A Newsletter from the Kavli Institute for Theoretical Physics at UC Santa Barbara

KITP

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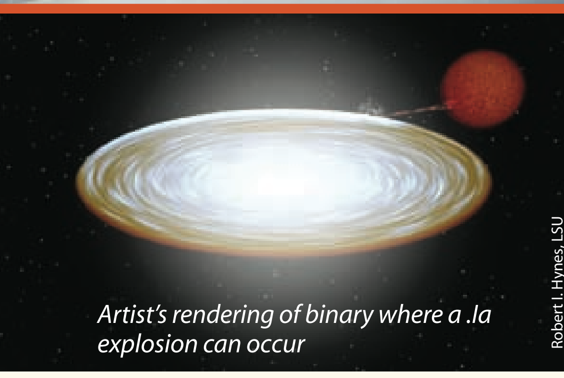


Artist's rendering of binary where a .Ia explosion can occur

Robert I. Hynes, LSU

Likely Discovery Of Faint and Fast Supernova Confirms Predicted Explosion

AN EXPLOSION—observable in theory, but never seen on the night sky–emerged a little over two years ago from calculations carried out by a team of astrophysicists, including KITP permanent member Lars Bildsten and postdoctoral fellow Nevin Weinberg, as well as UCSB physics graduate student Ken Shen and Bildsten's long-time Dutch collaborator Gijs Nelemans of Radboud University in Nijmegen. Those calculations enabled the team to predict the existence, in distant galaxies, of a new kind of exploding star or "supernova" that would—when detected—be fainter than most observed supernovae and would rise and fall in brightness in only a few weeks.

"As we talked about our work over the last two years, most astronomers in the audience reminded us that they had never seen such an event," said Bildsten. "We told them to keep looking!"

In the Nov. 5, 2009, "Express" edition of *Science* (the journal's online vehicle for expediting publication of particularly newsworthy developments), a UC Berkeley-based team, headed by postdoctoral fellow Dovi Poznanski, reported detection of a faint and fast event in a distant galaxy that likely represents the phenomenon whose existence the Bildsten group predicted.

Most stars end their lives sedately by collapsing into white dwarfs, with masses equivalent to the Sun's packed into a sphere with a radius akin to the Earth's. Though very dense, these objects (made of either a carbon-oxygen mixture or nearly pure helium) cool to temperatures so low that fusion reactions can no longer occur.

But in rare instances, two of these dwarf objects orbit each other so closely (orbiting every few minutes) that the helium from the lighter of the two gets pulled off by tidal forces and accumulates on the more massive carbon-oxygen white dwarf (as depicted above). This rare occurrence sets up conditions for explosive thermonuclear ignition and the consequent complete ejection of the accumulated helium ocean from the more massive dwarf. The plethora of unusual radioactive elements made in the rapid fusion of atoms leads to a bright light show from the freshly synthesized matter that lasts but a week or so.

Bright events from complete thermonuclear explosions of white dwarfs have been known for many decades, and are referred to as Type Ia supernovae. They are brighter than a whole galaxy for more than a month and are quite useful in cosmological studies.

The events predicted by the Bildsten team are only one-tenth as bright for one-tenth the time in comparison to Type Ia supernovae.

SEE **SUPERNOVA** ON PAGE 4

Earth's Climate: More Science Needed

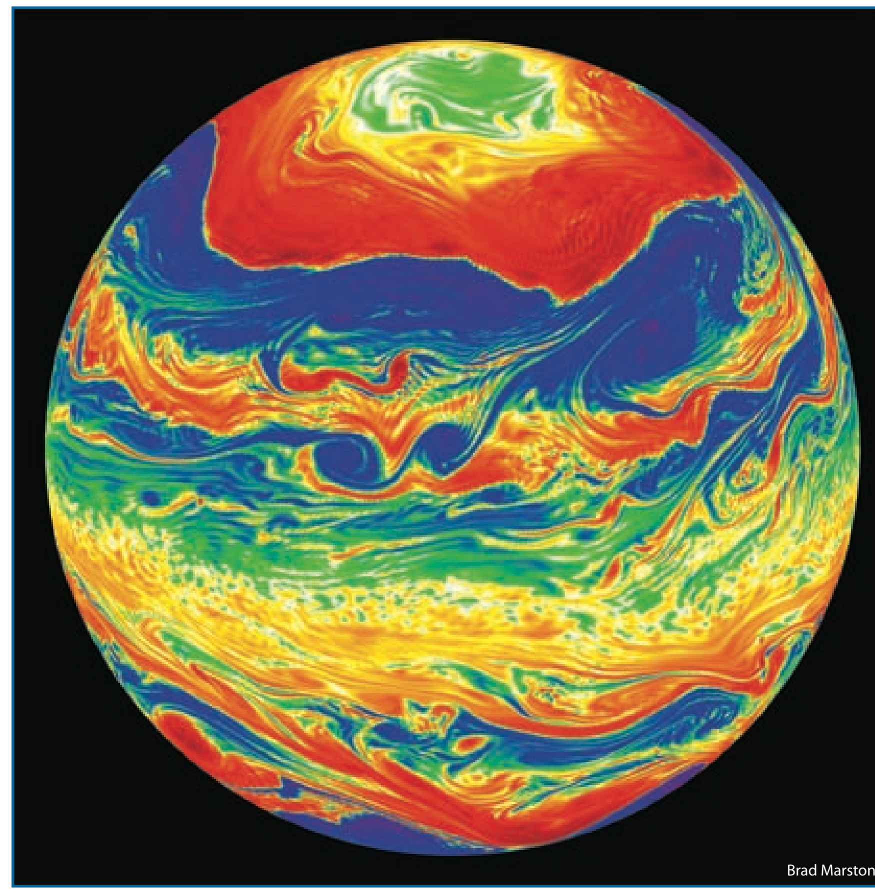
IF THERE WAS ONE OVERRIDING conclusion to be drawn from the KITP pioneering effort to look at "The Physics of Climate Change," it is "more science needed."

One is tempted to add "urgently needed," but the program's principal organizer, Brad Marston of Brown University, shies away from extremist and exhortative language when talking about climate change, especially in conjunction with isolated catastrophic events such as Hurricane Katrina. "Arguing from a single case is a poor way of reasoning scientifically," he said.

On the other hand, he notes, "Being told an isolated event can't be attributed to global warming does not mean that it isn't. The point is that we can't reason from one case. We need a pattern; and scientists need to look for patterns, and model them and do everything we do," said Marston. "It takes time and effort," he notes, "for a coherent story to emerge."

Indeed, making a coherent story of the "Physics of Climate Change" program does not work because good stories should have beginnings, middles, and ends. And this program was all about beginnings. It was, in a way, a program about how to have a program on the physics of climate change. Its profoundly exploratory nature signals, perhaps, the emergence of a new physics field.

At the outset of the week-long conference held in conjunction with the more than two months-long program, KITP director David Gross asked the assembled



Brad Marston

Even a simplified model of the Earth's atmosphere that has only two layers at different altitudes reproduces observed features of the general circulation such as jet streams, storm tracks, and trade winds. Colors in the image represent the wind vorticity averaged over the two levels.

SEE **EARTH'S CLIMATE** ON PAGE 6

In Honor of Mother, Son Endows Susan F. Gurley Chair In Theoretical Physics and Biology

Condensed Matter Theorist, Turned Theoretical Biologist, Named First Holder

Neil Campbell

Gus Gurley (l.) and Boris Shraiman

GUS GURLEY, co-founder of Santa Barbara based Digital Instruments (DI), has endowed a chair at the Kavli Institute for Theoretical Physics. The Susan F. Gurley Chair in Theoretical Physics and Biology honors the entrepreneur's mother. The first holder of the endowed chair is KITP permanent member Boris Shraiman.

David Gross, KITP Director, said, "I cannot emphasize enough how crucial Gus's gift is to our pioneering efforts to give direction to the newly emerging field of theoretical (or quantitative) biology."

The KITP runs scientific programs and conferences for the best scientists from around the world in order to address, in sustained fashion, edge research issues.

"The quality of our programming depends on the quality of our permanent members," said Gross, "because our permanent members shape the KITP programming experience, which in turn shapes the research direction of a given field globally. And the quality of our permanent members depends on our ability to attract the very best scientists in a given area to these positions.

"The Susan F. Gurley Chair is a powerful incentive that enables us to draw to the KITP leading scientific talent at the interface between physics and biology. Boris Shraiman is just such a scientist. He is immensely creative—one of the deepest thinking and most theoretically skilled of the leaders in this dynamic new field. His appointment sets a high standard for those who will hold this chair in years to come.

"Heartfelt thanks, to you, Gus Gurley, for having the perspicacity to see how very important endowing this chair is for the future vigor of our research efforts in theoretical biology," said Gross. "You have been a remarkable friend to the KITP. I treasure our long interaction and many conversations because your experience developing technology at the juncture of biology and physics makes you an expert able to offer invaluable insight and advice to the KITP as we develop what will likely prove to be a leading interdisciplinary direction for 21st-century science. You are as stimulating a conversant as you are generous a supporter."

John "Gus" Gurley graduated from UCSB with a 1978 bachelor's degree in physics and a 1983 master's degree in scientific instrumentation. The company Digital Instruments that he co-founded in 1987 with then UCSB physics professor Virgil Elings aimed to make the power of scanning probe microscopy readily available to scientists and engineers--enabling them to image and explore nanoscale features and structures unseen heretofore. The same year that they founded the company, they constructed and shipped the first commercially successful scanning tunneling microscope—the NanoScope.

Gurley designed the NanoScope and led the effort to develop its software. Thereafter he managed DI's new product development. He is one of the world's authorities on scanning-probe control systems.

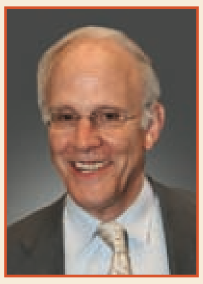
DI merged with Veeco Instruments in 1998. Since then Gurley has been exploring interests in systems neuroscience and neural networking.

In 2004 Gurley funded Distinguished Fellows in Biophysics, a three-year effort at KITP that was designed to attract and enable distinguished scientists to come for sustained visits and participation in KITP programming. He has also supported a UCSB lecture series in neuroscience.

A member of the KITP Director's Council (made up of leaders in fields other than physics, but with an interest in physics, who meet several times a year to advise the Director), Gurley was appointed a KITP Senior Fellow in 2007 "in recognition of his pivotal role in helping to establish the new field of theoretical biology at the KITP."

UCSB Chancellor Henry Yang emphasized Gurley's contribution in terms of support for the cultivation of top-notch talent at UCSB: "The Susan F. Gurley Chair will strengthen our tradition of excellence and will advance our research leadership in the field of theoretical biology. This special endowment

SEE **ENDOWED CHAIR** ON PAGE 2



Letter From the Director

Last April the KITP was reviewed by the NSF in a midterm review of our five-year contract. The first day of the site visit consisted of a presentation by us to the review committee. We have decided to make this presentation available to all via the KITP website (www.kitp.ucsb.edu).

We do this for two reasons.

First, the KITP is a national users' facility whose main purpose is to serve the general community of theoretical physics. Thus it is appropriate that we report on our functioning to the community as a whole. The KITP will only continue to flourish if the community of our colleagues is knowledgeable about, engaged in, involved with, and supportive of the Institute.

Second, we believe it is important to address some misconceptions that often arise with respect to the structure and the funding of the KITP. Some of these misconceptions, which I often encounter in conversations with colleagues, I will immediately address below. I urge all of you who are interested in the KITP to look at the presentation.

Permanent Members

Misconception: "UCSB is so lucky to have so many excellent NSF-funded positions at the KITP."

Reality: We are indeed lucky to have five such excellent permanent members at KITP. However, the NSF contract pays only ¼ of their academic salary (and no summer salary); the rest comes from UCSB. They are professors in the Physics Department, and they teach (although with a reduced load).

Kavli Funds

Misconception: "You are so lucky to have a big endowment from Kavli."

Reality: Almost all the generous gift from Fred Kavli went to build the new extension to the KITP. We have currently a very small endowment, which in good times can only cover a few percent of our budget. For the rest we are dependent on federal funding.

STIMULUS

Misconception: "You are so lucky to be federally funded. You must have lots of stimulus money."

Reality: We received no stimulus money. The NSF decided not to spend any stimulus money on supplementing existing contracts. In fact, in fiscal 2009 we received $300,000 less than in fiscal 2008.

UCSB

Misconception: "UCSB is so lucky to have the KITP in Santa Barbara, a bonanza for the university."

Reality: Although UCSB is indeed lucky that the KITP is situated in Santa Barbara, the University has greatly contributed to its success. It offers the NSF a 50 percent reduction in the overhead rate and contributes approximately $1,000,000 a year to our budget (the Director's salary, ¾ of the salaries of the permanent members, maintenance and infrastructure, *etc.*).

Budget

Misconception: "Given the vitality of the KITP and the increase in activity, you must be treated very well by the NSF. Your budget must have increased greatly over the last decade."

Reality: In 2001 we received (adjusted to 2009 dollars) $4,900,000 from the NSF. In fiscal 2009 we are receiving $4,300,000 a year from the NSF even though our activities (~12 programs a year, 1,000 visitors, 23,500 visitor days and new initiatives) have greatly expanded in response to the needs of the community.

You might wonder, given the clarifications above, how we are coping. The answer is—with difficulty. Some of our most successful initiatives, such as the "Rapid Response Program," are still funded by Kavli Institute funds that are running out. Also we have managed to support some of our biological initiatives with funds from NIH and Burroughs Wellcome. And, finally, our ability to cover the expenses of our participants has greatly declined. Our basic *per diem* support is, in adjusted dollars, about half of what it was 30 years ago. The fact that our colleagues continue to come is only because our programs are so exciting.

The only way this situation will turn around is if our user community makes its voice heard. The funding agencies* need to hear from our users.

David Gross

*The NSF can be reached at: abement@nsf.gov, hseidel@nsf.gov, jdehmer@nsf.gov, dcaldwel@nsf.gov.


Eva Silverstein (l.) and Shamit Kachru
Neil Campbell

Kachru and Silverstein Join KITP

SHAMIT KACHRU AND EVA SILVERSTEIN joined the Kavli Institute for Theoretical Physics in the fall of 2009, jointly filling one KITP permanent member position. Each holds half of two full-time positions. The other is as a visiting professor in the UCSB Department of Physics, while on leave from Stanford University, where they have served as faculty members for 12 years.

Kachru and Silverstein have broad interests in theoretical physics, with contributions to cosmology, particle physics, and string theory and its applications.

String theory is an ambitious theoretical enterprise that posits that the most fundamental constituent of physical reality is a vibrating string. Different vibrations of the string are thought to give rise to the different particles, such as the photon, electron, and quarks of the Standard Model of particle physics.

Among their diverse research efforts, both Silverstein and Kachru, working with collaborators, have found mechanisms connecting string theory to primordial cosmology, "a subject that has some sensitivity to the short-distance structure of quantum field theory and gravity through small fluctuations in the cosmic microwave background radiation," according to Silverstein.

Both researchers "motivate their work with physical questions, as opposed to particular techniques," said Silverstein. "We are interested in some of the questions that string theory set out to answer, such as: How does gravity work at very short distances? How does cosmology work at very early times? Is there a useful top-down formulation of particle physics? We are interested in those questions, and want to pursue whatever techniques answer those questions."

"One of the most exciting things about theoretical physics today," said Kachru, "is that answers to several of the most timely questions (the nature of electroweak symmetry breaking, the mechanism which explains early universe inflation, and the theory behind high temperature superconductivity, for example) may well involve interesting new strongly coupled quantum field theory dynamics of the sort that recent advances in string theory allow us to study qualitatively and, perhaps eventually, even quantitatively."

Kachru and Silverstein express "deep appreciation for the theorists at KITP and UCSB," with whom they have "enjoyed extensive interaction and collaboration." For instance, one of the primary papers on the "Landscape" of string vacua was a 2001 article that Kachru authored with UCSB physics professors Steve Giddings and Joe Polchinski. The latter is also a KITP permanent member.

Polchinski and Silverstein recently reported progress on the long-standing problem of providing a complete (*i.e.*, "non-perturbative") formulation of four-dimensional string vacua. Silverstein also maintains a very fruitful collaboration with UCSB physics professor Gary Horowitz on basic problems of gravitational physics.

Kachru and Silverstein have also collaborated on mathematical aspects of string theory with Sergei Gukov and David Morrison, UCSB professors of mathematics and physics.

What Kachru and Silverstein find especially attractive about the KITP are its panoply of physics programs and their accompanying promise of rich intellectual stimulation. Said Silverstein, "A special feature of the KITP is the way it naturally brings together many of the strongest contributors at a given time to a given problem in theoretical physics. Before a subject is fully understood, there are often competing views that are important to explore (or eliminate, as appropriate), and the programs here accomplish this very effectively."

Antidote to Boredom

"I get bored easily," Kachru said. "The prospect of being exposed to a constant stream of new ideas at KITP, and perhaps often finding new directions for research that interest me more than what I'm already doing, has great appeal."

For instance, Kachru enjoyed the summer 2009 mini-program on "Quantum Criticality and the AdS/CFT Correspondence," which explored newly realized convergences between condensed matter theory and string theory.

"Nobody is thinking," said Kachru, "that a condensed matter system is literally captured by strings in anti de Sitter [*i.e.*, 'AdS'] space. But there is a different way to compute quantities of interest in a field theory by using this duality, and that may be as good a starting point as the ones people have more normally used to model quantitatively new phenomena in these systems."

Both Kachru and Silverstein were also intrigued by the discussions in the other summer 2009 program on "The Physics of Higher Temperature Superconductivity."

"Here is Anderson talking," said Kachru, referring to Nobelist Phil Anderson of Princeton University. "And Fisher [i.e., Matthew Fisher, who recently moved from UCSB to Caltech] disagrees with what Anderson says. Subir [*i.e.*, Subir Sachdev of Harvard] believes that the central issue is a zero temperature quantum critical point, but various eminent people disagree with Subir. So," said Kachru, "what you hear here at the KITP are different competing points of view. They are all well represented by strong exponents. So somebody like me watching and listening to the discussions realizes there are competing views. I understand that what I am hearing are opinions rather than facts. That is the great thing about tuning into these presentations at the KITP, the opportunity to experience dueling ideas."

Said Silverstein, "I enjoyed this workshop tremendously precisely because I was not working in this area. It was all new to me." Such a program affords, she said, "a very easy mechanism for hearing about the problems of the subject in a way that gets you up to speed very fast.

"One of the real benefits of being a theorist," said Silverstein, "is that you can so readily think about all these different things. It is a trade-off, of course: there are obvious downsides to the speculation intrinsic in theory, so we should make use of its flexibility and freedom from programmatics."

Experimentalists encumbered by the necessity of large investments in laboratory facilities and long commitment for the conduct of experiments cannot so easily afford the same wide-ranging work style. For those so inclined, such as Kachru and Silverstein, the strong appeal of the KITP is that it facilitates and enhances intellectual versatility.

Silverstein and Kachru majored in physics at Harvard. Though undergraduates there at roughly the same time (he graduated in 1990; and she, in 1992), they didn't really get to know each other till graduate school in physics at Princeton University, where both had the same Ph.D. advisor, Edward Witten, of the Institute for Advanced Study. The two got married in 1999.

After spending time as a prestigious Junior Fellow at Harvard in 1994-95, Kachru along with Silverstein joined the theory group at Rutgers University in New Jersey. And both were appointed members of the Institute for Advanced Study in Princeton in 1999, the same year that Silverstein was named a John D. and Catherine T. MacArthur Foundation Fellow.

Appointed assistant professor at the Stanford Linear Accelerator Center (SLAC) in 1997, Silverstein was promoted in 2001 to associate professor (jointly in the Stanford physics department and SLAC) and promoted again in 2006 to full professor.

Kachru, moving from Berkeley, joined the Stanford faculty in 1999 and was promoted to a tenured joint appointment between the physics department and SLAC two years later. He also was promoted to full professor in 2006. Both express great admiration for close colleagues at Stanford and SLAC, many of whom also participate heavily in KITP programs.

Between them, Kachru and Silverstein have been awarded honors too numerous for individual mention in an article announcing both their appointments.

Said KITP Director David Gross, "We really could not have done better than appointing two of the very brightest lights of their generation. They are spectacular physicists. We are fortunate to have Eva and Shamit as colleagues, but I think that this opportunity for great intellectual stimulation is very good for them at this stage of their careers. I am delighted too that they are sharing a permanent member position at KITP—a first for us!"

Endowed Chair

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enhances the stature of our campus and will help us continue to attract and retain top faculty and advance the frontiers of this important field. Thank you, Gus Gurley, for your extraordinary commitment to the future of scientific excellence at UC Santa Barbara."

Earnings on the endowment for the Susan F. Gurley Chair will provide discretionary funds to enable its holder to support new initiatives in conjunction with the holder's research and allied KITP programming, as well as related public outreach efforts. The Chair, in other words, provides its holder with the means to be more creative, imaginative, and flexible, and therefore more productive.

Shraiman said, "This chair is not for me, but for the KITP. It is a real honor to be given the opportunity to interpret what the interface between theoretical physics and biology might be. I am not unaware of the great responsibility signified by the creation of this chair. KITP programming can appreciably affect the way the interface between theoretical physics and biology evolves."

Originally a condensed matter physicist, Shraiman made fundamental contributions to the theory of turbulence, chaos, pattern formation, magnetism and superconductivity, before turning in recent years to biophysics.

His life-sciences-oriented research of late has focused on fundamental issues in morphogenesis (such as the role of intercellular interactions in regulation of growth) and in population genetics (the effect of genetic interactions on the dynamics of natural selection).

Shraiman joined the KITP as permanent

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What Does Theoretical Physics Bring to Biology?

First Incumbent of Susan F. Gurley Chair Discusses Ideas That Animate His Research

THE KITP'S NEW professorship, endowed by entrepreneur Gus Gurley in honor of his mother, is called the "Susan F. Gurley Chair in Theoretical Physics and Biology. Why "theoretical physics and biology"? The chair's first incumbent, Boris Shraiman, addresses that question by first observing, "Biophysics is changing very rapidly.

"In the past," he said, "biophysics was rather well defined. Physicists studied the physical properties of molecules and cells. For example, protein folding is clearly a physics problem. There are interactions, and you look for essentially a ground state for the fold that minimizes free energy."

Another example of biophysics is the Hodgkin-Huxley model, according to Shraiman, "a beautiful combination of theory and experiment which established the mechanism for action potentials in axons," the projecting parts of nerve cells that conduct impulses from the cells. "Still," said Shraiman, "that work clearly deals with physical phenomena—electric currents and voltages—even though the phenomena are happening within cells."

Second Wave Driven by Data

Hodgkin-Huxley exemplifies biophysics 50 years ago. "What is happening now," said Shraiman, "is a second wave at the interface of physics and biology, driven by the overwhelming amount of data that now characterizes research in the life sciences."

Sequencing techniques keep improving, and the improvements in turn foster a steady and almost exponential increase in data: genomes of different species enable inter-species comparisons; and genomes of different individuals enable intra-species comparisons.

"Amazing," said Shraiman of the mounting mass of data, "and 'amazing' how little we learn from all this data." He points to the some million differences in the genetic code for two sequenced individuals, DNA discoverer James Watson and Stanford bioengineer Steve Quake. "The great dream," said Shraiman, "has been genetic medicine that will tell us whether a given individual will develop a given condition. But these genetic variants do not easily translate into phenotypes."

Genetic variants determine the individual's "genotype," a blueprint that in turn determines the "phenotype" or the actual features and properties of the organism. As an architectural blueprint does not account for all of the interpretive and selected actions entailed in the dynamic process of actually constructing a building, so similarly is the relationship between genotypes and their phenotypic manifestations.

Said Shraiman, "When scientists manage to identify the alleles by gene variance that contribute to a given disease, what typically happens is that those alleles contribute very little. They explain a very small fraction of cases and leave most unexplained." (An "allele" is one of a set of different forms for a given gene.)

"Alleles don't contribute alone but in combinations," said Shraiman, *i.e.*, "interactions between many genetic variants determine the phenotype. We are only beginning to develop the tools to disentangle interactions and map the complex, multi-dimensional relation between the genotype and the phenotype."

Need for Numbers

"Whenever you encounter complexity," said Shraiman, "a good tool is being more quantitative. There is now consensus in the biology community that biology collectively has to become more quantitative. And, then, of course, comes the question, how does one accomplish that?"

One answer is through viruses. They afford a simple model with comparatively few genes and a model system with (again comparatively speaking) rapid evolutionary dynamics. "There is no better way of trying to uncover the causal connection [between genotype and phenotype through interacting genes]," said Shraiman, "than through access to this dynamical data."

Richard Neher, KITP postdoctoral fellow working with Shraiman and recently named 2009 Harvey L. Karp Discovery Award recipient, has focused on the fact that to develop drug resistance a virus must generate not a single mutation, but a dozen mutations. Certain alleles (gene variants) will deliver an advantage in terms of drug resistance independent of what else is in the genome, but certain other alleles will only work well if in the company of "good friends," so to speak. In other words, certain gene variants have to occur in the right combination in order to work.

Neher in his KITP talk "Sex, Viruses, and the Statistical Physics of Evolution" compared that "in-concert" operation of alleles to a "team" sport such as soccer where the quality of the team depends not only on the performance of individual players, but also on the way they work together.

"Once you have this complexity of interactions," said Shraiman, "then the fundamental question is, 'What is the effect of recombination?'"—*i.e.*, sexual reproduction, which takes genes and reshuffles them. To recur to the sporting analogy, two very good teams can be reshuffled to yield a poor team.

"If you think, as physicists like to do, of a limit where a lot of recombination takes place, then it is intuitively clear, and can be shown mathematically, that these alleles start behaving independently in the sense that if you keep breaking up the teams, and still select the best, you are going to select genes that are beneficial independent of the background (of any other gene). These are genes that work well in all circumstances (all-stars)."

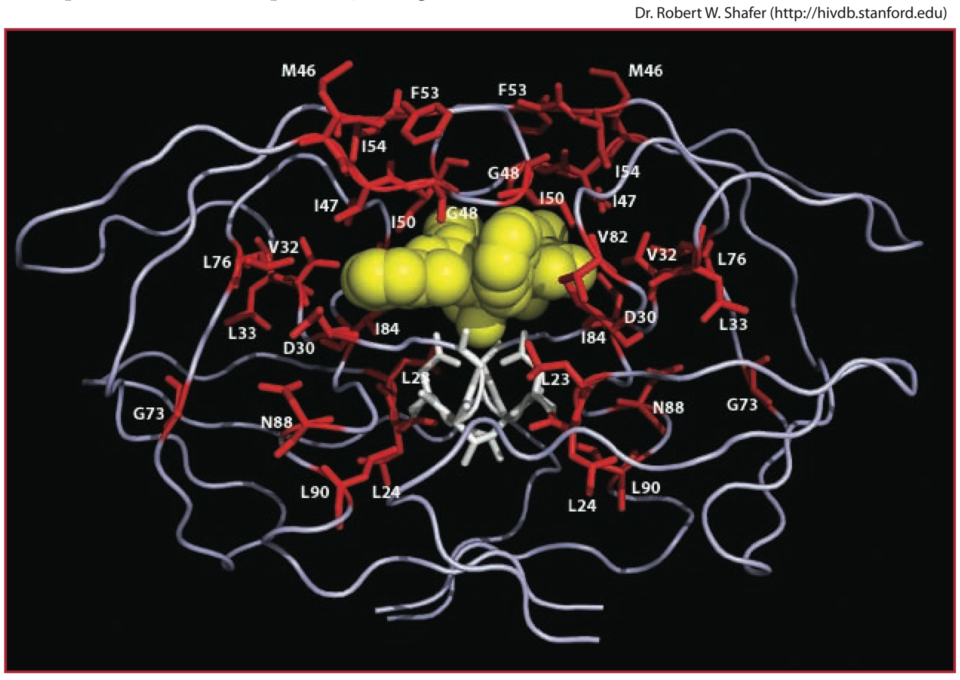
Selection means that these genes are going to spread through the population, so there will be more of these variants that are individually better. But in doing that, some of the best genotypes (some of the best teams) may be lost because there could be pairs within these genotypes that work well together (better than anything), but selection on the basis of individual ability means loss of these genetic pairs.

This is the selfish gene regime, touted by Richard Dawkins, whereby genes are propagated on the basis of individual merit.

"But," said Shraiman, "fitness is the property of the whole organism. You can think in terms of a capitalist society. How do you make a society work when all individuals only pursue their narrow self-interest? In population genetics, the answer is that the system works best if there is recombination, but not too much of it so that there isn't too much self-interest."

Shraiman explains the approach he and his collaborators at KITP have been developing. "We started with a population genetics problem," he said, "and we redefined it as a statistical mechanics problem."

Dr. Robert W. Shafer (http://hivdb.stanford.edu)



Rendering of the HIV protease enzyme (from Stanford HIV drug resistance database) shows amino acids involved in conferring drug-resistance—a process which requires multiple mutations. Understanding the dynamics of natural selection as it facilitates or inhibits the intermediate stages of this exemplary evolutionary process is one of many problems where ideas from statistical physics may stimulate dramatic progress.

From Thermo- to Population Dynamics

Statistical mechanics is the long-established theory of thermodynamic phenomena, describing states of matter in terms of thermal fluctuations and ensembles of particles. This theory basically provides a way of assigning probabilities to different configurations and then predicting the most likely outcomes of observations on these ensembles.

Of course, population dynamics is not governed by thermodynamics, but this statistical description of ensembles is still a useful way of thinking about the dynamics of populations. That creative and innovatively quantitative way of thinking suggests how the "Theoretical Physics" and the "Biology" of the Susan F. Gurley Chair go together.

"Once you start exploiting the mathematical analogy between these different descriptions" (of statistical mechanics and population genetics), said Shraiman, "it turns out to run surprisingly deep. We find essentially a phase transition between different regimes of selection: one regime of alleles selected on their own and another regime selected for the whole. This transition has a lot to do with glass transitions in spin glasses."

(Particles have spin. In magnetic materials the atomic forces cause neighboring spins always to align, thus producing a magnet. Glassy materials exhibit very disordered atomic interactions, and neighboring spins are confused as to which direction to align. Physicists call this phenomenon "frustration," and in glassy materials it leads to the existence of many different states of equilibrium, in contrast to ordered materials in which a unique state of equilibrium is easily achieved.)

Quantitative modeling of population dynamics that reveals phase transitions akin to those in spin systems affords a first-rate example of how the plethora of detail that now characterizes the life sciences may, at least in part, reduce to overriding principles expressed in sets of equations. Of course, the life sciences are already informed by a great overarching theory—Darwinian evolution. And "theory" in science does not mean, as it does in common parlance, "hypothetical," but "certain" with specified degrees of confidence ensuing from the scientific method of explaining, predicting, and verifying.

"In order to understand evolution," said Shraiman, "scientists have to understand population genetics: how selection acts to control the spread of genes in the population.

"One of the early questions for us was the following: 'Though we might expect great complexity of genetic interactions, is it possible that there is some dynamical evolutionary reason why actual living beings genetically would not be as complex as we could imagine?'

"Let me try to argue that case. If (for whatever reasons) a population will propagate itself through sex and recombination, then there would be selection against interactions—selection against genetic complexity—and, instead, selection for alleles that would work well independently of what other alleles are doing. When we decipher an individual's genome, it is not the variants that prove most useful and powerful in the population, but the units that have endured for millennia. Their endurance argues for selection for genetic simplicity."

Luck Matters

"What really matters," said Shraiman, "is existing a million years, and many genes have done just that, and within forms not imaginable at the time when the gene first appeared in the population. Thinking in terms of long-term survival means thinking in terms of units larger than single genes. A gene is a bunch of nucleotides, so already it's 500 individual little switches or base pairs. Maybe survival depends on a gene and its friend (another gene) or whole architectures of the genome such as its lifestyle understood in terms of mode of reproduction or sex.

"Ultimately, a gene survives a million years because it does, while millions of other variants haven't. The survivor has to be not only good, but also lucky."

Shraiman considers the opposite extreme: "Suppose the contribution of a given allele depends very strongly on what other alleles are doing. Then you ask what is the relation between the trait for the parents and the offspring? And you find there is none. Maybe that is the situation with intelligence—an ultimately complex trait that is not at all very heritable. That situation is called 'transgressive segregation,' and means that the distribution of offspring is much broader than the distribution for the parent."

Seventy-five percent of Shraiman's research now deals with questions raised by population genetics. The rest pertains to development or genetic unfolding morphologically. For instance, how does the fly progress from egg to larva to winged creature? His research, in other words, focuses on the two most obviously dynamical phenomena in biology—evolution and development. Why?

"Dynamics is where causal relationships become most easily observable," said Shraiman.

ENDOWED CHAIR CONTINUED FROM PAGE 2

member in July of 2004. He has been instrumental in the growth of its biologically related programs, which now account for some 15 to 20 percent of KITP activities. His efforts have generated new forms of support for the Institute with the addition of grants from the National Institutes of Health (NIH) and from private foundations, such as the Burroughs Wellcome Fund, that focus support on biologically related endeavors. KITP now runs two to three programs a year on biological topics that attract annually hundreds of new visitors to the Institute and to the UCSB campus.

At KITP ceremonies on Sept. 18, 2009, acknowledging the creation of the new Susan F. Gurley Chair in Theoretical Physics and Biology, Shraiman gave an inaugural lecture "Adventures at the Edge of Physics."

HIGH TECHNOLOGY EMERGES
From Low Dimensional Electron Systems

KITP Program Investigates Variety of Phenomena That Could Transform Our World

THE REAL ACTION of "high" tech devices occurs in "low" dimensional systems—those with one or more dimensions fewer than the three-dimensional space of our customary world. The branch of physics that contends with those low dimensional worlds (and which shades into engineering) is the largest in terms of number of practitioners and their published results—some 50,000 papers in the last 25 years. Accordingly, for so vast a field, last year's KITP program on "Low Dimensional Electron Systems" was the longest condensed matter program ever, spanning almost a half-year.

As the program name indicates, the relevant particles are electrons. To be an electron system in two dimensions means that particle movement is confined by various means to a single plane (as in transistors and in the multitudinous aggregates of transistors that make up computer chips). Electron systems in one dimension confine particle movement to a line, and such a one-dimensional system is called a "quantum wire," and one type of quantum wire is called a "carbon nanotube." Electron systems within a very small region of space, sometimes referred to as a "zero-dimensional system," are called "quantum dots."

Matter behaves differently in different dimensions. "Condensed matter in low dimensions often unlocks physics that is inaccessible or non-existent in three dimensions," according to the program description. Those differences are what the participants in the "Low Dim" program sought to find and explore and explain.

In addition to satisfying purely scientific curiosity about the often startling and profound nature of low-dimensional system realities, research into these realms has led to virtually all of what we think of as "high technology." And if the program's subjects and directions are any indication, much more is surely to come: "…some of the most important practical advances in materials physics in the last decade involve semiconductors of low-dimensionality and/or small structure at the nanometer scale," according to the program organizers.

Quantum Hall Only 2-D

Principal organizer Herb Fertig (of Indiana University) singles out two major topical emphases that dominated the program: (1) quantum Hall effects (integer and fractional, whose separate discoveries have already garnered separate Nobel prizes) and (2) graphene (See article on adjacent page).

Klaus von Klitzing discovered the quantum Hall effect in 1980 in a two-dimensional electron gas in a silicon-MOS-based system ("MOS," a much-used acronym in condensed matter physics, stands for "metal-oxide-semiconductor," characterizing the three successive layers of an important class of electronic devices). Two years later Horst Störmer and Dan Tsui discovered the fractional quantum Hall effect in a high-quality gallium arsenide sample prepared by UCSB's Art Gossard.

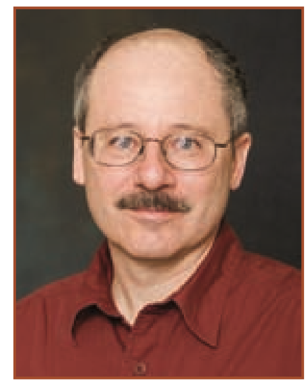
The quantum Hall effects are purely two-dimensional phenomena that show that resistance can be quantized. Until von Klitzing's discovery, most everybody who thought about resistance thought it took on a continuous range of values for a given system. Nobody, in other words, thought possible values of resistance would be determined directly by the rules of quantum mechanics; but they are, but only (so far) in two-dimensional systems.

The discoveries of the quantum Hall effects have been so momentous because they showed conclusively that there are phenomena in lower dimensions that exist only in lower dimensions, and thereby opened up whole new "lower" vistas for discovery in two, one, or zero dimensional systems.

One possibility much discussed in the program pertains to the relevance of the fractional quantum Hall effect to the dream of quantum computing—a paradigm for computing completely different from and vastly more powerful than our current binary mode. (See "Topological Quantum Computing: The Devil Is Not in the Details," 2006 *KITP Newsletter* available at www.kitp.ucsb.edu).

The fractional quantum Hall effect, explained by theorist Robert Laughlin (who shared the 1998 Nobel Prize with the experimentalist discoverers Störmer and Tsui), occurs when electrons are cooled to low temperature and subjected to high magnetic fields. The electrons organize themselves in a highly correlated state in which the ground state and low-energy excitations of the system are insensitive to local perturbations. The discovery of the quantized values of the Hall resistance and its independence from device characteristics means that the effect is robust–exactly the kind of physical system one is looking for in quantum computing.

In the system that is most exciting experimentally, the proposed "qubit" (the hypothetical fundamental unit for quantum computing analogous to a binary bit) is the



Ric Cradick at IU Photographics

Herb Fertig

presence or absence of a neutral fermionic excitation associated with a pair of electrical charges. When these two charges are far apart, the information is delocalized over the whole system.

The delocalization of the qubit is enabled by a subtle topological structure of the fractional quantum Hall state. In turn, the delocalization makes the qubit robust against errors that plague other architectures for quantum computing. Hence, the approach is known as "topological" quantum computing.

The qubit components—the delocalized neutral fermion and the charged excitations–are examples of "quasiparticles" in the fractional quantum Hall effect. As a result of the neutral fermions, the charged quasiparticles are non-Abelian "anyons." All particles are typically classified according to their statistics as either "fermions" or "bosons," except for quasiparticles first discovered in conjunction with the fractional quantum Hall two-dimensional systems (of which there are many) whose quantum states range continuously between fermionic and bosonic and are therefore called "anyonic."

The words themselves, "quasiparticles" and "anyons," convey how exotic and how potentially technologically transformative are the phenomena that exist only in the lower dimensional worlds.

In addition to the quantum Hall effects and the new and exciting study of graphene, another program emphasis–perhaps as much a matter of technique as of topic–concerns the use of atomic systems as analogues for investigating complex matter systems—a research mode pioneered, in part, through the concatenation of two KITP programs run simultaneously in 2004. One program looked at cold atom systems or Bose-Einstein condensates and the other at strongly correlated electron systems.

Bose-Einstein condensation (a big development in atomic physics acknowledged with more than one Nobel Prize) produced a coherent quantum state of cold atoms that Einstein had predicted. The big realization given impetus via the conjunction of the two 2004 programs is that these coherent quantum states can be used to construct models of condensed matter systems that are more controllable than had been imagined and attained heretofore.

Via the analogues between atomic and condensed matter states, said Fertig, "We are motivated to look at things that might not have occurred to us."

One big area for investigation is the Hubbard model, an idealized model for the simplest correlated electron systems. Despite the fact that the model is simple and has long been known, said Fertig, "We still don't know what the phase diagram is, don't know what kind of phases the system can have. We have some ideas, but there aren't rigorous proofs.

"A lot of people," said Fertig, "believe the Hubbard model in some form applies to the high temperature superconductors [whose mechanism is the biggest unsolved problem in condensed matter physics for the last 20 years]. We would like to know if we can use the Hubbard model or some variant to describe the high temperature superconductors."

Simulating Hubbard

Atomic gases, said Fertig, afford a possible way of simulating the Hubbard model in experiment, so that a set of outstanding theoretical questions might be addressed experimentally.

Fertig said that the program featured an "experimentalist of the week" to offer the theorists insights on progress being made. For most condensed matter theorists, said Fertig, "It is very important to be in touch with our experimental colleagues because we theorists are often wrong if we just guess what is going to happen in these systems."

Essentially what atomic physicists have done is to make a lattice-like structure for positioning atoms via interference patterns created with lasers. That structure is like a crystal made out of light.

"The complications of this atomic model," said Fertig, "capture what we think are the most important complications of the Mott insulators in a low dimensional electron system, which may be key to understanding high temperature superconductivity." Mott insulators are essentially materials that should theoretically function as conductors of electricity, but which act (contrary to expectation) as insulators especially at low temperature, as a consequence of the correlations induced by the strong interactions between the electrons.

The "Low Dim" program was designed deliberately to discourage talks on the mainstream research approaches to and developments in high temperature superconductivity because the subject now commands the attention of so many researchers that including it more centrally would have entailed doubling the length of the already longest condensed matter theory program in KITP history.

It is hard to imagine what technology will look like 15 or 25 or 50 years from now except to assume it will be different, and a significant driver of the difference is all but certain to come out of the Low Dim world contemplated in this program. But Fertig, as examplar of the theorist devotee of that Low Dim world, seems almost indifferent to the dazzling lure of transformative technologies. He is in it, seemingly, for the sheer pleasure of knowing, rather than picking material fruits.

Neil Campbell

Supernova

CONTINUED FROM PAGE 1

Bildsten (center) discussing the physics of detonations with UCSB graduate students Kevin Moore (l.) and Ken Shen.

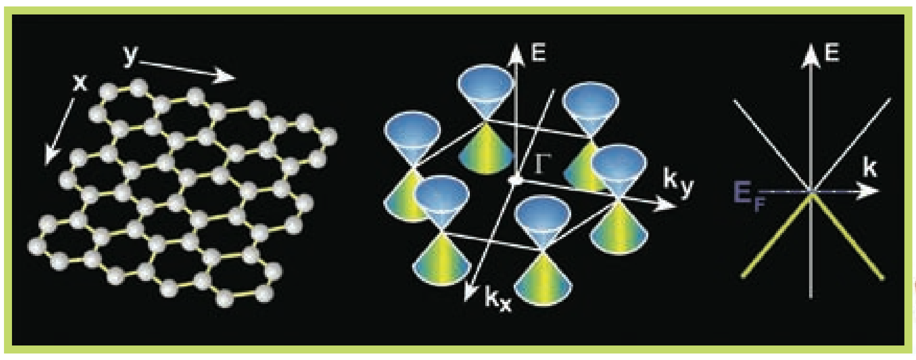
That fractional luminosity and its fractional duration led Chris Stubbs at Harvard to the witty christening of such events as ".Ia (*'point-one-a'*) supernovae."

The Bildsten group published their prediction in an article that appeared in the June 2007 issue of *Astrophysical Journal Letters.* Bildsten confesses that he worried whether the journal's editors would permit the naming—however clever—of an astronomical event yet to be detected, but they did. And, said Bildsten, "The name has stuck! Marketing is a big part of success for any idea, even in science."

When Bildsten was organizing the August 2009 KITP conference on "Stellar Death and Supernovae," he received an email from Poznanski, the lead author of the recent *Science* article, asking to give a talk at the KITP. Said Bildsten, "Dovi was vague about his intended subject. All he told me was that it was new and exciting, so I said, 'Sure!'

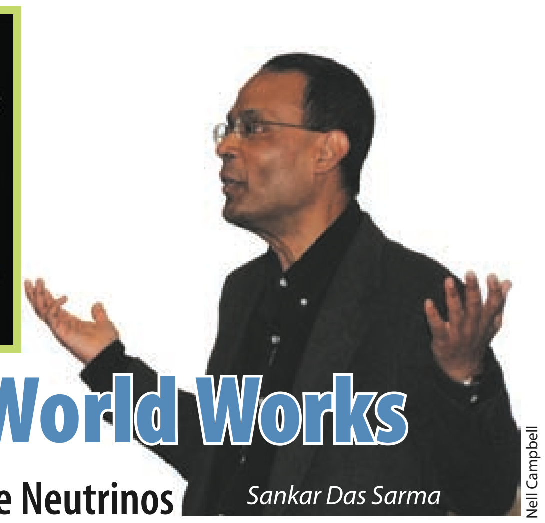
"By the time the conference occurred," said Bildsten, "Dovi was willing openly to discuss his discovery of a unique faint and fast supernova and to begin the interpretation of the event as a '.Ia' supernova." Bildsten recalls his excitement, "With the sky the limit, the observers are usually ahead of theory, so I am really happy that we were able to make a prediction that allowed for a rapid interpretation of a new phenomenon. Even though the supernova was observed in 2002, it took Dovi's keen eye to appreciate its import and relevance."

Despite the apparent success, more puzzles remain, and Bildsten and his collaborators, especially UCSB graduate students Ken Shen and Kevin Moore, are actively working on them. These include deep theoretical issues of how helium explodes, and whether or not the underlying white dwarf remains behind. Said Shen, "We were always interested in these new possibilities, but now we have a real motivation. Where there is one, there are many, so things are going to get exciting!"



Honeycomb 2-dimensional graphene carbon lattice (l); and frontal and side representations of Dirac cones touching in momentum space

Graphene May Change the Way the World Works



Sankar Das Sarma

Neil Campbell

But What Rivets Theorists' Attention Is Its Electrons Behaving Like Neutrinos

GRAPHENE IS A GOOD THERMAL conductor, better than silicon. That property means that a device—say, a transistor—made out of graphene could vent its own heat. Though the material itself dissipates heat, "graphene" as a research topic has been getting hotter and hotter.

In a recent assessment of frequency of search terms input on the *Nature* Magazine web site, "graphene" ranked first. Second and third places went respectively to "HIV" and to "cancer." The latter two terms, encompassing vast research enterprises, are household words. In contrast, few folks who are not physical scientists or engineers know for sure what graphene is, though they might make a homophonic-based guess that graphene has something to do with graphite—the substance whence pencils are made.

Graphene is, in fact, a sheet of graphite. Graphene consists of a single layer of carbon atoms arranged in a hexagonal or honeycomb lattice wherein electron movement is de facto confined to two dimensions.

Why is graphene such a hot scientific subject? Because, said Sankar Das Sarma of the University of Maryland who led the week-long graphene workshop that was embedded in the KITP "Low Dimensional Electron Systems" program, "With graphene comes the prospect of an enabling technology that could transform civilization."

How transform? One possible answer is that graphene may provide the material means for circumventing the projected silicon roadblock, whereby the exponential march of technological innovation based on the integrated circuit slows or even stalls. The pace of that innovation—doubling digital data density at roughly 1.5-to-3-year intervals (*i.e.*, Moore's law) has governed the development of business models in industries based on the integrated circuit (which comprise much of what we mean by "high tech").

Though agnostic about graphene's prospects for acting as a silicon substitute at the critical juncture where Moore's law begins to fail, Das Sarma points out that this new material exhibits properties enough different from silicon that graphene may enable applications so different and so remarkable that they can as yet not be envisioned.

As tantalizing to condensed matter theorists as the prospect of pioneering the next transformative technology is the fact that a real material exists wherein electrons moving from carbon atom to carbon atom in a two-dimensional honeycomb lattice obey the same equation that neutrinos follow or, in other words, the Dirac equation for massless particles in free space. (Actually, neutrinos have a very small mass, but so small that they can be treated as massless.)

"It is is mind-boggling," said Das Sarma. "Here is a two-dimensional electron system for which the basic equation comes from relativistic quantum mechanics."

When an object moves with velocity (v), it has kinetic energy. Electrons in an ordinary system obey Newton's equation whereby energy increases quadratically in relation to velocity ($E \sim v^2$). But in graphene the energy of electrons increases linearly with velocity ($E \sim v$), as if the electrons were relativistic, massless particles that obey Dirac's equation. The first equation is Newton; the second, Dirac; and the first is non-relativistic; the second, relativistic.

"So much of the 'fundamental' interest in graphene," said Das Sarma, "is coming from the fact that there is no material like it."

Physicists knew in the 1940s the unusual properties of a single sheet of carbon atoms, but back then, said Das Sarma, "Nobody thought you could actually have a single sheet of carbon atoms." Scientists thought that graphene was a hypothetical material.

In 2004 Russian scientists working at the University of Manchester in Great Britain discovered how to make graphene by using Scotch tape to peel off a graphene sheet from graphite. The following year they showed that the quasiparticles in graphene were massless Dirac fermions—*i.e.*, electrons behaving like neutrinos. They showed that the system exhibited a quantum Hall effect, and that the effect pertained at room temperature because it is so stable.

"Every graphene laboratory," quipped Das Sarma, "has a big supply of Scotch tape. Not all the flakes are a single layer of carbon atoms, but some are, and those are graphene. In these days of high tech fabrication," he said, "it is amazing that pencil flakes and Scotch tape should provide the gateway to a new material and likely a transformative technology."

Another distinctive property of graphene is its zero-width band gap. Das Sarma said, "That's a strange system because it can be classified as a metal or a semiconductor. We can dope the material and then add a metal gate and electric fields so electrons go in or out. Because the electrons can go in or out, applications based on such a system can use either electrons or holes," said Das Sarma. ["Holes" are electron absences with, therefore, positive charge.] "And," added Das Sarma, "an application can change from using electrons to using holes because the band-gap is zero. When a positive voltage is applied, holes flow because electrons are repelled; if a negative voltage is applied, electrons flow. So current can be manipulated, and that operation affords the prospect for a new kind of electronics."

As the program description for the KITP Rapid Response workshop ("Electronic Properties of Graphene," held at the outset of 2007) averred, "Because of its high electronic mobility, structural flexibility, and capability of being tuned from p-type to n-type doping by the application of a gate voltage, graphene is considered a potential breakthrough in terms of carbon-based nano-electronics."

Das Sarma, who led the effort to calculate the vacuum polarization for graphene (*i.e.*, its screening properties), structured the 2009 KITP graphene workshop around the reporting of experimental results. "Five experimentalists gave two-hour talks in the morning; all of them talked about new results. We theorists learned so many new things." He said that the flurry of results were harbingers of breakthroughs to come.

"Graphene is big," said Das Sarma, "and it is going to get bigger."

When Collaborators Are a Couple: Globular Clusters Provide Case Study

HE WAS an assistant professor at MIT; she was a postdoctoral fellow at Harvard. They met at one scientific conference, and married at another (the latter, at least, in scenic Aspen). Both now hold endowed chairs at the same university, Northwestern; and both are theoretical astrophysicists whose principal scientific interests include globular clusters—aggregates of old stars, which were the subject of the 2009 program "Formation and Evolution of Globular Clusters" that drew Fred Rasio and Vicky Kalogera to the KITP.

They emphasize that because they both had valid scientific reasons for participating in the same program, coming to KITP for an extended stay posed none of the customary hurdles couples may face when one wants to visit while the other is deterred by employment commitments tied to place of residence. And the KITP Family Fund, established two years ago by Ann Rice in memory of her husband Myron, enabled a grateful Kalogera and Rasio to accommodate duties as parents of a toddler to the exigencies of intense participation in a program Rasio served as coordinator. (See http://www.kitp.ucsb.edu/visitor-info/prepare-visit/family-fund)

Interviewing them together on the progress of the "Globular Clusters" program and listening afterwards to a recording of that interview revealed something of the couple's style in their approach to scientific collaboration. Instead of interrupting one another or talking over one another—as male theoretical physicists collaborating at KITP sometimes do—Rasio and Kalogera simply took turns addressing questions. And each did not tune out while the other was speaking, but instead listened attentively to the other, as demonstrated by frequent elaborations and clarifications and qualifications of each other's assertions.

Said Kalogera, "We could have collaborated on every single research project, but each of us tried consciously not to cross that line all the time."

"It doesn't add to the intellectual vitality of an academic department," said Rasio, "if two of its faculty are doing the same research." Both also noted that the intellectual vitality of the individual also requires some separation of interest.

So Kalogera and Rasio have diversified. In addition to globular clusters, Rasio also focuses on extra solar planets, among the "hottest" of topics in astronomy, as evinced by the 2010 KITP program on "The Theory and Observation of Exoplanets." And Kalogera is a member of the LIGO scientific collaboration that seeks to detect gravitational waves.

Globs Enable Death Star Collisions

Those waves and their detection are relevant to globular clusters because these globs of old stars are likely to contain within them the exotic binaries of stellar end products—neutron stars and black holes whose collision affords the most probable scenario for the production of gravitational waves detectable by the two-stage upgrades to basic LIGO.

"Cluster," with respect to "globular," means a large number of stars, ranging from as few as 10,000 stars to as many as seven million in a single gravitationally-bound, roughly-spherically-shaped entity within galaxies. The number of globular clusters within a given galaxy ranges from a few hundred in the Milky Way to many thousands in big elliptical galaxies. Some globular clusters exist in the galactic disk, where almost all stars in a given galaxy reside, but there are also—uncharacteristically for star location–many globular clusters in the galaxy halo. Their key feature is the density of their star components; that density means that clusters look like bright round entities to the observer, hence the adjective "globular."

Fred Rasio (l.) and Vicky Kalogera

Randall Lamb

"When we are able to resolve them," said Kalogera, "we see that the center is a lot brighter than the outskirts," which is an indication of the typical "mass segregation" within a cluster whereby not only more and more stars, but also the more massive ones congregate via gravitational attraction towards the center of the cluster.

Program participants split roughly into two groups. Said Rasio, "People like me and Vicky want to understand the details of what is going on inside these systems. There are a lot of reasons why they are very interesting. In particular the high densities lead to all kinds of exotic interactions between stars that never happen anywhere else." The other group, he said, focuses on what clusters reveal about how galaxies assembled and evolved, especially through mergers. Because the massing of stars makes clusters so bright, they can be detected within galaxies at time scales pertinent to cosmology.

As these two communities have tried to make progress and answer questions in more and more detail they have realized the interdependence of the two research foci. Said Rasio, "Part of what determines the evolution of globular clusters within their host galaxies is also what's going on inside of them." The program was designed to bring the two perspectives together so that each could inform the other and thereby foster productive collaborations utilizing the expertise of the two points of view.

One particularly interesting intersection focuses on the question, "How are globular clusters made?" Studies of their current character indicate that they formed 12 to 13 billion years ago and are, therefore, among the oldest objects in a universe thought to be some 13.7 billion years old.

A key indicator of cluster age is the mass of the stars that now shine. They are about 80 percent the Sun's mass, indicating that enough time has gone by since the inception of the clusters that all the more massive stars have devolved into white dwarfs or neutron stars or black holes (depending on the size of the initial star).

That low stellar mass signature, said Kalogera, also indicates that star formation is not an ongoing process within clusters. All the stars, in other words, were made about the same time a long time ago in contrast to galaxies as a whole, where star formation is ongoing. The key reason for the difference is that the clusters are not as a whole massive enough to exert a gravitational force sufficient to contain the gestational gas wherein new stars form.

The stars within globular clusters are also metal poor, again indicating that they formed long ago, before the interstellar medium had been enriched with heavier elements through successive supernova explosions of short-lived, super-massive stars. But some clusters are less metal poor than others, and one of the big puzzles the program participants tried to solve was why these two types of metal poor clusters tend to exist in two clumps rather than along a continuum of metallicity.

"It looks," said Kalogera, "as if there were multiple epochs of cluster formation in the same galaxy. We ask what could trigger multiple epochs and conjecture that the cause is galaxy mergers. We debated at length in the program whether the oldest globular clusters are telling us something about the first mergers of little entities in the universe" and, hence, the birth pangs of galaxies.

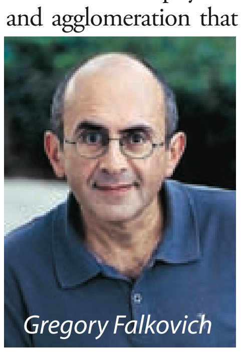
Clouds Raise Many a Question, Including the Curious Case of COVER CONSISTENCY

"I REALLY DON'T KNOW clouds at all" is the refrain that runs through a late 1960s popular song by Joni Mitchell. Her meaning is meant to be metaphoric—how little one knows of the seemingly familiar. But for scientists at the KITP program pioneering the "Physics of Climate Change," the meaning is far more literal than metaphoric. "Cloud physics is the largest source of uncertainty in the short term in predicting the climate," according to the program's principal organizer, Brad Marston of Brown University.

Clouds can function both as blankets and as mirrors with, respectively, either a warming or a cooling effect.

Wispy cirrus clouds, trailing high above the Earth, have a net warming effect because they reflect back down heat or infrared radiation emanating from Earth. Sunlight at visible wavelengths mostly passes through high cirrus clouds. Low-lying stratus clouds, the usual culprit of cool "cloudy" days, especially off the coast of California, have a net cooling effect because they reflect light back into space, and their behavior is among the hardest to model though modeling any cloud turns out to be very difficult.

What makes cloud modeling hard is the wide range of relevant length scales—from the microphysics of droplet formation and agglomeration that can lead to "rain" to the vast turbulent motions in the Earth's atmosphere which we call "wind."


Weizmann Institute of Science

Gregory Falkovich

Rain is the result of a two-fold process of condensation and collision inside a certain kind of cloud termed "cumulus" [from the Latin meaning "pile up"]. First is the process of nucleation whereby seeds of dust in the atmosphere augment the attraction of water molecules into drops. Turbulent movements within clouds foster collisions of drops that aggregate into droplets heavy enough to be gravitationally attracted to Earth.

How Raindrops Form

"It seems now in both these processes—condensation into drops and collisions between them—turbulence in clouds plays an important role," said Gregory Falkovich of the Weizmann Institute in Israel. "Small-scale inhomogeneities in the vapor concentrations determine the growth of properties due to condensation and strongly influence the collision rate of droplets."

Physicists attending the "Climate Change Program" tackled the problem of constructing equations that describe these processes of condensation and collision within the turbulent cloud medium.

"What is wanted is a theory that quantitatively describes these two phenomena," said Falkovich. "If we look at warm clouds and even if we know everything about them in the beginning, we cannot predict how fast those clouds will precipitate because the process of precipitation depends on turbulence, and turbulence in clouds is a function of both an internal process of convection and an external process of macro-turbulence, which happens on scales of 10s and 100s of kilometers."

In other words, there are two processes of movement within clouds: particle movement due to local phenomena, but also larger movements of air currents having to do with winds on larger scales.

"Clouds," asserts Falkovich, "comprise the biggest unknown of the various feedbacks in the process of global warming."

He points to another of the unsolved problems pertaining to clouds: the mysterious consistency of average global cloud coverage, according to recent observations, even though other observations indicate that the global climate is not only changing via Earth warming, but is likely changing relatively fast.

Cloud cover has changed very little since cloud cover has been being observed. That "little" change refers to an average cover area, not fluctuations from day to day because, as anybody knows, some days are cloudy in some places sometimes and not so in the same place at other times. And there are patterns of regional coverage, which can change year to year. But the average cloud cover over large portions of the globe is surprisingly stable, said Falkovich.

"We don't understand it at all, and it is very important because it affects the albedo [reflectivity index] of our planet and thereby the extent of the greenhouse gas effect. Cloud coverage seems to be stable, and we don't understand the physical mechanism behind this stability.

"There must be some negative feedback," he speculates, "while at every given part, the system is strongly fluctuating."

Because the mechanism for this cloud cover consistency is not understood, scientists do not understand if it could be broken and how stable it will be in the future.

The view from space indicates what percentage of the surface is cloud-covered, and the height of the clouds and therefore their albedo. "Those parameters," said Falkovich, "stay surprisingly stable over a period of years. I as a theoretician don't understand why those parameters are stable over the scale of a few years. I don't really understand clouds."

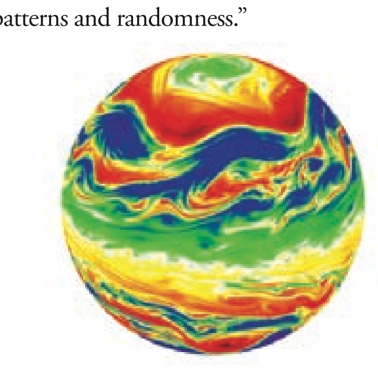
Global circulation models constructed to enable an understanding of the effects of global warming take into account the effects of clouds in, according to Falkovich, a "hugely oversimplified" way. A more realistic model, he contends, would at least take into account the differing effects of clouds at different heights and the concomitant role played as blankets or mirrors.

"We don't know, he said, "the effect of cranking up the temperature on cloud cover. We don't even know if the sign is negative or positive." That is the difference between feedback that enhances or diminishes the effect.

Modeling global circulation requires "parameterization," a mathematical process involving the identification of a set of effective coordinates or, as physicists say, "degrees of freedom" because one cannot describe all the smallest scales.

But, according to Falkovich, a long-time turbulence expert, who has recently been applying its insights to clouds, "Turbulence resists scaling. The statistics of turbulence change as you change your resolution. Understanding turbulence on the scale of kilometers doesn't mean it is understood on a scale of meters. The behavior of fluid flows," he emphasizes, "depends on the scale of resolution." In other words, a larger scale reveals more flow; and a smaller scale, more detail but the two pictures cannot be superimposed on one another to yield a composite because each picture is a function of its scale.

Turbulent phenomena are both random, on the one hand, and show patterns, on the other hand. That dual oxymoronic character of turbulence is "precisely what makes it resolution dependent," said Falkovich. "When you blur the resolution, you stop seeing the patterns. The climate is like turbulence—patterns and randomness."



EARTH'S CLIMATE

CONTINUED FROM PAGE 1

participants how many of them had doctorates in physics. Most raised hands. He then asked how many held appointments in Physics Departments. Few hands rose. It isn't that these climate physicists can't get jobs, but that their appointments are in academic departments and institutions other than what is traditionally labeled "physics."

The program was organized conceptually around three main areas:

(1) Macro-turbulence, pertaining basically to large-scale circulation of Earth's atmosphere and oceans. Both air and water are fluids, though changes in the former occur rapidly and in the latter slowly. An atmospheric example is the Hadley cell, whereby air rises in the tropics, flows towards the poles and descends in the sub-tropics to return towards the equator along a path closer to Earth's surface than the pole-ward flow. The Gulf Stream, originating in the Gulf of Mexico and carrying warming water north along the East Coast of the United States before dividing into two currents crossing the Atlantic, is an oceanic example.

Macro-turbulence is the most mature of the three conceptual areas around which the program was organized. But, said Marston, "there are still many unanswered big questions," such as explaining the prediction that as Earth warms, the storm tracks will move further towards the poles. That scenario would lead to more drying in the southeast and the southwest of the United States because those places would experience less rain. Large complicated computer models of climate, which have heretofore dominated the science of climate change, show that as Earth warms, storm tracks move away from the equator towards the poles. But why is not well understood, said Marston, and entails addressing "many interesting questions."

(2) Clouds afford "the largest source of uncertainty in the short-term," according to Marston. See "Clouds" (left) for insight into the scope of that uncertainty.

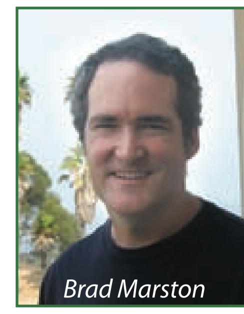
(3) Ecosystems, which change on a time-scale presumably longer than that for clouds, raise the prospect of feedback whose consequences are long-term. Much of the interaction between ecologists and physicists during the program focused on issues related to "feedback."

Most ecologists participating in the "Physics of Climate Change" program had particular expertise in fire ecology. During the program they conducted a workshop and wrote a paper, rapidly published in *Science* in April 2009, which argued that fire should be understood as a global phenomenon, rather than in a piecemeal, regional fashion, as it has previously been understood. In other words, ecologists have approached fire regimes in terms of specific regions in, say, Australia, South Africa, or California. The KITP working group advocates, instead, a global perspective, which in turn argues for incorporating fire into models of climate change in terms of the cause-and-effect chain reaction of "feedback"– *i.e.*, raging wildfires as both effect and cause of global climate change. (See "Fire," p. 7).

The role ecology plays in global climate change is, of course, broader than the fire-prone ecosystems. For instance, there is the dying off of the piñon forests in New Mexico. Drought stresses the trees and makes them more susceptible to the depredations of pine bark beetles. Most people who study this phenomenon think it is related to climate change, said Marston. "That is the sort of phenomenon that is occurring elsewhere.

"How ecosystems respond to climate change is a big unknown," he said. "Ecosystems are even more complicated and harder to model than clouds. From the standard physics point of view," said Marston, modeling ecosystems and incorporating them into models of climate change is "mind boggling. We are really just at the threshold for talking about these questions."

The program began with a working hypothesis that climate is changing. Said Marston, "We tried to understand how climate is changing and how much and in what ways. But we ended up trying to


Charmien Carrier

Brad Marston

understand the climate even apart from or as a prelude to understanding what will happen. We still have a long way to go to understand even the current climate: how general circulation works; how clouds function; how ecosystems evolve. I think the key development that has occurred as a result of the program is that types of scientists who have never talked to each other are talking."

Marston points to his efforts along with physicist colleague Paul Kushner to work with ecologists on feedbacks. "We physicists know the mathematics of feedbacks," said Marston, "but we don't really know much about ecosystems." Marston described hiking with David Bowman, the lead author on the fire ecology *Science* paper, in the Santa Barbara backcountry to survey a small portion of the vast Zaca fire burn-area that blackened some quarter-million acres from July to September 2007. Said Marston of the vista of charred and fledging vegetation, "It just looked like chaos to me. I asked myself, 'How can we have a quantitative description of this thing?'" But where Marston saw chaos, he could also see that his companion, Bowman, perceived order.

What happened at the "Climate Change" program was a meeting of scientific cultures unfamiliar with each other: a meeting between physicists especially the highly theoretical, turbulence types such as Marston and cloud investigator Gregory Falkovich and the empirically-minded ecologists such as David Bowman of the University of Tasmania and Jennifer Balch, a postdoctoral fellow at the National Center for Ecological Analysis and Synthesis. Falkovich, incidentally, returns in 2011 to KITP from his academic position at Israel's Weizmann Institute to act as organizer of a program "The Nature of Turbulence," that is, in part, a follow-up to the "Physics of Climate Change" program.

Marston characterizes this meeting of physicists and ecologists as a productive interaction because it showed, he said, that "We can't really do climate without ecology. It is absolutely primary, at least over long time scales. Modelers can hold the ecology fixed, and then ask what happens. But if we scientists really want to know what is going to happen to Earth in the next 100 years, we need to worry about how ecosystems are going to change."

In addition to that deep respect for the relevance of ecology, Marston also pondered at program end whether climate-change research belonged at the KITP. Or, another way of asking that question is "What does theoretical physics have to do with global climate change?" For him and most other participants the short answer is "modeling nature with equations, and then working to solve the equations."

"That kind of thinking popped up over and over again in the program in terms of what people were doing," said Marston. Understanding the significance of this effort requires a brief historical digression.

Climate science evolved out of weather forecasting. In fact, models used for climate study could be considered a scaling up of weather forecasting. Initially, weather models were adapted to run a long time without instabilities. Then the models were expanded to incorporate ocean circulation patterns, which represented a big leap because oceans operate on a much different time-scale than does the atmosphere. Climate science, said Marston, has basically been a history of augmenting the models—adding ice, for instance.

Constructing and running these giant models now require dedicated facilities and vast computational resources. This brute-force computational approach to climate science is akin to high energy physics experiments at accelerator facilities, in that both require large teams of experts.

Efforts at KITP, by contrast, focused on constructing a simplified theory and testing

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Novel Research Collaboration Leads to Discovery Of 'Fire in the Earth System'

David Bowman (l.) and Jennifer Balch

TO GAIN ACCESS TO the Bodleian Library at Oxford University, David Bowman, professor of forest ecology at the University of Tasmania, had to sign a pledge that he would not use a candle in the facility that dates back to 1602, a time when readers could readily be suspected of lighting up. The anachronistic pledge was not particular to Bowman; anybody seeking access has so to sign. But few could appreciate its significance as much as Bowman, who is an expert on fire ecology and the lead author on a recently published paper in *Science*, which argues that the spectacular wildfires (in Australia or California or France or Greece or South Africa that periodically erupt into the news) represent a singular global phenomenon particularly relevant to climate change.

That article, "Fire in the Earth System," states that, "…though the Intergovernmental Panel on Climate Change (IPCC) report concluded that global climate change will increase the risk of extreme fire events, its assessment did not quantify potential fire-climate feedbacks." The article's sustained argument for a dynamic global perspective concludes: "Indeed, future IPCC assessment of anthropogenic global climate forcing should include specific analyses of the role of fire." In other words, fire is to be considered not only as a consequence of global warming, but also causal in the inexorable chain reaction of a positive feedback mechanism.

The article was written at the KITP by a working group focusing on fire ecology in conjunction with the program "Physics of Climate Change." The animating force for both the workshop and the article came from Bowman and Jennifer Balch, a postdoctoral fellow at the National Center for Ecological Analysis and Synthesis (NCEAS).

The workshop itself represented a first-time-ever joint effort between KITP and NCEAS, both located at the University of California at Santa Barbara (UCSB) and both funded by the National Science Foundation (NSF). The article's 22 authors were workshop participants or "Climate Change" program organizers, including Brad Marston, principal program organizer, and Jean Carlson, UCSB physicist and expert on fire modeling who acted as principal liaison in the innovative research collaboration between physicists and ecologists that led to the published insights. (See article below.)

The authors note that, "there remains a serious lack of knowledge about fire's fundamental role in Earth System processes, as well as an insufficient appreciation of fire's interaction with anthropogenic global environmental change."

Bowman unpacks the implications of that coolly scientific observation by conjuring a hypothetical scenario featuring insurance industry risk assessment experts wondering how to lower exposure to losses due to fire. "Let's say," said Bowman, "that the insurance industry decide to ask the experts on fire ecology, 'How would you fix the problem?' All I can say is 'I have absolutely no idea!' What we are saying in this article is that we don't have a theory. We have only just realized these wildfires represent a global syndrome—that we are seeing a commonalty of process worldwide."

Wildfires Global

Before the KITP workshop, said Bowman, "Nobody had thought to think about fire in this holistic way. Look at the IPCC report, the gold standard for understanding global climate change [recognized with the 2007 Nobel Peace Prize]; there is no chapter on biomass burning."

The holistic perspective, advocated in the article, includes not only the current global context for fire as the climate changes, but also the historic and geological one that emphasizes the long human development affected by its use, as well as its shaping agency in terms of the evolution of habitats.

"Fire is a worldwide phenomenon that appears in the geological record soon after the appearance of terrestrial plants," begins the article. "Fire influences global ecosystem patterns and processes including vegetation distribution and structure, the carbon cycle, and climate. Although humans and fire always have coexisted, our capacity to manage fire remains imperfect and may become more difficult in the future as climate change alters fire regimes."

With respect to insurance industry concerns about burning structures, Bowman said, "The urban-woodland interface presents an intractable problem. We've got a lot of infrastructure in the wrong places."

Balch said, "Global warming appears to be changing the windows of opportunity for extreme fire events," and by "changing the windows," she means expanding fire season and fire size in fire-prone regions though data exist to support that contention mostly for California where, she said. "Increasing temperature is a major predictor of increasing fire occurrence and size."

Bowman and Balch agree that the insights of their published paper now seem "obvious," yet had been impeded by a strong regional bias characteristic of their discipline and understandable in a scientific endeavor such as ecology that ties the investigator to the natural habitat that he or she studies.

"The key word is 'theory,'" said Bowman. "We held this workshop at a theoretical physics institute. Ecologists are strongly phenomenological and pragmatic." In the environment of theoretical physics, he said, "we began to think of fire more abstractly in terms of models and equations"—in effect, "globally."

Smoke from multiple California wildfires drifts over the Pacific Ocean, 2007.

Complexity Expert Plays Key Role Mixing Physics and Ecology

Jean Carlson

THREE OR, PERHAPS, FOUR significant innovations characterized the "Physics of Climate Change" program: (1) it was the first KITP program to focus on climate and to investigate the relevance of theoretical physics to what may well be the 21st century's overriding scientific challenge; (2) it inaugurated the first collaboration between two NSF-funded scientific institutes—KITP and the National Center for Ecological Analysis and Synthesis (NCEAS) that have co-existed in proximity within the same university for decades; (3) it yielded the discovery of an insight "Fire in the Earth System," whose significance is suggested by its speedy publication in *Science* and the attendant flurry of notice in the popular media;(4) it catalyzed the probable advent, as the "Fire" article signals, of a new interdisciplinary endeavor that might come to be called "pyrogeography."

One of that new field's pioneers is physicist Jean Carlson, the head of the UCSB complex systems group, who served as a KITP program organizer and an author of the "Fire" article. Her role is pivotal because her efforts to model fire had already led her to tap NCEAS expertise so that she had the institutional experience and acumen to enable the highly productive interaction between physicists and ecologists.

The "Climate" program's overall organizer, Brad Marston, and the leaders of the ecology group, David Bowman and Jennifer Balch, all spoke about the challenges to collaboration posed by the very different "styles" of physics and ecology research.

Of the "Fire" article, Carlson said, "It is an attempt to make a public statement on the importance of integrating fire into climate change. That effort is challenging because climate models are investigated on spatial and temporal scales that are too coarse to account for individual fires or the extreme weather events that factor heavily into fire risk." But fires, she noted, emit large amounts of carbon in a short amount of time, and "play a central role in catalyzing ecological-type conversion on landscapes."

'HOT' to Handle Fire

To investigate common features of complex phenomena such as fires and to identify interplays among variations in the environment and tradeoffs in resilience and adaptation, Carlson, in collaboration with Caltech's John Doyle, has devised a research protocol called "Highly Optimized Tolerance" or "HOT" for short.

Carlson's and Doyle's work shows that basic mechanisms which underlie evolution and system organization in changing environments can be mechanisms for "heavy tailed distributions." For fires, this leads to a power law relationship between the frequency and size of fire. The result is, she said, "Most fires are small, but most of the trees are burnt in the few largest fires." Such findings, in turn, enable more informed decision-making about how to deploy resources to respond to wildfires.

HOT affords, Carlson said, "a particular way of thinking about the origin of variability in an organized system. The theory has been applied to systems that have been deliberately engineered, like communication and transportation systems, as well as systems that adapt over time by natural mechanisms, like an ecosystem and a fire regime. The trade-off that comes with that organization is at the heart of the HOT perspective on complexity."

This kind of system, Carlson said, "can be characterized as Robust, yet Fragile [RYF]—robust and resilient to common variations, yet fragile and vulnerable to rare events. One signature of RYF is a power law, which may occur even in optimized systems.

"Another important fragility," she said, "that occurs in a system tuned to its environment pertains to the system's natural sorting mechanisms, which may not be able to keep up with a rapid change in the environment. This failure leads to even larger catastrophic events whereby the system finds itself in unfamiliar territory. This chain reaction is particularly important for climate change."

Fire regimes and ecosystems may, in other words, be tuned to one another, but extraordinary input—such as humans firing off large swaths of rainforest or extraordinary climate change itself—tends, in turn, "to give rise to large system fragility."

What makes climate change "extraordinary"? Said Carlson, "Recent, human-induced changes are not slow enough to be consistent with the natural time scales for adaptation associated with Earth system processes—*i.e.*, burning down rain forests and increasing emissions may lead to rapid changes in weather, and temperature, which have cascading effects, disrupting what would be a natural fire regime."

EARTH'S CLIMATE

CONTINUED FROM PAGE 6

it against reduced, but still non-trivial models of, for instance, the jet stream, as Marston and his collaborator Tapio Schneider (a Caltech environmental science professor) have been doing. So, instead of huge simulations of climate that attempt to account for variables, this approach looks for key simplifications that can be modeled. That is the classic physics approach to problem solving, which seeks to identify the key parameter(s).

Marston and Schneider are trying to apply non-equilibrium statistical mechanics to probe climate instead of doing detailed minute-by-minute simulations. They have constructed a toy model of the jet stream flowing east to west along the equator, and then asked various statistical questions such as "what is the mean value of that field?" and "what is its time average?"

Essentially, said Marston, "We pick out some essential feature and throw out everything else." Such an approach seeks to understand a part thoroughly with the idea of eventually integrating it back into a more complicated model. Another way of describing that step-two effort is "adding layers of complexity to this kind of simple description," according to Marston. The most important result of this approach, he said, "is that it might recognize or 'pick out' fundamental processes, so that we don't, in effect, lose sight of the forest for all those trees."

If his speech is any indication, ecology metaphors seem to be shaping Marston's thought. Of the KITP and its "Physics of Climate Change" program, he said, "This is a planting place for ideas. People go off, and the blooms occur somewhere else."

Kavli Institute for Theoretical Physics
University of California, Santa Barbara
Santa Barbara, CA 93106-4030

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Editor / Writer: Jacquelyn Savani
jsavani@kitp.ucsb.edu

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