



# Journey to the stars

RIT is becoming a renowned center for astrophysics

In the next decade, breakthroughs in astrophysics could reshape our understanding of the universe. Observations of gravity waves could prove Einstein's theory of general relativity, or tip physics on its head. Other missions using Earth-based telescopes and space probes will pry into dark matter (an unknown material that makes up about 85 percent of the universe) and dark energy (a mysterious force linked to the expansion of the universe).

RIT is gaining a reputation in the realm of astrophysics at this exciting time, with faculty contributing to research initiatives that blend science fiction and reality.

If you weren't looking, it might seem that astrophysics popped up overnight at RIT, complete with an internationally recognized group of scientists and a doctoral program in the works.

By its nature, astrophysics combines physics, math and imaging science, and, increasingly, computer science. It brings together scientists from different disciplines within the College of Science and the B. Thomas Golisano College of Computing and Information Sciences to explore young and dying stars, centers of galaxies and black holes, and the technology to make new observations.

"Astrophysics – the physics of the universe – is an exciting area because it touches the most challenging questions that face contemporary physics from the very small to the very large," says David Axon, head of RIT's Department of Physics.

Adds Ian Gatley, Dean of the College of Science: "Astrophysics is a discipline where learning by doing is absolutely key. It involves building technology, using tech-

Joel Kastner and his team observed this planetary nebula, known as the Ant Nebula, in 2004 using the Chandra X-ray Observatory. Chandra's data are shown in blue, while green and red are optical and infrared data from the Hubble Space Telescope. (Image credits: X-ray: NASA/CXC/RIT/J. Kastner et al.)

nology and modeling phenomena using computers, and all of those are really very big issues indeed for RIT and its students."

## In the beginning

Astrophysics at RIT got a boost when Gatley joined the university in 1997 as director of the Chester F. Carlson Center for Imaging Science. Gatley, an internationally known scientist, may be best known for building one of the first multi-pixel infrared cameras used for astronomical research. While working as a lead astronomer at the



David Axon

Stefi Baum

Manasse Mbonye

David Merritt

National Optical Astronomy Observatories, Gatley devised a camera adapting infrared detectors from the military to point upward to penetrate the dust in interstellar space.

Gatley's passion for adapting technology to make new kinds of measurements led to new research opportunities at RIT beginning with an initiative to process data taken from a remotely operated telescope at the South Pole and the early stages of the Stratospheric Observatory for Infrared Astronomy (SOFIA), a project that RIT's Laboratory for Imaging Algorithms and Systems in the Center for Imaging Science is involved with today.

## The 'A' team

By 2000, the basic foundation for astrophysics research at RIT was in place with the presence of Gatley, Joel Kastner, a world expert on planetary nebula; Zoran Ninkov, a specialist in new sensor technology for astronomical imaging; and Michael Richmond, director of the RIT Observatory. Richmond contributes to the Sloan Digital Sky Survey, a ground-based project to digitally map the sky, and the Super Nova Acceleration Probe, a future endeavor to understand the dark energy linked to the universe's acceleration.

A core astrophysics group came together in the intervening years through the addition of seasoned scientists, internationally known and well reputed: Axon, previously affiliated with the Space Telescope Science Institute in Baltimore and the University of Hertfordshire, England, had written a paper with Gatley and knew David Merritt, an expert on galactic nuclei and black holes who came to RIT from Rutgers University. Merritt, in turn, knew Manuela Campanelli and Carlos Lousto, experts in numerical relativity simulations of black hole mergers, who, along with Yosef Zlochower, joined RIT from the University of Texas at Brownsville (see related story, page 20). Axon recruited Andrew Robinson, an expert in active galactic nuclei and polarimetry, a technique used to measure light in space, from the University of Hertfordshire, England. Manasse Mbonye, a relativistic astrophysicist

specializing in theoretical cosmology and black hole physics, came to RIT from the University of Michigan and spent a year at NASA-Goddard Space Flight Center.

Axon's connections also led Stefi Baum, now professor and director of the Carlson Center for Imaging Science, and Chris O'Dea to join RIT from the Space Telescope Science Institute, where they all had contributed to the Hubble Space Telescope. Baum had also worked with Don Figer, a leading instrumentalist in next-generation sensing technologies, at the Space Telescope Science Institute and recruited him to head the Rochester Imaging Detector Laboratory in RIT's Center for Imaging Science.

"All the players we've brought in were already established in the international astronomy community and this has allowed us to create a baseline that is already recognized by our peers," says Axon. "This was not achieved by chance, but by careful networking."

"Of equal significance, we have recruited fine young postdocs to work with this permanent core of faculty who give momentum to the research," he adds.

The reputations, publication records and grant-proposal writing expertise of the astrophysics faculty have helped them secure significant external funding from NASA and the National Science Foundation to support their research. Current funding totals approximately \$3 million. In the last five years, these scientists have won approximately \$17 million in funded research.

## Astrophysics Ph.D.

Pending state approval, RIT will launch its fifth doctoral program, in astrophysical sciences and technology (AST), in fall 2008. The program will depart from traditional astrophysical studies that focus mainly on theoretical and observational aspects of the discipline by adding the characteristic RIT twist of technology and applied science. An equal emphasis on theory, observational astronomy, and sensor and instrument development will set RIT's program apart.

Students will have the opportunity to earn masters' and doctoral degrees in three

tracks: the emerging field of astro-informatics and computational astrophysics; astronomical instrumentation and development of new technologies for application in astronomy and space science; and astrophysics. The program will draw heavily upon faculty from the Carlson Center for Imaging Science, the Department of Physics and the School for Mathematical Sciences.

"The breadth of the program we have here is extremely large," Axon says. "We go all the way from the fundamentals of tackling Einstein's field equations on supercomputers to how galaxies are assembled and how black holes work and grow through to the technology side of how we develop the detectors needed to make these investigations and those at the frontiers of cosmology possible."

## The RIT edge

"The AST program is a good match to RIT because of the program's dual emphasis on the 'end result' – groundbreaking science and the 'getting there' – developing the technology required to get the science done," says Kastner, who is on sabbatical at the Laboratoire d'Astrophysique de Grenoble in Grenoble, France. "At a place like RIT, one need not take precedence over the other. In my view, the same can't be said for very many research university astronomy programs, where generally the emphasis is on the Ph.D. theses that represent cutting-edge science. The supporting technology is often not given the same status."

The technological emphasis will give graduates from the AST program an edge. In addition to academic and research positions, graduates will have opportunities in a wide range of technical areas, including remote sensing, informatics, the aerospace industry, homeland security, computer technology and even business and finance.

"Astronomy is one of the oldest and most inspiring of sciences," Baum says. "From the earliest of times, as humans gazed in awe upward in the darkness, they wondered about our place in a seemingly vast universe. They studied the changing cycle of the sun and moon and the patterns of the stars, and then applied that knowledge to meter time, measure distance, and navigate over land and sea. Astrophysics has that same reach today and we have the opportunity to expose all of RIT, from the undergraduates to our alumni, to the excitement that comes from participating in the quest to understand the cosmos."

Susan Gawlowicz '95

# Big Bang, black holes and gravity waves

## RIT scientists look into the nature of the universe

Editors note: Astrophysics research at RIT moves in two directions. One group of scientists focus on theoretical work. Another group, the observational astronomers and instrumentalists, is involved in experimental astrophysical research.

The following story takes a look at the work of the theory group. The fall issue of the magazine will feature the work of the observational astronomers and instrumentalists.

Scientists at RIT's Center for Computational Relativity and Gravitation (CCRG) are producing groundbreaking research in computational astrophysics and numerical relativity, a research field that uses supercomputers to solve the complex equations in Einstein's theory of general relativity.

The center was created in January 2007 when Manuela Campanelli and Carlos Lousto joined RIT's School of Mathematical Sciences with post-doctoral fellow Yosef Zlochower (now an assistant professor in the School of Mathematical Sciences) and Hiroyuki Nakano. Also affiliated is David Merritt, a preeminent theorist.

Alessia Gualandris, also a post-doctoral fellow at the center, works closely with Merritt. Josh Faber, an expert in neutron stars and black holes from the University of Chicago, joined the team in December 2007.

Campanelli, director of CCRG and professor in the School of Mathematical Sciences, caused an international stir in 2005 when she, Lousto and Zlochower, simulated the merging of two black holes on a supercomputer following Einstein's theory of general relativity. The team had spent three years working on the 10 interrelated equations for strong field gravity that comprise Einstein's famous theory connecting matter, space and time.

The ability to simulate gravity waves has hinged for decades on a fresh approach to solving Einstein's equations – and the development of sufficient computer power to simulate these waves. Einstein predicted that the collision of huge masses, such as black holes or neutron stars, would produce gravity waves.

Campanelli's team, then at the University of Texas at Brownsville, was one of two independent groups of scientists to solve the equations in the same year. In fact, both groups presented their findings at the same academic conference. Their success thrust



Members of the Center for Computational Relativity and Gravitation include, from left, Manuela Campanelli, Carlos Lousto, Hiroyuki Nakano, Hans-Peter Bischof and Yosef Zlochower.

Campanelli's team to the forefront of their field and helped to revive interest in the study of general relativity.

For some astrophysicists, the quest to observe gravity waves is akin to the fabled pursuit of the Holy Grail. This is because gravitational waves pass through matter that blocks light, or electro-magnetic radiation, and that is very interesting to scientists. Tracing gravity waves back in time might lead them to the other side of the Big Bang.

"We can look at the origin of the universe with gravitational waves and extract information that is otherwise blocked to electro-magnetic radiation," explains Lousto. "Gravitational waves can also detect unexpected objects – things beyond the imagination of theoretical physicists and mathematicians, and maybe even science fiction writers. Many times it happens in science that when you develop a new technique, you discover unexpected objects."

### Searching for gravity

Scientists expect to measure actual gravity waves for the first time within the next decade. Astrophysicists will compare real waves coming from space with simulated ones such as those generated by research produced by Campanelli's team.

Scientists from California Institute of Technology and MIT designed the ground-based detector known as the Laser Interferometer Gravitational Wave Observatory (LIGO) to measure the detailed form of gravitational waves. The National Science Foundation-funded project consists of two separate observatories that work in unison – one located in Livingston, La., and the other near Richland, Wash. The observatories became operational full-time in November 2005.

LIGO could identify gravity waves from the merger of two black holes in space as soon as 2013. When Advanced LIGO, the next phase, begins operation in 2012, the instrument's vision will extend from 3 million to 300 million years into the past. (The Big Bang is thought to have occurred 13.7 billion years ago.)

A complementary gravity-wave seeking initiative in space is the upcoming NASA/European Space Agency space mission Laser Interferometer Space Antenna (LISA) that will fish the universe for gravity waves. LISA is expected to launch in 2015.

"In order to confirm the detection of gravitational waves, scientists need the modeling of gravitational waves coming from space," Campanelli says. "They need to know what to look for in the data they

acquire, otherwise it will look like just noise. If you know what to look for, you can confirm the existence of gravitational waves. That's why they need all these theoretical predictions."

Research at the center will support both LIGO and LISA initiatives, placing RIT among some 50 institutions in the LIGO Scientific Collaboration. In a November 2007 interview with Discover magazine, Kip Thorne, the Feynman Professor of Theoretical Physics at Caltech, author of *Black Holes and Time Warps* and a driving force behind LIGO, points to Campanelli and Lousto's black-hole simulations as some of the most exciting research taking place.

Others agree. The June 2007 issue of *New Scientist* featured an article about the orbital spin of black holes that RIT scientists Campanelli, Lousto, Merritt and Zlochower had produced.

About the same time Discover published its interview with Thorne, Campanelli's team simulated three black holes evolving, orbiting and eventually colliding, another computational feat never before done. The simulation of multiple black holes tested the formalism initially built for two masses and confirmed a robust computer code free of limitations. The results revealed the distinct gravitational signature three black holes might produce. This simulation was processed using the center's new super computer cluster named "newHorizons."

"Gravity waves can also confirm the existence of black holes directly because they have a special signature," Lousto says. "That's what we're simulating. We are predicting a very specific signature of black hole encounters. And so, if we check that, there's a very strong evidence of the existence of black holes."

"It's very timely research because it's on the verge of discovery," Campanelli adds. "And what we do is critical for this discovery to happen. We expect this area to keep expanding because the detection of gravitational waves will be the birth of gravitational wave astronomy, a new kind of astronomy. There will be a lot of interest in the world."

Campanelli anticipates the center expanding in the near future to include scientists specializing in LIGO analysis of gravitational waveforms. This area of research within the field of numerical relativity bridges the gap between simulation and experimentation. It makes connections between the waveforms Campanelli's team models with real data, and provides a necessary link in the pursuit of gravity waves.

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## Big Bangs from supercomputers

When black holes crash into each other at the center of a galaxy, the safest place to be is on the other side of the computer simulating the drama.

Scientists at the Center for Computational Relativity and Gravitation simulate cataclysmic collisions and the evolution of galaxies using supercomputers to churn out computations that would sizzle the latest desktop model.

In fact, the center is home to one of the fastest computers in the world: gravitySimulator, a special-purpose machine David Merritt purchased in 2004 with \$600,000 from RIT, NASA and the National Science Foundation.

Merritt, a professor of physics, uses gravitySimulator to study gravitational forces causing black holes to form, evolve and interact with stars and to predict what happens after black holes collide.

The cluster contains 32 nodes, each housing a special-purpose accelerator board called a GRAPE, or GRAVity PipE-line, and processes data at the speed of 4 teraflops, or four trillion computations (floating point operations) per second. The GRAPEs, imported from Tokyo, are specially designed to carry out gravitational force calculations.

"GravitySimulator is 1,000 times faster than a standard desktop computer," says Hans-Peter Bischof, associate professor of computer science and member of CCRG. "The machine can handle four million particles – each representing a star. And for this kind of problem, that's enormous."

Bischof illustrates the data Merritt collects from the gravitySimulator using a visualization system he designed. His mini-movies are among the first to depict gravity-force calculations of such large size.

Merritt hopes to double the size of the three-year old cluster and use the gravitySimulator to visualize other components of galaxies, such as gas clouds.

Currently, he is tooling up to use gravitySimulator for the first stage of the Virtual Galaxy, a scheme to simulate the entire Milky Way on a star-by-star basis.

"This project probably won't be completed in my lifetime," Merritt says, "but we hope to be able to simulate the central bulge of the galaxy, roughly a billion stars, in the next few years."

A second computer cluster known as "newHorizons," unveiled in October 2007, will maintain the center's competitive level of research in computational astrophysics and numerical relativity, a research field dedicated to proving Einstein's theory of general relativity. This state-of-the-art computer was designed to compute the numerical-relativity evolution of binary black holes. The \$470,000 computer was purchased with funds from separate grants, including an award from the NSF Major Research Instrumentation Program won by Manuela Campanelli, the principal investigator on the grant, Carlos Lousto, Merritt and Yosef Zlochower.

The computer, built with hardware from California-based Western Scientific, boasts 85 nodes – each with its own dual processor – and four amounts of computing units per node and high-speed Infiniband interconnections.

Today's typical desktop computer has 2 gigabytes of memory. By comparison, each node in newHorizons has 16 gigabytes or a total of 1.4 terabytes of memory. In addition, infinite band technology makes the computer especially fast, moving "packages" of information with a lag time or latency of 12.9 microseconds. The computer, which will have 36 terabytes of storage space, will – like the gravitySimulator – operate at its maximum capacity 24 hours a day for four to five years.

"Other scientists have satellites and telescopes to do scientific research," says Zlochower, an assistant professor in the School of Mathematical Sciences. "We have supercomputers. It's how we implement and test ideas. And because our simulations can take weeks, we needed the fastest machine possible."

The two computers share an air-conditioned room that never rises above 62 degrees Fahrenheit. They were configured to maximize airflow and space between the clusters to prevent heat-related damage. An automated alert system connected to a heat sensor will detect a rise in room temperature. And, if the electricity fails, powerful back-up batteries will keep the computers going for 15 minutes, allowing the machines to shut down without damaging hardware or losing data.

Susan Gawlowicz '95

## Black holes and galaxies

Also affiliated with the Center for Relativity and Gravitation, Merritt, a preeminent theorist at RIT, focuses on galaxies and the supermassive black holes typically found at their centers. While Campanelli and Lousto are concerned with space-time around black holes, Merritt is concerned with the interplay between black holes and the galaxies in which they live. Merritt, a professor of physics, collaborated with his CCRG colleagues on a paper published last year in *Physical Review Letters* predicting how fast a black hole can be thrown or “kicked” out of its galaxy.

Merritt studies the evolution of star clusters and galaxies with a dedicated computer known as a gravitySimulator. Now three years old, the supercomputer was one of the first in the world built to study how gravitational forces cause black holes to form in the densest regions in the universe. Merritt’s work was featured in the cover story about black hole research in the May 2006 issue of *Astronomy*.

Merritt and colleague Laura Ferrarese from the University of Victoria in Australia made what many consider to be a major discovery known as the M-Sigma relationship – a connection between the mass of supermassive black holes and the mass of their host galaxies. Their findings imply that black holes and galaxy growth are closely related. Merritt and Ferrarese suggest that the energy released by black holes might regulate the growth and evolution of their host galaxy – a result having potentially important cosmological consequences.

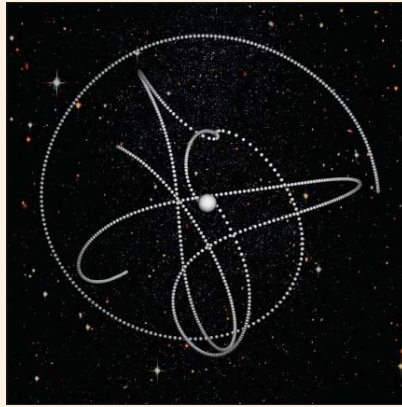
Merritt is also engaged in a long-term project called Virtual Galaxy to simulate the entire Milky Way galaxy, star by star.

“The astrophysics group is already unified,” Merritt says. “All of us are talking about the centers of galaxies where there are supermassive black holes from one point of view or another. There are lots of opportunities for cross-interaction.”

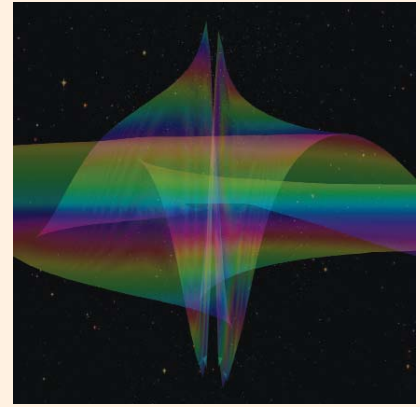
### From RIT to TV

In 2003, Merritt contacted Hans-Peter Bischof, associate professor of computer science, to write software visualizing his research. Now, a member of the CCRG team, Bischof, an expert in framework design, specializes in bringing black holes into view through computer graphics and animated movies illustrating the team’s results.

Some of Bischof’s images of black holes



Three black holes create interesting trajectories before final merging. This image was taken from a movie tracing the interaction of a trio of same-sized masses. Simulation by Manuela Campanelli, Carlos Lousto and Yosef Zlochower. Visualization by Hans-Peter Bischof. Background image: NASA, European Space Agency and The Hubble Heritage Team (Space Telescope Science Institute / Association of Universities for Research in Astronomy).



The collision of two black holes generates gravitational waves moving forward at the speed of light across the galaxy. Gravity waves, illustrated here, are warps in space-time and might provide clues to the origin of the universe. Simulation by Manuela Campanelli, Carlos Lousto and Yosef Zlochower. Visualization by Hans-Peter Bischof. Background image: NASA, European Space Agency and The Hubble Heritage Team (Space Telescope Science Institute / Association of Universities for Research in Astronomy).

simulated by Campanelli, Lousto, Zlochower and Merritt were used in the History Channel’s series *The Universe: Cosmic Holes*, which broadcast in December 2007.

“The science done at CCRG is very difficult to explain to the general public,” Bischof says. “A movie is one way to capture the essential information and let it speak for itself.”

### Big Bang and dark energy

Cosmology is another important area of astrophysics. It is the study of the entire universe and the behavior of its component parts. Currently, studies in theoretical cosmology fall to Manasse Mbonye, a relativistic astrophysicist who applies Einstein’s theory of general relativity to understanding space-time under extreme gravitational influences. Mbonye believes these properties can provide an understanding of the early universe and the nature of the Big Bang as well as the physics inside black holes.

“The interior of black holes may in some ways share attributes with the early universe,” he says.

Mbonye’s work in these areas is guided by his “cosmic equilibrium conjecture,” an idea maintaining that regions of infinite density and pressure known as singularities might not exist in space-time.

Mbonye’s conjecture implies that the

early universe may not have started from a physical singularity and that black hole interiors may be singularity-free. Based on this space-time paradigm, Mbonye searches for possible connections between black hole interiors and the early universe.

Mbonye also studies cosmic dynamics, including the current dark-energy driven cosmic acceleration. Being the only cosmologist at RIT doesn’t bother Mbonye, who takes a holistic look at the pending graduate program.

“Everything is complementary,” he says. “Our job here is to try to equip our students with the knowledge and understanding that we have of the kind of universe we live in. Each of us contributes a chunk of knowledge, and when you add those chunks in a complementary way you can create in the mind of a student a picture that comes as close as we can make it to understanding our world, our universe.”

“That’s how astrophysics works,” he continues. “That’s how science works. No one single area of physics can alone make you understand this reality.”

Susan Gawlowicz '95

For more information about RIT’s Center for Computational Relativity and Gravitation, visit <http://ccrg.rit.edu>.