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Neutrino astronomy

Two kinds of extraterrestrial neutrinos, solar neutrinos and supernovae neutrinos, have been observed and their measured fluxes, as well as energy spectra, shed a new light on astrophysics and particle physics. Neutrinos – unlike photons – are not required to have zero mass. Small but non-zero neutrino masses have major consequences for physics and astrophysics. Neutrinos are highly abundant in the universe and so even small neutrino masses can make significant contributions to the mass density of the universe. Non-zero neutrino masses requires new physics meaning that the Standard Model for elementary particles must be modified.

DAVIS' RADIOCHEMICAL EXPERIMENT

The neutrino was postulated in 1930 by Pauli to explain the continuous energy spectrum of electrons emitted in nuclear β decay. Fermi's theory for weak interactions was developed during the 1930's. At the time, neutrino interaction cross-sections were considered too small for neutrino detection. However, the large neutrino fluxes that later became available with nuclear reactors opened the field of neutrino physics. The experimental confirmation of the neutrino came in an experiment in 1955 by Cowan and Reines. Pontecorvo and Alvarez (Pontecorvo 1946, Alvarez 1949) suggested reactor experiments using the reaction $\nu + {}^{37}\text{Cl} \rightarrow {}^{37}\text{Ar} + e^-$ to detect the neutrino. At the time there was no clear distinction between neutrino and antineutrino. The reaction often goes by the name the Davis-Pontecorvo reaction. The threshold energy is 0.81 MeV and the Argon isotope decays via electron capture with a half-life of 35 days.

Gravity was long believed to be the energy source of the sun. By 1920 it was known that the sun was mainly composed of helium and hydrogen and Eddington proposed that nuclear fusion was the energy source. However, it took until 1938 before there was a complete theory of the nuclear reactions within the sun (Bethe and Chritchfield 1938, Bethe 1939). It was a challenge to prove experimentally that nuclear burning was the energy source of the sun.

Raymond Davis Jr did his first reactor-based chlorine neutrino experiment at Brookhaven in the early 1950s. He used a tank filled with 3,900 litres of CCl_4 as a target. Helium was bubbled through the tank to remove the few argon atoms. The radioactive argon could then be removed from the helium by passing the gas through a charcoal trap with liquid nitrogen ($-196\text{ }^\circ\text{C}$) which adsorbs the argon quantitatively and allow helium to pass. A proportional counter was used to detect the Auger electrons from the argon decay. The result of the experiment, an upper limit for the cross section of fission antineutrinos of $2 \times 10^{-42}\text{ cm}^2$ per atom as well as an upper limit of the high energy neutrino flux from the sun of $10^{14}\text{ cm}^{-2}\text{s}^{-1}$, was

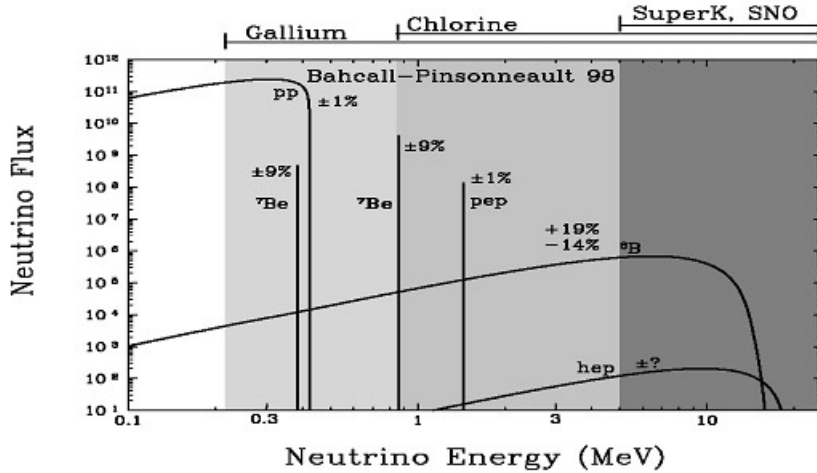


Fig. 1 The solar neutrino flux according to Bahcall (hep-ph/0009044, Nucl. Phys. Proc. Suppl. 91(2000)9). The sensitivity ranges for experiments using gallium, chlorine and water Cherenkov technique (Super-Kamiokande and SNO) are indicated. Electron neutrinos are produced in the sun from reactions in the proton-proton chain, starting with two protons that by fusion make a deuteron and ending in ${}^4\text{He}$. Electron capture of ${}^7\text{Be}$ gives lines at 0.4 and 0.9 MeV, and the reaction $p + e^- + p \rightarrow {}^2\text{H} + \nu$ at 1.4 MeV. Continuous electron neutrino spectra from ${}^8\text{B}$ give neutrino energies up to about 15 MeV. Fluxes are expressed as $\text{cm}^{-2}\text{s}^{-1}\text{MeV}^{-1}$ for continuous spectra, in $\text{cm}^{-2}\text{s}^{-1}$ for lines.

published in 1955 (Davis 1955). Already in this 1955 paper Davis considered the possibility of detecting neutrinos from the sun.

Neutrinos are very abundant in the Universe. Indeed, the ratio between neutrinos and nucleons (protons or neutrons) in the Universe is about 109. On the earth, the dominant source of neutrinos is our sun (fig. 1). Every second more than 10 billion (10^{10}) neutrinos pass through every cm^2 , the majority with low energy (< 0.4 MeV). Only 0.01% of the solar neutrinos have an energy larger than 5 MeV.

A crucial step for Davis and his radiochemical experiment was the availability of new results for the nuclear reaction ${}^3\text{He} + {}^4\text{He} \rightarrow {}^7\text{Be} + \gamma$ that occurs at a comparable rate with ${}^3\text{He} + {}^3\text{He} \rightarrow {}^4\text{He} + 2p$, followed by ${}^7\text{Be} + p \rightarrow {}^8\text{B} + \gamma$ that can take place in the sun. The β decay of ${}^8\text{B}$ gives neutrino energies up to 14 MeV, well above the threshold for the chlorine reaction. A new and more precise experiment gave a value for the cross-section that was 1,000 times higher than previously thought (Holmgren and Johnston 1959). Fowler and Cameron then suggested in letters to Davis that the boron-neutrinos from the sun might be detectable with the chlorine-argon method.

A new and 100 times larger experiment was proposed based on Davis' radiochemical method and on Bahcall's calculated rate of 40 ± 20 SNU (1 SNU = 1 Solar Neutrino Unit, 1 capture per second and per 1,036 target atoms) (Davis 1964, Bahcall 1964). Davis experiment was funded and installed in the Homestake Gold Mine, Lead, South Dakota (depth 1,500 m, corresponding to 4,200 metre water equivalent). The tank contained 615 tonnes of C_2Cl_4 , an agent normally used for dry cleaning. It was ready to start data taking in 1967. The extraction of argon by helium was done approximately once every two months to match the half-life of ${}^{37}\text{Ar}$.

The first results from Davis came in 1968, based on 150 days of data taking (Davis et al. 1968). An upper limit of the solar neutrino flux of 3 SNU was given, much lower than the then calculated rate of 20 SNU (Davis et al. 1968). In this 1968 paper is discussed different possibilities to improve the sensitivity and in particular how to reduce the background. The experimental challenge, that Davis was so successful in meeting, was to extract an average of only 17 argon atoms among the 2×10^{30} chlorine atoms in the tank every second month.

A crucial improvement was to introduce a measurement of the proportional counter pulse rise time (Davis et al. 1971). The Auger electrons following the electron capture decay of the

^{37}Ar nucleus have a total energy of 2.82 keV and their range is only about 0.1 mm in the proportional counter gas, small a distance compared to the counter diameter of 3-5 mm. The rise time of the Auger electrons is therefore short compared to background pulses from less well localised particles.

The reliability of Davis' results depends very much on the extraction efficiency of argon. This was very carefully studied. A known amount of ^{36}Ar was introduced regularly and the extraction efficiency was determined to 95%. Radioactive ^{37}Ar was produced in the tank and the extraction efficiency was also found to be high for this isotope. The production of molecules with the argon atom, that would have made extraction more difficult, was checked to be low (Davis et al. 1972). The total background (Cleveland et al. 1998) of ^{37}Ar from cosmic rays was estimated at 0.047 ± 0.013 atoms per day. Background from neutrons in the rock was estimated at 0.03 ± 0.03 atoms per day. Alpha particles in the tank walls gave a contribution to the background of no more than 0.017 atoms per day. Neutrinos produced in the atmosphere gave a calculated background of 0.0004 per day.

Davis experiment was running almost continuously from 1970 until 1994. The final results were published in 1998 (fig. 2, Cleveland et al. 1998). During this time it is estimated that a total of 2,200 argon atoms were produced in the tank. Of these 1997 were extracted and 875 counted in the proportional counter. Of the latter, 776 are estimated to be produced by solar neutrinos and 109 by background processes. The production in the tank was 0.48 ± 0.03 (stat.) ± 0.03 (syst.) argon atoms per day, corresponding to 2.56 ± 0.16 (stat.) ± 0.16 (syst.) SNU. Davis was a true pioneer and his successful mastering of the extraction of a few atoms out of 10^{30} gave birth to a new field of neutrino physics.

The calculation of the production of solar neutrinos is based on solar models with a large number of parameters. Detailed careful calculations of solar neutrinos have long since been done by Bahcall in particular (see e.g. Bahcall 2002a). With time, the uncertainties in the calculations have been reduced. The most recent result for the chlorine experiment is an expected rate of 8.6 SNU with an estimated error of about 1.2 SNU (Bahcall 2002b).

Davis discovered solar neutrinos. Solar neutrino fluxes measured by him have always been below the calculated ones, this being known as the "solar neutrino problem". Already in 1978 over 400 articles were published suggesting solutions to the problem. Solar neutrinos seemed to disappear on the way to the underground detector at the Homestake mine, suggesting a new property of the neutrino. In the Standard Model for elementary particles, the neutrino is assumed to be massless. If neutrinos instead have mass, the observed flavour states electron-, muon- and tau-neutrino can be linear combination of mass eigenstates. Neutrinos can then oscillate between different flavour states. The solar electron neutrino can disappear because of oscillations explaining Davis' result. Today many experiments are in progress or being planned to confirm the oscillation hypothesis. For a review see, e.g. Bahcall 2002b.

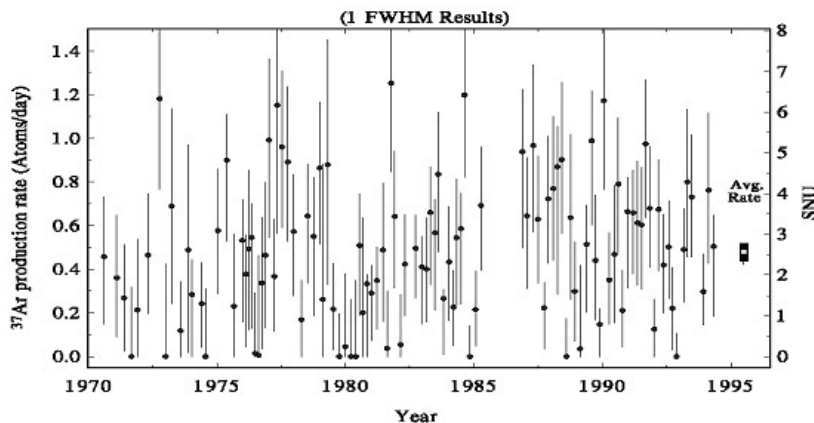


Fig. 2 Final results of Davis experiment (Cleveland et al. 1998). The average rate of about 2.5 SNU is much lower than the calculated rate of about 8.6.

KOSHIBA AND THE KAMIOKANDE EXPERIMENTS

Solar neutrinos

Around 1980, several experiments were made to study possible decay of the proton, e.g. $p \rightarrow \pi^0 + e^+$. According to Grand Unified Theories, one could expect a lifetime of the order of 10^{32} years or more. It was therefore necessary to use large volumes and also to go underground to reduce background. The Kamiokande experiment, which was designed by **Masatoshi Koshiba**, used a tank placed in a mine. It was filled with 2,140 tonnes of water and was first designed to search for proton decay by measuring the Cherenkov light emitted by the decay particles. In the proton decay the energy release is quite high, about 940 MeV, and so the requirements for the minimum detectable energy was well above solar neutrino energies. However, Koshiba wanted to lower the energy threshold of the water filled Kamiokande detector and initiated the development of a larger diameter more sensitive photomultiplier tube. A photomultiplier tube detects single photons. About 1,100 of the large 50 cm diameter phototubes surrounded the water tank and the threshold was about 30 MeV in the beginning. Koshiba was a pioneer in the use of the water Cherenkov technique for cosmic neutrinos.

Davis' result and the "solar neutrino problem" inspired Koshiba to use the water Cherenkov technique, with its directional sensitivity, to detect solar neutrinos. Solar neutrinos could be detected by the elastic scattering of neutrinos on electrons. The total intensity of light from low energy electrons and positrons in the water is proportional to their energy. It was therefore necessary to reduce further the energy threshold to detect the scattered electrons. This could be achieved by reducing the background. The water was purified reducing the radioactive background by a factor of 1,000. Anticoincidence shields to discriminate against background and new electronics were mounted. The upgraded Kamiokande detector, called Kamiokande II, was ready for solar neutrinos late 1986. The threshold was then about 8 MeV for a 50% efficiency. Only neutrinos from the ^8B decay could be detected. Davis' experiment was also sensitive to lower energy neutrinos from e.g. the pep reaction ($p + e^- + p \rightarrow ^2\text{H} + \nu$). In comparison with Davis' experiment Koshiba's Kamiokande experiment was running in real time and could determine the direction of the incoming neutrino.

The Kamiokande II experiment gave due to the direction sensitivity the final proof (fig. 3, Hirata et al. 1989, 1990, 1991) that the sun emits neutrinos, thus confirming Davis' result that fusion is the basis for the energy production in the sun. The experiment also confirmed

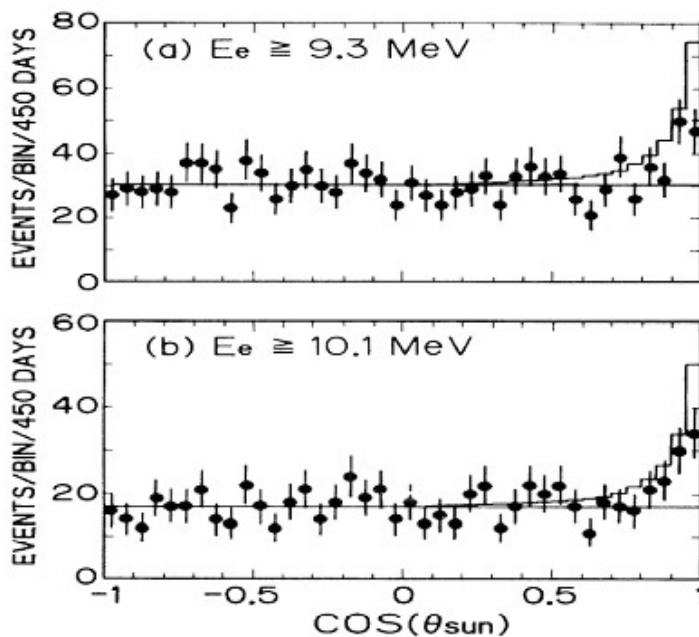


Fig. 3 The angular distribution of electron neutrinos measured by the Kamiokande collaboration. Data are shown for two different cuts on the electron energy. The histogram shows the calculated distribution from a solar model. Notice the deficit, confirming Davis' result. The direction towards the sun corresponds to $\cos(\theta_{\text{sun}}) = 1$. (Hirata et al. 1989).

Davis' result of a lower flux than calculated by solar models, the ratio of observed to calculated flux being $0.46 \pm 0.13(\text{stat.}) \pm 0.08(\text{syst.})$, giving further support for possible neutrino oscillations. It is interesting to note that atmospherically produced neutrinos were considered as a background to extraterrestrial neutrinos, but in reality they became an additional clue to new physics. The decay $\pi \rightarrow \mu + \nu_\mu$ followed by $\mu \rightarrow \nu_e + \nu_\mu + e$, that produces neutrinos in the atmosphere, gives by simple counting the ratio of muon neutrinos to electron neutrinos as 2. Detailed calculations increase this ratio slightly. If one of the neutrino species disappears before reaching the detector, it is a sign of new physics. The Kamiokande result was that the ratio of muon neutrinos to electron neutrinos was $46 \pm 12\%$ of the calculated one (Hirata et al 1990).

Supernova 1987A

Supernova 1987A in the Large Magellanic Cloud galaxy at a distance of 170,000 light years was observed optically on 24 February 1987. It was the first Supernova visible with the bare eye since Kepler's Supernova in 1604. The Kamiokande experiment could report the observation of a neutrino burst from SN1987A on 10 March 1987 (figs. 4 and 5), which was confirmed by another underground experiment, IMB (Irvine-Michigan-Brookhaven experiment, (Bionata 1987)) one day later. The discovery of the neutrino burst in Kamiokande was possible because of Koshiba's development of new photomultiplier tubes that lowered the energy threshold for neutrino detection.

If the core of a star that has finished nuclear burning exceeds about 1.3 Chandrasekhar masses there is a gravitational collapse, halted when all nucleons come as close as in nuclear matter. The process $e^- + p \rightarrow n + \nu$ gives a neutrino burst. Antineutrinos are also produced by annihilation. The final radius is about 10 km and the total energy released, equal for the different neutrino species, is about 3×10^{46} J (3×10^{53} ergs). The mean neutrino energies are 10–20 MeV. Of the 10^{16} neutrinos hitting the Kamiokande experiment, only 12 were detected. The observed neutrino burst confirmed the Supernova theory that an enormous number of neutrinos are emitted. The Supernova observation also gave an upper limit on the neutrino mass of 24 eV.

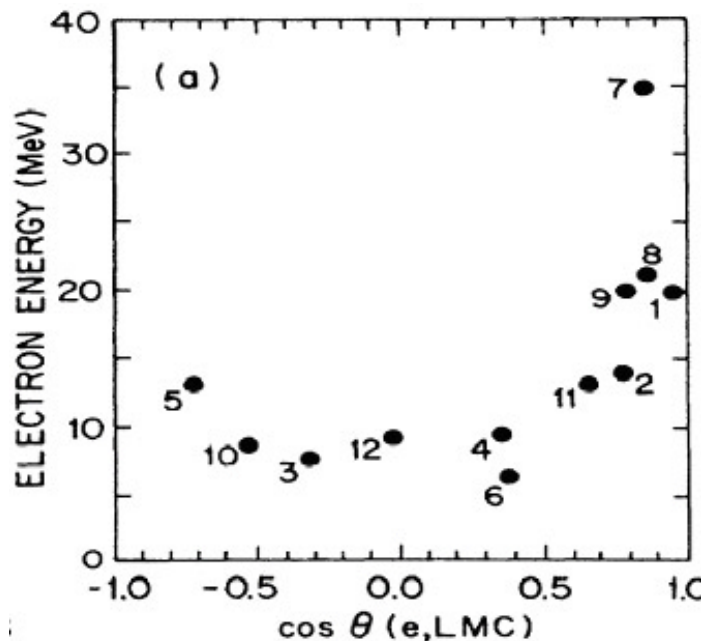


Fig. 4 Scatter plot of the detected electron energy and the cosine of the angle between the measured electron direction and the direction of the Large Magellanic Cloud. The number on each entry is the time-sequential event number. The direction of the positron from an anti-neutrino reaction has very small correlation with the direction of the neutrino. From Hirata et al. 1987.

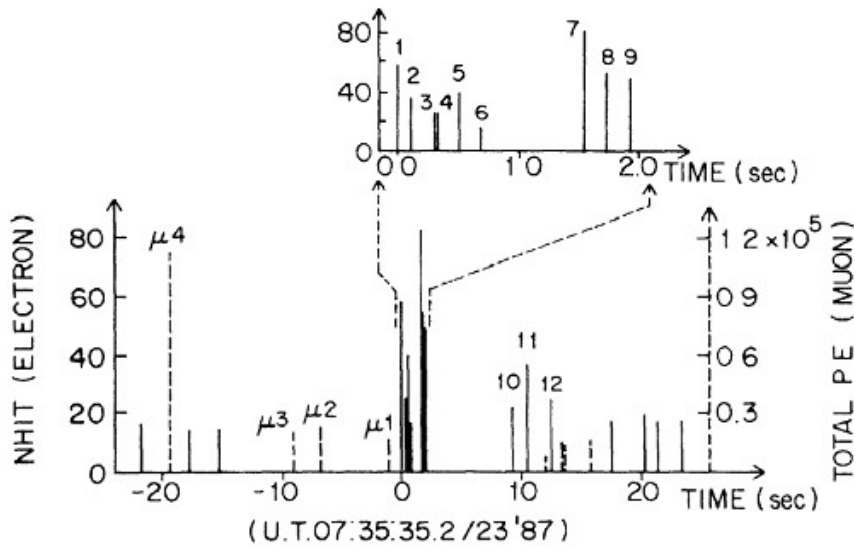


Fig. 5 Each vertical line represents the relative energy of a muon (dashed lines) or of an electron (solid lines). Events $\mu 1 - \mu 4$ are muon events preceding the electron bursts at time 0. The background events with $NHIT < 20$ are largely due to decay of ^{214}Bi , a decay product of ^{222}Rn . From Hirata et al. 1988.

OUTLOOK

The results of the radiochemical solar neutrino experiment and the results of the Kamiokande experiments started a new era in neutrino physics with many new experiments on cosmic and accelerator produced neutrinos. The results shed light on the basic properties of the neutrino as well as on the astrophysics of the Universe. Koshiba and collaborators proposed and built the Super-Kamiokande experiment with 50,000 tonnes water and over 10,000 photomultipliers. This experiment, started in 1996, gave the first indication for neutrino oscillations in 1998 (Fukuda et al. 1998) as well as very detailed information on solar neutrinos (fig. 6). Recently data from a large heavy water underground detector SNO (Sudbury Neutrino Observatory in Canada) show neutrino flavour transformation effects for solar neutrinos (Ahmed et al. 2002), confirming the Super-Kamiokande result and suggesting that the neutrino has properties that require the Standard Model for elementary particles to be modified. Many other experiments have followed or are being built, including reactor neutrino experiments, accelerator neutrino experiments and cosmic neutrino experiments.

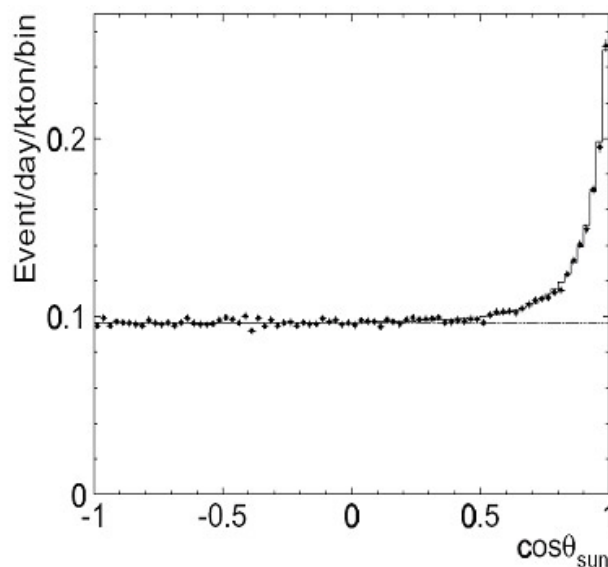


Fig. 6 The angular distribution for 1258 days of data of electrons with reconstructed energies 5-20 MeV from the Super-Kamiokande experiment. The histogram shows the best-fit signal level plus background. The peak for zero degrees is due to solar neutrinos. The Super-Kamiokande Collaboration, Phys. Rev. Lett. 86(2001)5651-5655; hep-ex/0103032

X-Ray Astronomy

PHYSICAL BACKGROUND

The very first Nobel Prize in physics was given to Wilhelm Röntgen in 1901 for his discovery six years earlier, of “the peculiar rays, later named after him”. He found the rays when studying electrical currents in evacuated discharge tubes, and named them “X-rays”. The discovery led to a surge of physical and medical explorations. Physicists that were early engaged were Arnold Sommerfeld, J.J. Thomson and Charles Barkla. Max von Laue made suggestions that led to the discovery of X ray diffraction in 1912 which rendered him a Nobel Prize in 1914. W. and L. Bragg got the Prize the year after for their studies of X-ray diffraction, and similarly Barkla became a prize-winner in 1917 for his studies of X-ray scattering. Manne Siegbahn developed X-ray spectroscopy of atoms and got the Prize for this in 1924. This intensive development took place more than half a century before X-ray astronomy could be developed.

The basic reason for the slow start of X-ray astronomy was the fact that X-rays from the universe are effectively absorbed by the Earth’s atmosphere. In order to observe the soft X-ray radiation at energies around 3 keV where relatively intensive cosmic X-rays may be expected, the detector must be elevated to such an altitude that only about one millionth of the column mass of the atmosphere remains between the detector and the source. This requires a rocket flight to at least 80 km above the ground. X-rays at higher energies penetrate further down into the atmosphere, e.g. at an energy of 30 keV to about 35 km which is accessible to high-altitude balloon experiments.

A second reason for the slow start of X-ray astronomy was the difficulty to obtain directional information from the X-ray detectors. The very weak refraction, with a refraction index very close to 1, could not be observed by Röntgen, and first in the 1920s A. Larsson, with I. Waller and M. Siegbahn, could prove that it existed at all. It was also found that the refraction index is indeed slightly smaller than 1, in contrast to the situation for visible light. This fact suggests optical solutions where total reflection is achieved by approaching grazing angles of incidence. The construction of imaging X-ray optics is thus a difficult problem, first attacked at the middle of last century at the construction of X-ray microscopes (by H.A. Kirkpatrick, A.V. Baez and H. Wolter).

THE PIONEERING YEARS OF X-RAY ASTRONOMY (1949-1970)

The possibility to study cosmic X-rays were opened up by the German V2 rockets that were shipped to the USA after the Second World War. In 1949 Herbert Friedman and his group at the US Naval Research Laboratory, using a Geiger counter in a rocket, discovered X-rays from the Sun (Friedman et al. 1951). However, the chances to study more distant objects in this radiation seemed small – a sensitivity 105 times higher than that available for detectors around 1960 seemed necessary to discover the nearest star, beyond the sun, provided that its X-ray luminosity was similar to the solar one. Thus, efforts were concentrated towards solar studies.

The opening angle of these first primitive “X-ray telescopes” was defined by a simple collimating mask. In an interesting attempt to increase the angular resolution, the NRL team used a solar eclipse in 1958 by firing a sequence of rockets during the progression of the Moon across the solar surface. In this way they could prove that the solar X-ray emission originated in confined regions related to sun spots, and from the extended hot solar corona. Two years later T.A. Chubb made a photograph of the Sun in X-rays using a simple pin-hole camera. The picture was, however, severely blurred by the rotation of the rocket.

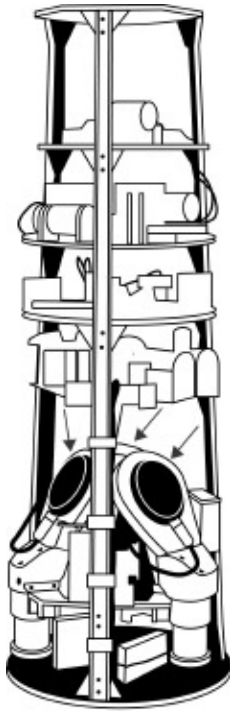


Fig. 7 Experiment payload flown by Giacconi's group in June 1962, with which the first X-ray sources outside the solar system were recorded. The three Geiger counters are denoted by arrows.

In 1959, the 28 years old **Riccardo Giacconi** was recruited to the private company American Science and Engineering (AS&E). The company was formed to enable young scientists, in particular from MIT, to get contracts from the Defence Department and NASA. Bruno Rossi, a well known cosmic ray physicist at MIT, was chairman of the board of AS&E. He served in a committee set up by National Academy of Sciences to assist NASA in formulating a strategy for space research. Giacconi was made responsible for space science in AS&E with the task to develop a program for X-ray astronomy.

In a pioneering paper Giacconi and Rossi (1960) discussed the possibilities of constructing imaging X-ray telescopes, inspired by earlier work on X-ray microscope design. They suggested an optical system of conformal paraboloidal segments, where the light rays parallel with the axis of the system would be collected in the focal point through grazing reflections with the inside of the segments. These ideas were later developed and tried out in practice by Giacconi and collaborators. His first observational work was, however, made with equipment of more simple construction.

tion.

A few years after its formation Giacconi's group discovered the first extra-solar X-ray source (Giacconi et al. 1962). They used three Geiger counters in an Aerobee rocket (fig. 7). The primary objective with the study was to try to find fluorescent X-rays from the lunar surface, generated by solar X-rays. However, as the rocket rotated, the detectors swept over the sky and this enabled searching for extra-solar sources. After two failures the experiment was successful on June 18, 1962, and a new source, as strong as 100 photons per second in the detector, was found (fig. 8). There was no mechanical collimator so that the directional information was poor. Therefore the source could not be identified with any known object. It was later named Scorpius X-1. Moreover, a homogeneous extended X-ray background was

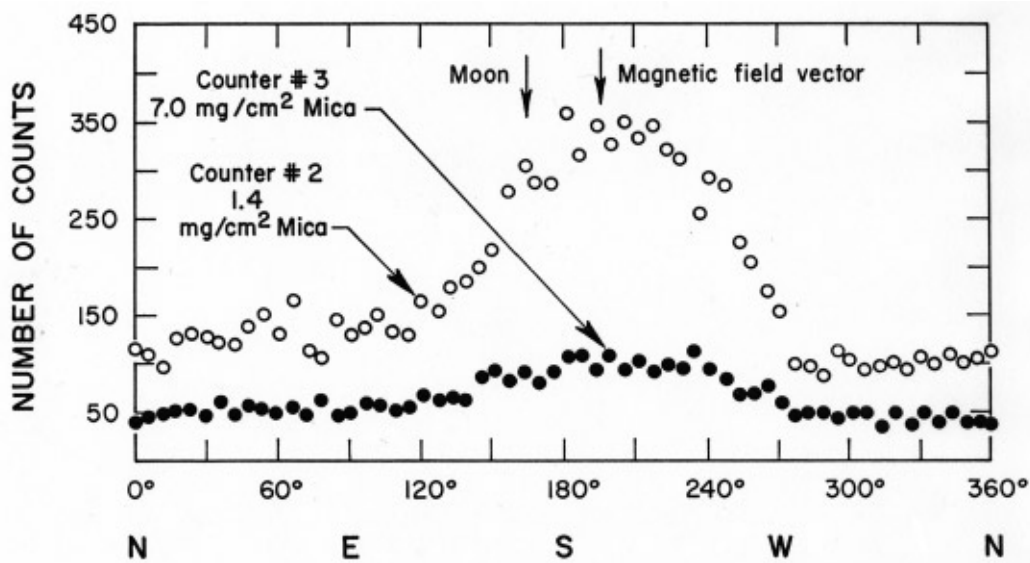


Fig. 8 Recorded counts from the Geiger counters of the payload in fig. 7. The count for two different counters, with different thickness of their Mica-windows, are shown. The results indicate the presence of an X-ray source, different from the Moon. A cosmic background radiation is also suggested.

discovered. Soon after, the group found two more sources; one identified by lunar-occultation studies by the NRL team to correspond to the Crab nebula, the famous remnant of the supernova observed by Chinese astronomers in A.D. 1054.

There had previously been pessimism about the prospect of detecting sources beyond the Solar System. This was based on the smallness of the ratio of X-ray to optical emission, estimated for known stellar objects. Scorpius X-1, emitting thousands of times more energy in X-rays than in the visible light was clearly an entirely new and unexpected type of source. And the Crab nebula was found to emit 10 billions more energy in X-rays than the Sun.

These discoveries opened the field of X-ray astronomy and stimulated a strong interest in it. Technical developments were made – the Geiger counters were replaced by proportional counters, new types of collimators improved the angular resolution to better than a few arc minutes. Also, the rockets were stabilized to keep the telescopes directed towards the source and systematically scan across it, which led to a great increase in sensitivity. The AS&E group could now localize Scorpius X-1 such that it could be identified with a star of 13th magnitude (Gursky et al. 1966). Another new source, Cygnus X-2 was also localized (Giacconi et al. 1967). During the following four years about 50 new sources were discovered, by rocket and balloon experiments. The first source in a galaxy beyond the Milky Way system was found already in 1965 by the NRL group in the active elliptical galaxy M67 in the Virgo cluster. Another remarkable discovery was the detection by the same group of pulsed X-rays from the Crab pulsar, with the same frequency as the optical pulses (30 per second).

In parallel with the exploration of the X-ray sources Giacconi and his collaborators also developed the techniques. The X-ray telescope ideas from the early 1960s were tried out in rockets experiments (Giacconi et al. 1965), and further developed for an instrument on board the Skylab (Viana et al. 1973) and later from the Einstein satellite. The implementation of focussing optics was a very important step in order to image the X-ray sky. Giacconi was the main driving force in this development.

THE SATELLITE ERA (1970 -)

The X-ray rocket missions only admitted a few minutes of observing time each, which strongly limited the sensitivity. The balloon experiments could last longer, but were useful only for energies above about 20 keV, where many sources are weak. Giacconi suggested in 1963 an X-ray satellite for surveying the X-ray sky. Such an observatory was later developed by Giacconi and his group at AS&E and was launched on October 12, 1970, from Kenya. It was named “UHURU” – “Freedom” in Swahili. The satellite was spin stabilized with two sets of proportional counters with a collecting area of as much as 840 cm². The satellite performed the first survey of the X-ray sky to an intensity of about 1/1000 of that of the Crab nebula or ten times weaker than achieved previously with rocket experiments for limited areas on the sky (Giacconi et al. 1971). The number of detected X-ray sources rapidly increased to 339 (Giacconi et al. 1972). For every week in orbit UHURU produced more data than had been collected in all previous experiments. Most unexpected was the large number discovered of X-ray binary stars with compact components. A great number of studies by Giacconi and collaborators were published in the following few years on the basis of these new data. Among the most important ones were the papers on the source Centaurus X-1, shown to be a rapidly rotating neutron star in orbit around a hot supergiant star. Matter from the supergiants is pulled by the gravity of the neutron star and accelerated to high speed until it reaches the surface, decelerates and give rise to bremsstrahlung at X-ray energies. The source Scorpius X-1 was found to be a similar object. The enigmatic source Cygnus X-1 showed rapid fluctuations, seemingly random with characteristic time scales of less than 0.1 seconds, and with very rapid additional erup-

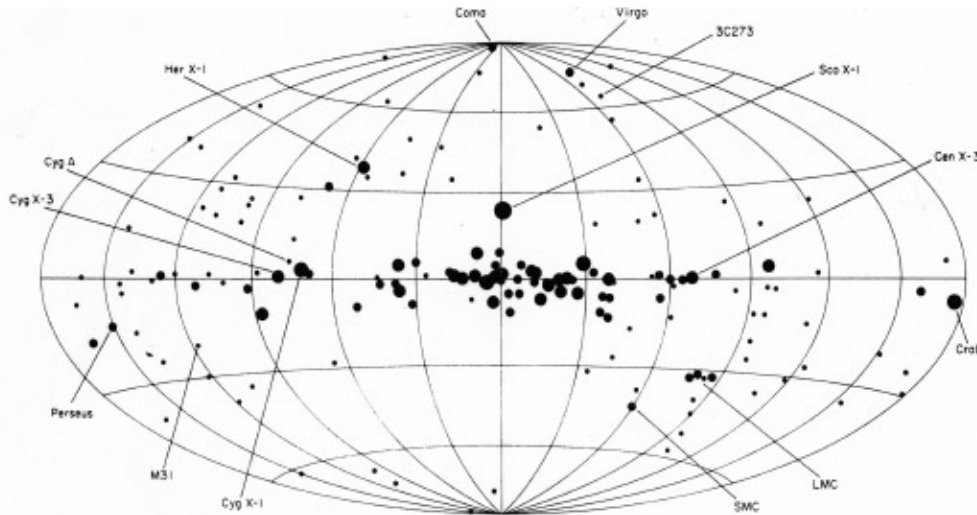


Fig. 9 A map of the X-ray sky in galactic coordinates derived from the 3U Catalog, based on UHURU data. The location of each X-ray source is approximately shown. The size of the dots is proportionate to the logarithm of the intensity. Several of the sources of outstanding astrophysical interest are shown.

tions, lasting for a few milliseconds (Oda et al. 1971). Another important discovery made by Giacconi and collaborators (Gursky et al. 1972) was that distant clusters of galaxies may be strong X-ray sources.

An intensive activity, following up the discoveries of UHURU (fig. 9), now started. Nine new X-ray satellites were developed and launched by different consortia. Considerable interest was devoted to Cygnus X-1, seemingly containing a compact object with a mass of about 10 solar masses, which makes it a very probable black-hole candidate. New discoveries were those of violent and sudden X-ray bursts from a globular cluster, NGC 6624, indicating thermonuclear reactions on the surface of a neutron star in the cluster, and the rapid variations of X-ray flux from the radio galaxy Centaurus A, suggesting that the emission originates from astonishingly small regions in the centre of the galaxy.

In 1977–78 two new very important X-ray satellites were launched by NASA, HEAO (High Energy Astrophysics Observatory) 1 and 2. HEAO-1 was a new more sensitive survey instrument, with Friedman and the NRL group playing a leading role. This mission led to the detection of 842 sources, and since its angular resolution was good enough, many of them could be identified with optical objects. HEAO-2, after its successful launch renamed the “Einstein X-ray Observatory” (fig. 10), carried an imaging X-ray telescope with an angular resolution of 2” and a wide field of view. Giacconi was the Principal Investigator and director of the Observatory. The construction, integration and testing of the instrument had been performed under his directorship at the AS&E. It should be sent in orbit, and this project was recommended by NASA Astronomy Missions Board in 1965; in 1978 these plans finally were made real.

The Einstein X-ray Observatory (Giacconi et al. 1979a) had, in addition to the light-collecting and imaging telescope with efficient cameras, sensitive spectrometers, which could give high spectral resolution. The principles of several of these instruments were especially developed for the Observatory.

The Einstein mission was a great success, very much due to the strong improvement in performance relative to earlier experiments. The sensitivity of the instrument at observations of point sources was 1,000 times higher than that of UHURU. The faintest source observed by the Observatory was a distant quasar from which 0.00003 photons were recorded per cm^2 and second. Giacconi could now observe sources one million times weaker than Scorpius X-1, which two decades earlier marked the beginning of his career as an X-ray astronomer.

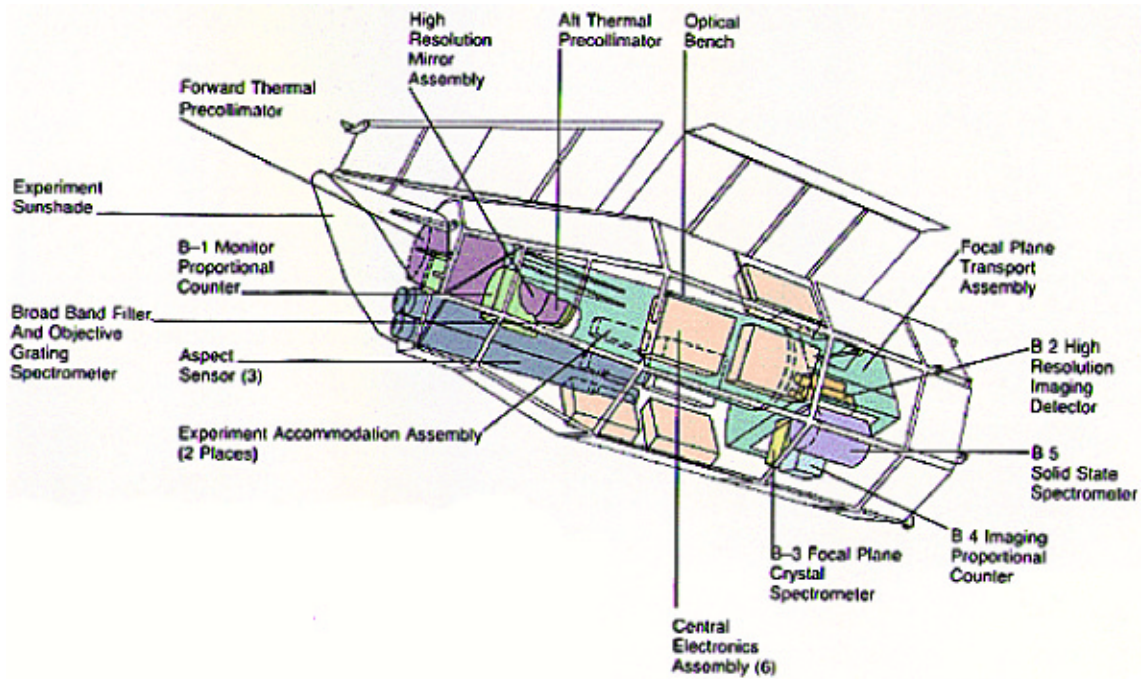


Fig. 10 Configuration of the Einstein Observatory. The construction was about five metres long.

A very great number of results came from the Einstein Observatory, which carried out projects for guest astronomers that were given time on application. Much more detailed investigations were made of already known X-ray sources. Also weaker sources, like normal stellar atmospheres, were studied. The high angular resolution made it possible to map extended objects, like supernova remnants, in detail. X-ray spectra showed that the remnants were enriched in heavy elements, produced by the exploding stars. Among results published by Giacconi and his group is the finding that the X-ray emission from late-type stars is strongly correlated with stellar rotation and convection in the outer stellar layers (Vaiana et al. 1981), the discovery of point-like X-ray sources in the Andromeda galaxy (van Speybroek et al. 1979), the discovery of jets in X-rays from the active centres in neighbouring radio galaxies (Feigelson et al. 1981, Schreier et al. 1982), the demonstration that quasars emit X-rays and that distant such sources contribute strongly to the diffuse X-ray background (Giacconi et al. 1979).

In 1976, when the Einstein Observatory (Giacconi et al. 1979) was under construction, Giacconi and Harvey Tananbaum proposed a new X-ray telescope to NASA, AXAF. A Science Working Group was set up by NASA, with Giacconi as chairman until 1981 when he left his leading role in X-ray astronomy for other important missions. The telescope was a further development of the Einstein telescope, with an angular resolution of $0.5''$, matching the high resolution now possible to obtain in optical observations. Its sensitivity is strongly enhanced relative to Einstein, and it carries a series of cameras, with CCD detectors and a microchannel plate imager, as well as spectrometers. After considerable delay due to financial problems at NASA the instrument was launched in July 1999, renamed to Chandra after S. Chandrasekhar. Chandra has produced a rich host of interesting results (see fig. 11).

What X-ray astronomy contributed to astrophysics, and what Giacconi contributed to X-ray astronomy.

No doubt, our view of the universe has changed very drastically since the first observations of X-rays from the Sun. Numerous objects characterized by processes at high energies have been discovered. Time scales of these are often short, indicating very compact objects, with

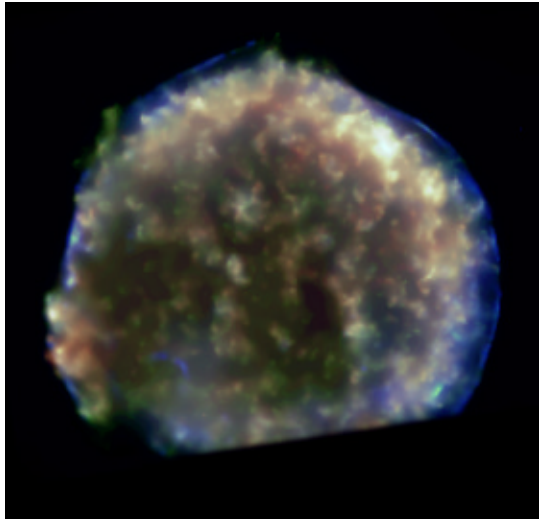


Fig. 11 Remnants of the supernova – an exploding star – in the Cassiopeia constellation which Tycho Brahe discovered in 1572 from Herrevadskloster and described in detail. The supernova lies at a distance of 7,500 light years from Earth and is 20 light years wide. This image was taken by the Chandra satellite in X-ray radiation. NASA/CXC/SAO. <http://chandra.harvard.edu>

extremely strong gravitational and magnetic fields, accelerating particles to relativistic energies. Plasmas with temperatures of hundreds of millions of degrees have also been discovered. The physics of neutron stars, of the neighbourhood of black holes and of hot intergalactic gas is essentially explored by X-ray observations. Thousands of X-ray sources have now been found. Active stellar coronae have been explored, very hot stars associated with enormous regions of hot gas, “superbubbles” presumably heated by intensive stellar winds, have been seen. An enormous exotic Zoo of X-ray binaries has been discovered and explored, X-ray bursters have been found and studied, black-hole candidates have been scrutinized. In fact, X-ray astronomy still provides the most promising means of studying the existence, the properties and the effects of black holes in the universe. New knowledge of supernova remnants has been collected, galaxies and not the least active cores of galaxies have been studied in considerable detail, with accumulating evidence as a result that they are driven by super-massive black holes. Clusters of galaxies have been discovered in X-rays (300 of them by the Einstein satellite) which leads to new evidence concerning the existence of dark matter and its properties. X-ray observations have also contributed to the identification of the enigmatic gamma-ray bursters with very distant galaxies.

All of this remarkable new knowledge is due to work by individuals, although joined in team efforts for obvious reasons. The most important leading persons through the first three decades of X-ray astronomy were, independently, Friedman and Giacconi. Also Rossi played a very important role, not the least as a senior colleague and mentor for Giacconi. These three persons contributed crucially to the development of methods and instrumentation, but also to the application of these methods to scientific work, leading to a very rich host of important discoveries. In that way they proved the fundamental significance of these new observations for astrophysics as a whole. This stimulated them, and others, to develop the techniques further. Friedman and Rossi are now dead. Giacconi initiated and developed the first X-ray satellite, and the first operating X-ray telescopes, and made pioneering discoveries with these instruments.

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