Summer 2000

Caltech PMA Communiqué

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INSIDE:

Physicists observe the quantum of heat flow

by Michael Roukes

In the everyday world, the flow of heat can vary in a smooth and continuous way. Heat is actually carried by collective, wave-like vibrations of atoms that make up a solid material. Usually immense numbers of such waves, each inducing a unique type of synchronous motion of the atoms, act simultaneously to carry heat along a material. Physicists know that waves sometimes act like particles and vice versa, so they've given these vibrations the particle-like name *phonon* – reminiscent of "electron" but after the Greek word *phon* for sound. For heat flow in the macroworld, since each phonon is just one amongst a sea of many others, an individual phonon's contribution alters the total almost imperceptibly.

But in the nanoworld, this "phonon sea" is actually rather finite, quantum effects rule, and the heat conduction can become radically different. When objects become extremely small, only a limited number of phonons remain active and play a significant role in heat flow. In fact, in small devices at temperatures close to absolute zero most types of motion become almost completely "frozen out", and heat must then be carried by the several remaining types of wave-like motions that persist. In this regime it has recently become apparent that a strict limit exists to the amount of heat that can be conducted in a small structure or device. Although never before observed, this maximum value is actually a fundamental law of nature, independent of composition or material. It stipulates that the only way thermal conductance can be increased in a very small device is simply to make the conductor larger. In a new study published in the journal *Nature*, California Institute of Technology physicists have observed this fundamental limiting value, called the *quantum of thermal conductance*, for the first time. Using tiny devices with specially-patterned features only 100 billionths of a meter across (about 300 atoms wide), a team led by Professor of Physics Michael Roukes has demonstrated that the maximum possible value of energy transported per wavelike motion (phonon mode) is a number comprised of only ▶

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Note From The Chair

by Thomas A. Tombrello, Jr.

This is the third newsletter in this series that was created to keep us in contact with our alumni and friends. The contents represent a few of the highlights of the Division's activi ties. This spring we have received acceptances from five new professors: Andrew Blain, Assistant Professor of Astronomy; Steven Gubser, Professor of Theoretical Physics; Lynne Hillenbrand, Assistant Professor of Astronomy; Anton Kapustin, Assistant Professor of Theoretical Physics, and Hirosi Ooguri, Professor of Theoretical Physics. Gubser, Kapustin, and Ooguri represent the next step in the expansion of our program in string theory. Hillenbrand works in the area of star formation; Blain makes sub-millimeter observations of distant galaxies.

We have received funding from The Sherman Fairchild Foundation and from Steve and Rosemarie Johnson for the endowment of postdoctoral fellowships in theoretical physics/astrophysics and mathematics. Their generosity makes possible a long term, expanded program to attract to Caltech the most creative young mathematicians and theorists.

We have just put together a plan for the next stage of our study with the University of California of the feasibility of constructing a 30 meter optical/infrared telescope. In about a year we should be able to make a proposal for a detailed design study for CELT (California Extremely Large Telescope). In next year's *Communiqué* we shall highlight this proposed design.

Please feel welcome to send any comments you may have on the content of the newsletter, including suggestions for future articles, to PMA Division Chair, Caltech, 103-33, Pasadena, CA 91125.◆

Searching for Neutrino Oscillations with MINOS

by Charles Peck

In the continuing quest to understand the fundamental structure of matter and the nature of the universe, a group of physicists, including Caltech Professors Barish, Newman and Peck and Senior Research Associate Michael, have designed a project called MINOS (Main Injector Neutrino Oscillation Search) to give a definitive answer to the question of whether neutrinos have mass. According to the Standard Model of particle physics, which gives us our best explanation of the behavior of fundamental particles and interactions, there are three kinds of neutrinos and all are massless. But if experiments show that neutrinos have mass, however tiny and there is now excellent but not definitive evidence that they do – the discovery will deeply change our view of the universe.

In 1930, Wolfgang Pauli invented a new particle with extraordinary properties, the neutrino, in response to a serious dilemma: when a radioactive nucleus β-decays, some energy, momentum, and angular momentum seem to vanish. Pauli postulated that they were carried off by a neutral particle with little or no mass and almost no interaction with matter. In fact, Pauli thought that experimenters might never find direct proof of the existence of his invention because neutrinos interact so weakly with matter. However, nuclear reactors produce prodigious numbers of them, and eventually, reactor development allowed Frederick Reines and Clyde Cowan to find direct experimental evidence for Pauli's neutrino in 1956. A few years later, in the first accelerator neutrino experiments, it was demonstrated that there are in fact not just one, but two types of neutrinos, and their antiparticles. One of them, the ν_e, is associated with the electron and the other, ν_μ, with the muon. With the discovery in 1975 of another particle with properties similar to the electron and muon, the τ lepton, we obtained strong indirect evidence for yet a third neutrino type, the ν_τ, which has just been observed directly at Fermi Lab.

Today, massless neutrinos are an integral part of the Standard Model of particle physics, in spite of the fact that ever since 1968 there has been a fly in the ointment – the number of ν_e neutrinos observed coming from nuclear reactions in the sun is far fewer than expected. Of course, this could just indicate that our theory of how the sun operates contains a small flaw, but by now enough other observations have been made that another explanation is favored today. Although not yet definitively proven, the favored explanation ▶

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Math Option embraces the "new core"

by Barry Simon

This year is the fourth year of the new core curriculum at Caltech, which had profound changes on the mathematics that is required all undergraduates at Caltech. The new core decreased mathematics and physics each from six terms (two years) to five terms in order to make room for one-term courses in Biology and Geology or Astronomy.

The term less of math was accommodated by presupposing more background (virtually every student comes in with AP Calculus) and by somewhat decreasing the time spent on series and vector spaces. In consultation with the Institute-wide Core Curriculum Steering Committee, a Mathematics Option committee chaired by Michael Aschbacher totally rearranged the order and scope of topics to meet the needs of other courses at the Institute.

The five terms in the current program are:

Math 1a: 5 weeks of "basic calculus" and 5 weeks of probability
Math 1b: Series, complex numbers, and vector spaces
Math 1c: Multivariable calculus
Math 2a: 5 weeks of matrix theory and 5 weeks of statistics
Math 2b: Ordinary differential equations

There are a number of unique features of this program. The initial five weeks of Math 1a include some review of manipulations (mainly on homework) but focus on proofs and making students — many of whom have seen little proof in high school — understand what proofs are. Included are extensive use of epsilon-delta proofs, convergence of Riemann sums, and a proof of Stirling's formula.

The split between probability and statistics is unusual and is motivated by two concerns: Several groups wanted probability done in the first year but it was felt that statistics required the greater maturity that we see in students after they return in the summer having incorporated their first-year experiences.

The math option would have preferred to postpone multivariable calculus until after matrix theory but the engineering options wanted multivariable calculus in the first year.

About 10–15% of incoming students advance place out of either one or two years of the core and, on the basis of a diagnostic exam, another 10–15% are found to have somewhat weaker backgrounds and so are placed in a special section of Math 1a (called informally Math 0.9, a name given by the undergraduates themselves).▶

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HONORS & AWARDS

Richard Ellis
- Honorary Professor of Observational Astrophysics, Cambridge University

Steven Frautschi
- ASCIT Lifetime Achievement Award

David Goodstein
- Sigma Xi's 2000 John P. McGovern Science and Society Award

Shri Kulkarni
- invited to give the David Harris Lectures for the year 2000 by the Physics Department at MIT

Hideo Mabuchi
- 2000 MacArthur Fellowship
- Office of Naval Research Young Investigator

Anthony Readhead
- named the Barbara & Stanley R. Rawn, Jr. Professor of Astronomy

Anneila Sargent
- Director of the Interferometry Science Center (ISC)
- Centennial Lecture, American Astronomical Society

Axel Scherer
- named the Bernard Neches Professor of Electrical Engineering, Applied Physics, & Physics

Alexander B. Soshnikov
- Young Mathematician's Prize of the Moscow Mathematical Association for 1999

Kip Thorne
- received an honorary degree (D.Sc.) from Utah State University and gave their Commencement Address
- Centennial Lecture, American Astronomical Society

Ahmed Zewail
- Faye Robiner Award from Ross University
- Elected a Foreign Member of The Royal Danish Academy of Sciences and Letters
- Honorary degree (D.Sc., h.c.) from the University of New Brunswick, Canada.

Passings

H. Frederic Bohenblust, Professor of Mathematics, Emeritus

Thomas H. Wolff, Professor of Mathematics

KAMLAND - a hunt for the neutrino mass

by Robert D. McKeown and Petr Vogel

Neutrinos have always been special among the elementary particles. The neutrino was actually the first particle proposed by a theorist to guarantee the validity of a symmetry principle. That happened seventy years ago when Pauli suggested that neutrinos (invisible then and remaining so for another twenty-five years) are emitted together with electrons in nuclear beta decay. This bold proposal allowed preservation of the fundamental laws of energy and angular momentum conservation in the beta decay process. Experimental confirmation of Pauli's hypothesis was very difficult because neutrinos have extremely feeble interactions with matter; in fact, neutrinos can travel light years through ordinary matter without interacting. The original discovery in the fifties and subsequent experiments in the early sixties ultimately led to the Nobel Prizes for Reines (1995) and Lederman, Schwartz and Steinberger (1988). Since then experimenters have made tremendous strides in studying neutrinos, but doing experiments with neutrinos is still a challenging endeavor.

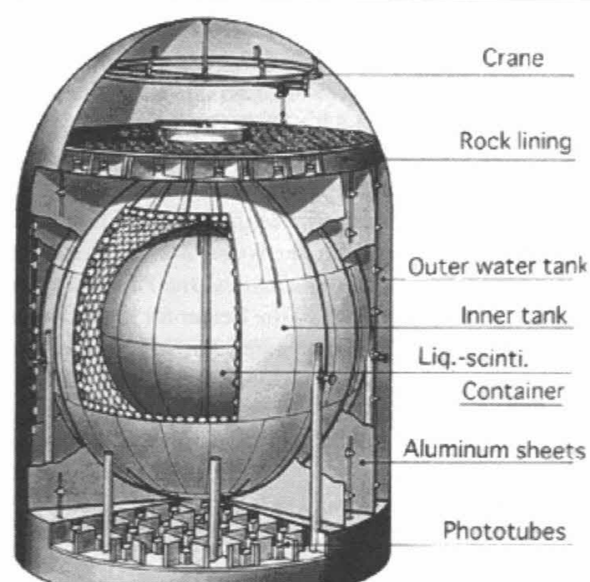

Figure 1: Schematic view of the KamLAND detector. The steel sphere has diameter of 18 m and is equipped with about 2000 large 17" photomultipliers. There is 1000 tons of liquid scintillator inside the inner transparent container.

Thus, it is perhaps not surprising that our knowledge of the intrinsic properties of neutrinos is still very incomplete. We do know that there are three " flavors" of neutrinos, ν_e, ν_μ, and ν_τ, but we do not know for sure whether they are massless (as most people believed until recently) or if they have some, albeit very small, mass. This problem has become a hot subject in particle physics lately, with several hints suggesting that neutrinos are not only massive particles, but that they "oscillate". That means that a beam which initially consists only of, say, electron neutrinos ν_e, later can oscillate into muon or tau neutrinos, ν_μ or ν_τ. The oscillations are possible only for massive particles. Definitive experimental evidence that neutrinos have these properties would have enormous consequences in many disciplines of fundamental science, including particle and nuclear physics, cosmology, and astrophysics.

There is a long tradition at Caltech of the search for neutrino oscillations. Based on the suggestion of Murray Gell-Mann and his then postdocs Harald Fritsch and Peter Minkowski, a reactor neutrino experiment was staged at the Institute Laue-Langevin in Grenoble, France in 1981. The experimental team was led by Professor Felix Boehm and former Caltech Professor Rudolph Mössbauer. That experiment did not find any sign of neutrino oscillations. It was then followed by a series of measurements at further distances from a reactor near Gösgen, Switzerland, with still no trace of oscillations. Thus it appeared that one had to go even further away from the reactor (with a correspondingly lower neutrino flux) to observe the oscillation effect. The most recent measurement, (again by the group led by Felix Boehm) at the Palo Verde power station near Phoenix was inspired by the observation of the Japanese Kamiokande experiment of a much reduced atmospheric ν_μ flux. The Palo Verde detector was placed nearly a kilometer away from the three reactors there, and still ▶

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LIGO Observatory Is Dedicated

by David Beckett

A ceremony formally dedicating LIGO was held at the Livingston site last November. The two-day inaugural event provided an opportunity to thank the many partners and agencies who contributed to LIGO's construction, as well as a way to open the Observatory to the public at large. The dedication was attended by notables from the sciences, politics, industry, and the media.

A collaborative venture between Caltech and MIT, LIGO's goal is to detect the gravitational waves predicted by Einstein. These waves, which are ripples in the fabric of space-time produced by stellar cataclysms, can be perceived only by equipment of the most extraordinary sensitivity. LIGO's mandate is to achieve that sensitivity through a complex amalgam of applied science and technological innovation. In so doing, LIGO hopes to observe phenomena in the Universe that are hidden to electro-magnetic probes.

The Observatory inauguration took place in the lush, tree-studded terrain of Louisiana. This LIGO site was chosen over its twin sister in Hanford, Washington, chiefly because of its closer proximity to the East Coast, Washington D.C., and overseas venues, areas from which many visitors would be traveling. The event consisted of two main attractions: a Scientific Symposium conducted the first day, and the Inaugural Celebration held the day after.

The Scientific Symposium featured scientists and thinkers whose contributions to astrophysics, LIGO-related science, and gravitational wave experiments provided the foundation for the creation of LIGO. Among the presenters were Clifford M. Will speaking on "General Relativity and Gravitational Waves," Michael S. Turner on "Cosmology and Gravitational Waves," John N. Bahcall on "Solar Neutrinos and LIGO: Any Parallels?," Kip S. Thorne on "Gravitational Waves: Sources and Signals," Peter R. Saulson on "Suspended Mass Interferometry," Stan Whitcomb on "LIGO," Adalberto Giazotto on "VIRGO/GEO/TAMA," Albert Lazzarini on "Detection of Gravitational Waves with LIGO/VIRGO," David G. Blair on "Resonant Bars," and Karsten Danzmann on "Gravitational Waves in Space."

The Inaugural Celebration the following day gave an opportunity for those involved in LIGO's management, funding and development to describe their experiences in making the project a reality. Featured speakers included Barry C. Barish, LIGO Director; Gary H. Sanders, Deputy Director; Rainer Weiss, MIT Professor of Physics; Kip S. Thorne, Caltech Professor of Physics; Robert A. Eisenstein, Director of the Division of Mathematical and Physical Sciences for the National Science Foundation; David Baltimore, Caltech President; Claude R. Canizares, Director of the Center for Space Research at MIT; The Honorable Richard H. Baker, Congressman of the 6th District of Louisiana; and giving the keynote address of the occasion, Rita R. Colwell, Director of the National Science Foundation.

A tour of the Livingston Observatory, as well as a briefing on the functions of the components of the detector, was also provided. More information about the Inauguration, including photos, video clips, and a full-coverage article can be found online at: http://www.ligo.caltech.edu/LIGO_web/200002news/200002main.html ◆

GALEX

by Christopher Martin

One of the keys to understanding the universe better is to look into its past. A Caltech/JPL-led international mission now under development will explore the evolution of galaxies and the origins of stars and heavy elements to help complete our picture of the history of the cosmos.

The Galaxy Evolution Explorer (GALEX), targeted for launch in November 2001 from the Kennedy Space Center, will map the history of star formation by looking back in time billions of years to point out where galaxies were evolving and star formation was very active. The 29-month mission will survey cosmic history from the present back to 20% of the age of the universe since the Big Bang about 15 billion years ago.

The major question GALEX will try to answer is how galaxies evolved over time. It is believed that Galaxies formed early in the Universe's history. Once formed, galaxies continued to manufacture stars out of gas to build the galaxies we see today. GALEX seeks to chart and begin to understand this building process. To do this, GALEX will utilize a 50-centimeter (20-inch) ultraviolet telescope, a very sensitive and accurate way to measure star formation. The instrument will allow detection of the most massive stars, which are hotter and have shorter lives than smaller stars. The number of these hot stars, and therefore the ultraviolet brightness of a galaxy, is directly related to the total number of stars recently formed in each galaxy. By measuring many galaxies at different distances (and therefore at different times in their history), GALEX will put together a statistical picture of the average star formation history in any given galaxy, and of all galaxies in the Universe together. The history of the formation of these massive stars is also the history of the formation of elements heavier than Hydrogen and Helium that formed the building blocks of life in the Universe, since these are formed by massive stars.

GALEX will obtain broadband imaging data for about 10 million galaxies, some of them billions of light-years from Earth. GALEX will also obtain spectra of about 100,000 galaxies using a slitless grism spectrograph. Both broadband and spectroscopic data will provide information about the distance, dust absorption, and star formation rate in these galaxies.▶

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Building a Virtual Observatory

by S. G. Djorgovski and T. A. Prince

Surveying the Sky

We are at the start of a new era of information-rich astronomy, and Caltech is at the cutting edge of this new development.

In the 1930's, Fritz Zwicky practically invented systematic sky surveys (in addition to discovering the dark matter, and predicting gravitational lensing, and neutron stars). He built the first telescope on Palomar Mountain, of a then-novel wide-field imaging design, the 18-inch Schmidt. Zwicky and his colleagues used it to search for supernovae (now a major fashion in observational cosmology), more-or-less discovered the large scale structure in the universe, and compiled some of the first major catalogs of galaxies, clusters, and various peculiar objects.

Caltech continued to lead the world in the field of sky surveys. In the 1950's, a bigger, 48-inch Schmidt telescope (now the Oschin Schmidt) was constructed and used to produce the first modern sky survey, in the form of a photographic atlas covering about two thirds of the entire sky. This (First) Palomar Observatory Sky Survey (aka POSS-I) served as the basic roadmap of astronomy for several decades, feeding countless investigations and leading to many discoveries. In its recently produced digital form, it continues to serve astronomers worldwide. In the mid-1980's the Second Palomar Observatory Sky Survey (POSS-II) was started; it is now just being finished. Its digital version, DPOSS, is also approaching completion: it will serve as one of the major digital sky surveys for years to come. The digitization of these venerable photographic atlases gave them a second lease on life in the modern computer era.

Sky surveys at other wavelengths also broke a new ground, for example the pioneering near-infrared survey by Bob Leighton and Gerry Neugebauer in the 1970's. This survey has only recently been surpassed by the modern, 2-Micron All-Sky Survey (2MASS), which is housed at our Infrared Processing and Analysis Center (IPAC), along with the first (and only) far-infrared survey of the sky done by the IRAS Satellite in the1980's. Continuing this process of surveying the sky at multiple wavelengths, the Caltech/JPL GALEX satellite will be launched in the near future to map the sky at UV wavelengths with the goal of probing the history of star and galaxy formation.

The Ongoing Data Flood in Astronomy

Ongoing or forthcoming sky surveys over a range of wavelengths will be soon generating data sets measured in the tens of Terabytes. The current surveys are already creating catalogs of objects (stars, galaxies, quasars, etc.) numbering in billions, with up to a hundred measured parameters for each object. Yet, this is just a foretaste of the much larger data sets to come. Petabyte (10^{15} byte) ▶

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is that, as with quarks, the neutrino types entering into interactions are not the neutrino mass eigenstates, but rather, non-trivial, quantum mechanical linear combinations of them. Thus, a neutrino initially of definite type, say ν_e, develops into a linear combination of all three types, ν_e, ν_μ, and ν_τ, as it propagates through space. If this neutrino couples significantly to just one of the other types then the probability that it will behave as a ν_e in a subsequent interaction is

$$1 - \sin^2 2\theta \sin^2 (1.27\, \Delta m^2\, L/E)$$

where $\sin^2 2\theta$ is the mixing strength, Δm^2 the difference of the squares of the masses of the two definite-mass neutrinos in eV^2, L is the distance the neutrinos have propagated in km, and E is their energy in GeV. For properly chosen parameters, this hypothesis fits all current solar neutrino observations (with neutrino energies in the MeV range). Professor Felix Boehm has performed several experiments at nuclear reactors, most recently at the Palo Verde power complex in Arizona, searching for ν_e oscillations in the MeV energy range; in the $\sin^2 2\theta - \Delta m^2$ range he was able to study, no evidence for oscillations was observed. However, other experiments have seen anomalous deficits of ν_μ neutrinos in the GeV range produced by cosmic rays in the earth's atmosphere, and the oscillation hypothesis provides a natural explanation for them. These observations were formally reported in the summer of 1998 by a Japanese-American collaboration operating an experiment in Japan called Super-Kamiokande. Furthermore, the massive neutrino hypothesis, with the same parameters as required by the Super-Kamiokande data, also explains a similar neutrino deficit observed by the just finishing MACRO (Monopole, Astrophysics, and Cosmic Ray Observatory) experiment in Italy, for which Caltech Professor Barry Barish was spokesman. Thus there is a sizable body of evidence that points in the direction of massive neutrinos, but it is conceivable that something other than mass alone is responsible for the oscillations among the different neutrino generations. One of the most intriguing alternative possibilities is the existence of the extra space dimensions predicted by String Theory, in which components of neutrinos rather than or in addition to gravitons could propagate in the extra "bulk" dimensions of spacetime. The existence of these new degrees of freedom would lead to exotic oscillations of the neutrinos, with oscillation probabilities as a function of energy (L/E) that differ from the formula given above, the usual prediction. Part of the theoretical "wiggle-room" arises because the important physical parameters, θ and Δm^2, and the nature of the other neutrino or neutrinos involved in the oscillation are only poorly determined. However, there is now enough known (approximately maximal mixing and Δm^2 in the few times 10^{-3} eV^2 range) to confidently design an experiment based upon a high intensity ν_μ beam, and that is what MINOS is. MINOS consists of four major components, three of them at the FermiLab Particle Physics Laboratory ▶

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fundamental physical constants and absolute temperature itself. [The relation is given by the product of pi squared, Boltzmann's constant squared, and absolute temperature, over three times Planck's constant ($\pi^2 k_B^2 T/3h$). Numerically, at an ambient temperature of one Kelvin, this quantized conductance roughly translates to a temperature rise of one Kelvin upon application of a thousandth of a billionth of a watt of power (its precise value is 9.4×10^{-13} W/K).]

Their new result has important implications for nanotechnology as well as for the transmission of information. Moore's Law, a popularized rule-of-thumb, can be used loosely to describe the continuous decrease in size of the individual building blocks (the transistors) that populate, now in the tens of millions, integrated circuits forming today's powerful computer chips. In the unrelenting technological drive toward increased function and decreased size, these individual transistor components have been scaled downward in size to a realm where the underlying physics of their operation can change. In the worst cases at the smallest size scales, conventional operation may completely break down. One example is the so-called "power dissipation problem" stemming from the fact that when each individual transistor on a microchip is turned on, each gives off a little heat. This accumulates to become a very significant problem when millions of such transistors, each in effect a microscopic heat generator, are placed in close proximity. "This will become especially serious for future molecular-scale devices" says Roukes. "No matter how small, you always have to put a finite amount of power into a device to turn it on. In this quantum regime, when only a limited number of modes are capable of transferring heat, it will be crucial to take this fundamental limitation into account." Separate theoretical studies carried out elsewhere indicate that this quantum of thermal conductance is universal, and independent of whether the heat is carried by electrons, phonons, or any other mechanism. It would seem there is no way of escaping this fundamental law of nature!

In separate theoretical studies, the maximum thermal conductance observed in this work has been linked to the maximum rate that information can flow in a device having a single quantum "channel." This surprising connection between information theory and thermodynamics is a manifestation of a deep connection between information and entropy. As we engineer smaller and higher speed computational elements, we will also encounter this fundamental quantum limitation in rate of information flow.

To carry out this work, Keith Schwab, a postdoctoral fellow in Roukes' group, developed special devices from silicon nitride with assistance from research staff member Erik Henriksen. The work was carried out in the group's nanofabrication and ultralow temperature laboratories at Caltech. At the heart of their devices is an isolated heat reservoir, which the researchers term a "phonon cavity", resembling a miniature plate that is freely suspended by four narrow beams. Each beam acts as a quasi one-dimensional "phonon ▶

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no neutrino oscillations were seen.

Now a new experiment, much further away (~150 km) from a whole group of nuclear reactors (in fact, all 17 nuclear power plants in Japan), is being built at the Kamioka mine in Japan. Despite the large number of big reactors, the neutrino flux at this distance is very low. So the detector must be very large (1000 tons of liquid scintillator) to yield a detectable event rate of less than 3 events per day. In addition, the background count rate due to cosmic rays must be reduced by locating the detector deep underground. Kamioka is an ideal place for it; the mine is inside a mountain, about a kilometer from the nearest surface, and has a long and successful tradition of hosting neutrino experiments.

KamLAND is a large international collaboration combining several Japanese and US groups. The Caltech contingent is led by Professor Robert McKeown, and actively participates in all aspects of the experiment. In particular, Caltech has major responsibility for the tests of the radio-purity of all components of the detector. It is vital for experiments of this type to insure that the background from radioactivity in the detector is very low and well understood. It will be extremely challenging to suppress all background events so that one will be able to reliably extract the rare neutrino events from the power reactors.

At present the civil construction is finished, including the stainless steel sphere, and the installation of the photomultipliers is progressing. Once that is done, the delicate task of filling the detector with the liquid scintillator will begin. The whole detector, including all of its complicated electronics, should be ready to start collecting data on April 1, 2001.

What are the chances that this reactor experiment will finally demonstrate the existence of neutrino oscillations? Unlike the previous attempts, this is no longer a shot in the dark, and again the story has its origin at Caltech. In 1963, Willy Fowler (1983 Nobel prizewinner in physics) and three research fellows in the Kellogg Radiation Laboratory (John Bahcall, Dick Sears, and Icko Iben) performed the first calculation of the flux of solar neutrinos based on a detailed model of the sun. These solar neutrinos arise from the nuclear reactions that occur in the solar interior that begin with the fusion reactions that generate the energy that causes the sun to shine. This initial work stimulated an active program of theory and experiment that continues to the present day.

Several careful measurements of solar neutrinos have been performed, and there is an apparent deficit in the flux of neutrinos observed in all these experiments. At present, the only viable explanation that is consistent with all these measurements is that the electron neutrinos indeed oscillate, which results in a lower flux detected at the earth. However, the analysis has four equivalently good solutions, corresponding to different neutrino masses and other parameters. One of them is directly accessible to the KamLAND reactor neutrino experiment. If that solution is the right one, the KamLAND team should be able to see it clearly. Thus, KamLAND offers a unique opportunity to test the hypothesis that the apparent deficit in the solar neutrino flux is due to neutrino oscillations in a well-controlled terrestrial laboratory experiment.▶

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waveguide" for heat flow, and it is precisely this reduced-dimensional flow that is the focus of the researchers' measurements. On top of the cavity Schwab and Henriksen patterned two small, separate patches of thin-film gold, described by Roukes as "puddles of electrons". In the course of a measurement, one of these is heated by passing a very small electrical current through it. Electrical connections allowing this current to flow were made using superconducting leads (patterned on top of the phonon waveguides). This insures that heat is deposited only within the resistive gold film and, therefore, transferred only to the phonon cavity. To escape from the suspended device, the heat must eventually flow through the phonon waveguides. Since the waveguides' thermal conductance is weak, the phonon cavity temperature ultimately rises to a new, and hotter, steady-state level that directly reflects the thermal conductance of the phonon waveguides.

Measurement of the current-induced temperature rise within the small devices is a significant challenge in its own right, and required both ingenuity and the investment of a significant portion of the researchers' efforts. Most available thermometry techniques applicable at the nanoscale are electrical and involve power levels that greatly exceed that used by the researchers in their measurements. "The power level we used to carry out these experiments, about a femtowatt, is equivalent to the power received your eye would receive from a 100W light bulb at a distance of about 50 miles", says Schwab. Instead of the standard electrical methods, the researchers coupled the second "electron puddle" to extremely sensitive dc SQUID (superconducting quantum interference device) circuitry. This allowed them to observe the feeble current fluctuations that have a magnitude that is directly proportional to the absolute temperature of the nanoscale device. This so-called Johnson/Nyquist noise, which is the origin of the electrical noise causing background hiss in audio systems, here plays a pivotal role by allowing the local temperature of the phonon cavity to be measured without perturbing the ultra-miniature device. In the end, because the researchers know precisely the amount of heat deposited, and can measure directly the absolute temperature reached by the phonon cavity in response to it, they can measure directly the thermal conductance of the narrow beams acting as phonon waveguides. Simply stated, the ratio of the heat flowing through the waveguides to the rise in cavity temperature is the phonon thermal conductance of the quasi one-dimensional waveguides.

This work was carried out over the past three years within the research laboratories of Caltech Professor of Physics, Michael Roukes. The principal author of the paper is Keith Schwab, formerly a Sherman Fairchild Distinguished Postdoctoral Scholar within Roukes' group. Schwab's life as a young postdoctoral scientist, and his role in the efforts to observe the quantum of thermal conductance, are the subjects of an upcoming documentary film by independent filmmaker Toni Sherwood. Co-authors of the paper are John Worlock, Visiting Associate at Caltech and Research Professor of Physics at the University of Utah, a long time collaborator with Professor Roukes, and Erik Henriksen, a former research staff member in Roukes' group.◆

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But what if this solution is not the one Nature has chosen? Careful purification of the liquid scintillator to remove trace radioactive elements would enable KamLAND to function as a solar neutrino observatory. This experiment would then provide a definitive answer to the question: which of the remaining solutions of the neutrino oscillation puzzle is the correct one? Stay tuned.◆

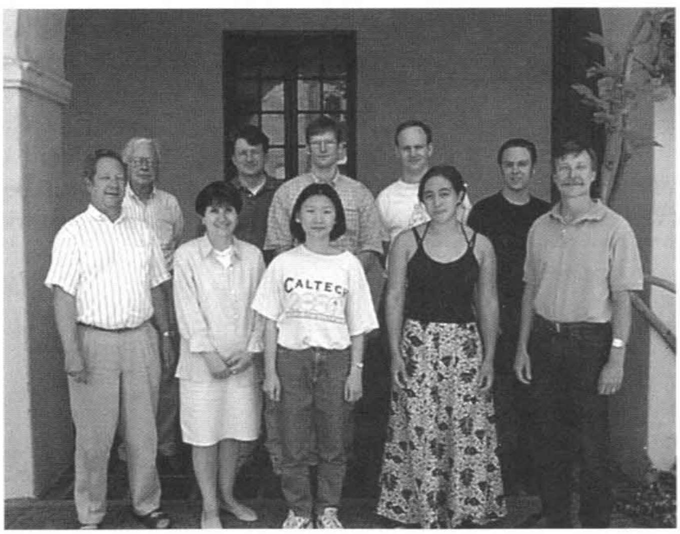

Figure 2. From Right to left, bottom row: Robert McKeown, Bevan Emma Huang, Jui-Ting Patty Lee, Sylvie Gertmenian, Petr Vogel. Top row right to left: James Hansen, John Beacom, Bryan Tipton, Johannes Ritter, Felix Boehm.

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Math 0.9 spends ten weeks on basic calculus. This "remedial" section is so only in the Caltech continuum. The instructor who taught it last year remarked that she had taught the honors class at the University of Maryland and Math 0.9 did "twice as much twice as fast." A 14-lecture probability course, Math 1d, is given in the third term that covers what the regular Math 1a does in its second half. This course is taken by the Math 0.9 students to make up for the fact that they have no probability. It is also taken by some of the regular Math 1a students who did passing work in the Calculus half of Math 1a but not passing work in the Probability half.

After the first quarter, the courses are offered in two tracks: analytic and practical. The analytic track is somewhat more abstract; for example, it does general vector spaces while the practical track focuses more on $\mathbf{R}^n$.

The first half of Math 1a uses notes written especially for it. The analytic track (through the first half of Ma 2a) uses the Apostol books used by a generation of Caltech students. The practical track has been using a book by current Caltech CDS Professor Jerry Marsden and by Alan Weinstein.

The mathematics core, taught in three faculty-taught lectures and one grad TA section, represents about 25% of the teaching of the senior faculty and about 60% of the graduate student teaching load.◆

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There is considerable controversy about the average rate at which galaxies are forming stars now, as compared to this rate in the early universe. Work by Professor Chuck Steidel of Caltech using the Keck telescopes has shown that many galaxies exist at early times, which may be forming stars at a rapid rate. These observations of distant, highly redshifted galaxies are measuring the ultraviolet flux in distant galaxies. Unfortunately, no comparable comparison sample of galaxies exists nearby or at intervening distances, since there has never been a deep, wide-field imaging ultraviolet survey. GALEX will provide this survey, and utilize a consistent observational method to relate ultraviolet properties of galaxies to their star formation rate and amount of dust absorption. Once this "calibration" is performed for well-understood nearby galaxies, ultraviolet properties can be used to trace star formation to the most distant galaxies, perhaps even those discovered by the Next Generation Space Telescope.

GALEX will also perform the first ultraviolet imaging all-sky survey. This survey should produce as many as a million Quasars, hundreds of thousands of white dwarf stars, and many other interesting objects that are hot and therefore radiate strongly in the ultraviolet.

Caltech has overall responsibility for the mission development and execution, led by Professor Christopher Martin. Caltech will provide science operations and data analysis after launch, and lead the science analysis effort. This mission represents a uniquely close working relationship between JPL and the campus. In addition to overall project management, led by Dr. James Fanson, JPL is responsible for developing the instrument electronics and software, structure, mechanisms, and optical assembly, as well as for performing integration and testing of the instrument. Incorporating near- and far-ultraviolet detectors developed by the University of California Berkeley along with Caltech, and three high performance optical assemblies supplied by Laboratoire d'Astonomie Spatiale in Marseille under sponsorship of the French national space agency, GALEX utilizes many state of the art technologies. Yonsei University in Seoul, Korea will support the science operations and data analysis effort. Johns Hopkins University is providing a state of the art data archive system developed for the Sloan Digital Sky Survey project.

The GALEX instrument is every bit as complex as the Wide Field/Planetary Camera-2 aboard the Hubble Space Telescope, but will cost about one tenth as much. GALEX's data rate will be twice that of Hubble and the Space Infrared Telescope Facility (SIRTF) combined.

The mission was selected for development in 1997 at a cost of $70 million under NASA's Small Explorer Program, administered by the Goddard Space Flight Center in Maryland. NASA confirmed GALEX for development in April 1999. Instrument integration is currently underway at JPL, with major tests scheduled for the early fall. Science calibration will begin in December. In February 2000, following calibration, the instrument will be delivered to Orbital Sciences Corp. to be integrated with the spacecraft bus.◆

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about 40 miles west of Chicago and the fourth, 735 km away in northeastern Minnesota. The FermiLab Main Injector, whose main job is to prepare a beam for injection into the Tevatron Accelerator, will produce a high intensity beam of 120 GeV protons. About 1 milligram (rest mass) per year of these high energy protons illuminate a target to produce a secondary beam of high energy pions and kaons that are collected and collimated into a 3/4 km long decay tunnel sloping gently into the earth, aimed for Minnesota. Some of the pions and kaons decay to muons and neutrinos and, after a beam stop, a pure neutrino beam, with energies in the 1 to 30 GeV range, is launched toward both a "near" detector at FermiLab and a "far" detector in Minnesota. The near detector allows detailed study of the intensity and energy spectrum of the beam sent north, and comparison of these with what is seen 735 km away is the crux of the experiment. The far detector consists of 486 layers of 2.5 cm thick iron sheets, each an 8 m by 8 m octagon, followed by a 1 cm thick scintillation counter that allows detection and energy measurement of the charged particles that result from neutrino interactions. The combined mass of the steel and scintillator is 5400 tons. Even with such a massive target/detector, only a few events from FermiLab will be observed per day and so it is essential to reduce, by as much as feasible, the relatively huge cosmic ray flux that the detector is also sensitive to. For this reason, the far detector is being built in an abandoned iron mine, in a hall just now being constructed, about 800 m below ground. Detector construction is expected to be completed about six months to a year before beam will be delivered, near the end of 2003.

The Caltech group, currently consisting of Barish, Michael, Newman, Peck, and Senior Postdoctoral Scholars Brajesh Choudhary and Hwi Kim has been a part of this experiment since well before it was formally proposed in 1995. We have been primarily involved with the particle detector system and currently Doug Michael has primary responsibility for the scintillation system. Furthermore, we are just establishing a factory for production of about 2000 of the large sheets of plastic scintillator which will be distributed throughout the iron.

So far all of the indications of neutrino oscillations have been negative, i.e., fewer than the expected number of events have been observed. But if our physics interpretations are correct, an energy scan at a fixed detector should show an oscillatory signal, a deficit at some energies and an enhancement at others, and it is this that MINOS hopes to observe for the first time. Further, if the physics parameters turn out to be favorable, we may also get the direct evidence for ν_τ. And perhaps most interesting of all, it may turn out that all the curious phenomena seen up to now are due to some unexpected behavior of the elusive neutrino and we will get the first glimpse into some new physics. In any case, we should have interesting things to report in a few years!◆

Cosmic Gall

"Every second, hundreds of billions of these neutrinos pass
through every square inch of our bodies, coming from
above during the day and from below at night, when the
sun is shining on the other side of the earth!"
—*From "An Explanatory Statement on Elementary Particle Physics," by M. A. Ruderman and A. H. Rosenfeld, in* American Scientist.

Neutrinos, they are very small.
They have no charge and have no mass
And do not interact at all.
The earth is just a silly ball
To them, through which they simply pass,
Like dustmaids down a drafty hall
Or photons through a sheet of glass
They snub the most exquisite gas,
Ignore the most substantial wall,
Cold shoulder steel and sounding brass,
Insult the stallion in his stall,
And, scorning barriers of class,
Infiltrate you and me. Like tall
And painless guillotines they fall
Down through our heads into the grass.
At night, they enter at Nepal
And pierce the lover and his lass
From underneath the bed—you call
It wonderful; I call it crass.
—John Updike

VIRTUAL OBSERVATORY continued from page 5

surveys will come next, involving repeated imaging of the sky (e.g., in searches for Earth-crossing asteroids, by the JPL NEAT team). Large digital sky surveys and data archives are becoming the principal sources of data in astronomy. The very style of observational astronomy is changing: systematic sky surveys are now used both to answer some well-defined questions which require large samples of objects, and to discover and select interesting targets for follow-up studies with space-based or large ground-based telescopes, e.g., the Hubble Space Telescope (HST), or the Kecks.

This vast amount of new information about the universe will enable and stimulate a new way of doing astronomy. We will be able to tackle some major problems with an unprecedented accuracy, e.g., mapping of the large-scale structure of the universe, the structure of our Galaxy, etc. The unprecedented size of the data sets will enable searches for extremely rare types of astronomical objects (e.g., high-redshift quasars, brown dwarfs, etc.) and may well lead to surprising new discoveries of previously unknown types of objects or new astrophysical phenomena. Combining surveys done at different wavelengths, from radio and infrared, through visible light, ultraviolet, and x-rays, both from the ground-based telescopes and from space observatories, will provide a new, panchromatic picture of our universe, and lead to a better understanding of the objects in it. These are the types of scientific investigations which were not feasible with the more limited data sets of the past.

For the first time in the history of astronomy, we will have data sets whose full information content greatly exceeds the original purposes for which the data were obtained. This opens the new field of data-mining of digital sky surveys, using the data for newly conceived projects and exploring the vast data parameter spaces. It is inevitable that the previously poorly explored parts of the observable parameter space will contain new discoveries and surprises.

The Technical Challenges

This great opportunity comes with a commensurate technological challenge: how to manage, combine, analyze and explore these vast amounts of information, and to do it quickly and efficiently? We know how to collect many bits of information, but can we effectively refine the essence of knowledge from this mass of bits?

The problem is not unique to astronomy, but indeed exists in any modern science (e.g., the experimental high-energy physics, genomic biology, etc.), and in many fields of the modern information-based economy. However, the problems posed by the new massive data sets in astronomy may be "just right" for our computer scientist friends: interestingly hard, but actually solvable.

The data volumes here are several orders of magnitude larger than what astronomers are used to dealing with, and the old methods simply do not work. There are issues on how optimally to store and access such complex data, how to combine sky surveys done at different wavelengths, how to visualize them, to search through them, etc. Many of these issues are being tackled in the Digital Sky project at Caltech, using the DPOSS, 2MASS, and some other digital sky surveys as a testbed for testing and development of the necessary software technologies.

A lot of powerful techniques already exist and can be used or tested in these new astronomical applications; others may be developed in our collaboration with applied computer scientists. Caltech astronomers have already developed very fruitful and mutually beneficial collaborations with applied computer scientists at JPL. We fully expect that such partnerships will grow and multiply.

The Need for a Virtual Observatory

Many individual digital sky survey archives, servers, and digital libraries already exist, and represent essential tools of modern astronomy. However, in order to join or federate these valuable resources, and to enable a smooth inclusion of even greater data sets to come, a more powerful infrastructure and a set of tools are needed. For example, it is now easy to obtain data on a given object or a small set of objects, or to obtain images of a given small patch on the sky. However, we do not have easy and generally available tools to join several multi-Terabyte sky surveys quickly and to perform sophisticated queries in the resulting complex data sets. In other words, we can do old astronomy with subsets of the new data — but we really want to do the new type of astronomy which these enormous data sets can support.

The concept of a "*virtual observatory*" thus emerged. A virtual observatory would be a set of federated, geographically distributed, major digital sky archives, with the software tools and infrastructure to combine them in an efficient and user-friendly manner, and to explore the resulting data sets whose sheer size and complexity are beyond the reach of traditional approaches. It would help solve the technical problems common to most large digital sky surveys, and optimize the use of our resources.

Within the United States, there is now a major, community-driven push towards the National Virtual Observatory (NVO). Its creation was given a very strong recommendation by the recently completed report by the National Research Council's Astronomy and Astrophysics Survey Committee, "Astronomy and Astrophysics in the New Millennium".

The New Astronomy

The NVO will federate the existing and forthcoming digital sky archives, both ground-based and space based. Caltech and JPL groups are very actively involved in its development, and will certainly be among the key partners of the NVO for many years to come. We aim to become the Mt. Palomar of the new digital astronomy, to break the new ground and make some of the first major discoveries which a virtual observatory would enable.

This is nothing less than a birth of a new way of doing astronomy, through a systematic exploration of the universe at a range of wavelengths. Historically, many astronomical investigations involved studies of individual objects or relatively small samples of objects, and usually in a limited range of frequencies (e.g., optical, or radio, or ...). Whenever a serious attempt was made to cross wavelengths, ▶

See VIRTUAL OBSERVATORY page 12

Thomas Wolff (1954-2000)

Thomas Wolff, professor of mathematics at the California Institute of Technology, was killed Monday night, July 31, in an automobile accident in Kern County. He was 46.

A native of New York City, Wolff grew up in a mathematical environment. His uncle, Clifford Gardiner was a professor at NYU's Courant Institute of Mathematics for many years and Wolff's mother Lucile was a technical editor of volume 1 of the English translation of the celebrated book *Methods of Mathematical Physics* by Courant and Hilbert.

Wolff was a specialist in analysis, particularly harmonic analysis. Professor Wolff made numerous highly original contributions to the mathematical fields of Fourier Analysis, Partial Differential Equations, and Complex Analysis. A recurrent theme of his work was the application of finite combinatorial ideas to infinite, continuous problems.

While a Berkeley graduate student, Wolff surprised mathematicians worldwide with a new proof of Lennart Carleson's corona theorem about bounded analytic functions in the plane. His papers with Peter Jones of Yale University on harmonic measure showed that a random moving particle in the plane will with large probability first hit a given frontier set along a given set of finite length.

Wolff also worked in analytic problems arising in the fundamental equations of quantum mechanics. He proved new results on uniqueness of solutions of partial differential equations such as the Schrödinger equation by recasting all previously used inequalities in terms of oscillatory integrals. With Barry Simon, also at Caltech, he provided fundamental criteria for the localization of electrons in random media that have been used in virtually all related work in the past fifteen years. In a 1995 paper, he disproved three different outstanding conjectures about steady state of heat flows in three-dimensional space.

His two papers on the Kakeya problem (in 1995, 1997) gave new bounds on the size of subsets that include a line segment in every direction. This result gave sharper bounds on several important operators in Fourier analysis and differential equations and it established a link between discrete combinatorial mathematics and continuous harmonic analysis. The implications of this work are under intense study by analysts worldwide.

Wolff's most recent work has been similarly groundbreaking. In a paper to appear in the Annals of Mathematics, he obtained a striking new understanding of the wave equation that promises to have significant effect on the study of nonlinear physics.

Wolff was mild-mannered and unassuming but broke through his shyness to be a mentor and teacher with enormous impact on his graduate students, postdocs and coauthors.

Wolff earned his bachelor's degree in 1975 from Harvard, where he often played poker with his fellow student Bill Gates. He received his doctorate in mathematics at UC Berkeley, and afterward was acting assistant professor at the University of Washington and an NSF Postdoctoral Fellow at the University of Chicago.

He came to Caltech in 1982 as an assistant professor and was named full professor in 1986. From 1986 to 1989 he was a professor of mathematics at New York University, was at Caltech from 1988 to 1992, and from 1992 to 1996 was at Berkeley. He returned to Caltech in 1995, where he was a professor at the time of his death.

Among his major awards were the 1999 Bôcher Prize and the 1985 Salem Prize as well as a Sloan Fellowship and invited named lecture series at the University of Chicago and Stanford. He was a member of the editorial boards of three publications: Communications in Analysis and Geometry, AMS Electronic Journal of Research Announcements, and the Journal of Functional Analysis.

He is survived by his wife, Carol Shubin, a mathematics professor at Cal State Northridge; two sons, James Herbert Wolff, age 3, and Richard Thomas Wolff, age 5; his parents Frank and Lucile Wolff and his sisters Virginia and Caroline.

A fund for the educational expenses of the Wolff boys is being planned. If you would like to make a contribution to this fund, please contact Michelle Vine at vine@cco.caltech.edu; phone: 626-395-3817; or PMA Division 103-33, Caltech, Pasadena, CA 91125.

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major discoveries were made: recall the discovery of quasars in the early 1960's, from the optical follow-up of radiosources; or the cracking of the puzzle of cosmic gamma-ray bursts in the past few years; in both cases Caltech astronomers made the crucial contributions.

This systematic, panchromatic approach will enable new science, in addition to what can be done with individual surveys. It would enable meaningful, effective experiments within these vast data parameter spaces. In the words of a "white paper" developed to promote the cause of the NVO, it will be the "*engine of discovery*" for the new astronomy. The NVO would also facilitate the inclusion of new massive data sets, and optimize the design of future surveys and space missions. Most importantly, the NVO would provide access to powerful new resources to scientists and students everywhere, who could do first-rate observational astronomy regardless of their access to large ground-based telescopes. Finally, the NVO would be a powerful educational and public outreach tool.

Similar activities are now also being pursued in Europe, and the NVO will likely grow into a Global Virtual Observatory, serving as the fundamental information infrastructure for astronomy and astrophysics in the next century. We envision a productive international cooperation in this rapidly developing new field.

In order to facilitate the progress towards the NVO, Caltech and JPL sponsored an international conference, "Virtual Observatories of the Future", at the Caltech campus on June 13-16, 2000. The goals of this conference were to define clearly the scientific motivation and needs, and to focus on the technical problems and challenges related to the conception of the NVO and its global equivalent.

More information can be found on the following websites:

http://digital-sky.org
http://astro.caltech.edu/nvoconf/
http://www.srl.caltech.edu/nvo/

CBI Update

by A. Readhead

The Cosmic Background Imager (CBI) has been in full operation at 5000m in the Chilean Andes since the first week of January this year. The instrument is performing superbly: each night of good weather (about 50% of the time) we obtain two or three good images of the microwave background radiation (previously it took months to make a single good image), and we are confident that the instrument can do the job it was designed for. The only serious difficulty we have encountered has been the weather, which has been the worst in 10 years. We have had to contend with a lot of snow, which makes access to the site difficult much of the time, and sometimes impossible. However, the site infrastructure is operating smoothly, even at temperatures which are often -15° C and with heavy snow and winds of 50 mph. We are most grateful to Ronald and Maxine Linde, and to Cecil and Sally Drinkward for their generous support of this project. We have just received our third year's funding from the National Science Foundation.◆

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