Physics Nobel Prize Is Awarded to Giacconi, Davis, and Koshiba

This year's Nobel Prize in Physics goes to three men who have created and peered through new windows on the cosmos. Half the prize is awarded to Riccardo Giacconi, director of Associated Universities Inc, in Washington, DC, "for pioneering contributions to astrophysics, which have led to the discovery of cosmic x-ray sources." The other half is shared between Raymond Davis Jr, retired from Brookhaven National Laboratory, and Masatoshi Koshiba, retired from the University of Tokyo. They are cited "for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos."

In 1962 Giacconi discovered the first x-ray sources beyond the Solar System, and he headed the effort that led, in 1978, to the launch of the Einstein Observatory, the first x-ray telescope capable of imaging distant sources. A few years later, in the bowels of a South Dakota gold mine, Davis and a handful of collaborators built the first detector capable of measuring the Sun's output of neutrinos. In the 1980s, Koshiba's group in Japan built the first detector that could record the directions, energies, and arrival times of individual neutrinos from the Sun, and even from supernovae.

When physicists and astronomers got to look at the heavens in x rays and neutrinos, they found wondrous surprises.

The x-ray sky

Born in Genoa in 1931, Giacconi earned his PhD in 1954 at the University of Milan, working on cosmic rays under Giuseppe Ochiallini. "It took me two years to record just 80 protons," says Giacconi. "So I swore I'd never do low-statistics work again. That's what started me thinking about how to concentrate and focus the meager flux of x rays one could expect from sources beyond the Solar System."

X rays cannot be focused by refraction, but they do exhibit total reflection off metal or glass at grazing angles. In 1960, Giacconi and Bruno Rossi published a paper on how one might concentrate x rays by reflecting them off paraboloid surfaces.[1] Rossi was then board chairman of American Science and Engineering (AS&E), a private research firm near Boston, and Giacconi was its scientific director.

The Giacconi–Rossi design could concentrate x rays, but not focus them. "We soon learned, however, that Hans Wolter in Germany had already done most of the mathematical analysis needed for focusing," recalls Giacconi. Wolter had calculated that a reflector combining both paraboloid and hyperboloid segments should do the trick. Giacconi tested this geometry with light reflected internally off the surfaces of a plastic mockup. It worked well at optical wavelengths. But for x rays, one would have to polish the reflecting surfaces to smoothness on a scale of angstroms.

X-ray detectors have to fly aboard satellites, rockets, or balloons, because the atmosphere is opaque to x rays. Not until 1973 did Giacconi and coworkers launch the first focusing x-ray telescope. But already in 1962, his group at AS&E provided the first glimpse of x-ray sources beyond the Solar System. The detector was simply three Geiger counters aboard a US Air Force rocket. And what this first look found was quite unexpected.[2] It revealed an amazingly bright source, which was later localized to the constellation Scorpius and nicknamed Sco X-1. "We knew it was something truly novel," says Giacconi, " because its ratio of x-ray to optical brightness was a billion times that of the Sun." And the brief rocket flight yielded a second important surprise: an unresolved x-ray background, apparently from everywhere in the sky.

We now know that Sco X-1 was the first of many binary stellar x-ray sources to be discovered. The first x-ray orbiter, Uhuru, was launched by NASA in 1970. It was built by Giacconi's group, which had moved from AS&E to the Harvard–Smithsonian

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Center for Astrophysics (CfA). Even without a telescope, Uhuru provided convincing evidence that intense stellar x-ray sources like Sco X-1 are powered by the gravitational infall energy of material being accreted from a star onto a compact binary companion—either a neutron star or a black hole.

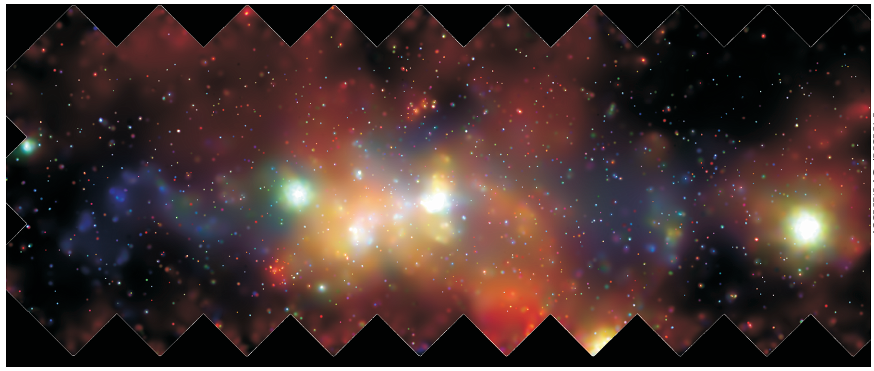
The x-ray background has now been largely resolved into discrete sources—the active nuclei of very distant galaxies—by NASA's orbiting Chandra x-ray observatory, launched in 1999 (see PHYSICS TODAY May 2000, page 18). Even before Chandra, much of this background deciphering, especially at x-ray energies below 2 keV, had already been accomplished by the Einstein Observatory and by the German ROSAT orbiter, launched in 1990.

In 1973, five years before the launch of the Einstein Observatory, Giacconi's group built the first real x-ray telescope. It flew aboard the Skylab orbiter, but it was used only to image the Sun's x-ray output. X-ray study of the Sun had been pioneered in the late 1940s by Herbert Friedman at the Naval Research Lab, with captured German V-2 rockets.

The conceptual model for the gargantuan x-ray output of active galactic nuclei is provided, in miniature, by the stellar x-ray binaries. Chandra observations have made a compelling case that supermassive black holes at the centers of these young galaxies are continually accreting material, which radiates in x rays as it becomes very hot en route to its doom.

"The Chandra telescope is eight orders of magnitude more sensitive than the detector with which we discovered Sco X-1," says Giacconi with pride. He led the campaign in the 1970s for its design and construction. When Giacconi left Harvard in 1981 to become director of the Space Telescope Science Institute in Baltimore, the leadership of the Chandra effort at CfA passed to Harvey Tananbaum.

Chandra's four nested hyperboloid–paraboloid reflectors provide an unprecedented imaging angular resolution of better than 1 arcsecond (see the image above). With this resolution, Chandra can identify a very distant x-ray galaxy with as few as 10 photons recorded by its CCD detector array in a week-long deep exposure. Having found 350 x-ray galaxies in one such deep exposure of a patch of sky no bigger than a quarter moon, Giacconi and coworkers concluded in 2001 that the entire sky offers 10^8 x-ray galaxies accessible to Chandra.[3] High angular resolution is also essential for identifying the optical and radio counterparts of x-ray sources in crowded fields.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CENTER OF THE MILKY WAY imaged in x rays by the Chandra Observatory. This mosaic, 400-light-years high, reveals accumulations of hot gas and many white dwarf stars and x-ray binaries. The supermassive black hole at the Galaxy's center lies within the bright patch at the image's center. (From Q. Wang et al., *Nature* **415**, 148 [2002].)

"An important discovery of x-ray astronomy is the intergalactic gas that pervades clusters of galaxies," says Giacconi. "It's too hot to be seen at optical wavelengths." This hot gas accounts for much more of a cluster's mass than do the all stars in the galaxies. And its distribution serves as a tracer for the even greater nonbaryonic mass—"dark" at all wavelengths—that is presumed to dominate the gravitational binding of galaxy clusters.

The neutrino shortage

Davis was born in 1914 in Washington, DC. He received his PhD in chemistry at Yale University in 1942. Davis's interest in the then still hypothetical neutrino began when he joined the new Brookhaven National Laboratory in 1948. Two years earlier, Bruno Pontecorvo had suggested that one might prove the existence of the neutrino (ν) by looking for the production of radioactive argon-37 in chlorine by the reaction

$$\nu + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + \mathrm{e}. \qquad (1)$$

In 1954, Davis mounted such a search with 1000 gallons of carbon tetrachloride in the basement of a nuclear reactor. He found no ^{37}Ar, which is what we would expect in hindsight, knowing that reactors produce only antineutrinos ($\bar{\nu}$). This null result can be regarded as the first demonstration that the ν is different from its antiparticle.

So Davis began thinking about using reaction 1 to detect neutrinos from the Sun. The problem was, however, that the maximum neutrino energy expected from proton–proton fusion, the Sun's principal energy source, was only 0.42 MeV, hopelessly below the 0.8-MeV threshold for reaction 1. But in 1958, astrophysicist William Fowler came to the rescue by calling Davis's attention to a new Naval Research Laboratory measurement of the helium fusion reaction $^{3}\mathrm{He} + {}^{4}\mathrm{He} \rightarrow {}^{7}\mathrm{Be} + \gamma$. The cross section for this minor branch of the solar pp cycle turned out to be a thousand times bigger than previously thought. Therefore, Fowler pointed out, the Sun might be producing enough boron-8, through proton capture by beryllium-7, for a chlorine detector to see the high-energy neutrinos (up to 15 MeV) emitted by ^{8}B decay.

The next issue was the competition, in the Sun, between two rival ^{7}Be capture processes: the desired proton capture, which produces ^{8}B and detectable high-energy neutrinos, and the unwanted electron capture, which results in neutrinos of lower energy. The need to evaluate this crucial competition initiated the four-decade-long close collaboration between Davis and theorist John Bahcall, now at the Institute for Advanced Study in Princeton.

In 1962, Bahcall had published an analysis of ^{7}Be electron capture at high temperature. So Davis asked him to calculate the abundance of ^{8}B neutrinos one could expect from the Sun. "To give an answer, I had to know the temperature profile of the solar core," recalls Bahcall. So he availed himself of the stellar-evolution computer codes being developed by Fowler's group at Caltech. "We concluded," says Bahcall, "that the flux of ^{8}B neutrinos would be far too meager to be measured by the largest practicable chlorine detector.

A year later, however, the enterprise was back in business. To estimate the expected solar-neutrino signal, one had to calculate the rates of nuclear processes not only in the Sun, but also in the detector. And Bahcall realized that he had badly underestimated the rate for reaction 1 by considering only the ground-state transition. He now predicted a superallowed transition to an excited "analog" state of ^{37}Ar that would increase the solar-neutrino capture in a 600-ton detector to an acceptable rate of a few events per day.

Soon after that, Brookhaven director Maurice Goldhaber approved the project and Davis found a home for it—a mile underground in the Homestake gold mine in Lead, South Dakota. A tank was built to hold 615 tons of perchloroethylene (C_2Cl_4), a common dry-cleaning fluid. Data-taking began in 1967 and continued with few interruptions until 1994. Over the years, Davis's principal experimental collaborators were Brookhaven's Bruce Cleveland and Paul Wildehain at the University of Pennsylvania.

The routine involved bubbling helium through the tank every month or two, to collect the ^{37}Ar atoms that had been created since the previous purge, and then passing the gas through charcoal to trap the argon. The halflife of ^{37}Ar is 35 days. The number of atoms collected was measured by their decays in a proportional counter designed for very low counting rates. To augment and monitor the efficiency of the ^{37}Ar collection, measured amounts of nonradioactive argon were introduced into the tank after each purge.

In three decades of running, the Homestake experiment, with remarkable consistency, gave the same astonishing result: Solar neutrinos produced about half an argon atom per day in the massive tank.[4] This was the first observation of neutrinos from the Sun, and thus the first direct evidence that the Sun shines by nuclear fusion. But the observed rate was barely $^1/_3$ of what Bahcall's solar model predicted. Here was the beginning of "the solar-neutrino problem."

As Bahcall and coworkers have incorporated improved nuclear measurements and refined their calculations over the decades, the quoted uncertainly of the "standard solar model" (SSM) prediction for a chlorine detector has shrunk to 14%. When the Homestake experiment finally ended, the uncertainty of its measured neutrino flux was 9%. The measurement and the SSM are quite irreconcilable—unless we assume that neutrinos do funny things en route from the solar core to the detector.

Soon after the first shortfall was reported in 1968,[5] Pontecorvo had another seminal idea. He and Vladimir Gribov suggested that solar neutrinos might "oscillate" between their original state and some other state invisible to the chlorine detector. This conjecture, much elaborated over the years, is now the dominant view among neutrino physicists.

Neutrinos pointing back home

Koshiba was born near Nagoya, in 1926. He received his undergraduate physics degree at Tokyo University, and then earned his PhD under Morton Kaplon at the University of Rochester in 1955, studying high-energy cosmic rays. Returning to Tokyo University, Koshiba became active in organizing Japanese participation in international collaborations at several electron–positron colliders in Europe.

In the mid-1970s, attempts to unify the theories of the strong and electroweak interactions of elementary particles into "grand unified theories" (GUTs) led to predictions that the proton is not immortal; that it decays with a lifetime that might be as short as 10^{29} years. So by monitoring a few thousand tons of material, one might hope to see a few hundred proton decays per year.

So in 1978, Koshiba began to plan for the 3000-ton Kamiokande water-Čerenkov detector inside a zinc mine west of Tokyo. A relativistic charged particle from a proton decay would generate Čerenkov light in the water. More than a thousand photomultipler tubes, arrayed around the water, would record the Čerenkov pattern and thus determine the identity, energy, and direction of the decay products.

In the US at just about the same time, the Irvine-Michigan-Brookhaven (IMB) collaboration was planning a water-Čerenkov detector with more than twice Kamiokande's water volume, to be placed in an Ohio salt mine. "So I had to think hard about how we could compete with this larger rival," Koshiba told us. "I concluded that we had to go for much bigger phototubes than IMB was using, so that Kamiokande could better determine the branching ratios of the various decay modes one might find, and thus distinguish between different GUTs variants."

In collaboration with the firm Hamamatsu, the Kamiokande group developed and installed state-of-the-art 50-cm-diameter phototubes, and the detector began looking for proton decays in 1983. Of course, none were found. Two decades later, we still haven't seen proton decay. "But we did find that our big phototubes could see the light from electrons with energies as low at 12 MeV, and that meant we could see ^{8}B-decay neutrinos from the Sun," Koshiba recalls. "Looking for proton decay is like gambling." But solar neutrinos, in the light of the still unconfirmed Homestake result, had a less chancy future.

So the Kamiokande group reconfigured the detector for solar neutrinos by augmenting its shielding and, together with collaborators from the University of Pennsylvania, refining the phototube timing electronics. Solar-neutrino data-taking began in 1986. (See the article by Koshiba in PHYSICS TODAY, December 1987, page 38.)

A water-Čerenkov detector sees solar neutrinos only by the recoil of electrons off which they scatter. The energy and direction of the scattered electron approximates that of the incident neutrino. Thus, unlike a radiochemical chlorine or gallium detector, water-Čerenkov facilities can determine the energy spectrum and angular distribution of incident neutrinos, and even their arrival times. On the other hand, they are limited by higher threshold energies than the radiochemical detectors. Kamiokande would eventually be able to see neutrinos down to almost 7 MeV, and SuperKamiokande, its 50-kiloton successor, has an energy threshold of 5 MeV. Koshiba first proposed this colossal second-generation detector in 1984.

By the time Koshiba handed the reins of Kamiokande over to Yoji Totsuka in 1987, it was clear that the detector was seeing only about half the ^{8}B neutrino flux predicted by the SSM.[6] That's not in conflict with the larger Homestake shortfall. The oscillation theory actually thrives on the observation of different shortfalls by different detectors.

Kamiokande's ability to estimate the direction from which a neutrino came made it clear to any remaining skeptics that those neutrinos were indeed coming from the Sun. "And the detector's real-time capability provided a wonderful retirement gift for me," recalls Koshiba. On 24 February 1987, the detector recorded a sudden burst of a dozen neutrinos with energies up to 40 MeV, all within the space of 13 seconds. This was clearly the harbinger of the nearby supernova SN1987A, which would become visible a few hours later. The IMB detector saw a similar burst, but with somewhat fewer neutrinos, because its threshold was 20 MeV.

Kamiokande's ability to distinguish between electrons and muons in the water yielded the first strong evidence that neutrinos produced by cosmic-ray collisions in the atmosphere might be exhibiting oscillations much like the solar neutrinos. Soon after SuperKamiokande began operating in 1996, it convincingly clinched the case for this atmoshperic-neutrino oscillation (see PHYSICS TODAY, August 1998, page 17). And it has also contributed a wealth of crucial detail on solar neutrinos.[7]

In 1999, a new kind of water-Čerenkov detector made it possible, for the first time, to measure directly the total ^{8}B neutrino flux from the solar core, regardless of any metamorphosis along the way. The Sudbury Neutrino Observatory in Canada, with heavy water (D_2O) at its heart, can detect a neutrino of any flavor and even, to some extent, distinguish between neutrino flavors (see PHYSICS TODAY, July 2002, page 13). The result has been a triumph for the SSM and a major step on the road to a detailed theory of the very rich neutrino sector of particle physics.

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Chemistry Nobel Laureates Helped Develop Tools to Study Large Biological Molecules

> This year's recipients helped adapt mass spectroscopy and nuclear magnetic resonance to the study of proteins.

John Fenn, Koichi Tanaka, and Kurt Wüthrich will receive the 2002 Nobel Prize in Chemistry for helping to develop tools for the study of large biological molecules. Fenn, a professor of chemistry at Virginia Commonwealth University in Richmond and professor emeritus of Yale University, and Tanaka, an R&D engineer with Shimadzu Corp in Kyoto, Japan, will share half of the prize for "their development of soft desorption ionization methods for mass spectrometric analyses of biological macromolecules." Wüthrich, a professor of molecular biophysics at ETH Zürich, will receive the other half for "his development of nuclear magnetic resonance spectroscopy for determining the three-dimensional structure of biological macromolecules in solution."

Too big to fly

Mass spectrometry (MS) determines the mass of an ionized molecule from the mass-to-charge ratio, thus providing an important and sometimes sufficient clue to its identity.[1] Nuclear magnetic resonance (NMR) helps decipher the three-dimensional structure of a molecule by observing its nuclear spins.

Until the mid-1980s, neither MS nor NMR was widely applied to analysis of biological molecules. The stumbling block was the large size of most biomolecules of interest. Proteins, for example, can range from a few thousand atomic mass units (daltons), such as for the hormone insulin, to more than 5 million Da for large enzyme complexes.

For MS, the challenge was to convert such large and thermally unstable molecules into the gas-phase ions required by the technique. As Fenn quips, "It was like teaching an elephant to fly." Fenn adapted the concept of electrospray ionization (ESI) to do the job, and Tanaka showed that laser desorption could work.

Today, one of the most important applications of ESI and laser desorption is to protein identification. Using enzymes, researchers can break a protein into constituent peptides and analyze the fragmentation pattern. This pattern acts as a fingerprint to be matched against a protein database. As a check, each peptide can be further fragmented using tandem MS.

Biological macromolecules also posed a challenge for NMR. How could one sort through the NMR signals from so many atoms and deduce any useful information about the molecule's structure? The methods developed by Wüthrich helped lead the way.

For more than a decade now, NMR has served as an alternative to x-ray crystallography, especially for structure determinations of those biological molecules that must remain in solution or that can't be crystallized. By May 2002, NMR had been used to determine about 20% of the roughly 15 000 atomic coordinate sets deposited in the protein data bank. Both MS and NMR are expected to play a role in the growing field of proteomics—the study of how proteins

FENN

TANAKA

WÜTHRICH