Opening new windows in observing the Universe

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The 2002 Nobel prizes in Physics underline the close relationship between physics and astronomy in understanding the Universe and its stellar constituents via novel detection technics like giant underground particle detectors or space born X-ray telescopes. Raymond Davis (retired from the University of Pennsylvania) and Masotoshi Koshiba (retired from the University of Tokyo) obtained one half of the prize for discovering and detecting neutrinos from the sun or respectively from supernova explosions. The other half of the prize went to Roberto Giacconi (Director of Associated Universities Inc. in Washington) for the discovery of cosmic X-ray sources. As X-rays cannot penetrate the Earth's atmosphere, their detection was only possible via rocket or balloon flights (or later with satellites). In all three cases pioneers were honored who opened new windows in observing the Universe (www.nobel.se/physics/laureates/2002) and founded vastly expanding research fields leading to additional exciting discoveries.

Cosmic Neutrinos

Neutrinos were postulated by Pauli in 1930 as essentially massless particles without charge and with a spin 1/2, in order to permit the conservation of energy, charge and angular momentum in nuclear beta-decay $(Z,N) \rightarrow (Z\pm1, N\mp1) + e^-(e^+) + \bar{\nu}_e\,(\nu_e)$, where Z and N stand for the number of protons (p) and neutrons (n) in a nucleus, $e^{\mp}$ for an electron (or a positron), $\bar{\nu}_e$ for an (electron-) antineutrino and ν_e for a neutrino. This decay mode is equivalent to neutrino (antineutrino) or electron (positron) capture when moving these particles from the right side of the reaction equation to the left in form of their antiparticles (and assuring energy/mass conservation). Antineutrinos, originating from nuclear reactors, were discovered in 1955 by Reines and Cowan via $\bar{\nu}_e + p\ n + e^+$, which corresponds to the reaction for Z=1 and N=0.

The Lack of Solar Neutrinos

Davis, with a Ph.D. in physical chemistry from Yale, spent almost his entire scientific life at Brookaven National Laboratory. He specialized in radiochemical detection methods, concentrating on low level technics and background reduction. This was an excellent preparation for his plan to detect neutrinos produced in hydrogen burning deep in the solar interior from where the weakly interacting neutrinos escape (almost) freely. In the 1960s a good basic understanding of stellar evolution and solar hydrogen burning had emerged, based on the reaction cycles proposed by Bethe and von Weizsäcker and many cross section measurements made at Caltech by W. Fowler's group. The pp-cycles which dominate hydrogen burning in the sun, with a net result of $4^1H \rightarrow {}^4He + 2e^+ + 2\nu_e$, produce neutrinos in four different reactions, shown in Table 1 for temperatures of roughly 1.5×10^7 K.

▼ **Table 1:** Neutrino Production in Solar Hydrogen Burning

Reaction			rel. ν_e-emission	E_{ν_e} (MeV)
(pp) $^1H+^1H$	$\rightarrow$	$^2H+e^+ + \nu_e$	100	<0.420
(pep) $^1H+e^-+^1H$	$\rightarrow$	$^2H+\nu_e$	0.235	1.442
$^7Be+e^-$	$\rightarrow$	$^7Li+\nu_e$	8.017	0.861
^8B	$\rightarrow$	$^8Be^*+e^+ + \nu_e$	0.009	<15.000

The relative ν_e-emmission rate indicates how many neutrinos are emitted relative to 100 neutrinos from the pp-reaction. Beta-decays lead to a distribution of the energy release among neutrinos and positrons, whereas electron captures release the neutrino with the total reaction energy gain. Due to the vanishingly small interaction of neutrinos with matter, it is/was extremely difficult to detect them, although 6×10^{10} solar neutrinos penetrate the earth per cm^2 and sec. Table 2 lists a number of possible detection reactions, E_{thr} is the minimum neutrino energy requirement, cc and nc stand for neutral current or charged current reactions, involving a Z^0 boson or $W^{\mp}$ bosons.

▼ **Table 1:** Neutrino Detection Reactions

Reaction			E_{thr}(MeV)
$\nu_e+^{37}Cl$	$\rightarrow$	$^{37}Ar+e^-$ (cc)	0.814
$\nu_e+^{71}Ga$	$\rightarrow$	$^{71}Ge+e^-$ (cc)	0.233
$\nu + e^-$	$\rightarrow$	$\nu' + e^{-\prime}$ (nc+cc)	>5.00
ν_e+^2H	$\rightarrow$	2^1H+e^- (cc)	1.442
$\nu+^2H$	$\rightarrow$	$\nu'+^1H+n$ (nc)	2.224

Raymond Davis used a tank filled with 400 000 liters of the cleaning fluid C_2Cl_4 (perchloroethylene). About one fourth of the chlorine exists as the isotope ^{37}Cl, which permits to detect only neutrinos with energies exceeding 0.814 MeV, i.e. essentialy only neutrinos from ^{7}Be and ^{8}B decay. The location at the Homestake Gold Mine in South Dakota, 1.5km under ground, permitted to exclude cosmic ray reactions. Radio chemistry methods allowed to extract the ^{37}Ar noble gas atoms and detect their decay with a half-life of 35 days. This experiment ran from 1967 [1, 2] until 1994. On average about 0.45 decays (i.e. neutrinos) per day were detected, a result of the right order of magnitude, but only amounting to about 34% of the expected flux predicted by the "standard solar model". With this extremely precise radiochemical experiment Davis and his collaborators revealed the "solar neutrino problem" which waited for its solution about 36 years.

The Detection of Supernova Neutrinos

Masotoshi Koshiba had a background as cosmic-ray and experimental particle physicist and close connections to the University of Chicago, CERN in Geneva and DESY in Hamburg. In the Kamioka zinc mine he built the Nucleon Decay Experiment (KamiokaNDE). It was based on the detection of Cerenkov light emitted by energetic charged decay particles from nucleon decay (or e.g. energetic electrons scattered by such particles) moving with velocities larger than the speed of light in the medium water. This leads, similar to sonic booms, to radiation emitted in a narrow forward cone along the incident direction of the moving particle. The resulting light flashes can be detected with an array of photo multiplier tubes. Early versions of Grand Unified Theories (GUTs), unifying strong, weak and electromagnetic forces had predicted decay half-lives of the "stable" proton of the order 10^{30} years. The total amount of protons in 3 000 tons of water would have permitted to observe a sufficient number of decays, the non-detection provided only lower limits for the half-life. Koshiba's achievement was to adapt KamiokaNDE in 1986 to a

Neutrino Detection Experiment based on neutrino-electron scattering $\nu + e^- \rightarrow \nu' + e^{-\prime}$ (see Table 2). With improved photo-tubes it was possible to first reduce the detection threshold down to 12 MeV, later to 7 and finally to 5 MeV in the successor experiment Super-Kamiokande (also planned by Koshiba). The IMB detector in a salt mine in Ohio, built initially also for proton-decay experiments, had a detection limit as high as 20 MeV. Thus, Kamiokande was utilizable as a solar neutrino detector, permitting to see neutrinos from ^{8}B-decay.

The 2002 Nobel prizes in Physics underline the close relationship between physics and astronomy

In 1987, on February 23rd, about three hours before the optical detection of Supernova 1987A in the Large Magellanic Cloud, Kamiokande detected a flash of 11 neutrinos with energies up to 40MeV within about 12s [3] while IMB detected 8 neutrinos. The Cerenkov detectors could indicate the precise (collision) time, energy and incident direction of the neutrinos. In addition, all neutrino types (ν_e, $\bar{\nu}_e$, ν_μ, $\bar{\nu}_\mu$, ν_τ,$\bar{\nu}_\tau$) were detectable, because elastic scattering of $\nu_{\mu,\tau}$ with electrons is possible via neutral currents, while beta-decay or neutrino capture (via charged currents) involves only electron neutrinos.

The energies and direction clearly pointed toward SN 1987A. This was not only the first detection of supernova neutrinos, but also the proof that massive stars experience a core collapse to nuclear densities, after passing through all nuclear burning stages (hydrogen, helium, carbon, oxygen and silicon burning) and the formation of a central Fe-core with the highest binding energy per nucleon (see Figure 1). The change of the gravitational binding energy from the size of the Fe-core to that of a neutron star of 10km is of the order of 10^{53} erg. In an environment of about 10^{11} K neutrinos of all types are created and are the fastest escaping particles due to their minute interaction cross sections, carrying away the binding energy of the neutron star. However, for nuclear densities ($\approx 2 \times 10^{14}$ g cm^{-3}), these neutrinos do not leave without scattering, requiring several seconds for their escape. Within the statistics this was consistent with the observations.

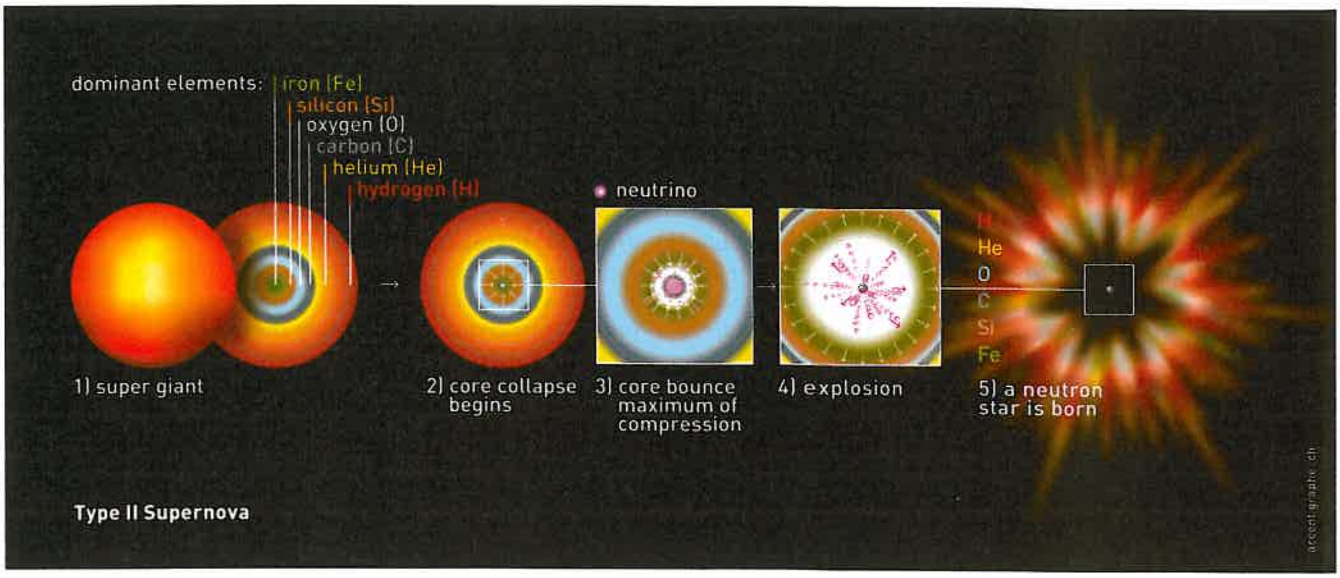
◄ Fig. 1: The onset of a (type II) supernova explosion of a massive star via Fe-core contraction to nuclear densities and the release of neutrinos of all types carrying away the gravitational binding energy gain of about 10^{53}erg. Interaction of these neutrinos with the envelope is thought to lead to a total (kinetic) explosion energy of about 10^{51}erg, a central neutron star and an essentially untapped neutrino flash.

Recent Developments

While the pioneers had seen the first solar and supernova neutrinos, the solar neutrino puzzle remained [4]. The European GALLEX experiment and the Russian-American Experiment SAGE, both radiochemical experiments based on ν_e capture on ^{71}Ga, had a small detection threshold (see Table 2) and could also see neutrinos from the dominant pp-reaction for the very first time. But also these experiments detected only about 56% of the expected neutrino flux from the Standard Solar Model. Super-Kamiokande (if assuming that the detections originate from $\nu_e + e$ scattering, which permits a neutral and a charged-current branch) found only about 47% of the expected solar neutrino flux. The so-called atmospheric neutrino problem, related to the ratio $(\nu_\mu + \bar{\nu}_\mu)/(\nu_e + \bar{\nu}_e) = 2$ expected from cosmic ray interaction with the earth atmosphere, seemed to create another puzzle. In 2001 and 2002 a heavy water based detector in the Sudbury nickel mine in Ontario (Canada) made ground-breaking news. According to Table 2, deuterium ^{2}H can undergo charged current reactions with ν_e and neutral current interactions with any type of neutrino. This led to the option to detect ν_e and any $\nu_{\mu,\tau}$ independently and showed that the sum of all neutrino events is consistent with the total number of emitted solar neutrinos. However, about 68% of the initially produced neutrinos (all ν_e) were converted into $\nu_{\mu,\tau}$ [5], requiring an extension of the Standard Model of particle physics and finite (albeit small) neutrino masses. Very recent results of the KAMLAND collaboration with a new scintillation detector at the old Kamiokande site, which detects neutrinos from a number of Japanese nuclear reactors within a radius of about 100km, are consistent and support the so-called large (mixing) angle solution [6]. Thus, there may be new Nobel prizes in the making, but in 2002 the pioneers were honored.

Cosmic X-ray Sources

Riccardo Giacconi, with a Ph.D. from the University of Milan, started out to work in cosmic ray physics. Frustrated by the low count rates he converted to a different spectral range in astrophysics, not visible before the earth atmosphere could be overcome. In 1962 X-ray astronomy was born with the start of an Aerobee rocket with three Geiger counters on board. Giacconi and his collaborators had discovered the X-ray source Scorpius X-1 and an apparently isotropic X-ray background [7]. Giacconi became the father of extrasolar X-ray astronomy by planning and building increasingly efficient X-ray satellites during his years at the Harvard-Smithonian Center for Astrophysics. In 1970 Uhuru was the first satellite dedicated to X-ray observations. With Bruno Rossi of American Science and Engineering he developed a method to concentrate X-rays by reflecting them off paraboloid surfaces. By making use of calculations by H. Wolter (Kiel) they also achieved focusing of X-rays by a combination of paraboloid and hyperboloid segments, this permitted to build X-ray telescopes. In 1978 the Einstein X-Ray Observatory was launched [8]. The Chandra X-ray telescope, launched in 1999, was strongly based on Giacconi's plans from 1976.



▲ Fig. 2: The nearby galaxy NGC 4697 as seen by the Chandra X-ray observatory. The hot gas in the galaxy radiates only weakly. The bright spots are black holes and neutron stars, accreting gas from a binary companion star (http://chandra.harvard.edu/photo/2002/1140/).

Combined with other efforts, e.g. the European X-ray satellites ROSAT, BeppoSAX and XMM-Newton, the Russian Granat and MIR-Kvant missions, and the Japanese satellites Ginga and ASCA, this led to a wealth of discoveries, related to different types of X-ray radiation from astrophysical sources. These include (i) thermal black body radiation with temperatures corresponding to X-ray energies, (ii) synchrotron radiation from electrons moving in strong magnetic fields, and (iii) X-ray line emission from excited atoms. A wealth of phenomena and objects have been observed with XMM [9].

X-ray line emission from a hot gas can be observed in supernova remnants (revealing their element composition) or in clusters of galaxies [10]. Compact objects like white dwarfs, neutron stars or black holes in binary stellar systems can accrete matter into their deep gravitational potential holes from the binary companion star, leading to a hot gas which emits thermal X-rays or in some cases also to the ignition of thermonuclear burning (type I X-ray bursts). Figure 2 shows a Chandra image of such compact X-ray sources in the galaxy NGC 4797. Mass-accreting black holes emit X-rays and in some cases jets, relativistic electrons in these jets emit synchrotron radiation. Supermassive black holes (of the order of 10^6 solar masses) in the center of galaxies cause "active galactic nuclei". In some cases their jets extend over millions of light years. The (initially) apparently isotropic X-ray background can now be resolved into individual sources of active galaxies with distances up to and exceeding 12 billion light years (visible with XMM and Chandra).

The study of this wealth of phenomena and objects, visible in the X-ray range, became possible after the pioneering efforts of R. Giacconi. He combines the qualities of a scientist and a manager in an exellent way, and served the astronomical community also as director of the Space Telescope Science Institute in Baltimore, director of the European Southern Observatory (ESO), and since 1999 as director of American Universities Inc. which builds together with ESO a giant telesope for cosmic infrared radiation in Chile.

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About the authors

Gustav A. Tammann studied astronomy in Basel under W. Becker. He came in 1963 to the Mount Wilson and Palomar Observatories (now: Carnegie Observatories) to work with Allan Sandage on the expansion rate and the age of the Universe; the collaboration continues to the present day. From 1977 to 2002 he was professor of astronomy at the University of Basel. Among other honors he received in 2000 the Tomalla Prize for Gravitation and Cosmology.

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