FRONTLINE

Volume 24 - Issue 03 :: Feb. 10-23, 2007
INDIA'S NATIONAL MAGAZINE
from the publishers of THE HINDU

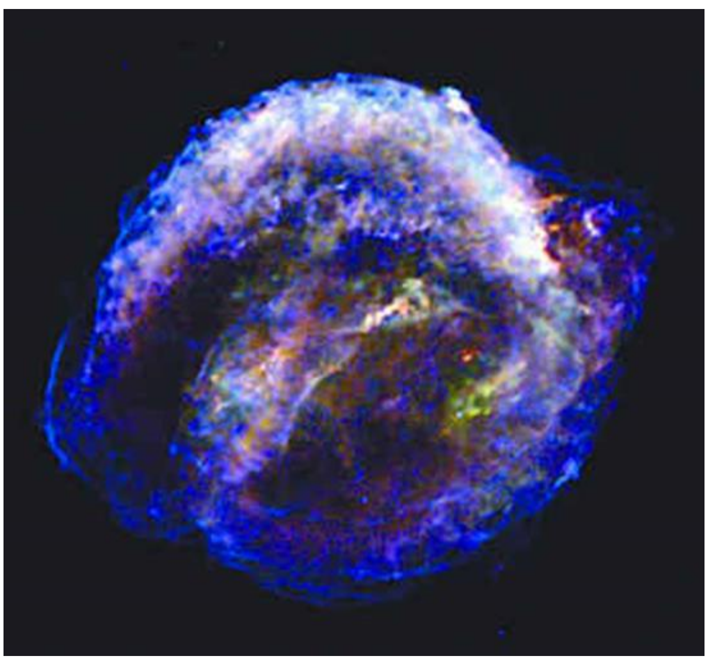
SCIENCE

Story from a stone

BIMAN NATH

A meteorite that fell in Piplia Kalan, a western Rajasthan village, has changed the way scientists think about the birth of the solar system.

NASA/AP



The remnants of one of the youngest supernovas. This image was created using NASA's Chandra X-ray Observatory. Shockwaves from stellar explosions can trigger the collapse of nearby gas clouds.

PIPLIA KALAN is a small, nondescript village in Pali district in western Rajasthan. People outside the district would not even have heard its name. Yet, it is a name familiar to planetary scientists and astronomers, and a casual search on Google for `Piplia Kalan' will fetch you many entries. It does not owe its fame to any natural calamity or scandal but to a piece of a meteorite.

A shooting star fell on an uncultivated farm on the outskirts of Piplia Kalan on June 20, 1996, around 8-30 in the evening. Most villagers were probably enjoying the summer evening outside their homes, and the meteor that streaked brightly across the sky did not escape their notice.

The `Piplia Kalan' meteorite was rather small by the standards of famous meteorites. I t did not even weigh 50 kg - so it was far from being dangerous like the one that is believed to have brought about the extinction of the dinosaurs, or even the one that in 1908 exploded over Siberia and destroyed a forest there. The Piplia Kalan meteorite was tiny in comparison. Yet, the surviving fragment of this meteorite contained an extraordinary piece of information, which has changed the way scientists think about the birth of the solar system. A group of Indian scientists has taken a leading role in the analysis of this meteorite, and some other meteorites around the world, and in shaping this new look at the origin of the solar system.

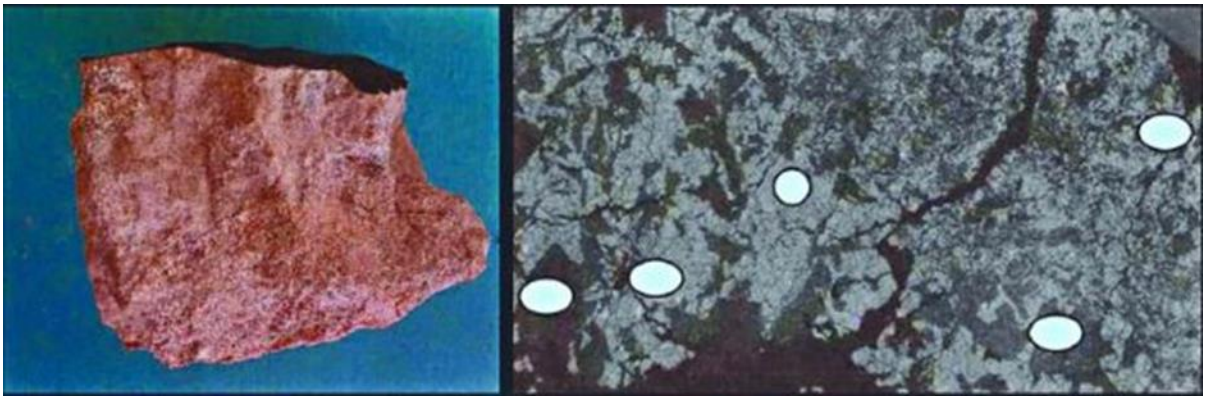
Traditionally, it is believed that the solar system formed roughly 4.6 billion years ago out of a gaseous cloud in space. Such clouds are abundant in our galaxy; they hover in the space between stars and are often seen either by the light falling on them from nearby stars or as silhouettes against a bright starry background.

Material inside a nebula can, however, begin to contract and decrease in size at some point of time - either collapsing on its own or being influenced by some extraordinary event in its neighbourhood, such as being hit by shocks from stellar explosions. As it contracts, it forms a star (or a number of stars) in its dense core. Then the leftover material surrounding the central star cools slowly and forms small grains of solid particles, which gradually coalesce to form large objects such as planets, asteroids and comets.

It is a straightforward calculation to work out how much time a typical interstellar cloud takes to contract and form a star. Astrophysicists such as Frank Shu of the University of California, Berkeley, United States, have estimated that in the case of a sunlike star this process takes around 10 million years. Then, the residual cloud surrounding the nascent star would need another 100 million years or so to produce planetesimals and planets. Forming large planets would take an even longer time.

One can then ask whether the solar system too followed this timetable or whether it formed in a quicker or in a more lethargic fashion than prescribed in this scenario. And is there some way one can test this hypothesis? Is there a way of knowing what the script the solar system followed during its birth? It turns out there is.

BY SPECIAL ARRANGEMENT



(Left) A fragement of the Piplia meteorite. The black surface on the top is crust produced by theheating and burning that occurs during its atmospheric transit. (Right) A slice of the meteorite showingthe portions where material was taken out for analysis.

The secret lies in finding radioactive elements in the material that formed soon after the birth of the solar system. Radioactive materials have atoms that are markedly different from their normal, run-of-the-mill counterparts. Consider, for instance, an atom of radioactive aluminium. It has 13 neutrons in its nucleus, as opposed to the 14 neutrons an ordinary aluminium atom has (both varieties contain 13 protons). This makes radioactive aluminium change its identity after a certain amount of time. For instance, if one took a certain amount of radioactive aluminium, half of it would have changed into a bizarre form of magnesium after three-quarters of a million years. This particular type of magnesium is slightly heavier than the normal variety and is easily identifiable as the odd one out.

There are many such radioactive elements, but there is something special about radioactive aluminium. Aluminium happens to be an element that requires very high temperatures to turn into its gaseous phase - in the jargon of science, it is called a `refractory' element. If it needs very high temperatures to turn gaseous, then it follows that if a hot mixture of gaseous substances is allowed to cool aluminium (and other refractory elements) would also be among the first to turn back into the solid phase. As an analogy, consider high-rise buildings in a flooded city. As the flood water rises, the tallest buildings are the last ones to drown - they are like the refractory elements in a gas that is being heated. By the same token, when the flood water subsides, the tallest buildings are also the first ones out of the water - in our case, refractory elements such as aluminium becoming cool and solid again. In other words, one would expect aluminium and other refractory elements to form the first solid particles as the pre-solar nebula slowly cooled down. One would also expect a small, but perceptible, amount of radioactive aluminium to be mixed with the normal aluminium in such material. Since meteors that haunt the dark reaches of the solar system and occasionally dart inside the earth's atmosphere are actually leftovers from the process of the formation of planets, they provide scientists with a method of pinning down the story of the birth of the solar system - they act as a sort of fossil to track its birth history.

The idea then is to try to detect traces of radioactive aluminium, or its decay product - the odd form of magnesium - in meteorites, the surviving fragments of meteors that reach the earth's surface, and to determine when the meteorite formed. Since one knows the time taken by radioactive aluminium to change its identity, it is easy to "date" the formation epoch of ancient meteorites.

This is exactly what a group of Indian scientists attempted to do when they came by the Piplia Kalan meteorite, and they were rewarded with an interesting result. As one can imagine, the method involves sifting through slices of meteoric rock for tiny, almost elusive, quantities of a particular element, and it requires extremely accurate measurements.

One research institute in India, the Physical Research Laboratory (PRL) in Ahmedabad, has instruments to measure minute quantities of different elements in small volumes of matter. The institute was founded by Vikram Sarabhai 60 years ago and is currently celebrating its diamond jubilee year. A group formed in the institute in the 1970s around Devendra Lal (now Professor of Nuclear Physics, Scripps Institution of Oceanography, Geosciences Research Division, University of California, San Diego) specialised in studies of the history of the objects of the solar system, particularly that of the earth, moon and meteorites. Among the scientists who have helped this group flourish over the years are Dr. Jitendra Goswami and Dr. Narendra Bhandari. It is not surprising that this institute has gained importance in the wake of the mission to the moon being planned by the Indian Space Research Organisation.

When the PRL scientist G. Srinivasan along with Goswami and Bhandari measured the amount of the odd form of magnesium in the meteorite from Piplia Kalan, they estimated that in the beginning the amount of radioactive aluminium was a mere one part in a million compared with ordinary aluminium. In other words, when the rock that fell in Piplia Kalan formed, the ratio of radioactive to ordinary aluminium was one in a million.

This measurement in itself does not reveal much. But when one compares this ratio with the ratio found in refactory phases in ancient meteorites - such as the famed Allende meteorite that crashed into Mexico in 1969 - one can get an idea of the formation epoch of the Piplia Kalan meteorite. The ratio of radioactive to ordinary aluminium in the Allende meteorite - which is thought, from other measurements, to be among the most ancient pieces of material in the solar system - is hundred times larger than that for the Piplia Kalan meteorite. This means that the Piplia Kalan meteorite formed slightly later than the Allende meteorite, by which time only a fraction of the radioactive aluminium had changed into magnesium. Scientists at the PRL pegged their estimate of the formation era at within five million years of the solar system's formation.

By this time, the PRL scientists had gathered another piece of information from the piece of rock. Its composition clearly hinted at its origins. They found that the meteorite was a piece broken off from a well-known asteroid named Vesta - which is the brightest asteroid and the second largest (although it will now be the largest asteroid since Ceres, which was the largest asteroid to date, has been promoted to the status of a "dwarf planet").

These two pieces of information taken together boggle the mind. Vesta is a large object, with a radius of around 530 km, and it certainly must have taken a considerable time to form such a large object in the early solar system - certainly longer than the estimate of five million years.

But this is too rapid compared with the theorists' estimate of how long it takes a gaseous nebula to form a star like the sun, let alone forming solid particles in it after cooling. Recall that the theoretical estimate of a cloud contracting on its own to form a star is approximately 10 million years.

Moreover, the very existence in meteorites of radioactive nuclei that "live" for a short time is hard to understand. Any short-lived radioactive atom from the original gas cloud would have decayed by the time the solid particles formed in the solar system. How is it that these atoms hung around when the meteorite formed?

There are only two processes that can explain their existence in that epoch. They were either produced in a nearby star and then transported to the site of the formation of the solar system by shockwaves, or wind, from an explosion, or they could have been produced by bombardments of energetic particles produced by the baby sun.

But when Goswami and his collaborators worked out the details of the particle bombardment case, they found that this scenario could not explain the observed abundances of the radioactive elements such as aluminium, and especially calcium (with a "lifetime" of around a tenth of a million years) that coexisted with radioactive aluminium in the refactory phases of ancient meteorites. The only alternative then is to ascribe their presence to a nearby star. In that case, the short lifetime of these radioactive nuclides would also mean that the collapse of the pre-solar nebula took place within a million years or so, much too rapidly to be compatible with the scenario of the unassisted collapse of a cloud.

Astronomers have long been suspecting that a nearby cataclysmic stellar event may have triggered the formation of the solar system. Perhaps, the pre-solar nebula did not begin to collapse on its own, and perhaps, it was nudged and prodded into its fateful collapse. The rest was, as they say, history, and eventually, the sun was born and, later, the planets. A view has emerged in the last decade that the sun owed its birth to a stellar accident of some sort. And a few strands of support for this concept have come their way in the last few years.

Stars usually shine and produce light with the help of nuclear reactions in their cores. In the case of the sun, for instance, four protons combine to form a helium nucleus and a fraction of the total energy leaks out in the form of radiation. The "lives" of stars then depend crucially on this supply of nuclear material in the core, and stars undergo monumental changes when this supply runs dry. The sun will one day (after five billion years) bloat and engulf the orbits of Mercury and Venus and shine menacingly red in sky. Stars more massive than the sun are doomed to a more fiery finale: they explode and regurgitate the material of their innards into space at high speed. Shock waves from such explosions tear into nearby gas clouds and can trigger one into collapsing and contracting under its weight. Such an explosion is called a supernova.

In addition to the triggering by shock waves, there can be material strewn around in space from such explosions. This strewn material includes elements such as nitrogen and oxygen and others, which are created inside stars and which then fly out inspace after a supernova - next-generation stars form out of this stellar ash. The calcium in our bones and the iron in the haemoglobin of our blood were all created inside stellar furnaces eons before being expelled in supernova explosions.

BY SPECIAL ARRANGEMENT

A supernova remnant (N 49) in the Large Magellanic Cloud, a satellite galaxy of our Milky Way.

But present in the ash raining from these explosions were some exotic elements that were created during the cataclysmic event. In fact, a supernova can produce some radioactive elements that cannot be produced otherwise or anywhere else in the universe.

Radioactive iron, for instance, is one such element. Existence of such telltale material points surely towards a supernova near the pre-solar nebula. Radioactive iron - with 60 particles in its nucleus compared with the 56 in the normal iron nucleus - only lives for 1.5 million years, and so its existence also indicates the time when the supernova could have happened.

Interestingly, a group of scientists led by Gary Huss of the Arizona State University, Tempe, U.S., analysing a piece of another Indian meteorite, Semarkona, found trace amounts of a decay product of this radioactive iron in it. An odd from of iron, remnant of a heavier counterpart of chlorine (chlorine-

36), which, like radioactive iron, could have been produced in the aftermath of a supernova (and only lives for 300,000 years), has also been detected in ancient meteorites.

It then adds another piece to the jigsaw puzzle. First, one finds evidence that a nearby supernova could have triggered the birth of the solar system, and then one finds a bit of the stellar ash that must have rained on the early solar nebula. One then wonders whether this was an extraordinary event or whether this is more or less a rule in the universe - that the death of a star foretells the birth of another.

Biman Nath is an astrophysicist at the Raman Research Institute, Bangalore.