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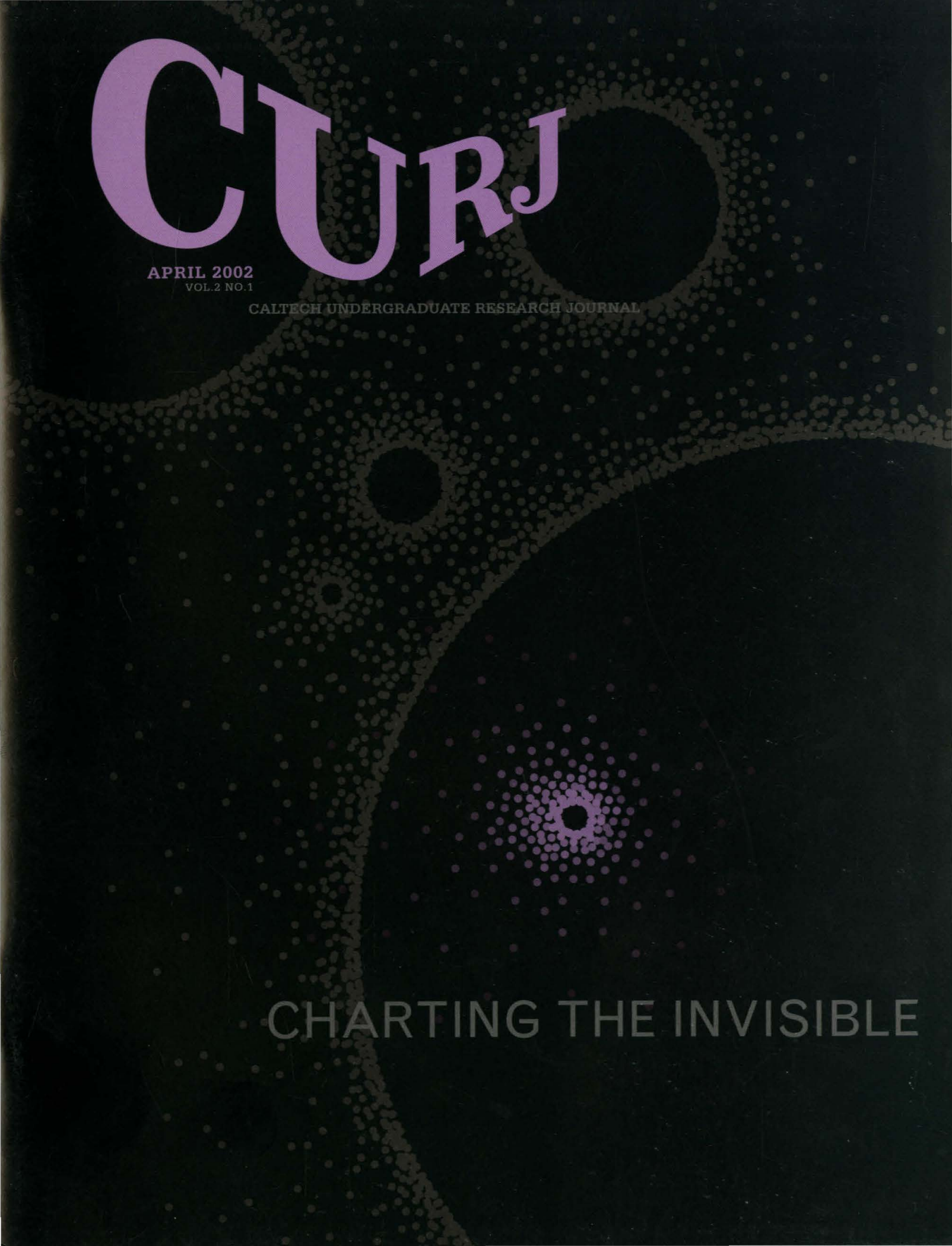
APRIL 2002
VOL.2 NO.1

CALTECH UNDERGRADUATE RESEARCH JOURNAL



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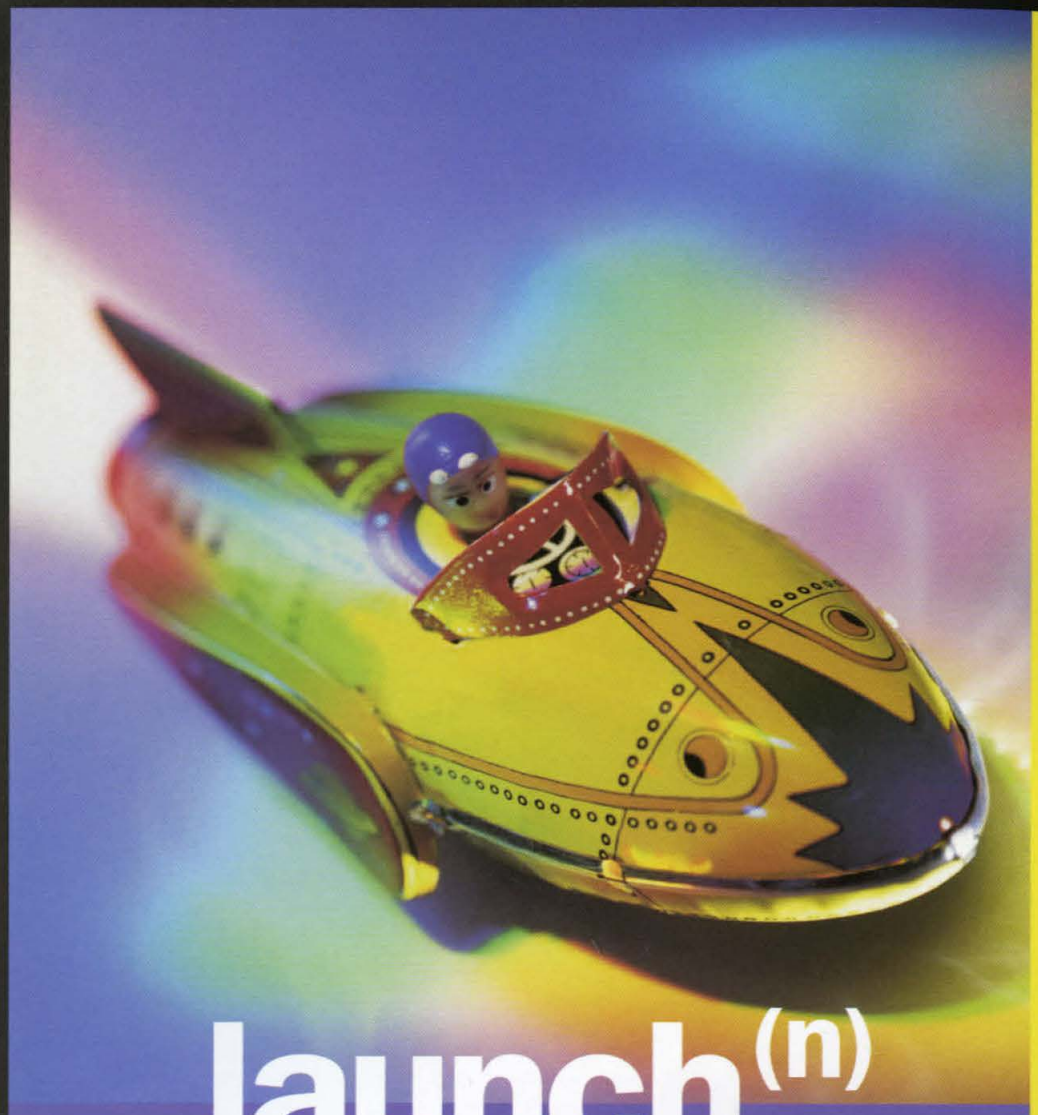

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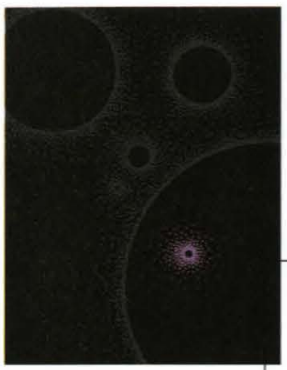

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CHARTING THE INVISIBLE:
REFINEMENTS ON THE SHAPE OF DARK MATTER
by **Lisa Wang**

Discrepancies in existing models of dark matter inspire a subtle method for deducing mass distribution in parts of the universe we cannot see.

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FROM THE EDITOR

Forced to choose between apparently conflicting priorities, today's private and public research universities struggle to guarantee undergraduate educational quality. Careful course development can take forty hours each week in and out of the lecture hall. At the same time, competitive research demands countless more hours in the laboratory and office. To university administration, requiring strong research and teaching is an impractical gold standard when there are not enough hours in the week for superlatives in both. But the moral defense of the need for good undergraduate instruction is simple: today's students are tomorrow's researchers.

Some professors rise to the gold standard, propelled by a love for teaching or an obligation to teach, communicating information with accuracy, and engaging students in the inherent beauty of a subject. Others are less driven to teach. The resulting instruction, inaccurate, impertinent, and insipid, can squelch a student's enthusiasm for a new subject. The mixed lot of extremes confounds undergraduates, frustrating or encouraging academic pursuits irrespective of any rational guidance.

A research institution nevertheless offers strong advantages to the undergraduate, irrespective of classroom instruction. The creative environment attracts an ambitious and intelligent group of classmates. Laboratory facilities immerse students in the cultures of science and engineering. Undergraduate research programs afford the incomparable opportunity to investigate and discover. For students aspiring to academia, learning is directed under the guidance of strong research role models.

But undergraduate instruction lags behind these strengths because existing incentives for good teaching are insufficient. Curriculum steering committees and course evaluation forms have little effect if teaching quality is only tangentially tied to tenure and pay scale. And a pervasive attitude of educational responsibility is rare.

Quality teaching requires commitment from professors. Administration at research universities must reform teaching incentives and come to terms with the logistics of undergraduate education. Teaching universities that devote themselves, often exclusively, to undergraduate instruction, will have experienced guidance to offer. Once established, a basic standard in undergraduate education at our research institutions will better enable more students to channel their creativity and secure our future of intellectual prosperity.

Ram Srinivasan
Editor-in-Chief

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Dark Matters Kristen-Sara Stiers

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CALTECH UNDERGRADUATE RESEARCH JOURNAL VOL.II NO.I

Original CURJ Design by Aniko Hullner Grau

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PRESERVING COPYRIGHT'S COMMONS

BY WENDY SELTZER

We are at a critical moment in this country's intellectual development. The Internet now gives millions of Americans a new medium through which to create and exchange information and ideas, yet even as it reaches that potential, old media interests press Congress to restrict technological dissemination of information because it hurts their old-fashioned business models. Against these pressures, we must reinforce openness and the public domain.

The Internet has been called the most participatory form of mass speech yet. It enables its users to be both readers and publishers, in forums as diverse as email lists, websites, web logs, bulletin boards, and chats. Yet intellectual property protectionism threatens to "chill" that speech, to change the Internet from a vibrant communications network to just another form of few-to-many broadcast. This legal climate threatens to stifle the scientific innovation that fueled the network's growth.

The threat comes from lobbyists, legislators, and lawyers advancing maximalist interpretations of the various intellectual property laws, most notably copyright. Copyright derives originally from constitutional language granting Congress the power "to promote the Progress of Science and the useful Arts, by securing for limited Times to Authors and Inventors the exclusive Right to their respective Writings and Discoveries." The Framers acted on the belief that these limited monopolies would serve as an incentive to creation and publication, ultimately for public benefit and progress.

That original balance between the public and copyright holders proved resilient, even as Congress added to the variety of works that could be copyrighted and the scope of those copyrights. Copyright holders were granted rights including the exclusive right to copy, to distribute, and to perform their works in public. The public got access to published works, fair use rights to make even unauthorized excerpts, parodies, and personal copies, and full use rights when copyright terms expired and works entered the public domain.

This longstanding balance is being tested by claims that because digital copying is somehow different, the Internet requires a radical reshaping of copyright law. Within the last decade, Congress has extended copyright terms to twenty years through the Sonny Bono Copyright Term Extension Act. Congress has also blocked access to, and full use of, works barred by "technological protection measures" with the Digital Millennium Copyright Act's anticircumvention provisions. Instead of being a limited grant to further the public interest, copyright is becoming an instrument of censorial control.

The Sonny Bono Act has prevented an Internet publisher from adding Robert Frost's poetry to his library and slowed historians in documenting the Jazz Age. The Digital Millennium Copyright Act's anticircumvention provisions have been invoked to bar independent programmers from developing players for DVD movies and to block scientific publication of research on the weakness of digital watermarks. The provisions were used to prosecute

the developer of an e-book reader that would enable blind people or children to use the e-book with a text-to-speech processor. These laws slow the filling of Internet libraries and archives and hinder the development of technology to read, play, or interact with new media works.

The recently proposed Consumer Broadband and Digital Television Promotion Act pushes the excesses of protectionism even further. It would mandate that every "digital media device" incorporate anti-copying technologies, technologies that presume every computer user to be a "digital pirate" rather than a potential author and producer of his or her own content. Under rules such as those, developers could not build computers capable of reading and writing to disk or tape without first vetting their designs against these no-copy dictates.

We quickly forget the lessons of the Betamax case, Sony Corp. v. Universal City Studios, in which movie studios sued Sony to block manufacture and sale of the VCR, a device they claimed would strangle their markets. Studios argued that they would have no incentive to produce films once viewers could tape and archive the movies broadcast into their homes. The Supreme Court instead upheld viewers' fair use right to "time-shift" broadcasts. The technology the studios fought to shut down now accounts for nearly half their revenues in the form of video sales and rentals.

New technologies may threaten old business models built around previous-generation technologies, but technical innovations should not be discarded over old business models. Few of us mourn the decline of the typewriter, yet if their manufacturers had been able to shut down production of word processors for personal computers, we might still be replacing ribbon cartridges and correction tape. Publishing technologies change, but we all lose if artificial limits on the technology stop us from communicating about art or drawing on a rich public domain to create art of our own. We all lose if scientific research is stifled by laws based in publishers' paranoia.

We must preserve an environment in which today's students have room to found the next Yahoo! or AOL, to write the new great American novel or multimedia symphony. Creativity and technical innovation depend critically on establishing a balance between respect for copyright and respect for its limits. By embracing open technologies and unencumbered publications, the public can counter this movement toward stifling copyright legislation. By pushing their senators and representatives, they can give the Internet the vitality of the open public library, not the pallor of one-way broadcast that leaves the public as a mere consumer. Our consumer and political action can reclaim the Internet public space, the intellectual commons that begins where copyright's control ends.

Wendy Seltzer is an intellectual property litigator and a Fellow with the Berkman Center for Internet & Society at Harvard Law School. She taught Internet Law at St. John's University School of Law and is a founder of the Chilling Effects Clearinghouse. (www.chillingeffects.org).

REVELING IN CONFUSION

BY STEVEN E. KOONIN

"Scientists like being confused," I heard early in my research training. That didn't really sink in thirty years ago. But after publishing some two hundred research papers, supervising many graduate and undergraduate students, and helping to define and implement research programs in several institutions, I grew a deep appreciation for that statement.

Developing scientists are taught science[1] in several different guises as they move from elementary school through graduate work. In the early grades, unless they have exceptional teachers, science is portrayed to them as a collection of facts and a test of memory. Just remember the names and their context and you do well. No reason at all for confusion, and no sense about how science really works. (There is however a significant, on-going debate about the relative merits of "fact-based" versus "inquiry-based" science teaching. As usual, the optimum is probably some mix of these two limits.)

Somewhat later in a scientist's career, explanations move to the fore and parts of the world and the facts that describe them become connected causally and rationally. For example, physics informs the earth sciences, and biology informs the social sciences. But again, there's not much confusion. If something is unclear, just ask the class instructor or teaching assistant, and it's usually cleared up. Indeed, the answer is often right there in the textbook.

Confusion begins with the research career, as one moves from the realm of "is" to the ambiguous areas of "maybe" or "could be" or "perhaps." Here you don't know the answer, and probably no one else does either! You might not have a clue about how to start to find it. You might not even know the question properly. Scientists must learn to manage confusion or even seek it out. If we weren't confused, we'd know the answer and we wouldn't be doing research.

Of course, the "being confused" line is really about how to think your way through a novel situation. For example:

- What do I know and what don't I know?
- How firmly are these facts or non-facts established?
- Which explanations are consistent with what I know?
- Which are most plausible?
- What information would narrow down the range of solutions?
- How do I get that information?

Asking questions like these is natural to a research scientist, but not necessarily to a developing scientist. The transition from repeating facts and applying existing methods to generating new knowledge can be rough. Some students never do make it. But the capacity for discovery is what defines a research scientist.

Problem sets or laboratory exercises that pose mock unknowns and retrace famous routes of discovery go some way toward teaching the process (as distinct from the art) of research. But these tasks are acrobatic routines with a safety net. There is always the security of knowing that an answer exists and that there is a way to find it, unless of course, the professor is particularly malicious or inept!

No, the best way to learn to be productively confused is by apprenticeship: a one-on-

[1] I use the word "science" in its broadest sense to include mathematics, engineering, and the natural and social sciences.

one relationship in which the student first observes, and then is guided by, an experienced researcher confronting a problem. Among the many skills to observe, practice, and learn are:

- How to ask the right question—not so simple as to be useless, not so tough as to be unanswerable.
- How to form, test, reject, and refine hypotheses.
- How to persevere through tedium or setbacks, and how to savor flashes of insight.
- How and when to interact with others.
- How to be self-critical, to keep asking yourself and others what's wrong with the results rather than blindly exalting in what's right.
- How to get your message across in papers and presentations.

Research apprenticeship is the bedrock of both graduate education and postdocing, as well as for the training of a few fortunate undergraduates such as those writing in these pages. Beyond the specific research accomplished, the apprenticeship gives the developing researcher some benchmarks for cultivating their own research style. Apprenticeship is by its nature, time consuming, personal, and customized. These qualities and their implications for the structure and financing of our research institutions are not well understood or appreciated by the many who haven't had the experience themselves.

The problem-solving skills of the research scientist are also useful in other realms more ambiguous than the comfortably factual scientific. Social, political, personnel, and economic problems are not solved solely by the usual rational methods, because the human dimension adds at least one extra layer of confusion. Scientists don't have a corner on rationality or problem solving. Rather, thinking through complex situations is natural to us. I continue to be surprised by the extent to which rationality isn't second nature for many nonscientists.

Each of the articles in this journal documents its author's beginning steps, from the certainty of their training to the uncertainty of their research. I hope they will always enjoy and benefit from being confused.

Steven E. Koonin is Professor of Theoretical Physics and Provost at the California Institute of Technology. His research interests include theoretical nuclear and many-body physics, computational physics, and global change.

LOIHI
AND THE HAWAIIAN HOT SPOT

BY SARAH COOKE

BEYOND THE TOURIST CENTERS OF OAHU, MAUI, AND THE BIG ISLAND, the entire Hawaiian-Emperor island chain tells a seventy-million-year-old tale of creation and destruction. The Hawaiian vacation paradises are just a few of the islands at the southernmost end of a chain stretching 5600 kilometers all the way from Alaska to the mid-Pacific Ocean. Following the chain from one end to the other is like tracing the story of volcanic development millions of years back into time (see Figure 1). At the northernmost end of the chain are the old Emperor Seamounts. As a result of erosion and sinking ocean floors, the seamounts fail to break the ocean's surface. A little further south lie small pinnacles, atolls, and sunken coral rings like Midway. Finally, at the southern end of the chain lie the familiar Hawaiian Islands. The southernmost Big Island rises 30,000 feet above the sea floor, making it 2000 feet taller than Mt. Everest. The progression of the Hawaiian-Emperor chain provides snapshots of the hundred-million-year evolution of a volcanic island. Northern islands reflect the eventual fate of the others, and someday the Big Island itself will be no more than a seamount. At the southern end, the youngest volcano grows underwater, offering clues about volcano formation.

HAWAII'S UNIQUE VOLCANOES

A unique type of volcanism formed the Hawaiian-Emperor islands. Molten rock in the Earth's mantle, or hot, middle layer, is one component in volcano formation. Above the mantle is the Earth's crust, which is broken into pieces called tectonic plates. Together, the crust and upper mantle make up the Earth's rigid lithosphere. The lithosphere sits on a hotter, more fluid layer called the asthenosphere, and convection currents in the asthenosphere set the tectonic plates in motion.

Most volcanoes occur at boundaries between separating or colliding plates (see Figure 2). For example, at a subduction zone, one plate dips down underneath another plate and plunges into the mantle. Volcanoes form on the overriding plate from the melted remains of the subducting plate. At spreading centers, plates move apart and pull melted material up from the asthenosphere. These tectonic processes account for the most common volcanoes.

The Hawaiian Islands are in the middle of the Pacific Plate, far away from any plate boundary, so they must have formed from a different process. In certain places on the Earth, hot material from the deep mantle of the asthenosphere rises up in plumes, melting the lithosphere into magma. Magma builds up in chambers until a vent forms at the surface, tapping the magma reservoir to produce one or more volcanoes. Underneath Hawaii is one of these "hot spots" where hot plumes rise up from the asthenosphere. Although the hot spot remains stationary, a spreading center pushes the overlying Pacific Plate northwest at a rate of 9 centimeters per year. Volcanoes are born over the hot spot, but they eventually move away from the supply of magma and become inactive. Then, a new vent forms as an outlet for the magma, creating a new volcano over the hot spot. This process drives the cycle of island chain volcanism.

The newest volcanoes from this cycle are located on the Big Island, including Mauna Loa, Kohala, and Hualalai (see Figure 3). The youngest volcano in the Hawaiian-Emperor chain is the underwater Loihi Seamount, found 28 kilometers south of the Big Island, 980 meters below sea level (mbsl). Loihi provides the chance to observe a new volcano rise up from the sea floor. Researching Loihi has given insights into the birth and maturation of volcanoes, including a previously unknown chemical development that young volcanoes undergo.

FIGURE 1. A 1986 eruption of the volcano Kilauea on Hawaii's Big Island. The still-growing Hawaiian Islands are the youngest members of the Hawaiian-Emperor chain. The oldest members are inactive, now little more than underwater seamounts.
Source: U. S. Department of Interior, U. S. Geological Survey.

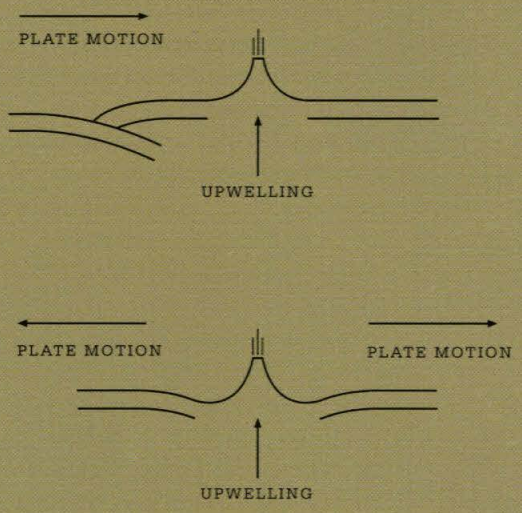

FIGURE 2. (A) Volcanism at a subduction zone. At a subduction zone, one plate dips underneath another and melts. Melted material from the subducted plate rises and forms volcanoes on the overriding plate. (B) Volcanism at a spreading ridge. At a spreading ridge, plates move away from each other. Material from the asthenosphere rises up in the gap and erupts onto the seafloor.

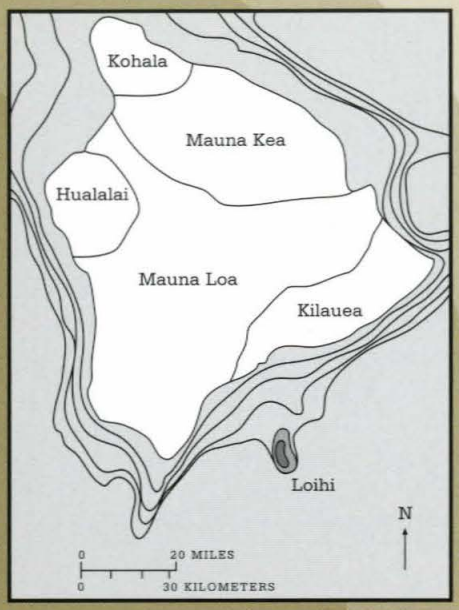

FIGURE 3. Volcano map of Hawaii's Big Island and Loihi. The Big Island is the southernmost island in the Hawaiian-Emperor chain and home to several active volcanoes. Submerged underwater and eighteen miles south of the Big Island, Loihi is the youngest addition to the Hawaiian-Emperor chain volcanoes.
Source: U. S. Department of Interior, U. S. Geological Survey.

DISCOVERY OF LOIHI

Kenneth O. Emery discovered Loihi in 1955 through echo sounding. Radio signals bouncing off the sea floor revealed a bump on the side of Mauna Loa. Emery named the elongated, banana-like shape Loihi, based on the Hawaiian word for long. He did not know it was an active volcano, only a structure on the flank of Mauna Loa.

Research on Loihi was sparse in the following years until a seismic network around the Big Island detected large earthquake swarms in early 1972 and late 1975 at Loihi's summit. Fred W. Klein from the Hawaiian Volcano Observatory observed that the epicenters were shallow and less than 20 kilometers deep. Earthquake swarms accompany eruptions on Kilauea and Mauna Loa, so the swarms left little doubt that Loihi was active. In 1981, this realization motivated sample recovery missions that began dredging, or indiscriminately scooping up, hundreds of kilograms of rock from Loihi. The rocks were unquestionably volcanic in nature, but they were not very fresh. In 1996, another swarm of 4000 earthquakes over a three-week period prompted more sample collections. Observers described the audible "bangs, pops, and grinding noises" accompanying the swarm, characteristic of undersea eruptions. Rocks collected at the summit immediately after these earthquakes looked very fresh, as if they had formed from eruptions around the same time as the swarm.

CLUES TO VOLCANO FORMATION

The samples collected in 1981 led to new discoveries about the early growth stages of Hawaiian volcanoes and their relation to the Hawaiian hot spot. James G. Moore of the U. S. Geological Survey found that the 1981 suite of basalt rocks were definitely a product of volcanic activity, although their rims of iron oxides and alteration products meant they had not come from recent eruptions. Many rocks had glass around their exteriors, indicative of magma erupting underwater and cooling instantly. Moore's analysis found that some of the samples were surprisingly alkalic in nature. Alkalic lavas have large amounts of alkali metals like potassium or sodium relative to silica. The main body of a Hawaiian volcano, called the shield, consists of tholeiite, a rock with high silica content. Only small caps on the tops of old volcanoes were known to contain alkalic rock. Most of the rocks collected from Loihi were tholeiites, but it was still surprising to find that Loihi had erupted some alkalic lavas as well, more like an aging volcano than a very young one. The records of alkalic lava suggested that Loihi had erupted lavas of different composition over time.

These unexpected results prompted a more systematic and controlled study. Instead of dredging for samples, researchers picked rocks out of strata with the mechanical arm of a submersible vehicle, precisely noting their location within the volcano. Michael O. Garcia of the University of Hawaii recovered and analyzed a new suite of samples over a thousand-meter range. Below 1450 mbsl, he found that the first products to erupt from Loihi were alkalic. Above 1450 mbsl, most samples were tholeiitic, characteristic of typical volcanic eruptions. Transitional samples occurred over a 100 to 200 meter interval around 1450 mbsl, indicating a time when the Loihi's lavas underwent a

"Scientists knew that volcanoes only produced lavas when they passed over the hot spot, but this **new discovery** refined the idea."

rapid chemical change. The summit crater area formed from the freshest lavas yielded only tholeiitic rocks, indicating that Loihi had recently been erupting exclusively tholeiitic material (see Figure 4). Old volcanoes usually undergo the opposite transition from initial tholeiitic lavas to later alkalic ones, and an early alkalic phase like Loihi's was a new phenomenon.

An older theory proposed that Hawaiian volcanoes had only two growth stages. In the first shield-building phase, a volcano generated most of its volume by producing large amounts of tholeiitic lava. Kilauea, Mauna Loa, and Loihi are currently in this phase. In the second phase, after the volcano moved away from the hot spot and stopped most of its activity, a small volume of alkalic lavas might erupt and form a cap on top. The volcanoes Hualalai on the Big Island and Haleakala on Maui have erupted lavas of this composition within the last 250 years. Rock samples from Loihi showed a new initial phase, where the volcano produces small amounts of alkalic lava, accounting for 4 percent of the volcanic volume. Scientists knew that volcanoes only produced lavas when they passed over the hot spot, but this new discovery refined the idea. When a volcano is directly over the center of the hot spot, it produces large quantities of tholeiitic lava, and volcanoes that are on the sides of it, either approaching or moving away, produce alkalic lava. The two alkalic phases are not identical and are the result of different mechanisms.

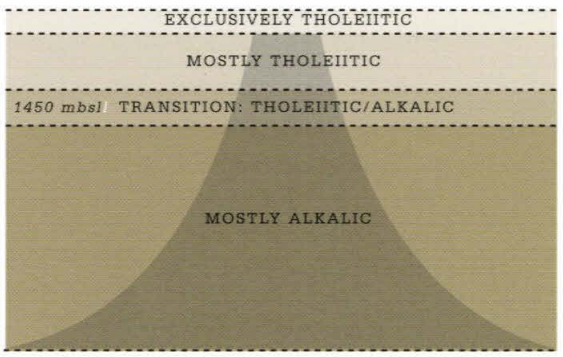

FIGURE 4. Composition of rocks sampled from Loihi. Samples from the base of the volcano are mostly alkalic, indicating that Loihi's earliest lava was rich in the alkali metals. Samples from the upper parts of the volcano are mostly or exclusively tholeiites, indicating that Loihi's current lava is rich in silica. Alkalic and tholeiitic rocks are found in similar proportions at the transition around 1450 meters below sea level (mbsl).

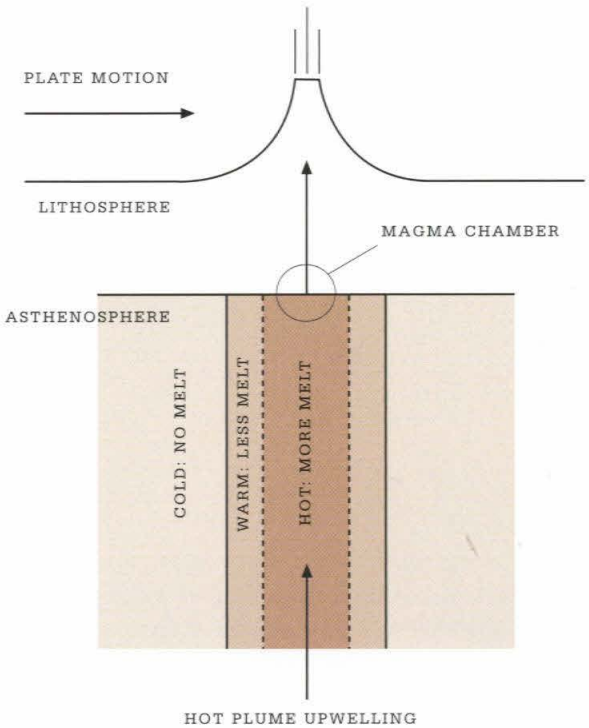

FIGURE 5. Plate motion over a hot spot. The mantle plume warms a cylindrical column of the asthenosphere, creating a hot spot under the tectonic plate. The hot spot is warm on the edges and hottest in the center. The warm edges primarily generate small quantities of volatile, alkalic melt, while the hot center generates large quantities of siliceous melt. This melted material collects in the magma chamber and erupts onto the seafloor, forming a volcano. When the plate moves away from the hot spot, there is no magma left beneath the volcano, and its activity ceases.

DEVELOPMENT OF A VOLCANO

To explain the early alkalic phase, geologists adjusted their theory of volcano development. When fresh Pacific Ocean crust approaches the hot spot, a Hawaiian volcano is born. As the volcano moves away from the hot spot, its lavas undergo chemical changes. Partial melting of the Earth's mantle as it passes over a hot spot produces changes in the composition and volume of magma (see Figure 5).

Think of the hot spot as a cylindrical area in the asthenosphere that is hotter in the center than at the edges. As fresh portions of lithosphere pass over the hot spot's outer zone, the upper mantle heats up a little and starts to melt. At these low temperatures, only small amounts of rocks rich in carbonates, sodium, and other volatile compounds melt. This melt rises to the ocean floor and erupts as alkalic lava, corresponding to the rocks recovered from Loihi's base.

As the crust continues to migrate, the volcano moves over the center of the hot spot. Here, the mantle is hot enough to produce large volumes of melt. The same volatile-rich rocks melt as before, but a greater volume of silica-rich rocks also melts. On the whole, the melt is largely siliceous in composition, rather than alkalic. This siliceous melt produces tholeiitic rocks like those erupting from the adult volcanoes Loihi and Mauna Loa.

As the volcano continues to develop, it migrates away from the center of the hot spot. It continues to erupt tholeiitic lava in decreasing amounts until the volcano is no longer connected to the hot spot and the supply of lava ends. The volcano lies dormant as it drifts away from the hot spot and begins to erode at the top. When the seemingly extinct volcano has moved far away from the hot spot, it may once again erupt, but this time giving a small volume of alkalic lava. This alkalic lava is not from the hot spot, because the volcano is too far away. Geologists believe that latent heat in the crust left over from the hot spot causes the residual, volatile-rich magma in the chamber to melt. Although these late-phase lavas are alkalic, they are not from the same source as the pre-shield alkalics. The late-phase alkalic lava comes from the bottom of the crust or very top of the mantle in the residual magma chamber, whereas the earlier lavas originate from hot plumes in the deeper asthenosphere. The timing, location, and composition of the lava are intertwined.

"As the volcano continues to develop, it migrates away from the center of the hotspot."

WATCHING LOIHI GROW

The 1996 earthquake swarm provided an opportunity to find out specifically where Loihi's lavas originated. The earthquakes were centered about 7 to 8 kilometers below Loihi's summit, indicating that melted material from the lithosphere rose and collected in the crust's magma chamber at this depth before erupting. Mauna Loa and Kilauea have magma chambers 3 to 4 kilometers below their summits, suggesting that the magma chamber rises as the volcano matures. The nature and location of Loihi's magma chamber continues to be an area of active research.

Current research focuses on detecting and analyzing the periodic large eruptions that still occur at Loihi. Researchers monitor Loihi's seismic activity using underwater hydrophones, hoping to detect another large earthquake swarm. The hot, mineral-rich waters that issue from cracks in Loihi's surface also provide sites of active study. Chemists monitor the minerals that enrich the water, while biologists observe the sea life that thrives on the heat and nutrients from these hydrothermal vents.

Our perception of Loihi has changed from that of a mere bump on Mauna Loa to that of a geological opportunity inviting study from a range of disciplines. Studies of Loihi led to unexpected findings about the way Hawaiian volcanoes form. For the first time, we learned how a young volcano passes through its chemical adolescence, and we saw the unexpected composition of the young magma chamber's lava. As Loihi moves over the hot spot, scientists will continue examining it through seismic monitoring and sample recoveries. Comparing Loihi with its older cousins, we see that Loihi is poised to become the next Hawaiian island, perhaps forming a new vacation paradise millions of years from now.

Sarah Cooke is a fourth year undergraduate in Geology at the California Institute of Technology. *The author wishes to thank John Eiler, Assistant Professor of Geochemistry at Caltech.*

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EXTRACTING LIGHT FROM WATER:

SONOLUMINESCENCE

BY RYAN GUTENKUNST

WATER IS ONE OF THE MOST ABUNDANT compounds on Earth. No known form of life can survive without it, and for a human, a day without water is a day of suffering. Water is such a familiar element in everyday life that one might assume that it is completely understood. Unfortunately, that is not true. Our ignorance is well illustrated by sonoluminescence, the astounding ability of water to concentrate energy from sound waves into flashes of light. After over a decade of intense study, the scientific community is still unable to provide a complete explanation for this phenomenon, but its work has pushed the frontiers of fluid mechanics and expanded our understanding of physics at high pressures and temperatures.

A LONG FORGOTTEN PHENOMENON

In 1934, two German scientists, Frenzel and Schultes, were surprised to discover that a photographic plate submerged in an acoustically driven water bath became dark, indicating exposure to light. Only 40 years earlier, Henri Becquerel had discovered that uranium salts would darken a photographic plate. His observation led to the discovery of radioactivity that took decades to understand, but led to fundamental advances in our understanding of

atomic and nuclear physics. Frenzel and Schultes' observation led to the discovery of sonoluminescence, which is still not understood, and may lead to great advances in our understanding of fluid mechanics.

Frenzel and Schultes initially attributed the light produced in their bath to the sound field itself. It took them time to realize that the sound was not directly exposing the plate. Instead, the sound was creating bubbles in the fluid, and when these bubbles collapsed they generated the observed light. Researchers subsequently studied this light emission, but made little progress as the random nature of multiple bubble formation and collapse limited them to measuring only the time-averaged properties of the phenomenon, which revealed few details about the underlying physics. It took over fifty years for researchers to develop the tools necessary to study sonoluminescence deeply.

D. Felipe Gaitan, a graduate student at the University of Mississippi working under Lawrence A. Crum, made the breakthrough in 1988. Crum had developed a simple, inexpensive apparatus from off-the-shelf parts to acoustically levitate bubbles in water. Gaitan found that by adjusting the parameters of the apparatus he was able to reliably create single, stable, light-emitting bubbles. Gaitan's basic apparatus to produce single-bubble sonoluminescence is simple. It costs only a few hundred dollars and fits easily on a tabletop, a far cry from the multi-million dollar and several-mile-long particle accelerators used in modern high-energy physics.

A sealed quartz cell is filled with water. An attached speaker sends sound waves into the cavity at a level of 110 decibels. This is comparable to the intensity of a smoke alarm from a few centimeters away, but the frequency of the sound used is generally just above the range of human hearing. If the frequency is chosen carefully, a standing wave forms inside the container. To generate bubbles, some of the water is boiled by inserting a heated wire.

The bubbles migrate toward the center of the container where the pressure fluctuations are greatest. There they are trapped by sound waves and coalesce into a single bubble approximately 100 microns across, which pulsates at the frequency of the sound field. Above some critical value for the amplitude of the driving field, the bubble emits dim flashes of blue light during each compression cycle. Under ideal water conditions and in a perfectly dark room, this light is bright enough to see with the naked eye (see Figure 1).

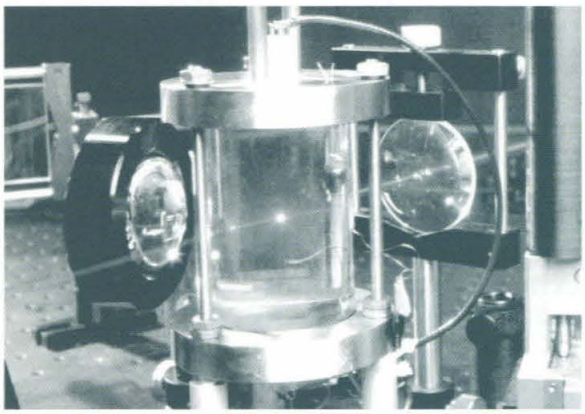


FIGURE 1. A laser beam illuminates a bubble trapped in the center of the containment vessel. Measuring the laser light scattered from the bubble is the easiest way to determine its radius. *Source: S. J. Putterman, Scientific American 272, 46 (1995). © Ed Kashi*

A SIMPLE SYSTEM WITH COMPLEX BEHAVIOR

Although the basic apparatus for producing sonoluminescence is simple and inexpensive by modern standards, there was little further interest in the phenomenon for several years after Gaitan's work. Then Bradley P. Barber and Seth J. Putterman of UCLA attempted to measure the duration of the light flash emitted during each compression. They were surprised to discover that their photomultiplier tubes were not fast enough to resolve the flash, and were even more surprised to find that the flash was quicker than one of the world's fastest pulsed lasers. Currently, the best measurements can only tell us that the sono-

luminescence flash is shorter than 50 trillionths of a second; the actual time is too short for modern equipment to gauge. This simple mechanical system concentrates the energy of the acoustical wave into an emission that is shorter than a millionth of the period of the wave itself, resulting in flashes shorter than those seen in high-energy particle physics.

Barber and Putterman were more successful at measuring the period between the flashes, which typically varies by less than 40 trillionths of a second. This extraordinarily consistent period is remarkable because the variation in the time between the flashes is about one one-hundredth of the variation of the output from the precision device generating the driving sound. That is, the flashes occur with greater regularity than the period of the sound that generates it. Barber and Putterman's measurements of the period and duration of the light flashes brought sonoluminescence to the attention of a wider scientific community and inspired almost all subsequent research. No one expected such precise behavior from a crude macroscopic system, and to this day no one can explain it.

The best information about the interior of the bubble collapse comes from the spectrum of emitted light. In general, sonoluminescence spectra are featureless. One might expect to see spectral lines from the gases inside the bubble, but the pressure and temperature inside the collapsing bubble distort the lines to the point where they are unrecognizable. A typical spectrum is shown in Figure 2. There is a peak near 230 nanometers, just outside the blue end of the visible range. This peak appears since more energetic photons are absorbed by the water in which the bubbles are produced, so the radiation is probably emitted at much higher energies. From the spectrum of the emitted light, one can estimate the temperature of the interior of the bubble. In room temperature water, the temperature at the center of the collapsing bubble is 16,000 kelvins—roughly three times as hot as the surface of the sun. Lowering the water temperature reduces the presence of water vapor inside a bubble and allows for the creation of more photons with even higher-energy spectra. Consequently, temperatures inside the bubble reach as high as 30,000 kelvins. However, since surrounding water absorbs the highest energy photons, the calculated values are most likely underestimates. Theoreticians have speculated that the temperature at the very center of the bubble may rise to millions of kelvins, hot enough to initiate fusion. However, whether one can rigorously speak of "temperature" in processes that last for such short times and in such small volumes is debatable. Explaining how water vapor can interfere with such light emission is a major test for any model of sonoluminescence.

The intensity of sonoluminescence depends critically on the driving pressure. Light emission begins at a pressure of 1.1 atmospheres. Here, the mean radius of the bubble decreases dramatically, which has yet to be explained, but at higher pressures the bubble size increases again. As the driving wave pressure increases, so does the intensity of the light that is emitted, simply because the higher-pressure wave carries more energy for the bubble to convert into light. However, at 1.5 atmospheres the pressure becomes too high, thus destroying the bubble.

The radius of a bubble can be easily determined by measuring the amount of light that it scatters from a laser beam. A typical profile of the radius versus time is shown in Figure 3. The bubble slowly expands when the driving pressure is negative, then rapidly shrinks as the pressure becomes positive. The light emission happens at the extreme of the first collapse, after which the bubble rebounds many times, but these smaller oscillations do not produce observable light. The slow expansion and subsequent violent collapse is repeated with each cycle of the driving wave.

Unfortunately, it is difficult to determine the absolute minimum radius, since the bubbles do not persist long enough to make measurements. Knowledge of the minimum radius would allow calculation of the ultimate interior pressure, an important parameter in almost all models of sonoluminescence.

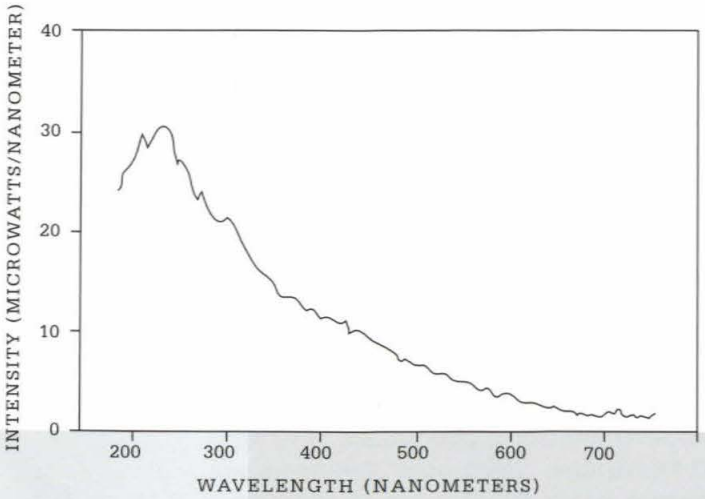


FIGURE 2. The spectrum of a sonoluminescence bubble. The only significant feature is the peak at 230 nanometers, but this peak exists because the water surrounding the bubble absorbs higher energy photons.
Adapted from: L. A. Crum, Physics Today 47, 28 (1994).

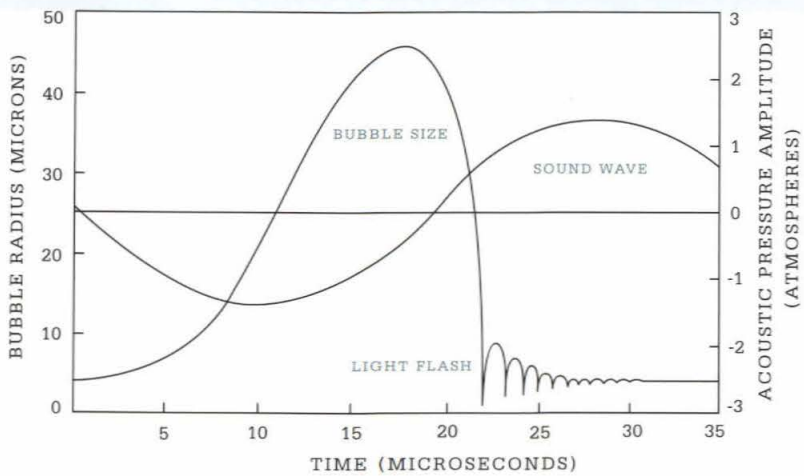


FIGURE 3. The radius of a sonoluminescence bubble and the pressure amplitude of the driving sound wave plotted against time. After the first dramatic collapse during a cycle, the bubble rebounds several times, but these small collapses are not violent enough to emit detectable light.
Source: S. J. Putterman, Scientific American 272, 46 (1995).

The intensity of the sonoluminescence flash also depends greatly upon the amounts and types of gases dissolved in the fluid. The interior of a bubble contains vapors from both the fluid itself and from any gases that may have been dissolved in it. Attempts are being made to induce sonoluminescence in fluids other than water, but this has proven to be very difficult. Only very faint bursts of light have been observed, and those were in fluids that are very similar to water. No one understands what properties of water make it so uniquely amenable to sonoluminescence.

Based on measurements with various dissolved gases, Putterman's group demonstrated that the presence of a noble gas is vital to sonoluminescence. The brightest flashes are seen at noble gas concentrations of about 1 percent. A higher concentration lowers the brightness. It is not understood why a small concentration of a chemically inert gas is so vital to sonoluminescence or why too much suppresses it.

The extremely short duration and consistent period of the flashes that first excited scientists about sonoluminescence only hint at other, even more interesting conclusions that can be drawn from the observations. The production of highly focused energy from such a crude mechanical system is remarkable. The unique properties of sonoluminescence have prompted many models coming from a diverse cross section of physics, fluid mechanics, and chemistry, though a complete explanation has only recently started to emerge.

A MULTITUDE OF EXPLANATORY MODELS

The simplest model that might explain sonoluminescence involves adiabatic compression. Such compression is the reason why, for example, a recently used can of compressed air will be very cold. The rapid expansion of the gas in the can cools it dramatically, and the process happens so fast that no energy is exchanged with the environment. Conversely, compressing a gas raises its temperature. Therefore, when a bubble is squeezed by a sound wave, its interior heats up. Although scientists have not yet determined the mini-

mum size of the bubble, they have estimated that its collapse to one-hundredth of its initial radius could create temperatures as high as 10,000 kelvins at the center. However, this predicted temperature is not quite high enough to explain the emitted light, so researchers look to more complex models to explain the missing energy.

According to fluid dynamics, a collapsing spherical bubble is very unstable, and one way a bubble can break down is through the ejection of a jet of water from one side of the bubble to the other. Traveling perhaps as fast as 4,000 miles per hour, the jet may "fracture" the bubble wall as it impacts the other side, releasing the energy necessary to create the observed light. Proponents of this theory speculate that the atoms of noble gas introduce defects into the bubble wall that serve as starting points for the fractures. However, since the fluid dynamics of the bubble interior are vaguely understood, scientists have modeled the formation of these defects as random processes. Unfortunately, this only makes the jet theory less credible as it is difficult to imagine that something random could produce such an amazingly consistent period of sonoluminescence emissions.

Another model is based on the electric properties of water molecules. In regions of large pressure changes over small distances, such as at the collapsing bubble wall, water can become polarized so that the negative and positive charges may separate slightly. Known as the flexoelectric effect, it creates a strong electric field that can ionize molecules outside the imploding surface of the bubble. Freed electrons may interact with the trapped noble gas atoms and emit radiation. The high temperatures suggested by spectral analysis would correspond to the energy of the free electrons, not the gas atoms inside the bubble, so the bubble's interior would not need to reach such astonishingly high temperatures to create the observed emissions. Most scientists are uncomfortable with the extreme temperatures claimed by some models, so the fact that this model only requires the electrons to be at

these temperatures is an advantage. Unfortunately, the interaction between free electrons and noble gas atoms is poorly understood, and how that interaction could generate light is unclear. The chemistry and physics involved in the model are too subtle to be well understood at this time.

Perhaps the most exotic model was Nobel laureate Julian Schwinger's proposal that sonoluminescence was a quantum mechanical effect. In quantum theory there is an uncertainty relation between energy and time. That is, the more accurately you measure a particle's energy, the less accurately you can measure exactly when the particle was at that energy. One of its implications is that even empty space is filled with energy, the so-called "zero-point" energy. At the very high pressures predicted at the center of a sonoluminescence bubble, Schwinger thought that the zero-point energy might be converted into the observed light—the bubble squeezes space so much that out pop real photons. Detailed quantum field theory calculations showed that this was possible, but experiments have ruled out Schwinger's proposal. Conservation of momentum requires that the photons be produced in pairs traveling in opposite directions, and this correlation was never observed. If Schwinger's model had been correct, it would have been the most significant example of energy extraction from quantum zero-point energy.

The most popular of the current attempts to explain sonoluminescence is an extension of the adiabatic model based on shock waves. A model by Sacha Hilgenfeldt, Siegfried Grossman, and Detlef Lohse incorporates many of the ideas of the previous models. Rather than relying on the unstable bubble wall to compress the interior, their model predicts that the collapsing wall launches a shock wave into the core. This shock wave surges ahead, compressing the interior gas much more than a primitive adiabatic compression and creating higher temperatures and pressures. Under these extreme temperatures, noble gas atoms trapped inside the bubble ionize, changing into plasma. Electrons freed in this process would undergo extreme acceleration, causing them to radiate the observed light. As the model proposed by Hilgenfeld *et al.* does not require any fundamentally new physics or chemistry, it may seem less exciting than previous speculations. However, by making detailed considerations of the optical properties of the plasma and by incorporating a quantum description of the electronic states of the noble gases, they produced the first quantitatively correct prediction of the sonoluminescent spectrum and duration of the light flashes.

STAR IN A JAR

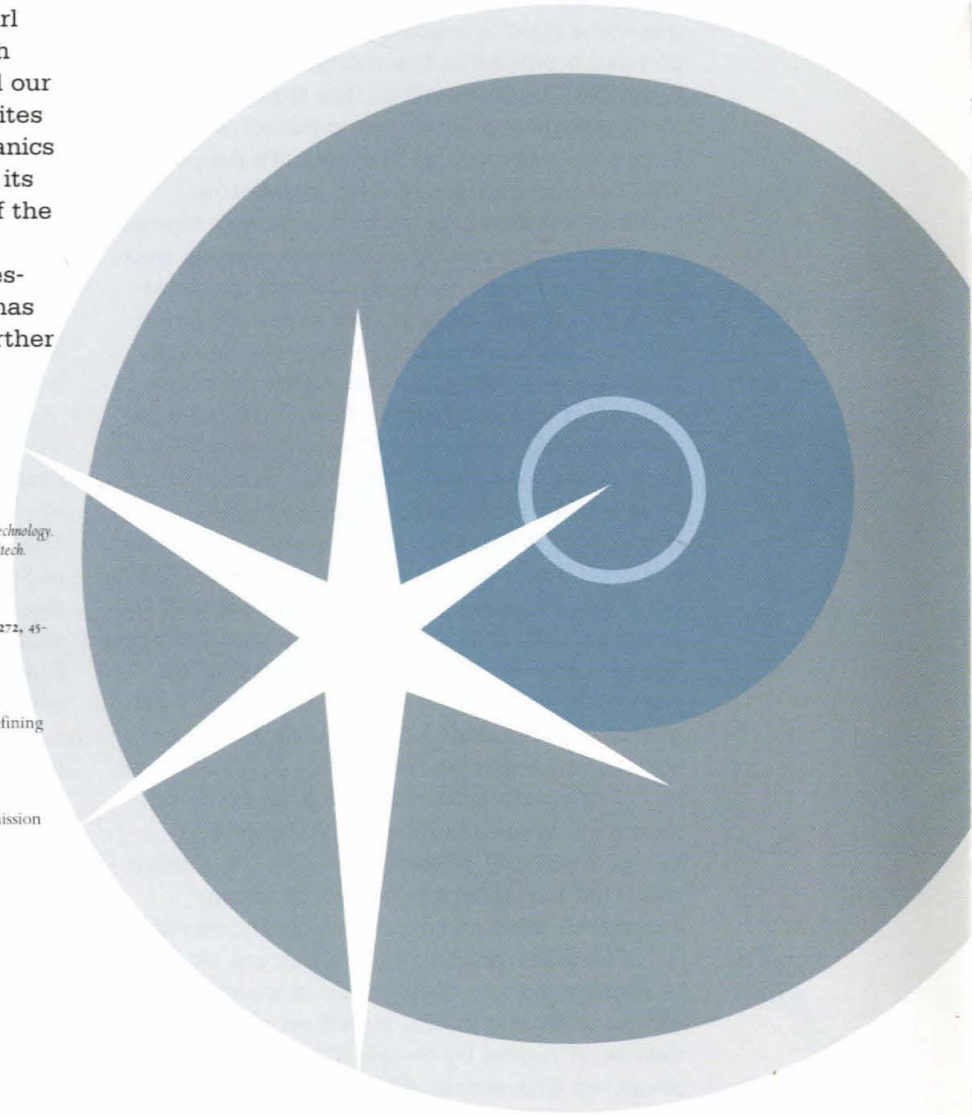
Practical applications of sonoluminescence research tend to be indirect, although the enhanced understanding of fluids at very high pressures is important in many engineering applications. Although a long shot, sonoluminescence could even enable cold fusion, which if possible, has the potential to revolutionize society.

It is speculated that the pressures and temperatures produced during the collapse of a sonoluminescence bubble might be high enough to ignite small bursts of fusion in heavy water. As mentioned previously, the temperature at the core of a hundred-micron diameter bubble is in the tens of thousands of kelvins. In terms of pressure and temperature, this environment might be similar to the core of our sun. If these conditions were present in heavy water, nuclei would fuse, releasing significant energy. Fusion has been the Holy Grail of energy research for decades, and sonoluminescence may make fusion possible on a tabletop.

Admittedly, the prospect of fusion from sonoluminescence is remote. It is unclear whether or not the extreme temperatures and pressures necessary for fusion are achieved in the bubble collapse. A millimeter-sized bubble may also be too large for the

necessary chemical transport processes to operate. Finally, even after nuclei fuse and energy is released, extracting it from the water without disturbing other fusion events may prove impossible.

Even given the uncertainties that swirl around the concept of cold fusion, research into sonoluminescence has already refined our understanding of the physical world. It unites physics, chemistry, optics, and fluid mechanics into one beautiful and simple system, and its study has sharpened our understanding of the wonderful subtleties in all four fields. Sonoluminescence raises fundamental questions concerning water. Answering them has pushed the limits of our understanding further than we once thought possible.



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The author wishes to thank Anthony Leonard, von Kármán Professor of Aeronautics at Caltech.

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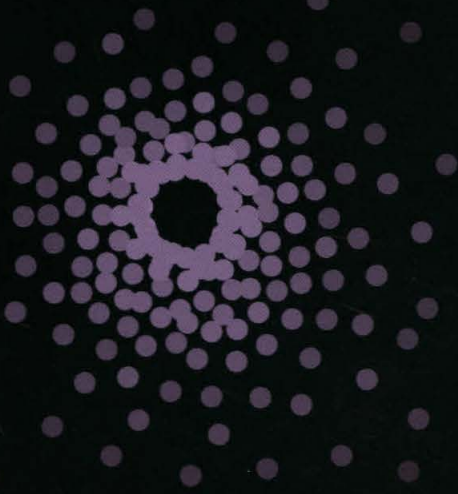

CHARTING THE INVISIBLE:

Refinements on the Shape of Dark Matter

BY LISA WANG

NEARLY EVERYTHING IN THE UNIVERSE IS INVISIBLE TO US. THE STARS PEPPERED THROUGHOUT the night sky comprise only a tiny fraction of the total mass of the universe. Everything else is hidden in the black expanse, the dark matter that does not emit light. This mysterious material makes up seventy-five to ninety-nine percent of the mass of our universe, yet no one knows what it is made of or exactly where it all is. The only way to understand dark matter is indirectly, by observing how its gravitational attraction affects the optical image of surrounding gases and stars that we can see.

The pull of dark matter manifests itself in two ways: through its gravitational effect on interstellar gas between clusters of galaxies and by a phenomenon known as gravitational lensing in which light is bent by the mass of the dark matter. In some special cases, the same cluster can be studied using both methods. Ideally, the theories should independently agree on the quantity and distribution of dark matter, but often they do not. Results from gravitational lensing are reliable because the phenomenon is fairly simple and well understood, and this pushes astrophysicists to modify the current theory of intracluster gas to bring its predictions in agreement with those of gravitational lensing.

Refining the intracluster gas theory is vital to the study of dark matter in clusters since gravitational lenses are not always available to look at. Our research attempts to reconcile gravitational lensing results with interstellar gas x-ray predictions by varying parameters such as temperature that are incorrectly assumed to be constant in such gas models.

FINDING DARK MATTER IN CLUSTERS OF GALAXIES

Galaxy clusters provided the first evidence for dark matter. Containing between 100 and 10,000 galaxies, these clusters are the largest known objects in the universe that are held together by gravity. In 1933, Fritz Zwicky first proposed dark matter to account for an odd observation. Galaxies on the edge of many clusters rotate as if matter were spread evenly throughout the cluster, but visible mass in the cluster (mostly galaxies) is more densely packed around the center. Zwicky's conclusion was that unseen matter exerts a gravitational force on the outer stars.

Intracluster gas makes it possible to measure the dark matter in a cluster. All clusters have some amount of gas that lies between its galaxies. The origin of this gas is unknown, but it may be produced during collisions between galaxies in which gas from inside is blown out by the force of the collision. This could explain why the intracluster gas is several million kelvins, hot enough to emit high energy x-rays when two gas particles collide. The x-ray intensity emanating from a part of a cluster indicates how much gas is there. The mass of dark matter attracts x-ray-emitting gas through the gravitational force, allowing astronomers to observe its existence indirectly. This mechanism requires several assumptions about the state of the cluster and the gas, making the results of the theory questionable.

Gravitational lensing provides a more direct measure of dark matter. In 1917, Einstein predicted that the path of light is bent by the presence of mass. His general theory of relativity predicts that a massive object distorts space-time in the same way that a bowling ball distorts a rubber sheet held parallel to the ground. Anything traveling through this distorted space-time follows a curved path. This phenomenon was verified during a solar eclipse in which light was observed to bend as it traveled near the sun. Any light traveling near dark matter bends, creating a distorted image of the light source to an observer on Earth. A gravitational lens is any such dark matter that significantly distorts the space-time path between Earth and a distant light source.

A gravitational lens can assume a variety of shapes that depends only on how its mass is distributed. A cluster of galaxies may serve as a lens; much of its mass is due to dark matter. Telescope photographs of distant galaxies situated behind a cluster lens will exhibit unique characteristics depending on the shape of the lens. By examining these characteristics, astronomers can infer the distribution of dark matter mass. Lensing effects can provide an independent way to verify other methods that predict dark matter distribution based on features of the cluster, such as x-ray analysis of the intracluster gas.

FOCUSING ON A SINGLE CLUSTER

Extremely dense and three billion light years across, Abell 2218 is one of the most impressive gravitational lenses yet discovered (see Figure 1). The gravity from the Abell 2218 cluster is strong enough to produce multiple

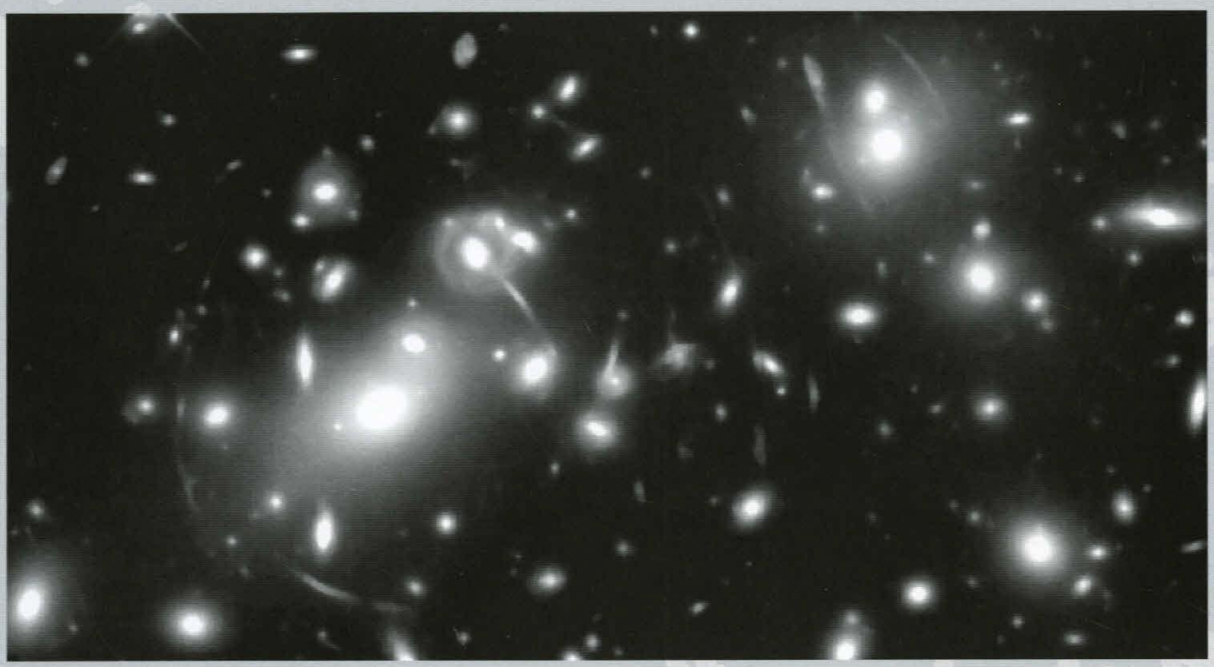

FIGURE 1. A massive object bends light as a pair of glasses can bend light to correct vision. Sometimes, a large object will bend light coming from a distant source, enlarging the image of the distant object and serving as a natural telescope. Shown here is a picture from the Hubble Space Telescope of how the cluster of galaxies known as Abell 2218 bends light from galaxies further behind it. The curved arcs that form a halo are actually multiple images of an extremely remote object. The scale is approximately 1.5 million light years across and 0.75 million light years high.
Source: NASA, 2000.

images of the galaxies behind it. Ancient and distant, these galaxies formed when the universe was only one quarter of its present age. The great interest in studying these primordial galaxies led to many studies of Abell 2218 and its gravitational lensing effect. Astronomers know the mass distribution needed by Abell 2218 to produce the gravitational lensing effect, but that mass distribution disagrees with the mass distribution obtained from studying x-ray emissions of the cluster's interstellar gas. Because gravitational lensing is the rarer but more trusted technique to determine mass distribution, Abell 2218 presents an opportunity to refine the gas model against the lensing model.

To its discredit, x-ray analysis requires many simplifying assumptions. In a relatively static cluster, pressure differences within the gas balance the pull of gravity, a condition called hydrostatic equilibrium. The model assumes Abell 2218 to be in hydrostatic equilibrium and also isothermal, with all its gas at the same temperature. Guided by experimental observation, the model further assumes that the matter within Abell 2218 is arranged in a spherically symmetric manner.

Given these assumptions, it is possible to calculate the distribution of dark matter throughout the cluster. While dark matter does not emit x-rays, it does determine the pattern of x-ray emission. The gravitational force exerted by dark matter and the hydrostatic equilibrium constraint affect the way visible matter is arranged. The distribution of dark matter is inferred from knowing the arrangement of visi-

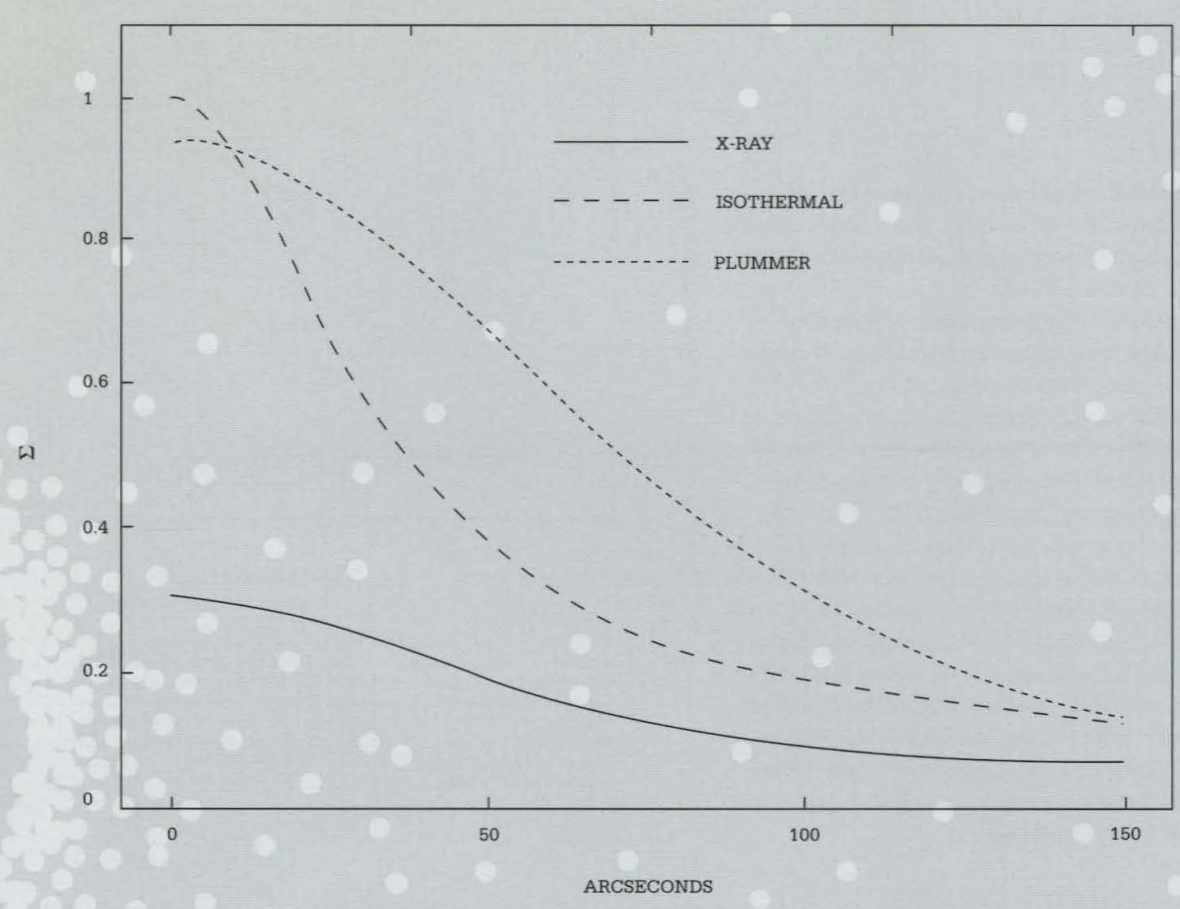

FIGURE 2. Gravitational lensing and x-ray emissions are two ways to independently study the dark matter distributions in clusters of galaxies. Shown here are surface density distributions of dark matter from the cluster Abell 2218 calculated from x-ray observations (solid line) and gravitational lensing (short and long dashed lines). The two possible lensing models do not agree with the x-ray emission data, suggesting that some of our assumptions about the state of the gas in the cluster are wrong.

ble, x-ray-emitting gas throughout the cluster.

The x-ray intensity or surface brightness from a spot on the cluster is found by integrating the square of the visible matter density along the line of sight. Surface brightness data is then used to model the density of visible gas both within the cluster (three-dimensional) and on the surface (two-dimensional). From this, astrophysicists can deduce the distribution of dark matter.

Astronomers have developed various predictions of the Abell 2218 cluster mass distribution. A widely accepted model due to Saraniti and Petrosian accounts for mass due to visible galaxies and predicts two possible ways in which dark matter could be distributed throughout the cluster to reproduce the observed action of Abell 2218 as a gravitational lens. These two arrangements are known as the spherically symmetric, pseudo-isothermal potential and the Plummer potential.

TWO MODELS PRODUCE DIFFERENT RESULTS

The ROSAT (ROentgen SATellite), developed jointly by Germany, the United States, and the United Kingdom, operated as an x-ray observatory between 1990 and 1999. X-ray intensity data from ROSAT allowed scientists to produce mass distribution estimates of Abell 2218 dark matter using gravitational lensing and x-ray interstellar gas models. The resulting models painted widely disparate pictures of the size, shape, and density of Abell 2218 dark matter. The discrepancy between the lensing-derived and x-ray-derived density distributions is shown in Figure 2. The two lens-

ing-based models from the isothermal and Plummer potentials disagreed with each other in addition to clashing significantly with the x-ray determination.

Between the Plummer and the isothermal potentials, the latter is the simpler and more appropriate lensing model for constructing a three-dimensional dark matter density distribution. The isothermal prediction nevertheless dramatically differs from the x-ray prediction (see Figure 3). Indeed, the x-ray-derived model requires a central dark matter density approximately five times less than the lensing-derived model requires. Because gravitational lensing depends only on the spatial arrangement of mass and on the extremely well verified equations of general relativity, our study assumed the mass distribution derived from gravitational lensing was correct and reexamined the assumptions of the x-ray analysis.

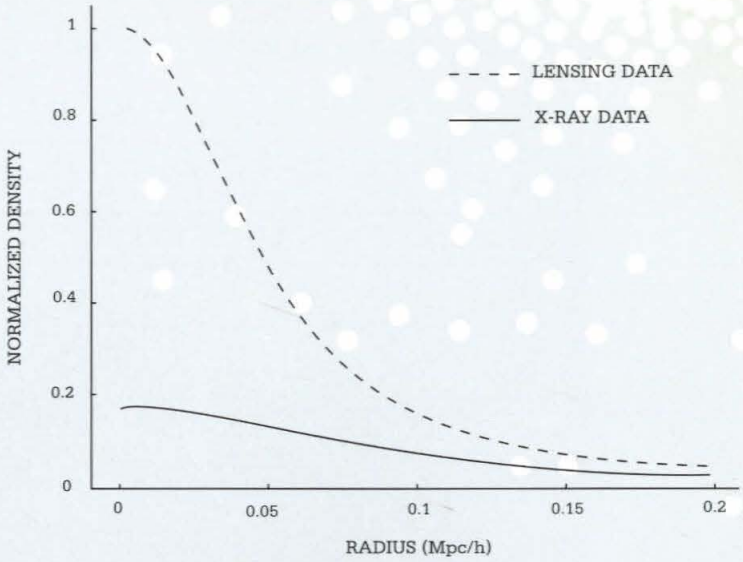

FIGURE 3. X-ray emissions and gravitational lensing can be used to find a three-dimensional density distribution of dark matter within a cluster. Shown here are the curves calculated from x-ray surface brightness when the temperature is assumed to be constant (solid line) and from lensing data (dotted line). These profiles are different shapes indicating that one of our assumptions about the cluster is incorrect. Most notably, the core mass density of Abell 2218 is predicted to be five times smaller by the x-ray model.

RETHINKING THE ASSUMPTIONS

A key assumption of the x-ray analysis is that the Abell 2218 interstellar gas is isothermal. Recent temperature mapping observation suggests the contrary, that Abell 2218 interstellar gas temperature decreases with radius. Variable temperature alters two points of the analysis. First, since x-ray emission is temperature dependent, the determination of the visible gas density changes. Hotter gas emits more x-rays, so a given observed surface brightness at one spot on the cluster can be accounted for either by a large amount of emitting matter behind it or by less matter that is hotter. Second, the temperature variation changes the hydrostatic equilibrium equation to account for the rate of change of temperature as well. Consequently, the necessary dark matter distribution to maintain hydrostatic equilibrium will be different.

Moving one step beyond the isothermal gas assumption, we postulate that the gas temperature is instead highest at the center of the cluster and decreases outward following a power law with exponent g. Figure 4 shows what the resulting dark matter density distrib-

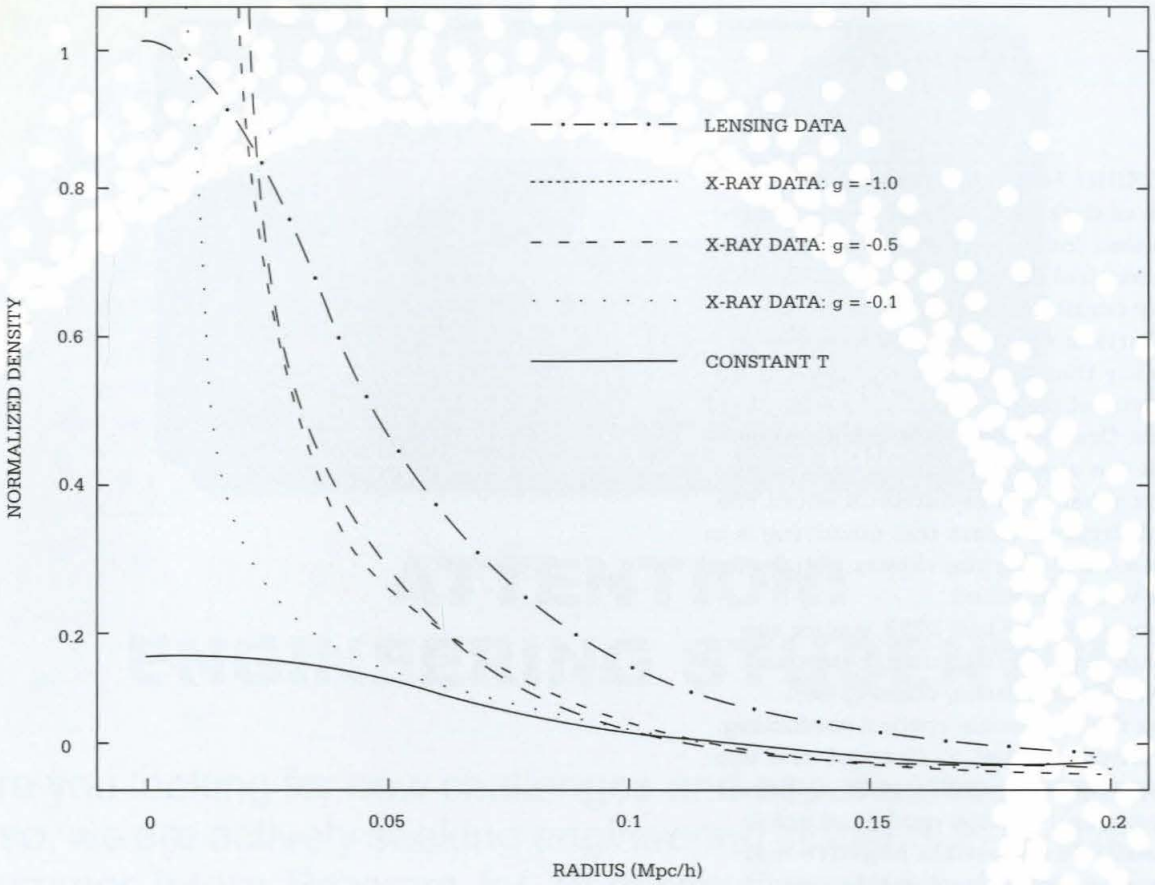

FIGURE 4. Recent evidence shows that temperature falls off with radius in Abell 2218. We attempt to model this by a temperature profile that decreases as a power law with exponent g. Shown here are dark matter density distributions calculated from the x-ray surface brightness while the temperature is held constant (solid line), and when the temperature falls off as a power law of exponent g = –0.1 (dotted line), g = –0.5 (long-dashed line), g = –1.0 (short-dashed line). Although the power law is a better fit to the dark matter density derived from the lensing data (dotted-dashed line), temperature variation alone fails to completely reconcile the results.

utions would look like for g values of –0.1, –0.5, and –1.0, along with the constant temperature case and gravitational lensing result. When using the power laws, the x-ray derived dark matter distribution curves more closely match the lensing-derived distribution curve because the density of gas is notably higher near the core of the cluster. This occurs because a power law temperature gives rise to a power law density. Although the four curves lack an identical shape, this is indeed a huge improvement over the discrepancy in Figure 3.

The equation for the temperature profile (temperature versus radius) of the cluster gas may also be calculated. This is done by numerically solving the hydrostatic equilibrium equation for the temperature given the dark matter distribution from lensing and x-ray surface brightness data. This implicit solution predicts that temperature must decrease rapidly near the center of the cluster. The solution loses validity at high radii since the temperature falls below absolute zero.

Temperature variation alone cannot account for the differences between x-ray and gravitational lensing determinations. In contrast to the isothermal assumption, a steeply decreasing temperature profile provides a better x-ray determination of dark matter mass distribution in clusters and should be the starting point for improved theories. Varying hydrostatic equilibrium or the shape of the cluster will afford astrophysicists finer control over the estimated mass distribution.

STILL LOOKING FOR DARK MATTER

The nature of dark matter has been a puzzle to astronomers for more than sixty years. To this day scientists do not know what the stuff is, and they continue to study it in various contexts. Particle physicists are considering the possibility that dark matter is some large, unknown type of particle that generally does not interact. Cosmologists have made predictions about the abundance and type of dark matter from what they understand about the big bang. Astronomers are still observing it in many places, including the cluster of galaxies in which it was first found.

Clusters such as Abell 2218 inspire the study of dark matter. They emit x-rays and act as gravitational lenses, offering two approaches that currently predict conflicting mass distributions. Abell 2218 requires a temperature that declines rapidly with radius for both the x-ray and lensing models to agree, but also needs an impossible negative temperature at the edges. Varying other assumptions and studying similar clusters may provide a more accurate theory of intracluster x-ray emission. If the analysis of clusters is improved, dark matter density distributions can be determined with much greater accuracy, shedding light on the shrouded and most massive portion of our universe.

Lisa Wang is a second year undergraduate in Physics at the California Institute of Technology. *This work was completed with Vahé Petrosian, Professor of Physics and Applied Physics at Stanford University, co-mentored by Harvey Newman, Professor of Physics at Caltech, and funded by the 2001 Caltech Summer Undergraduate Research Fellowship. The author wishes to thank Vahé Petrosian, Nicole Lloyd-Ronning, Keith Thompson and Harvey Newman.*

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SUSTAINING A MICROLITER BIOSPHERE:

CHEMICAL COMPOSITION OF TERMITE GUT

BY NHA NGUYEN

THE MEAL CHOICES OF WOOD-EATING TERMITES MAY DISMAY the unlucky homeowner, but the symbiotic relationships these insects have developed to digest their food are intriguing to microbiologists. A dense microbial community of dramatic diversity resides in the termite gut (see Figure 1), including different microbes that specialize in cellulose digestion, fermentation, methane production, nitrogen fixing, and more. What seems like a costly pest houses in its gut a highly evolved microcosm of interacting organisms.

The concentration of such diversity in the termite gut is a special opportunity for microbiologists searching for new organisms, since the majority of gut microbes are still poorly characterized. Microbes are ubiquitous, so discovering a new class or property of microbes in termite guts has far-reaching implications about their broad role in ecosystems. Even more tantalizing is the chance to study how nature optimizes biological systems. The theoretical framework from such studies could enable scientists to create new systems of symbiotes.

Microbes that fill specialized niches in the termite gut have very specific chemical requirements. Some microbes require oxygen while others thrive in anaerobic conditions. Microbes require certain ions for cellular processes, and each type of microbe survives best in a different range of pH. The termite gut provides a unique chemical environment, accommodating the needs of the various microbes. However, duplicating the correct conditions in the laboratory is quite difficult. A serious obstacle in studying the gut microbes is isolating and cultivating large numbers of them.

Current bacterial growth solutions for termite microbes are based on the incomplete results of a few old experiments. Although the ionic composition of a nutrient solution is critical to its success, data on the ionic composition of termite guts is not thorough. We extended previous research with a more complete determination of which ions are present and in what concentrations.

OBSTACLES TO CULTIVATING GUT MICROBES

Descriptions of the termite gut remain incomplete, limiting how well researchers can isolate and study gut microbes. Examining the gut environment presents unique challenges. The small termite gut only holds 1 to 10 microliters but is complicated by steep chemical and physical gradients. By 1997, groups at Michigan State University and the University of Konstanz in Germany made progress by using microelectrodes to probe the radial and axial gut profiles of H_2, O_2, and pH for several species. One of the rare successes in cultivating gut microbes occurred in 1999, when researchers at Michigan State University used the latest findings to isolate pure cultures of bacteria called spirochetes. Following this success, the researchers explicitly demonstrated that spirochetes catalyzed the formation of acetate, a key source of energy for termites. Last year, groups at Michigan State University and the California Institute of Technology found that spirochetes could also fix nitrogen.

Most cultivation attempts still give poor results, and one reason is the shortage of data on the ionic composition of gut fluid. Twenty-five years ago at The Rockefeller University, Michael Yamin partially determined the concentrations of major ions. However, Yamin's methods were poorly detailed, and the literature records little about the concentrations of iron, calcium, cobalt, and manganese, all of which are important for the growth and activity of microbes. Using modern mass spectroscopy methods, we determined the elemental composition of termite gut fluid. From the elemental analysis, we deduced ion concentrations, allowing us to check Yamin's results for the more common ions and to determine new concentrations for trace elements.

FIGURE 1: Low magnification micrograph of termite gut fluid. Large cells of the cellulose-decomposing protozoan *Trichonympha*, about 70 micrometers in length, are observed swimming among smaller protozoa, bacteria, and particles of wood.
Source: J. R. Leadbetter.

ANALYZING GUT FLUID

Termites of the species *Zootermopsis angusticollis*, also known as the California dampwood termite, were collected in the San Gabriel Mountains north of Azusa, California. This species is a wood-feeding termite from a simpler branch of the evolutionary tree. We

FIGURE 2: *Zootermopsis angusticollis*, also known as the California dampwood termite. Termite colonies consist of reproductives, soldiers, and young workers. The brown heads and dark mandibles disinguish the soldiers from the young workers in this picture. The termites are about 1 to 2 cm in length.
Source: E. S. Ross.

studied worker larvae because of their substantial amounts of gut fluid, about 5 to 10 microliters each, and their presence in great numbers. The worker larvae would already have received gut microbes from the elder generation. Other than the workers, termite colonies also include smaller numbers of the morphologically distinct reproductive and soldier castes (see Figure 2).

After obtaining the larvae, we extracted gut fluid from 200 chilled specimens. The unpurified gut fluid, called particulate fluid, contained small particles of cells, wood, or soils. We divided the particulate fluid into two portions of 100 microliters each. Rapidly spinning the sample in a centrifuge removed solids from the first portion, yielding a dark brown liquid called the clarified fluid. We left the microbe cells, wood particles, and other solids in the second portion. Following preparatory treatment with acid and heat, we diluted the two solutions with water to obtain suitable concentrations for analysis by an inductively coupled plasma-mass spectrometer (ICP-MS). An ICP-MS uses hot plasma to dissociate molecules and atoms into simple ions and a mass spectrometer to identify the presence of elements according to their atomic masses.

To ensure that our results were accurate, we reduced the possibility of sample contamination during handling. Contamination is a serious problem, since low metal concentrations in gut fluid are very sensitive to even trace contaminants. We minimized sample contact with sources of ions, such as glass or metal. The only exposure to glass occurred when the samples were collected using a glass micropipette. Control experiments evaluated the amount of ions introduced during sample handling so that the final results take into account the effect of any contamination.

GUT ION CONCENTRATIONS

Our final results include the gut concentrations of major elements and trace elements, all of which participate in key biological functions (see Figures 3 and 4). The results for major elements mostly match Yamin's data, but our potassium and phosphorus levels are substantially higher than Yamin's recorded levels. Our high potassium (K) levels mean that the positive potassium ion, K^+, is the dominant metal ion in gut fluid. High phosphorous (P) levels indicate that phosphates like PO_4^{3-} or HPO_4^{2-} are major negative ions in gut fluid.

Since the gut fluid affects biological functions, the levels of the major elements are critical. For example, potassium is required for carbohydrate metabolism, phosphorus for nucleic acids and energy structures, calcium for intracellular regulation, and magnesium for enzyme cofactors. An imbalance of these major ions could slow down or completely inhibit the growth of gut bacteria.

Trace elements are also essential to gut microbes. The gut concentrations of some ele-

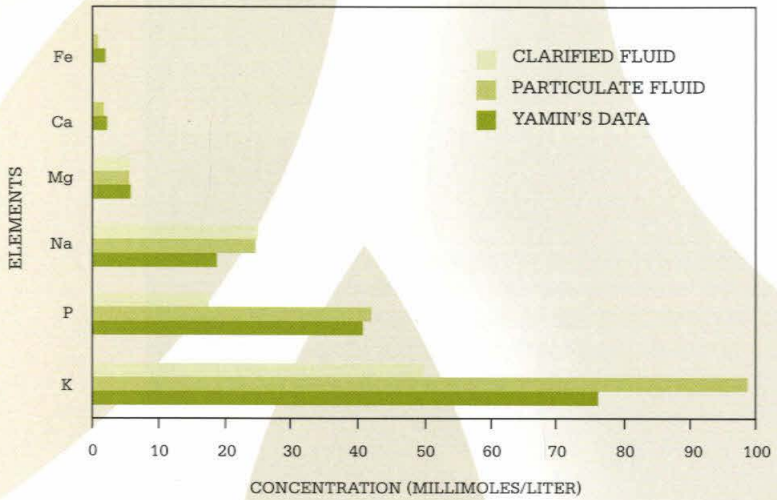

FIGURE 3: Concentrations of major ions in gut fluid of worker termites. The particulate fluid includes soil, wood particles, and cells from the gut, while the clarified fluid does not. There are some discrepancies, but our results generally match older data from Michael Yamin at The Rockefeller University.

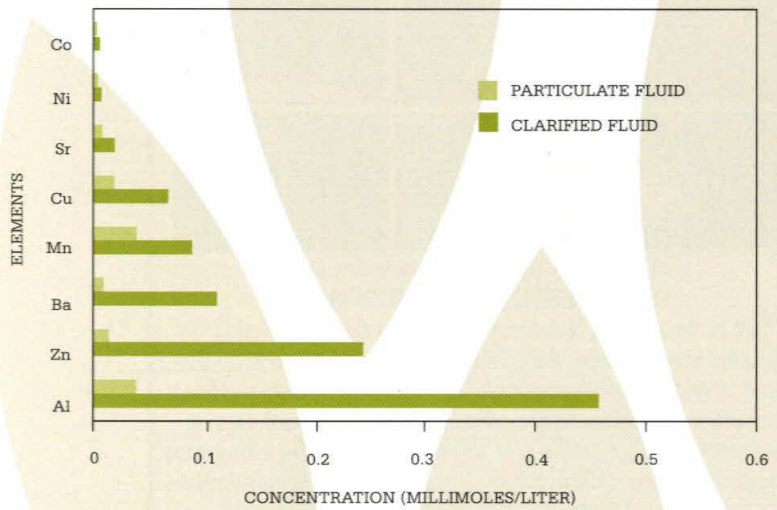

FIGURE 4: Concentrations of trace elements in gut fluid of worker termites. The concentrations of trace elements were previously unknown. The results indicate unexpectedly high levels of aluminum (Al) and zinc (Zn).

ments like aluminum and zinc are surprisingly high, especially in the particulate fluid. The expected concentration for these metals was 0.01 – 10 micromoles per liter. Perhaps the discrepancy stems from a transient phenomenon or a local contamination of the food source. Experiments conducted at different geographical sites throughout the year could establish whether or not the concentrations are a norm.

It is unclear why these termites accumulate such high concentrations of trace elements, or how the termites obtain them given that these elements are rarely present in wood. Although some of the metals, such as cobalt and nickel, are cofactors for gut enzymes, it is not known whether termites accumulate the elements specifically for the microbes or if the termites themselves need them. The supposedly wood-feeding termites may adopt significant amounts of soil as an additional food source to obtain the necessary nutrients.

IMPROVING CULTIVATION

In addition to raising new questions about termites, our results indicate ways to improve the performance of nutrient solutions. About 90 percent of the bacteria observed by direct microscopy counts in termite guts are lost in current cultivation attempts. There are many factors that determine the success of cultivation, but our findings show that nutrient solutions based on older results lack sufficient potassium, phosphates, and trace elements. The poor performance of growth media hinders efforts to explore the microbial diversity of termite guts.

To probe microbial diversity in spite of inadequate cultivation methods, researchers have relied on molecular biological methods. Instead of cultivating complete bacteria, microbiologists extract and amplify nucleic acids such as ribosomal RNA. Then, by comparing the genetic sequences, they can identify the bacteria and determine evolutionary relationships. Molecular methods have led to the identification of new classes of microbes in the termite gut.

Molecular methods alone, however, cannot explore microbes to the fullest extent. Isolating and observing the bacteria, while difficult, is a direct method that allows us to learn even more. If we isolate a pure strain of bacteria, we can see the genetic code in action in the living organism. The recent success with spirochetes demonstrates the rewards of cultivation methods. We have already made key discoveries about gut microbes. The development of growth solutions with more accurate ionic compositions will facilitate better microbe cultivation, revealing the nuances of biodiverse life in the microcosmic termite gut.

Nha Nguyen is a second year undergraduate in Chemical Engineering at the National University of Singapore. This work was completed with Jared R. Leadbetter, Assistant Professor of Environmental Microbiology at the California Institute of Technology, and funded by the 2001 Caltech Summer Undergraduate Research Fellowship. *The author wishes to thank Jared R. Leadbetter, Nathan Dalleska, and Bob Becker.*

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AMINOALCOHOL SPECTRA:

COSMIC FINGERPRINTS OF NASCENT LIFE

BY KATHRYN DYL

ASTROBIOLOGY CONNECTS STRONGLY TO EARTHLY MATTERS. KNOWLEDGE of life on Earth guides the search for extraterrestrial life. Discoveries in space extend the understanding of terrestrial life.

Life depends on the formation of complex organic molecules like amino acids and sugars from precursors such as methane, water, and ammonia. Two competing theories describe the original formation of Earth's complex organics. One theory suggests that complex organic molecules formed on the turbulent surface of a young Earth. The other hypothesizes that complex organic molecules were present in space before planets even formed.

Classical geological surveys have been unable to confirm or refute the terrestrial theory. Geological methods focus on the composition of ancient rocks to deduce surface conditions on the young Earth. Geologists then evaluate the possibility of organics forming under those conditions. For example, amino acid synthesis on the Earth's surface would require a methane-rich atmosphere for starting materials, but geologists still disagree on the nature of Earth's early atmosphere.

Astronomy offers a radically different approach to evaluating the competing theories. Radio telescopes record microwave emissions from distant stellar objects, and spectroscopic analysis reveals patterns in the frequencies of the signals. Astronomers relate the frequency pattern of an object's emissions to its chemical makeup using a database of known frequency patterns. Thus, astronomers can use spectroscopy to search for organic molecules in space.

We characterized the absorption frequency patterns for chemicals that would help search for interstellar amino acids. Since detecting related chemicals could also indicate the presence of amino acids, we characterized aminoalcohols, a class of chemicals that can react to form amino acids.

SEARCHING THE STARS

Amino acids define the chemistry of life on Earth. An organism's structural and metabolic functions depend on these complex organics that form the building

blocks of proteins. With amino and carboxyl terminuses and a characteristic side chain (see Figure 1), each of twenty types of biological amino acids displays a unique chemical property bestowed by its distinct side chain. The discovery of extraterrestrial amino acids and their relation to Earth's formation would provide compelling evidence for the exogenous accumulation of Earth's complex and biologically relevant organics.

Preliminary findings indicate that extraterrestrial amino acids do exist. Scientists at NASA's Ames research center first discovered extraterrestrial amino acids while analyzing the Murchison meteorite in 1969, shortly after its landing in a small town north of Melbourne, Australia. Scientists found interstellar ammonia, formic acid, and acetic acid, all of which are structurally related to amino acids, in 1969, 1970, and 1996 respectively.

Three years ago, astronomers at the University of Illinois discovered formic acid in the molecular cloud Sagittarius B2 (see Figure 2), about three hundred light years away from the center of the Milky Way galaxy. These organic acids were found in hot cores, the high-temperature, high-density regions in molecular clouds where stars and planetary systems can form. The Sagittarius B2 discoveries suggest the possibility that amino acids in hot cores are incorporated into planets like Earth just as they are born.

Simulations of hot core conditions suggest synthetic routes to amino acids from precursors that occur in molecular clouds like Sagittarius B2. In one synthetic route, ammonia and acetic acid combine to produce glycine, the simplest amino acid. In another predicted route, an aminoalchohol joins with formic acid to release an amino acid and a water molecule. Aminoalcohols contain amine and alcohol terminuses. The aminoalcohols aminomethanol and aminoethanol condense with formic acid to yield the amino acids glycine and alanine respectively (see Figure 3).

By characterizing the spectra of these aminoalcohols, our work revealed the radiowave signatures needed to identify the presence of these amino acid precursors, light years away in hot cores.

RADIOWAVE SIGNATURES

To understand how spectroscopy works, imagine yourself at a basketball game with red and blue jersey teams. Even from stadium distance, you can tell the team identity of the player. Of the light incident on the blue player's jersey, most frequencies are absorbed except the blue. The reflected blue light that reaches your eye from the jersey tells you his team allegiance. Likewise the absorption spectrum obtained from a radio telescope pointed at a distant hot core reveals the core's molecu-

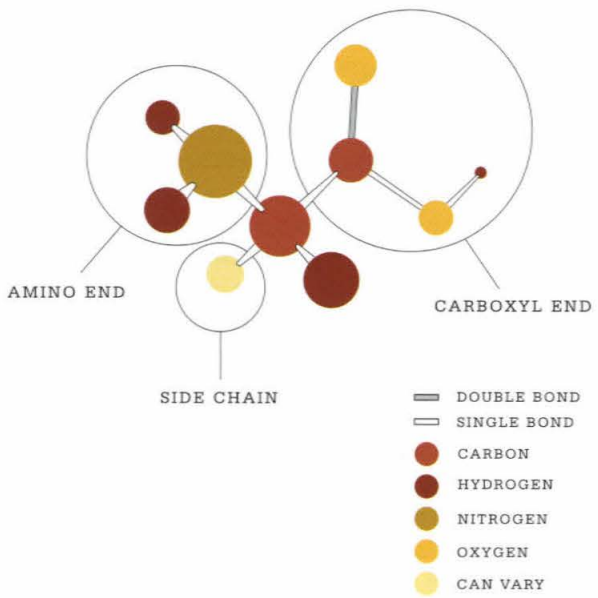

FIGURE 1. An amino acid. Amino acids contain amino and carboxyl terminuses and a side chain. The specific side chain controls the chemical properties of an amino acid. Astronomers search for interstellar amino acids to determine if the first amino acids on Earth could have originated from space.

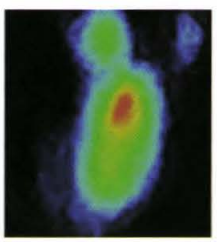

FIGURE 2. X-ray image of the molecular cloud Sagittarius B2. Molecular clouds contain hot cores, the high-temperature, high-density regions where stars and planets can form. The hot cores in Sagittarius B2 contain many organics, including formic acid and acetic acid. The dense center of the cloud is about 10^{16} meters across. *Source: NCSA Astronomy Digital Image Library.*

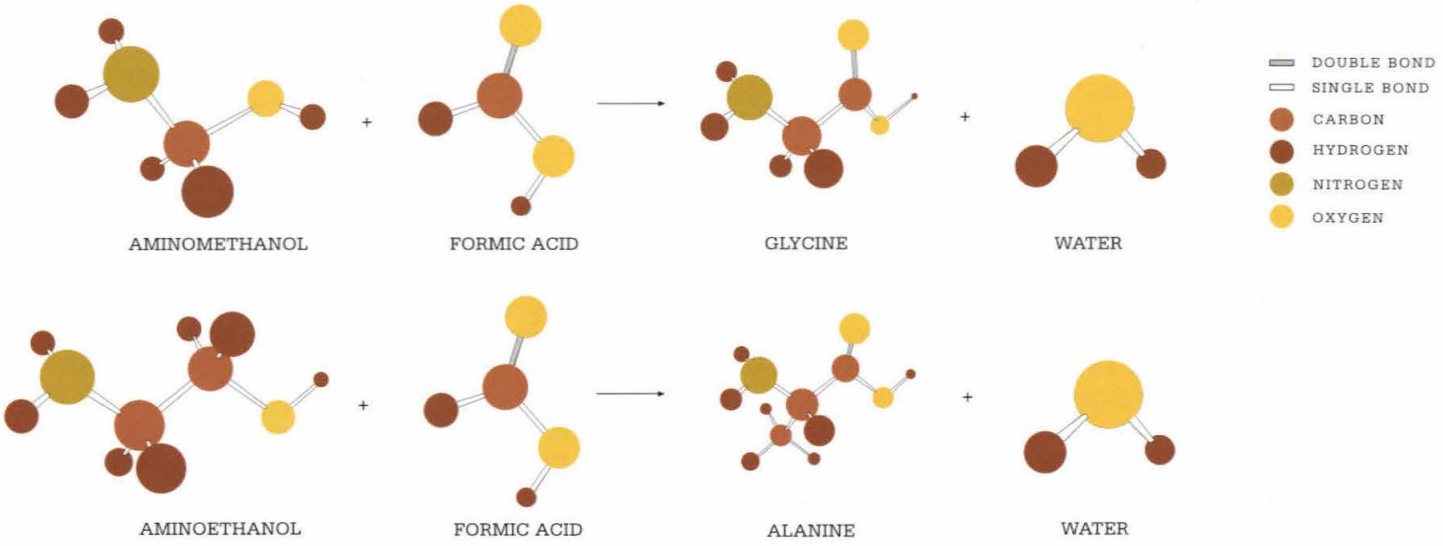

FIGURE 3. Synthesis of amino acids. One possible mechanism for the formation of amino acids in space involves a dehydration synthesis, where an aminoalcohol and formic acid react to form an amino acid and water. The two examples in the figure show the formation of glycine and alanine from aminomethanol and aminoethanol respectively.

lar composition from a distance of light years.

The rules of quantum mechanics govern the absorption spectrum, which like a finger's print pattern, uniquely reflects the identity of a particular molecule. A molecule absorbs electromagnetic radiation to furnish energy for many different mechanical processes, such as bending its bonds or spinning like a top. The energy levels for these processes are quantized, or confined to certain discrete values. Quantized energy levels are analogous to a flight of stairs, with steps at only certain heights, in contrast to a ramp with a continual slope. The energy in light is similarly quantized into packets called photons. On a staircase, we move up by one step or two steps, but not by one and a half steps. Likewise, a molecule can absorb a photon only when the photon's energy matches the interval between its energy steps (see Figure 4). The light's frequency determines the photon's energy, so molecules only absorb light at specific frequencies. A spectrum, then, is a plot of absorption versus frequency.

Telescopes record the spectra of stellar objects over different frequency ranges. Microwave emissions, at frequencies of 1 to 300 gigahertz (GHz), are easy to collect from hot cores and can provide the information to identify molecules like amino acids. However, the spectroscopic signals of amino acids from space are weaker than the signals of their aminoalcohol precursors, so it is more efficient to first search for aminoalcohols in space. Also, formic acid is a known interstellar molecule, so the presence of aminoalcohols suggests the synthesis of amino acids by the condensation reactions in Figure 3. Before searching in space for the microwave signatures of organics, though, we have to take reference measurements in the laboratory. For these reasons, we tried to characterize the microwave spectra of aminoethanol and aminomethanol.

CHARACTERIZING AMINOETHANOL

A complete picture of a chemical's spectrum is essential when sifting through complex observations. If an astronomer looks at a hot core that contains many chemicals, he will see the overlapping spectra for each chemical. The result can be difficult to interpret. The Owens Valley Radio Observatory (OVRO), located in Bishop, California, has advanced resolution and filtering features to clarify spectra containing many organics. The OVRO array (see Figure 5) can effectively search for aminoethanol in hot cores, except it can only detect microwaves between 85 and 110 GHz. Our knowledge of aminoethanol's spectrum is incomplete for frequencies between 80 and 120 GHz, so we characterized aminoethanol in that specific region.

To obtain the spectroscopic data for aminoethanol, we used the experimental setup in Figure 6. We sent microwaves, generated by a frequency synthesizer, through the aminoethanol vapors in the flow cell. A detector

measured the intensity of the microwaves after they passed through the sample. Measuring the absorption at different frequencies gave the final spectrum (see Figure 7(A)).

Each line in a spectrum yields a piece of information about the molecule's physical characteristics. More specifically, the microwave spectrum reveals the nature of the rotations of a molecule. The energies of rotation depend on the shape and mass of the object. For example, it takes less energy to spin a dime on a table than to spin a quarter at the same rate. Spectroscopy tells us more than simple structural details, because quantum mechanics dictates spectra through selection rules. We know that rotational energies are quantized into discrete steps, much like a staircase. When we absorb a photon, we are essentially walking up the steps of the staircase. A selection rule decides how we can walk up the steps. As a rough analogy, a selection rule might instruct us to skip every other step, taking two steps at a time.

INTERPRETING THE SPECTRUM

Theoretical models incorporate the selection rules along with a molecule's physical characteristics to predict spectra. The key results of spectroscopy are the rotational parameters that describe a molecule's physical characteristics. Although each chemical's spectrum is unique, the spectrum varies depending on the conditions of the chemical. For example, at a higher temperature, molecules will have a higher average energy so different energy transitions will dominate. The rotational parameters allow us to predict the spectrum if the temperature in a hot core is different from the temperature in our experimental setup. We can even predict the spectrum at frequencies outside the 80 to 120 GHz range of our observation (see Figure 8).

To find the rotational parameters, we had to determine the meaning of all the lines in the spectrum. Each line corresponds to a transition between two energy steps. By using the selection rules and noting patterns

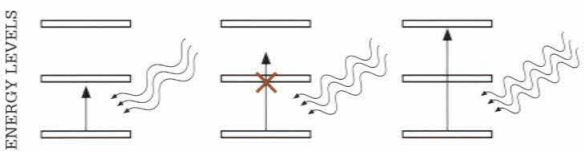

FIGURE 4. Quantized energy levels and photon absorption. Molecules can only have certain discrete values for energy. A molecule absorbs photons of light only when the energy in the light matches the interval between two energy levels. The light's frequency is proportional to the energy of a photon.

FIGURE 5. Radio telescope from the Owens Valley Radio Observatory. Astronomers can use radio telescopes to record microwave emissions from stellar objects and deduce chemical compositions. The pictured radio dish has a ten meter diameter.
Source: Owens Valley Radio Observatory.

in the spectrum, we assigned each line to a specific energy transition. With the aid of a computer program, we then extracted the rotational parameters from the spectrum.

Our rotational parameters for aminoethanol confirm and extend previous results. The rotational parameters in simple models are called rotational constants. Complex models use additional correction terms called centrifugal distortion constants, which take into account factors such as bond lengths changing while the molecule rotates. Our rotational constants agree with previous measurements. However, some of our centrifugal distortion constants are different from previous measurements, and we also determined new correction terms (see Figure 7(B)). The higher-order corrections provide the accuracy needed to interpret complex spectra.

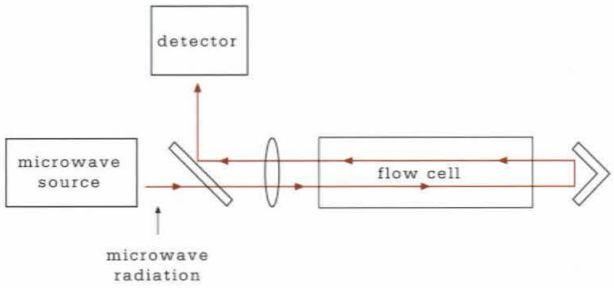

FIGURE 6. Setup for aminoethanol experiments. Microwave radiation from the synthesizer passes through the sample in the flow cell before reaching the detector. The various optics control the path and intensity of the radiation. Measuring the absorption of light at different frequencies gives a spectrum.

CHALLENGES TO STUDYING AMINOMETHANOL

After studying aminoethanol, we approached the more difficult problem of characterizing aminomethanol. Theory predicts that aminomethanol should be at least two orders of magnitude more abundant than aminoethanol in hot cores. However, aminomethanol is extremely unstable and no one has been able to characterize its spectrum. Aminomethanol is probably the first product from a series of reactions between ammonia and formaldehyde. The problem is isolating and studying the unstable aminomethanol before it reacts with itself to form other products.

Continuous flow methods can solve the difficulty of handling an unstable intermediate. In continuous flow methods, fresh aminomethanol is generated continuously while old aminomethanol is removed quickly before forming unwanted products. We send ammonia and formaldehyde through a flow cell, where they react to form aminomethanol. Before the aminomethanol reacts further, a vacuum pump removes the aminomethanol from the cell. In the meantime, additional

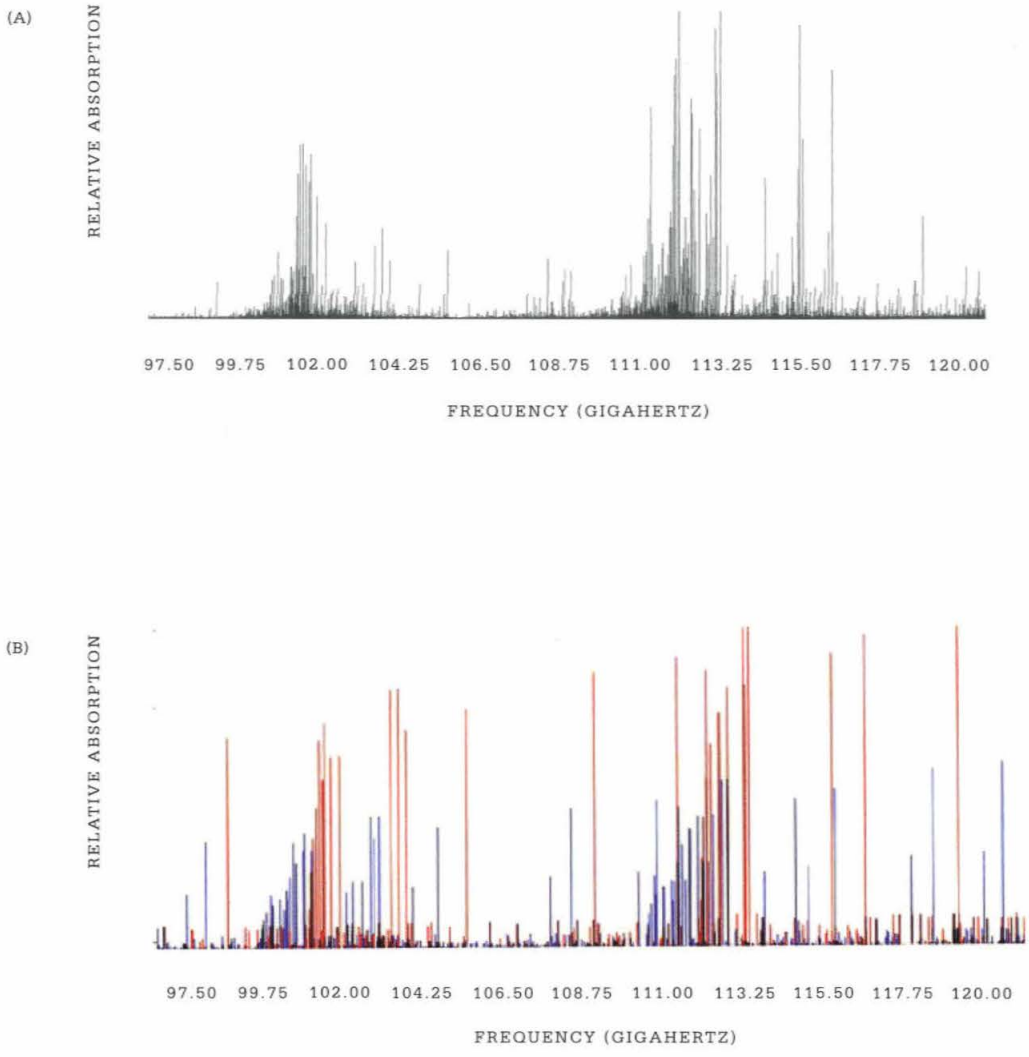

FIGURE 7. (A) Experimental aminoethanol spectrum in the region 97.5 to 120 gigahertz. The spectrum indicates the absorption of microwave radiation by aminoethanol at specific frequencies. The frequency patterns in a spectrum can serve to identify chemicals. (B) Predicted aminoethanol spectrum in the region 97.5 to 120 gigahertz. The red spectrum is based on theoretical models using literature data, while the blue spectrum incorporates our data. Our results refine the theoretical model and give more accurate predictions for aminoethanol's spectrum. Accurate models are necessary for identifying molecules in interstellar emissions.

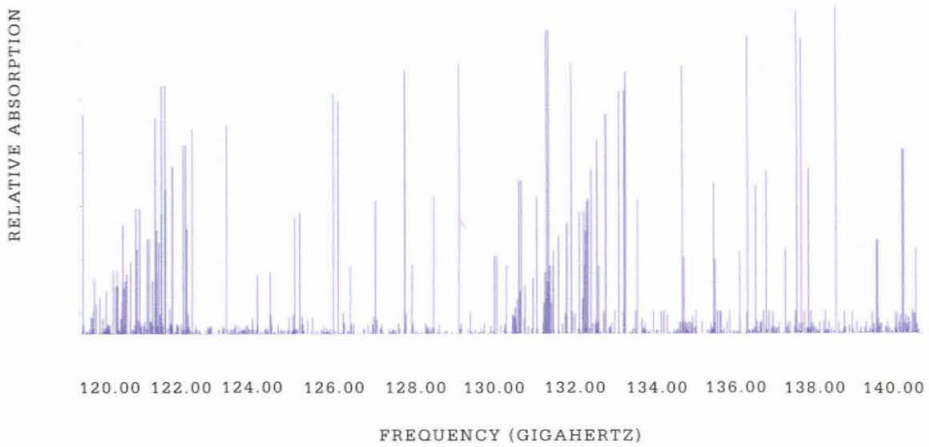

FIGURE 8. Predicted spectrum of aminoethanol in the region 120 to 140 gigahertz. From the observed spectrum, we can extract rotational parameters that allow us to predict the spectrum in new frequency regions. This gives astronomers more flexibility in analyzing observations based on limited spectroscopic data.

"Searching for precursors like aminoalcohols is an indirect but necessary strategy for detecting amino acids in space."

ammonia and formaldehyde flow into the cell and form fresh aminomethanol. Inside the cell, it looks as though we have a quasi-stable sample of aminomethanol.

Apart from the flow setup, we tested just the reaction of ammonia and formaldehyde to give aminomethanol. We collected an unknown liquid product that we believe includes aminomethanol, but the product requires further characterization. The isolated product, if it included aminomethanol, would certainly contain additional products of the reactive aminomethanol. We are constructing the necessary flow cell and completing other technical details for the continuous flow experiment. Obtaining a spectrum for aminomethanol, the precursor to the simplest amino acid, is crucial to the search for interstellar organic molecules.

EXPANDING THE SPECTRAL DATABASE

From the microwave spectrum of aminoethanol, we extracted detailed rotational parameters. With these parameters, astronomers can begin analyzing microwave observations of stellar objects to see if aminoethanol is present. Observing aminoethanol in a stellar object

would imply that the amino acid alanine is also present. Searching for precursors like aminoalcohols is an indirect but necessary strategy for detecting amino acids in space.

The development of life required more than just amino acids. Sugars are another class of chemicals serving a variety of functions in organisms. Jan Hollis from NASA's Goddard Space Flight Center recently observed spectroscopic signs of the simple sugar glycolaldehyde in the molecular cloud Sagittarius B2.

Untangling the signs of glycolaldehyde from a complex spectrum is difficult, and like the aminoalcohols, the spectrum for glycolaldehyde is incomplete. For future work, we will analyze glycolaldehyde's spectrum using the same methods as we did for aminoethanol in order to confirm Hollis' analysis. The key to positively identifying organic molecules in stellar objects is a comprehensive spectral database.

The discovery of amino acids and sugars in space adds support to the theory that the simplest organic molecules of life had an extraterrestrial origin. As early as 1961, Juan Oro at the University of Houston proposed that comets from space seeded Earth with organic molecules. A natural extension of this theory is that comets seeded other solar systems as well. Furthermore, finding both amino acids and sugars together in the same molecular cloud, such as Sagittarius B2, would suggest that the recipe of life is no secret. Earth may not be that unique after all.

Kathryn Dyl is a second year undergraduate in Chemistry at the California Institute of Technology.
This work was completed with Geoffrey A. Blake, Professor of Cosmochemistry and Planetary Science and Chemistry at Caltech, and funded by the 2001 Caltech Summer Undergraduate Research Fellowship. The author wishes to thank Geoffrey A. Blake, Susanna L. Widicus, and Brian J. Drouin.

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FACES, OBJECTS, TIE IN RACE FOR RECOGNITION

BY CATHERINE CHANG

ONE OF THE EXTRAORDINARY FEATURES OF THE human visual system is its ability to recognize faces and discern facial expressions. Without making a conscious effort, people rely on the quickness of their visual processing to make important judgments in all sorts of situations. Reading fear on a distant face might alert one to be wary in approaching; even something as simple as a mountain hiker being able to immediately distinguish a bear from another human, or from the wooded surroundings, could be vital to his safety. Recent research in neuroscience has sought a better understanding of this ability; in particular, the question of whether the human brain processes images of human faces faster than images of other objects has been the focus of much debate.

Studies have shown that the human visual system can analyze a complex natural scene in only 150 milliseconds, a phenomenon known as ultra-rapid visual categorization (URVC). Interestingly, other studies measuring peoples' responses to human faces in particular reported neuronal activity as early as 50 to 100 milliseconds, though these results have been contested. Yet evidence for brain regions specific to face processing supports the theory that faces might be processed faster than other objects. Researchers point to a region in the fusiform gyrus of the human brain, described as the fusiform face area (FFA), that has been known to demonstrate selective activity to images of human faces. The face-selective firing of neurons in the temporal lobe of humans and monkeys supports the existence

of such specialized modules as well.

However, the specificity of such modules to face stimuli is challenged by evidence that the representation of animals at a neural level engages the same structures as those representing faces. Whether faces are indeed processed faster is a highly relevant topic in current scientific literature.

A related question of equal importance is whether the speed of processing human faces depends on the facial expressions observed. For example, can humans more quickly decide that a visual scene contains a human when an expression of fear, rather than a neutral stare, is present? If there is a time difference for the processing of these different types of images, it may indicate an evolutionary advantage.

From our experiments we found that the speed of processing of face images failed to exceed that of animal images. Additional investigation into the relative processing rates of human images displaying scared, angry, happy, and neutral facial expressions revealed a slight but significant difference in the reaction times to scared versus positive expression human images.

MEASURING VISUAL PROCESSING SPEED

We developed a simple experiment to measure the speed of human visual processing. The procedure is known as a "go/no-go speeded visual categorization task," which presents subjects with a sequence of briefly-flashed images and requires them to respond immediately to each image. Each person performs this task in two alternating conditions: a "reference" condition, which observes responses to the presence of animals, and a "test" condition, which observes responses to humans. To keep the task uniform, subjects are instructed to respond to humans, rather than to human faces, since entire animals are shown.

Each condition contains equal numbers of target and non-target images. In the test condition, the targets are pictures of humans and the non-targets consist of animal images and distractors. A distractor is an image containing neither humans nor animals.

Subjects are seated 120 centimeters from a computer screen in a dark room and initiate each trial by pressing and holding a mouse button. An image, subtending approximately 5 degrees of visual angle, is flashed in the center of the screen for 26.6 milliseconds. The subject must release the button as soon as possible within 1 second if the image contains an element of the target category, and maintain pressure otherwise. The computer then records the delay time of the person's response. Two seconds, plus or minus a random delay of less than 200 milliseconds, elapses before the next image presentation. The randomized delay between images prevents subjects from responding automatically based on anticipation of the next presentation, and the brief duration of the flash excludes the possibility of subjects making eye movements.

At the end, the response times to target images in both conditions are compared. The processing speed for animal images has been verified to be 150 milliseconds, the current bound on URVC. Since a subject's motor response time should not depend on the image category, significantly faster responses to human images would indicate that visual processing of human images is actually occurring more quickly.

A final set of control experiments is performed on other subjects repeating the procedure outlined above, with one key exception: distractor images are not included. This design provides vital statistics that support our findings.

WHAT THE SUBJECTS SAW

The 1,920 images contained 720 animals, 720 humans and 480 distractors, and were collected from a database of digitized photographs and photos taken by our research group. Sample images are shown in Figure 1. Target elements (humans and animals) appear in varying positions and sizes within complex natural scenes. Of the human pictures, 75 percent have positive expressions divided equally between happy and neutral faces. The remaining 25 percent are negative expressions with angry

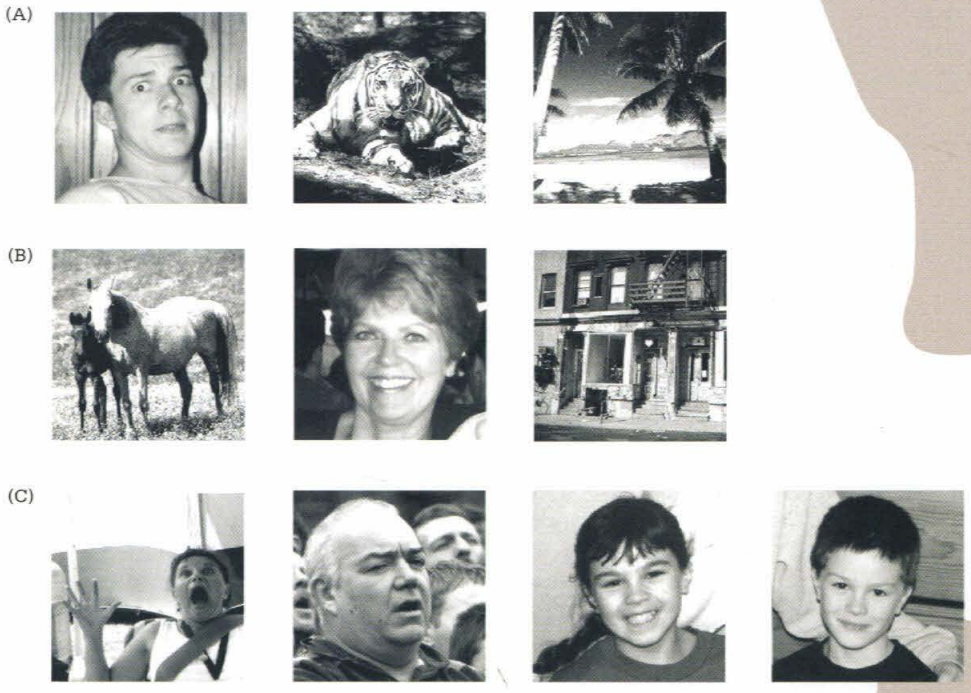

FIGURE 1. Examples of images used in the categorization experiment. (A) Images from the human task. Targets are images containing humans; non-targets include images of animals and distractors. (B) Images from the animal task. Targets are images of animals; non-targets include images of humans and distractors. (C) Images of various facial expressions. From left to right: scared, angry, happy, neutral.

and scared faces in equal proportions. To prevent subjects from learning, images are never repeated during an experimental session. Also, the image sequence is randomized between subjects, as is the order in which the reference and test conditions are performed.

OUR EYES DECEIVE US

Upon first glance at our data, we noted a trend of faster responses to target humans than to target animals (see Figure 2(A)). In fact, there is a 29-millisecond median time difference between these different types of responses. Although this evidence suggests that the brain processes images of humans faster, it is not sufficient to draw definite conclusions. Indeed, subjects tend to respond incorrectly in the test condition (i.e., selecting an animal or distractor) significantly faster than in the reference condition (i.e., selecting a human or distractor). The sensitivity index (see Figure 2(B)), which takes the false alarm rate into account, reveals that the time in which subjects are able to discriminate between target and non-target images in each condition is the same.

How can we explain this discrepancy? The absence of a discrimination-time difference, coupled with the observed trend of earlier responses to human pictures, implies that subjects were employing a strategy of responding earlier to all images, targets and non-targets alike, in the test condition. The fact that two out of fourteen subjects did not respond significantly faster to target humans suggests that subjects can overcome biases. Therefore, we cannot conclude it a property of the visual system to recognize human

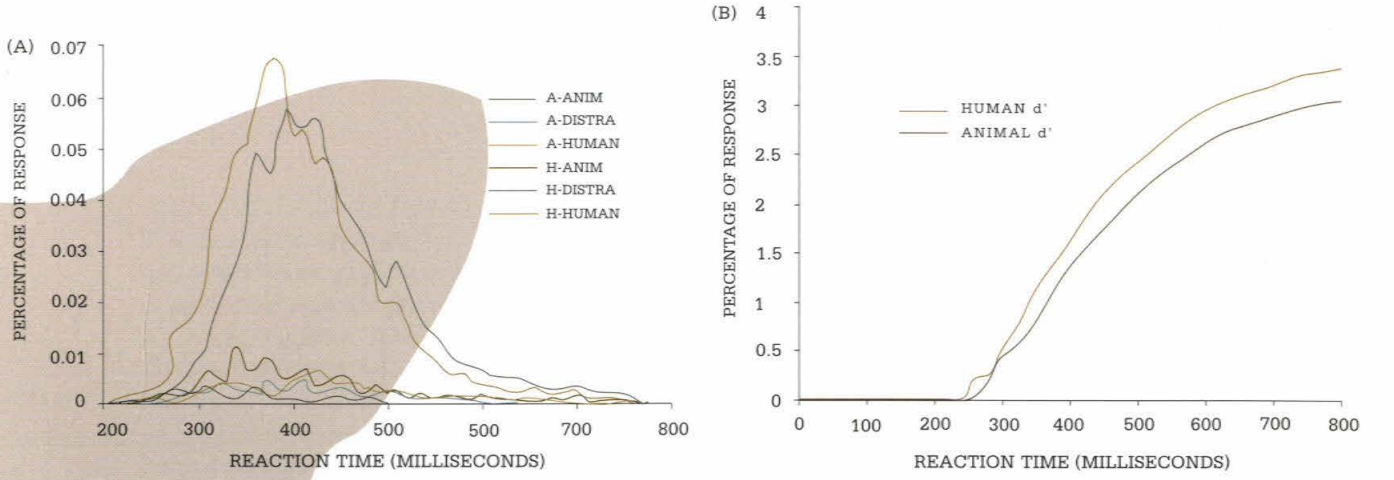

FIGURE 2. (A) Reaction time histogram averaged over 14 subjects. Legend entries are of the form "Task-Category," where "A-Human" represents the response to human images in the animal task, and so on. The H-Human response curve begins earlier than the A-Anim curve, suggesting that subjects are able to respond in the human task at an earlier time. However, curves for false positives (H-Anim and A-Human) show a similar trend, demonstrating that subjects may not be capable of discriminating targets earlier in the human task. (B) Evolution of the sensitivity index d' as a function of reaction time (averaged for 14 subjects). The higher amplitude of d' in the human task observed for longer reaction times reflects a better (but not faster) ability to discriminate targets from non-targets. Both curves significantly differ from zero at the same time, indicating that discrimination is performed equally fast in both tasks.

faces faster than non-human objects.

Convincing evidence for such "strategically biased" performance stems from the wide variation of response times recorded for the distractor images. All distractor images contain neither humans nor animals, and are derived from the same pool of images. The selection is carefully controlled for any biases, so the response times should not vary from one condition to the other. However, we found a 77-millisecond lower average response time to distractors in the human task compared with the animal task. One possible explanation for this behavior is that subjects were, possibly unknowingly, choosing to perform one task faster than the other.

The observed actions could also arise from an asymmetry in the discriminations required of subjects in each task. For example, if subjects got the impression that distractor images were more akin to animal images, then they might attempt to accelerate their performance in the test condition by dismissing anything remotely animal-like.

The two conditions were made symmetric in the control experiment by simply removing the distractors leaving only animal and human

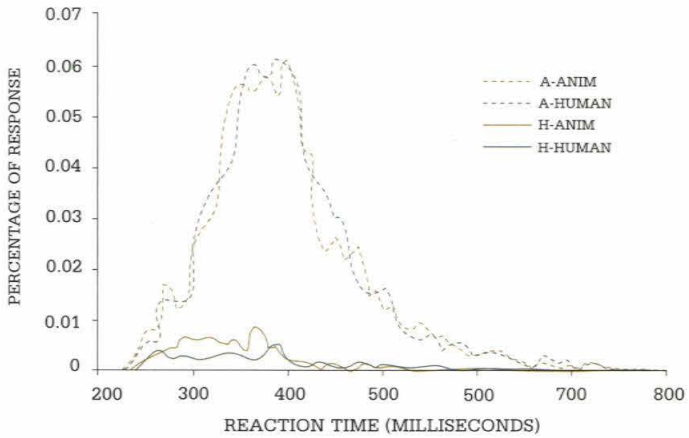

FIGURE 3. Reaction time histogram averaged over 8 subjects in the control experiment. Legend entries are of the same form as described in Figure 1. When discrimination in the two tasks is made symmetric by removing the distractor images, no bias in favor of human pictures is observed.

images in equal numbers. Logically, discriminating animals from humans should be no more difficult than discriminating humans from animals, and the postulated bias should no longer exist. Eight subjects responded alternately to the two categories, and this time we found no significant difference in the correct mean or median response times between the human and animal conditions (see Figure 3). Categorization of human faces and animals is performed equally fast and no strategic bias is observed, thus answering the fundamental question of our study.

SCARED FACES CAPTURE OUR ATTENTION

Turning our attention to the other question

posed at the beginning, we investigated the possibility that faces displaying emotional expressions, especially negative ones such as fear or anger, could induce faster visual processing. A comparison of correct responses to positive and negative expression images in the test condition shows lower mean and median reaction times to the latter. This distinction between positive and scared faces is significant, but unfortunately very slight—about 9 milliseconds. A clear difference is not apparent in both the reaction time histogram (see Figure 4(A)) and the sensitivity index plot (see Figure 4(B)).

Differences in response times to different emotional image categories in the control experiment are minor as well. While average time delays are significantly less for scared expressions, median values point out no difference. It remains difficult to conclude whether emotionally relevant human images affect categorization speed.

NO SUBSTANTIAL DIFFERENCE IN PROCESSING TIME

Our results show that human facial-image processing cannot be accomplished faster than the processing of other image categories under conditions of URVC. The earlier onset of the responses to target humans for all but two subjects cannot be accepted as evidence that specialized pathways exist for analyzing faces. Rather, it implies that subjects were adopting the tactic of responding more quickly to all images when told to identify humans. Taking into account false positive responses, subjects actually take the same amount of time to discriminate between target and non-target images in both conditions.

The reason that subjects were perhaps unknowingly employing this strategy may rest with the unevenness of discrimination imposed by the paradigm. Our data points out that targets and non-targets are more easily differentiated in the human task compared with the animal task. Simply removing distractor images reestablishes symmetry and eliminates bias.

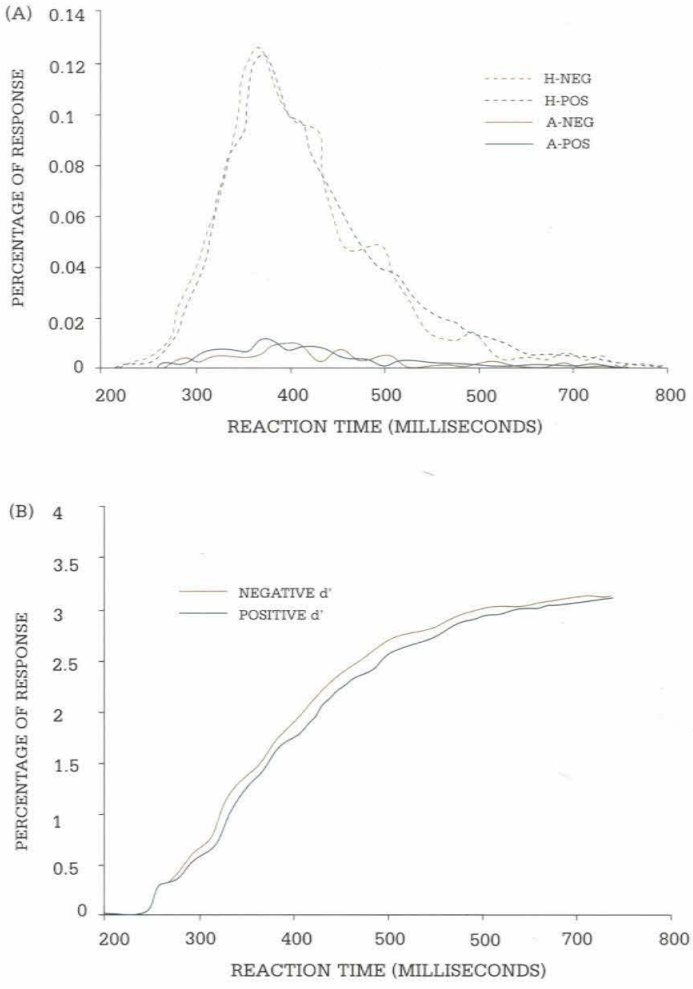

Figure 4. (A) Distribution of reaction times for negative and positive expression human images averaged over 14 subjects. Legend entries are similar to those in Figure 1. For example, "H-Neg" denotes the response to negative expression images in the human task. Note the similarities between the early parts of the response curves to target positive and negative images. The slight yet significant difference of mean and median reaction times is not visible in this histogram. (B) Evolution of the sensitivity index d' as a function of reaction time for positive and negative images over 14 subjects. Responses to both categories of images begin at 275 milliseconds.

NEW AVENUES OF RESEARCH

The human visual system may have a small but significant propensity to handle faces with scared expressions faster than those with positive expressions. This particular attentiveness agrees with previous studies concerning the nature of unconscious processing. Esteves *et al.* and Ohman *et al.* demonstrated that subjects could be conditioned at the unconscious level when the conditioning stimuli were fear-relevant faces. This has implications on the processing speed of fear-relevant stimuli, as processing is assumed to occur most rapidly at the unconscious level. Yet the notion that unconscious processes are specific to fear-relevant stimuli has been challenged. Deheane *et al.* demonstrated that images of numbers shown to subjects at a level below consciousness were able to influence conscious processes. The minute differences obtained in our experiment make it difficult to decide whether there is a real advantage in processing time for fearful versus neutral visual stimuli, under conditions of URVC.

Future work will resolve these ambiguities. One clear avenue is to include more images and trials. Recording an electroencephalogram (EEG) while subjects perform the experiment would also allow for the comparison of electrical responses when human faces are used as both targets and non-targets. Similar experiments with the human, animal, and distractor images all drawn from a single database might even narrow the gaps in reaction times.

The significance of our work lies in the observation that despite the incredible relevance of the human face as a stimulus, it appears not to pose an exception to the speed of ultra-rapid visual categorization.

Catherine Chang is a second year undergraduate in Electrical Engineering and Computer Science at the Massachusetts Institute of Technology. *This work was completed with Rufin Van Rullen and Christof Koch, Professor of Cognitive and Behavioral Biology at Caltech, and funded by the 2001 Caltech Summer Undergraduate Research Fellowship. The author wishes to thank Rufin Van Rullen and Christof Koch.*

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DON'T EAT BY ALBERT CHOW

Don't Eat
Acrylic, 30"x 10"
Artist's Private Collection

2038 A. D. Our reckless pollution has wasted the Earth: plants and animals are too toxic to feed humankind. Skin tones left the happy pink of yesteryear for a more suitable grayish green. "Don't eat," says the SpacePower, Inc. ad campaign, "Look to the sky and you'll see it!" The drug company claims that their latest pill is the complete substitute for eating. If SpacePower can really help, why not give it a try?

Albert Chow
Art Center College of Design

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