2.090 million which included a $139 thousand career grant to Wojciech Jadwisienczak of Electrical Engineering and $36 thousand grant to Jeffrey Rack in Chemistry, and the Astrophysical Institute (ApI) had funding of $627 thousand. More information about these institutes including a list of affiliated faculty can be found on the departmental website.

Recognition of Physics Majors

Our majors have achieved many successes during the past year. Below we include some of the more significant achievements:

Honorary Societies: The following students were inducted into the Physics Honorary Society Sigma Pi Sigma **(ΣΠΣ): Joshua Kaisen**, **Arianne Saunders**, and **Nathan Turner**, while **Sai Dong** and **Gary Canter** were inducted into Phi Beta Kappa **(ΦBK).**

Undergraduate Research: During the past few years under the leadership of Ken Hicks, we have been increasing the number of our majors engaged in summer research with faculty. For the summer of 2011 these include the following undergraduates listed with their research mentors: **John Kerr** (Böttcher), **Tyler Barton** (Braslavsky), **Derek Miller** (Castillo), **Arianne Saunders** (Chen), **Yashashree Jadhav** (Clowe), **Joe Zeallear** (Frantz), **David Bauer** (Govorov), **Peng Zhao** (Hicks), **Paul Adams** (Ingram), **Austin Way** (Kordesch), **Gary Cantor** (Prakash), **Brooks Ziegler** (Roche), **Shaila Meeker** (Roche), **Jared Ray** (Sandler), **Alan Savage** (Smith), **Kyle Baldosser** (Stinaff), **Nate Turner** (Stinaff), and **Aaron Burdette** (Tees).

Undergraduate research projects often lead to interesting results. The undergraduate SPS advisor, Gang Chen, organized an Undergraduate Research Conference held on Saturday, January 22, 2011. Five students gave excellent presentations: **Keith Hawkins**-*The CNO Bi-Cycle in the Open Cluster-NGC752*; **James Ralston**-*Neutron Induced Fission Fragment Tracking Experiment*; **Vince Roberts**-*Scanning Microscopy and Atomic Manipulation*; **Joshua Kaisen**-*Summer Internship at Jefferson Laboratories*; and **Courtney Gusbar**-*Investigating CAS Parameters in Nearby Galaxies.*

Awards and Recognition

Professor **Carl Brune**, director of INPP, was named a Fellow of the American Physical Society this past year. Carl was recognized "For his numerous significant and carefully executed experiments which have advanced our understanding of nuclear astrophysics and the nuclear structure and reactions of light nuclei." He is the latest in a growing number of our faculty who have received this highly visible recognition. Other APS Fellows among current Ohio University faculty are **David Drabold**, **Charlotte Elster**, **Steve Grimes**, **Ken Hicks**, **Peter Jung**, **Daniel Phillips**, **M. Prakash**, and **Sergio Ulloa**.

Graduate Student **Desiree Cotto-Figueroa** was awarded an Ohio Space Grant Consortium Fellowship and received honorable mention for a Ford Foundation Fellowship. Desiree works with Tom Statler. **Brett Ragozzine** (graduate student working with Doug Clowe) and undergraduate **John Kerr** received Grants-in-Aid from Sigma Xi. Graduate Student **Cody Parker**, working with Carl Brune, was a finalist for a DOE National Nuclear Security Administration Stewardship Science Graduate Fellowship. Graduate Student **Chandrasiri Ihalawela** won the 2011 American Ceramic Glass & Optical Materials First Place Poster Award. This year, **Sean Krupa** won the Arts & Sciences Outstanding TA Award while alternates were **Rami Amro** and **Amenah Mohammadalipour**.

There was good news for students who attended the American Vacuum Society annual meeting in Albuquerque in October of 2010. Graduate student **Kangkang Wang** was selected as the 2010 winner of the Leo M. Falicov Student Award for his work on manganese-induced stripe phases on gallium nitride, receiving a certificate and a $1000 cash prize. The Falicov Award is given for best student presentation in the Magnetic Interfaces and Nanostructures Division at the AVS International Symposium. Graduate student **Abhijit Chinchore** was one of 3 finalists for the 2010 Falicov Award for his work on Mn-containing structures on N-polar GaN, receiving a certificate and a $500 cash prize.

Professor **Ken Hicks** has been selected as Chair of the CLAS Collaboration at Jefferson Laboratory in Norfolk, Virginia. CLAS stands for CEBAF Large Acceptance Spectrometer and is one of the very large research collaborations at Jefferson Lab.

Suvendra Dutta, a former post-doctoral fellow with the Astrophysics group, has joined a group at MIT Lincoln Laboratory that is building and running large telescopes for the Air Force. He will focus on the data analysis part of their work. Suvendra spent several years working at Harvard with the Mazur group on technology and education.

The Astro Group held an Ohio University reunion at the January 2011 American Astronomical Society meeting in Seattle. This included those shown in the figure in addition to **Anca Constantin** (Ph.D. 2004), **Jerry Orosz** (M.S. 1991), **Mangala Sharma** (former research faculty), and **Tom Statler** (faculty).

Left to right: **Megan Krejny** (B.S. 2001), **Omar Jamil** (postdoc), **Sarah Wyss** (undergrad), **Joe Shields** (faculty), **Keith Hawkins** (undergrad), **James Steiner** (B.S. 2006), **Rojin** and **Parisa Roustazadeh** (grad student), **Markus Boettcher** (faculty).

Transitions

Charles Chen, Professor of Physics, died Friday, Oct. 22, 2010. He was born on May 22, 1929 in Taiwan. Charles earned his PhD at the University of Maryland in 1962 in statistical physics and after continuing as a post-doctoral research fellow at Maryland for an additional year joined the faculty at Ohio University in the Fall of 1963. Charles was awarded tenure and promoted to Associate Professor in 1967 and promoted to Professor in 1977. He served as advisor to the Overseas Chinese Student Club on campus for many years, was very active in the Honors Tutorial program, and was a stalwart of the graduate program, teaching quantum mechanics and mathematical methods for many years. Charles took early retirement beginning in the Fall Quarter of 1994 and full retirement in June of 1999. Charles organized the PhD Comprehensive exams for many years and supervised three doctoral dissertation students. He attended school in Taiwan during the Japanese occupation and was fluent in Japanese in addition to Chinese and English. Charles was the Ohio University Visiting Professor at Chubu Institute of Technology (now Chubu University) in Japan for the Spring Quarter of 1980. He and his wife, Anne Cooper-Chen, maintained active involvement with colleagues in Japan, particularly retired Professor Tomoyasu Tanaka of our department.

Roger William Finlay, Ohio University Distinguished Professor of Physics, died suddenly on Sunday, March 13, while hospitalized near his home in South Carolina. Finlay became Ohio University's first nuclear physicist in 1962. Despite starting with limited resources, he led the development of a highly successful research program. During his illustrious career, he published or co-published more than 100 papers and secured more than $5 million in grants. Finlay obtained the University's first physics research grants from the National Science Foundation and National Institutes of Health. In collaboration with Distinguished Professor **Ray Lane,** he led the development of a major grant proposal to the Atomic Energy Commission, which resulted in a $1 million award for the acquisition of a 4.5 MeV tandem Van de Graaff accelerator in 1967. Among his many honors, Finlay was selected for Fellowship status in the American Physical Society and was recognized as Distinguished Professor at Ohio University in 1991. He was awarded the College of Arts and Sciences Outstanding Teacher Award in 1989 and honorary membership in the Lambda of Ohio Chapter of Phi Beta Kappa in 1992. Finlay supervised Richard Castle, who became the first Ph.D. graduate in physics in 1963, and was primary adviser for a department-record 19 dissertations. Roger Finlay was an excellent physicist who was very good at seizing initiatives that helped create our excellent department. He played a leading role in recruiting other outstanding nuclear physicists in the department including Distinguished Professors Ray Lane, **Jack Rapaport** and **Steve Grimes**. In addition, he wrote a successful NSF Development Grant Proposal that helped the department move to a higher level of research in the late 1960s. A native of Pittsburgh, Finlay earned his A.B. and Ph.D. in physics from Johns Hopkins University. He moved to part-time early-retired status in 1995 and fully retired in 2001. A memorial service jointly organized by the department and Roger's family was held in Galbreath Chapel on May 14, 2011. In honor of Roger, the conference room he designed in the extension of the Edwards Accelerator Laboratory has been named the Roger W. Finlay Conference Room and a large framed copy of the photograph below is on the wall.

Roger Finlay with colleagues breaking ground for the extension of the Edwards Accelerator Lab in 1991

Donors to the Department

During the past academic year the department received contributions from many alumni, friends and members of the faculty and staff. We are very thankful to all of our donors. Donors between July 1, 2010 and June 30, 2011 are listed below: (We apologize if we have overlooked any contributions made during this period.)

Arnold Aronson
Athens Realty
Clyde & Karen Baker
Markus Böttcher
Carl Brune
Horacio Castillo
Michael Cervenak
Gang Chen
Phillip Chute
Bruce Danner
The Estate of John Edwards
Thomas & Linda Finlay
Thomas Fox
Justin Frantz
George Giakos
Alexander Govorov
Steven Grimes
Robert Haight
Harold Hulleman
Kenneth Hicks & Theresa Murphy
Saw Hla
Peter & Betty Hoffmann-Pinther
Harold & Linda Hulleman
Marie Huwe
David Ingram
Joy & Paul Jacobs
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Daniel & Donna Sayre
Andreas Schiller
Joseph Shields & Ann Fidler
Arthur Smith
David Straw
Eric Stinaff
Folden & Margaret Stumpf
David Tees
David Thompson & Elizabeth Howells
Sergio Ulloa
Shirley & Robert Williams

Staff

The retirement of **Candace (Candy) Dishong**, Administrative Assistant to the Condensed Matter and Surface Science (CMSS) program, was an occasion that generated mixed emotions. Candy joined the Department of Physics in 1980 as departmental secretary and following the formation of CMSS moved to that position along with continuing to work part-time for the department. Candy handled the searches for new faculty for more than 15 years. In many cases, she was the first person at Ohio University who had contact by email or telephone with prospective candidates. Her professionalism and friendly manner created a very positive impression of the department and Ohio University. There was a large turnout for Candy's retirement reception on June 28, 2011. We will all miss her greatly and wish her all the best in retirement.

During the 2011-2012 academic year, Departmental Administrator **Wayne Chiasson** will be spending part of the year in France and Brazil with his spouse **Morgan Vis**, Professor of Environmental and Plant Biology. Wayne will be working part-time via the internet and former Assistant Departmental Administrator **Ennice Sweigart** will come in part-time to help out. **Meg Van Patten** has joined the department as Assistant Department Administrator on a permanent basis and **Jean Andrews** is working part-time on special projects.

Candy Dishong receiving a retirement gift from Joe Shields with **Wayne Chiasson** in the rear.

Physics Major Scholarships

Keith Hawkins was awarded a Goldwater Scholarship while **Sarah Wyss** received honorable mention. In addition, due to the generosity of alumni, faculty and friends, our majors have access to a number of scholarships which assist them in achieving their educational goals. We are very grateful to your previous support to these scholarship funds and we would encourage you to be as generous as you can in providing continuing contributions. Continuing students with departmental scholarships for 2011-2012 include: **Paul Adams** (Edwards), **David Bauer** (Dist. Prof., P. Jung), **Aaron Burdette** (Edwards), **Gary Canter** (Dist. Prof., S. Grimes), **Henry Cornell** (Stocker), **Keith Hawkins** (Edwards), **Josh Kaisen** (Edwards), **Derek Miller** (Singh), **Vincent Roberts** (Gecsy), **Desmon Roger** (Edwards), **Alan Savage** (Edwards), **John Stahl** (Edwards/Ewers), **Yashashree Jadhav** (Edwards), **Austin Way** (Edwards), **Soo Hyun Wang** (Dist. Prof, D. Drabold), **Austin Wood** (Stocker) and **Brooks Ziegler** (Huwe). Incoming students with departmental scholarships include: **Samantha Thrush** (Shipman), **Natalie Klco** (Edwards), **Andrew Dewald** (Shipman) and **Taylor Grueser** (Shipman). The average GPA of the continuing students was 3.6 and the total scholarship support apart from the Distinguished Professor scholarships which cover tuition was $21,798. The current Chair of the Scholarship Committee is **Julie Roche**.

Previous Graduates

1900-1969

Richard C Fernow, BS 1969, is a physicist at Brookhaven National Laboratory. After graduating from Ohio University, he obtained his PhD degree in particle physics from Syracuse University in 1973. Prior to joining BNL he was a postdoctoral researcher at the University of Michigan and participated in polarized proton scattering experiments at the ZGS accelerator at Argonne National Laboratory. He joined the Physics Department at BNL in 1978 and worked on meson spectroscopy experiments at the AGS. From 1981-1985 he worked in the Magnet Division at BNL on the design of superconducting magnets for the Isabelle/CBA, RHIC and SSC projects. In 1985 he returned to the Physics Department and worked on experiments on the Smith-Purcell effect and ideas for laser acceleration of electrons. Since 1994 he has been working on the design of muon colliders and neutrino factories. He wrote the simulation code ICOOL, which is used for the design of ionization cooling channels for muon beams. He is currently the Level 1 Manager for Design and Simulation for the national Muon Accelerator Project (MAP).

Roger Richards, MS 1968, lives in Mystic, Connecticut and after earning a PhD in acoustics from Penn State, worked at the Naval Undersea Warfare Center in Newport, RI. His masters research in acoustics was done with Seung Yun.

Harold Knox, BS 1964, PhD 1972, returned to campus for a visit and to present a very interesting colloquium on April 22, 2011 entitled Historical Development of the Periodic Table and Chart of the Nuclides. After his PhD, Harold worked at Rensselaer Polytechnic Institute and Texas A& M before returning to Ohio University as a postdoctoral Fellow. Since 1989 he has worked for Knolls Atomic Power Laboratory and has been a major participant in the compilation of the Nuclear Data Chart issued by Knolls. Harold's doctoral research in experimental nuclear physics was directed by Roger Finlay.

1970-1979

Clement Lam, PhD 1970, retired from North Harris County Community College and lives in nearby Spring, Texas. His doctoral research in experimental acoustics was directed by Burt Stumpf.

Harold Knox in the center with Ray Lane and Louis Wright on the left and Steve Grimes and Ernst Breitenberger on the right.

Tim Golian, BS 1971, Vice President for Advanced Technology in the Energetics Division of the Titan Group, returned to campus for a visit March 2 and 3 of 2010. He gave a guest lecture on the use of explosives in oil exploration to Greg Nadon's Geography 476/576 Subsurface Methods course and then an open presentation to students and faculty about his work. Joe Shields hosted a faculty open house that evening for continued discussion with Tim.

Tim Golian discussing careers in the oil industry with graduate students

Deborah Roudebush, BS(HTC) 1974, returned to campus on April 17-18 to present a special colloquium entitled Physics Education: A High School-University Partnership and to meet with local science teachers. Deborah was a member of the first tutorial class at Ohio University and is now recognized as an outstanding high school science teacher. She teaches at Oakton High School in Herndon, VA and was awarded the 2009 AAPT Award for Excellence in Pre-College Physics Teaching. Deborah's visit and interaction with local teachers was coordinated by Mark Lucas. She is a strong proponent of active teaching of science including involving students in research and gives workshops illustrating these techniques. The faculty enjoyed informal discussion with Deborah at a social gathering Monday night.

1990-1999

Benjamin Tan, who was in our graduate program in 1990, retired from teaching at Chiayi Teachers College in Chiayi, Taiwan. He now lives in Linkou. While at Ohio University Benjamin did research in experimental acoustics with Burt Stumpf.

Deborah Roudebush relaxing with retired faculty Roger Rollins, Louis Wright, David Onley and Burt Stumpf.

Raul Esquivel-Sirvent, PhD 1995, on the faculty at the Institute of Physics, National University of Mexico (UNAM) visited the department in February to present a CMSS seminar entitled, *Casimir forces in nano devices*. Raul did his doctoral research under the joint direction of Seung Yun of our department and Doug Green of the Department of Geology at Ohio University. Raul was on sabbatical at Northwestern University in Chicago.

Markus Löcher, PhD 1997, has accepted a faculty position in the Business and Economics Department of the Berlin School of Economics and Law in October, 2011. Markus did his doctoral research with Earle Hunt in the field of non-linear dynamics.

Zainuriah Hassan, PhD 1998, reports that in 2009 she was promoted to Professor in the School of Physics of the Universiti Sains Malaysia and in 2010 she was appointed Dean of the School of Physics. She reports that life has been hectic professionally but that she has married again in April of 2011 to a colleague in her department. Zainuriah remains active in research and will be presenting an invited talk in India entitled, *Fabrication and characterization of nanostructured porous GaN on Si(111)**, at the Asia-Pacific Workshop on Materials Characterization (Sept 22-24, 2011). Zainuriah did her doctoral research with Marty Kordesch.

Jarrod Schiffbauer, BS (HTC) 1998, MS 2002, reports that he has successfully defended his doctoral dissertation at West Virginia University in October of 2010. He is collaborating on some projects related to various electrokinetic effects in micro-nano-fluidic systems, both theory and experiments. He is currently visiting Gilad Yossifon's group at the Technion in Haifa, Israel for a month and is anticipating a postdoctoral position there.

Derek W. Beck, BS (HTC) 1999, moved back to Los Angeles in 2008 to pursue filmmaking as both a writer and director. He has dedicated much of the last three years to writing a previously secret historical project, inspired by his time spent in Boston while studying at the Massachusetts Institute of Technology, while continuing his service to the US Air Force (he was recently promoted to major in the USAF Reserves). He has only recently unveiled his project as the nonfiction history book entitled *1775*. *1775* follows the forgotten Dr. Joseph Warren through the beginning of the American Revolution in Boston, from the Boston Tea Party to Paul Revere's Ride and the Battle of Bunker Hill (Warren gave Paul Revere his orders for that famous ride!). The story then shifts to George Washington and culminates in his driving the British from Boston. *1775* presents new conclusions based on original source material as well as entirely new research utilizing previously unknown material. *1775* is a completed and fully revised manuscript, and Derek is presently shopping it around with literary agents and has received considerable interest, but no deals yet. He welcomes any leads and support from interested alumni. If you are wondering what *1775* has to do with Derek's pursuit of filmmaking: his aspiration is to bring it to HBO as a miniseries, similar to Band of Brothers, the recent John Adams, or the upcoming *1776* miniseries. For more information, check out the book site at **www.1775thebook**.com where you can find sample excerpts, follow the publication progress, or connect with facebook and twitter.

2000-present

Bassem Sabra, PhD 2000, has been promoted to Associate Professor at Notre Dame University in Louaize, Lebanon. He also reports that there is now a separate department of Physics and Astronomy in contrast to the past where all the sciences were combined into a single department. Furthermore, Bassem reports that their new M.S. in astrophysics is developing nicely and they even have plans to build an observatory. Bassem did his doctoral research in astrophysics under the guidance of Joe Shields.

Mark Little, PhD 2001, will begin a new job with International Rectifier in St. Paul, Minnesota as a characterization engineer at their epi-GaN wafer facilty. The end use of the wafers is for GaN based HEMT's (high electron mobility transistors). Mark did his doctoral research with Marty Kordesch.

Suhita Nadkarni, PhD 2005, now at the Salk Institute in California co-authored a paper in the Public Library of Sciences (PLoS, Computational Biology) entitled *Modelling vesicular release at hippocampal synapses*. Suhita did her doctoral research with Peter Jung.

Ghanim Ullah, PhD 2006, has taken a postdoctoral position at the Theoretical Biology and Biophysics Division at Los Alamos National Laboratory. He recently co-authored a paper in the Public Library of Sciences (PLoS, Computational Biology) entitled *Assimilating seizure dynamics*. Ghanim did his doctoral research in biophysics with Peter Jung.

Andreas Weichselbaum, PhD 2004, currently at the Arnold Sommerfeld Center for Theoretical Physics at LMU in Munich, has co-authored a recent article in Physical Review Letters entitled *Many-Body Dynamics of Exciton Creation in a Quantum Dot by Optical Absorption: A Quantum Quench towards Kondo Correlations*. One of his co-authors is Sasha Govorov of our department. Andreas earned his PhD in condensed matter theory working with Sergio Ulloa.

Chris Bade, PhD 2006, is changing jobs. He was accepted for transfer into the Meteorology and Oceanography Officer (METOC or OCEANO) community in the Navy. He reports that his next job will be working in the Anti-Submarine Warfare (ASW) field in Yokosuka, Japan. He will be working in teams that go out on Naval vessels supporting the battle-groups with ASW advice and recommendations. Chris will be in Yokosuka for the next 3 years with his wife, Cheryl and pets. Chris was promoted to the rank of Lieutenant (third officer rank or O3) on the 1st of May and is considering going to the Naval Postgraduate School in Monterrey CA for a Master's Degree in Meteorology and Physical Oceanography. Chis did his doctoral research in experimental nuclear physics under the direction of Ken Hicks.

Deepshikha Shukla, PhD 2006, and **Shaleen Shukla**, PhD 2008, welcomed a new addition to their family in February 2011. On February 21, Deepshikha gave birth to a son, Neelay. Shaleen has accepted a lecturer position at James Madison University for the 2011-12 academic year. Note that **Anca** (PhD 2004) and **Chris** (PhD 2006) **Constantin** are also faculty at JMU.

Saima Khan, PhD 2007, reports that after working as a postdoctoral Fellow from Jan 2008-March 2009 in the department of Civil Engineering and Environmental Sciences at Ohio University she took off some time for the birth of a son, Baryal Khan, in May 2010. She and her husband, **Aurangzeb Khan**, PhD 2006, returned to Pakistan in July 2010. The Khan's then accepted faculty positions at the University of Tabuk (KSA) in Saudi Arabia. After some delay, they began their position at KSA in May 2011. Saima and Aurangzeb both did their doctoral research under the direction of Marty Kordesch.

Babatunde Moses Oginni, PhD 2008, has accepted a permanent position with Areva Corporation in Meriden, Connecticut. After doing his doctoral research in experimental nuclear physics under the direction of Steve Grimes, Moses held a post-doctoral position at the University of North Carolina.

Daniel Hoy, BS 2008, is completing a Masters in Physics at Ohio State University in the area of Spintronics. A paper is soon to appear on ferromagnetic semiconductor heterostructures. Daniel will be looking for a technology/ engineering job in the Columbus area.

Aderemi Adekola, PhD 2009, will be moving to a permanent position at the Areva Corporation, located in Meriden, Connecticut. He will be starting this October and will be working in the Nuclear Measurements Division. His current position is a postdoctoral appointment at Oak Ridge National Laboratory, through Rutgers University. Aderemi's doctoral work in experimental nuclear physics was performed under the supervision of Carl Brune.

Fakharul Inam, PhD 2009, has joined the faculty of LUMS School of Science and Engineering in Lahore, Pakistan as an Assistant Professor. Fakharum did his MSc in Physics from Punjab University in 1999 and a one year diploma in Condensed Matter Physics from Abdus Salam ICTP in 2002 before entering the doctoral program at Ohio University. Fakharul's doctoral research in condensed matter theory was directed by David Drabold.

Chieh-Jen (Jerry) Yang, PhD 2010, is a postdoctoral researcher at the University of Arizona. He is doing work on nuclear structure with Profs. Bruce Barrett and Bira van Kolck. Jerry did his doctoral research in nuclear theory with Daniel Phillips.

Joel Vaughn, PhD 2010, works at Diamond Innovations in Worthington, Ohio in the Advanced Development team for Stratapax (the Oil and Gas Division). A goal is to develop better Polycrystaline Diamond Cutters for oil and gas drilling. Joel reports that he has 4 patent applications being written up for submission. Joel's doctoral research was directed by Marty Kordesch.

Divya Swaminathan, PhD 2010, has taken a postdoctoral position at the Department of Neurobiology and Behavior at UC Irvine. Divya did her doctoral research with Peter Jung.

Recent Graduates

Daniel Bergman, BS 2011 in Applied Physics with a Math Minor will be entering graduate school at the University of Toledo.

Tianjiao Chen, BS 2011 in Engineering Physics plus Mechanical Engineering (HTC) is entering graduate school at MIT.

Sai Dong, BS 2011 in Physics is applying for graduate school.

Courtney Gusbar, BS 2011 in Astrophysics with a Math Minor will be entering the workforce.

Robert Hatton, BS 2011 in Applied Physics received Departmental Honors and will be biking to Nova Scotia and entering the workforce.

Anthony Lamerato, BS 2011 in Astrophysics will be entering the workforce in Detroit.

James Ralston, BS 2011 in Physics (HTC) will be going to graduate school at Ohio State University.

Greg Rosen, BS 2011 in Physics (HTC) will be going to graduate school at the University of Illinois at Urbana-Champaign.

Kevin Sweeney, BS 2011 in Astrophysics received Departmental Honors and will be entering the workforce.

Abhijit Chinchore, MS 2001, completed a Masters project with Art Smith and is now working on his dissertation.

Kuangmin Li, MS 2011, completed a Masters project with Gang Chen.

Nicole Free, MS 2011, completed a Masters Thesis with Joe Shields and now has a job as a software developer with the Reynolds and Reynolds Company in Dayton.

Norman Palma, MS 2011, completed a Masters Thesis with Markus Böttcher and returned to his lecturer position at the Universidad Autonoma de Honduras.

Heath Kersell, MS 2011, completed a Masters Thesis on molecular machines with Saw Hla and continues in the doctoral program at Ohio University.

Kenneth Moore, MS 2011, completed a Masters project entitled *The Equation of State of Supernova Matter* with Prakash. Kenneth has a job with the software firm PC-BSD.

Kellen Murphy, MS 2011, completed a Masters Thesis in nuclear theory under the direction of Daniel Phillips. He is now in the doctoral program working with Doug Clowe.

Dustin Keller, PhD 2010 in experimental nuclear physics, is now a postdoctoral Fellow at Jefferson National Lab in association with Ohio University. Dustin did his doctoral research under the direction of Ken Hicks.

Anh Ngo, PhD 2010 in condensed matter theory, stayed on as a postdoctoral Fellow at Ohio University until July, 2011. He is currently a postdoctoral Fellow with the group of Juana Moreno and Mark Jarrell at Louisiana State University. Anh did his doctoral research under the direction of Sergio Ulloa.

Gayani Perera, PhD 2011, had several postdoctoral offers, but decided to accept a SPIRE postdoctoral position with Saw Hla at Ohio University. Gayani performed her doctoral research under the direction of Saw Hla and her dissertation was entitled, *STM Investigations of Charge-Transfer and Spintronic Molecular Systems*.

Carol Abott, PhD 2011, has taken a position at Ohio University-Lancaster. She did her interdisciplinary doctoral research under the direction of Marty Kordesch with a dissertation entitled, *A 21st Century Investigation of the Historical, Musical and Acoustical Contexts of a 19th Century Comic Opera, Schermania in America, Composed by Dr. Gabriel Miesse, Jr*.

Mohammad Ebdah, PhD 2011, will be joining Intel in Oregon. He did his doctoral research under the direction of Marty Kordesch. His dissertation was entitled, *Engineering of the Optical, Structural, Electrical, and Magnetic Properties of Oxides and Nitrides of In-Ga-Zn Films using Nanotechnology*.

Wenzhi Lin, PhD 2011, is holding a short-term postdoctoral position at Ohio University to finish up some projects that arose out of his doctoral dissertation, *Growth and Scanning Tunneling Microscopy Studies of Magnetic Films on Semiconductors and Development of Molecular Beam Epitaxy/Pulsed Laser Deposition and Cryogenic Spin-Polarized Scanning Tunneling Microscopy System*. His doctoral research was directed by Art Smith.

Daniel Sayre, PhD 2011, started a postdoctoral position at Lawrence Livermore National Laboratory in July. He reports that he and his wife Crina (former postdoctoral researcher in Chemistry) have settled into a new apartment in Pleasanton and the initial onslaught of training is tapering off. His new job will be part data analysis, part instrumentation, with the focus being on determining the low-energy ($E < 1$ MeV) portion of the neutron spectrum that results from the implosion of a DT capsule at the National Ignition Facility (NIF). There is much interest in the astrophysics community for using NIF as a tool to perform nuclear reactions in a star-like environment. Preceding this science program, the nuclear diagnostics need to be well characterized, and a reliable determination of the low-energy neutron spectrum will be very important for the study of s-process reactions. Daniel reports that after initially focusing on the instruments, he hopes to have a part in the scientific application of them. Daniel's doctoral research in experimental nuclear physics was directed by Carl Brune.

Anton Wiranata, PhD 2011, succesfully defended his doctoral dissertation entitled *Transport Properties of Interacting Hadrons* under the direction of Prakash in July 2011. He received the Huada Postdoctoral Fellowship in Nuclear Theory, a joint position at the Lawrence Berkeley laboratory and the Huazhong Normal University, Wuhan, China and will take up this position starting in Septemper, 2011.

Gifts to Ohio University

Please consider designating the Department of Physics and Astronomy when you give your gift to Ohio University. The Department needs money for scholarships, books, travel funds for students, support of student research, and paying the expenses of visiting speakers. In this list, the greatest need is for undergraduate major scholarships. Our major endowment funds include:

- **John Edwards Scholarship Fund**—Distinguished Professor John Edwards left a bequest of approximately $300,000 to endow this scholarship fund. The Scholarships are given to majors who have financial need and have demonstrated some initial success at Ohio University.
- **Robert Gescy Scholarhip Fund**—Endowed by Jeanette Grasselli-Brown in memory of her brother who was a physics student.
- **Darrell Huwe Scholarship Fund**—Endowed by family and friends in memory of Professor Darrell Huwe. The scholarship is preferentially given to students from a rural background with financial need.
- **James Shipman Scholarship Fund**—This fund was initiated by Professor Jim Shipman and Will Konneker (MS 1947) in the 1970s and has been supplemented greatly since then by Jim Shipman using money generated from his very successful physical science textbook. It provides our primary support for incoming freshman majors.
- **Abhishek Singh Scholarship Endowment**—This endowment has been launched with gifts from faculty, staff and students of the department along with contributions from friends of Abhishek to honor his memory.
- **Mark Grimes Memorial Fund**—Created to honor Mark Grimes and his interest in the undergraduate physics program. The purpose is to provide enrichment of the undergraduate experience of physics majors.
- **Edward R Sanford Astronomy Fund**—Created to honor Professor Sanford, the income from this endowed fund is used in support of the astronomy program in the department.
- **Department of Physics and Astronomy Fund**—A general endowed fund with major contributions from Professors Wright and Rollins.

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Signature _____ Date _____

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Alumni News

We like to maintain contact with our alumni and friends and we would like to help you stay in contact as well. In particular, if there are any changes or new developments in your career or in your family that you wish to share, please let us know by email to wright@ohio.edu or a letter to the address above. Doctoral graduates should check out our webpage entitled Ph.D. **Alumni: Where Are They Now?** found under People on the departmental website www.phy.ohiou.edu. We are hoping to hear from you.