Unraveling the Sun, neutrino and X-ray astronomy

Man's first gods were the forces of nature. Terrifying and unpredictable, they were feared rather than revered by our ancestors. They also worshipped gods that were beautiful to behold, luminous and colourful. In ancient times Apollo was the Sun God of the Greeks and the Romans. Amon-Ra was believed to be the Sun God in ancient Egypt and the lord of the universe. The Hindus also worship the Sun by chanting the mantra:

\textit{Om jayaasama sunkaashh mano khaashyapayam mahaadantim}

\textit{Tanomir sarvapatapagham pranato-smi divaakaram}

\textit{Om suryaaya namah}

Literally it means:

\textit{Om}, I bow down with devotion to the shining light that is shining red like a hibiscus flower (jabah), shining onto the earth, removing all the darkness and removing sin. \textit{Om}, I bow to the Sun.

The ancient man wondered as to what causes the Sun to shine brightly in the sky! They realized slowly that, the heat and light emanating from the Sun is the sole cause of life on earth and were anxious to know as to how long it is going to shine like that, which is so essential for their survival.

In the early nineteenth century it was thought that the energy released by the Sun is due to gravitational contraction. This leads to an expected life-time of 20 myr for the Sun. Knowing the fact that the age of the Earth is 5 byr – much higher, this theory seemed untenable. By 1920 it was known that, the main constituents of the Sun were hydrogen and helium. Sir Arthur Eddington, a British astrophysicist realized that, only a nuclear reaction caused by fusion of hydrogen atoms to helium atom can generate the kind of energy actually emitted by the Sun. Gravitational energy cannot fit the bill.

Formation of one helium atom is accompanied by two neutrinos, which are sub-atomic particles with almost zero mass, no charge and spin $\frac{1}{2}$. The Nobel Laureate Prof Hans Bethe along with Chritchfield proposed a theory in 1938 that explained the reactions that lead to the formation of helium from hydrogen. The mass difference between the reactants and end products ($m$) was converted to an enormous amount of energy ($E$), governed by Albert Einsteins' formula $E = mc^2$, where $c$ stands for the velocity of light.

It was a challenge at that time, however, to prove experimentally that, nuclear reaction is indeed the source of energy of the Sun. This is because, although $10^{10}$ neutrinos/cm$^2$ pass through the Earth every second, only about one out of $10^{15}$ neutrinos is actually stopped by the earth! In other words, these neutrinos pass through the earth without meeting any resistance and leave no signature! The problem is how do you detect them on the Earth? If one is able to capture the neutrinos and prove that, indeed these are coming from the direction of the Sun, then our objective is achieved.

It was Raymond Davis (Jr) at Brookhaven, USA who tried the impossible in late 1950s. He started investigating neutrinos that were produced in Brookhaven's Graphite Research Reactor and in a reactor at the Savannah River Plant in South Carolina, USA. He was able to detect neutrinos coming out from the reactor, using a tank filled with 3900 litres of CCl$_4$. Neutrinos with high enough energy will react with chlorine in the tank to produce radioactive argon and an electron. This argon decays by electron capture with a half-life of 35 days. The decaying argon atoms can then be counted using a proportional counter. This is the so-called chlorine-argon technique. Even at that time, he thought it possible to detect the neutrinos from the sun.

It was theorized that in the Sun, hydrogen atoms fuse to yield helium, helium atoms fuse to yield beryllium, beryllium in turn combines with a proton
or hydrogen to yield radioactive boron, which in turn decays to yield a neutrino, with an energy of up to 14 MeV. This neutrino, which is very rare but having much higher energy over the threshold energy for the chlorine reaction, is possible to be detected by the above chlorine-argon technique.

Davies placed a tank containing 615 tonnes of CCl₄ at a depth of 1500 meters in the Homestake Gold Mine, Lead, South Dakota, USA for the purpose in the 1960s. It is essential to do the experiment underground, as it helps remove the background radiation noise to the minimum. The neutrinos with high energy react with chlorine atom (³⁷Cl) producing radioactive argon (³⁷Ar) and an electron. He bubbled helium gas through CCl₄ when argon got attached with helium. The radioactive argon was then removed from helium by passing the gas through charcoal with liquid nitrogen. Argon is absorbed allowing helium to pass. A proportional counter was used to count the electrons due to the decay of the radioactive argon atoms. Davies calculated that, with a tank of this size containing 2x10⁹ chlorine atoms 20 argon atoms should be created in a month and he proposed to count them! It is perhaps worse than looking for the proverbial 'needle in haystacks'!

His pioneering achievement was in the development of this method for extracting these argon atoms and count. All precautions were taken to eliminate background radiation and improved sensitivity of measuring technique. The space outside the detector was filled with water to slow down any neutrons coming from the rock walls of the chamber. These neutrons could lead to a series of reactions that could produce argon, which would increase the signal. So, it would be a higher signal, but a false one. After all these precautions, he could count only 17 every second month. Some of them must have got absorbed on their way to the Earth. The other alternative is that, may be our understanding of the reactions in the Sun is incomplete. This was known as the solar neutrino problem.

Masatoshi Koshiba of University of Tokyo, Japan, also attacked the solar neutrino problem in 1986. He used a tank, filled with 2140 tonnes of water, which was initially designed for a proton decay experiment. This detector was called Kamiokande. In order to detect solar neutrinos, he surrounded the water tank with 1100 photomultiplier tubes each with a 50 cm diameter. He used the Water Cerenkov technique with its directional sensitivity, to count the neutrinos. He also purified the water in the tank, reducing the background radiation further. Anti-coincidence shield to obviate background radiation and new electronic devices were also employed to that end. Finally, the minimum detectable threshold energy could be reduced to 8 MeV, making it suitable for detection of boron decay neutrinos from the Sun. This device was called Kamiokande II with which he established the results of Davis and also proved, beyond doubt that, indeed the neutrinos detected were coming from the direction of the Sun.

With the Kamiokande, Koshiba and his team could also detect and count the neutrinos coming from space due to explosion of supernova 1987A in the Large Magellanic Cloud galaxy. This is situated at a distance of 170,000 light years (1 light year = 10¹⁶ meters). Interestingly the explosion was visible to the naked eye on 24th February 1987 and the neutrino burst coming there from were detected and counted by the Kamiokande on 10th March 1987. More importantly, discoveries made by Davis and Koshiba, and sophisticated and accurate instrumentation developed by them laid the foundation of the new field of neutrino astronomy, with enormous application in particle physics, astrophysics and cosmology.

For these outstanding contributions half the Nobel Prize money in 2002 was given to Raymond Davis (Jr) of the Department of Physics an Astronomy, University of Pennsylvania, Philadelphia, USA and Masatoshi Koshiba of the International Centre for Elementary Particles Physics, Tokyo University, Tokyo, Japan. The other half of the prize money went to Riccardo Giacconi of the Associated Universities Inc, Washington DC, USA, for his pioneering contribution Astrophysics, leading to the discovery of Cosmic X-ray sources, the story behind which will unfold the following:

Wilhelm Conrad Röntgen discovered X-rays accidentally, in 1895, when he was experimenting on cathode ray emissions in highly evacuated glass tubes, called Crookes tubes, named after the British scientist William Crookes. For this discovery, whi
had enormous medical applications, Röntgen got the first Nobel prize in physics, in 1901. Since then, however, 48 years passed before X-ray astronomy evolved in 1949, when solar X-rays were detected by Herbert Friedman of US naval Research Laboratory, by sending up a Geiger Müller counter, using a German V2 rocket of World War II fame. This time-lag is mainly because of the fact that, our atmosphere absorbs the entire X-ray radiation coming from the universe outside. As a result, from the ground base, X-ray sources in outer space could not be detected.

In 1960, Riccardo Giacconi and Bruno Rossi suggested the use of a simple parabolic reflector to design an X-ray telescope for the purpose of imaging the X-ray sources other than the Sun. In 1962, Giacconi gave shape to his pioneering ideas and mounted three Geiger counters on his payload and launched it with an Aerobee rocket. With this telescope he could image two sources, Scorpius X-1 coming from the Scorpio constellation and Cygnus X-1, X-2 and X-3 coming from the Swan constellation. These sources were, in fact, binary stars, with a central compact neutron star or a black hole with a smaller one going round it. That apart, a diffuse distribution of X-rays was observed, coming from all directions. These surprise findings gave birth to the field of X-ray astronomy.

What makes the field of X-ray astronomy interesting is the fact that, it takes a lot of energy to generate X-rays, which is at a very high level in the electromagnetic energy spectrum (frequency of X-rays > UV > visible light). Study of X-ray astronomy as a result can give us a glimpse of not only the explosive and high energy phenomena that are taking place in this vast universe around us, but also study the signatures left behind by the events that have already taken place, years ago.

The problem of this pioneering effort using a rocket was that, the time of observation of the telescope was only 350 seconds, resulting in, at best, blurred images. With the use of balloons, this time span could be increased, but the minimum energy of X-ray observable was 20 keV, as lower energies got absorbed in the air present above the balloon and a balloon can attain a maximum height of around 35 km only. Giacconi desired an X-ray satellite to do the job, which he succeeded in launching in 1970 - named UHURU (meaning 'Freedom' in Swahili - a language of African origin). It was launched from Kenya into an orbit of 560 km apogee, 520 km perigee. It could detect X-ray sources in the 2-20 keV range, i.e. with energy of one-tenth that is possible with a rocket borne X-ray telescope. It had a collecting area of 840 cm² with the help of two sets of proportional counters.

UHURU launch led to a sudden influx of observational data on X-ray sources. By 1972, as many as 339 X-ray sources were identified, a notable one being, Centaurus X-1, comprising a rotating neutron star, orbiting around a hot supergiant star. The intense gravitational pull of the neutron star pulls matter away from the super-giant star and accelerates it, till it reaches the surface of the neutron star, at which time, it is suddenly decelerated leading to Bremsstrahlung, emitting X-rays. Bremsstrahlung literally means 'braking radiation' in German, so it stands for radiation emitted by a charged particle caused by deceleration when passing through the field of atomic nuclei. Scorpius X-1 was another similar X-ray source. Cygnus X-1 showed a fluctuating source, with a periodicity of 0.1 second.

The success of UHURU created great excitement and as many as nine such satellites were launched by different groups. Thereafter, more sensitive telescopes HEAO-1 and HEAO-2 were launched. HEAO-1 detected 842 sources. HEAO-2 later named as Einstein X-ray observatory was headed by Giacconi. Its angular resolution was 2" with a wide field of view and sensitivity 1000 times more than UHURU. Distant faint sources such as those in Andromeda galaxy were recorded. Spread over remnants of past supernova, explosions were studied and were found to be rich in heavy elements. Not only were the distant and faint sources studied, but well-known sources were studied in much greater details.

A more sensitive telescope was proposed to NASA by Giacconi in 1976. Angular resolution of this telescope was to be 0.5", comparable to a contemporary optical telescope. Its sensitivity is much improved over its predecessor HEAO-2, and it carries a number of cameras with charge-coupled device detectors (CCD detectors in short), a micro-channel space imager and a spectrometer. Despite the proposal being made in 1976, the actual launch of the payload was delayed due to financial
problems. Finally, it was launched on 23rd July 1999, riding on the space shuttle Columbia. It was named ‘CHANDRA’, after the famous Astronomer of Indian origin Prof Subramanyan Chandrasekhar, who was awarded the Nobel prize in Physics in 1983, for his contribution in theoretical studies of the physical processes of importance to the structure and evolution of the stars.

Chandra has three major parts: (1) the X-ray telescope, whose mirrors focus X-rays from celestial objects; (2) diffraction grating spectrometers, which record the X-rays so that, X-ray images can be produced and analyzed; and (3) the spacecraft itself, having a gyro mechanism, booster rockets, solar sail and backup battery, which provides the environment necessary for the telescope and the instruments to work. The incoming X-rays are focused about 30 feet away by the mirrors. The science instruments capture the sharp images formed by the mirrors and provide information about the incoming X-rays: their number, position, energy and time of arrival. Diffraction grating spectrometers provide detailed information about the X-ray energy. The science instruments have complementary capabilities to record and X-ray images of celestial objects are analyzed and their physical conditions probed with unprecedented accuracy. Its improved sensitivity makes more detailed studies of black holes, supernovas, and dark matter possible, and thus, increases our understanding of the origin, evolution, and destiny of the universe.

Chandra’s operations have, so far, provided spectacular examples of the remnants of one of the most dramatic events in the cosmos—supernovas that signal the end of massive stars. Chandra’s images enable astronomers to determine the energy, composition, and dynamics of these explosions.

After launch of Chandra, thousands of X-ray sources have been located and studied, many binary stars have been discovered and studied, black-hole candidates have been scrutinized and cores of galaxies have been studied in great details.

It goes without saying that, so much new exploration and knowledge cannot be the handiwork of a few individuals. However, prominent names that crop up are, Herbert Friedman, B B Rossi and Riccardo Giacconi who were involved in not only, the development of the required hardware but also, their application leading to understanding physics. The only survivor of the three Riccardo Giacconi, made many pioneering discoveries in X-ray astronomy, and was the first to operate an X-ray telescope as also to develop an X-ray satellite, (http://www.nobel.se/physics/laureates/2002/adv.html)

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