Comets – fascinating cosmic objects

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Bose Einstein Lecture

India International Centre, New Delhi

17 November 1998

I am extremely pleased to be here in Delhi at the India Internatinal Centre and I want to thank the organizers of this lecture: The Embassy of the Federal Republic of Germany, the Federation of the Indian-German-Societies in India and the India International Centre most cordially for this inviation. It is a great honour for me to give the 9th Einstein Lecture on Science, Technology and Environment.

Both, Bose and Einstein, were outstanding physicists. Albert Einstein is regarded as the greatest scientist of our century. The famous French physicist de Borglio wrote in 1925: *"The scientific world of the hung on every one of Einstein's words, for he was then at the peak of his fame."*

In the summer of 1924 he received from Satyendra Nath Bose, at that time a physicist of Dakka University a short paper on "Planck's Law and the Hypothesis of Light Quanta", which considered radiation as a form of a gas consisting of photons. Einstein was so impressed by the paper that he himself translated it into Germand and sent it to the editor of the "Zeitschrift für Physik" who published it in July. At that time German was the language of the physicists. The reason for Einstein's interest was simple. He had seen immediately that it was possible to extend Bose's statistical methods to ordinary atoms – "Bose-Einstein-statics" as they become known.

Bose was born on January 1, 1894 in Calcutta, he was a graduate of the University of Calcutta, thaught there in 1916, at the University of Dakka from 1921 – 1945 and again in Calcutta 1945 to 1956. He died on February 4, 1974.

The Bose Einstein statistics accounts for instance for the friction less creeping of superfluid helium. Just during the laste year the physicists had been fascinated by new experiments where the Bose-Einstein-Kondensation of sodium atoms could be observed. This phenomenon occures at extremely low temperature (2μK), that means a temperature very near to the absolute zero point –273 ° Celsius.

The phenomenon which I will discuss today are occuring also in a space, where the temperatures are rather low, but certainly not as low as just mentioned before. The space, I shall try to draw your attention this evening, is the space where our earth is moving around the sun, the so-called interplanetary space.

I do not know how many people have consciously seen the comet Hale-Bopp last year. Very rarely in the past was such a bright comet visible in the evening sky in such a good position for a period of several weeks. Even if only a small proportion of the public was aware of being so privileged, they actually took part in this astronomical event – something that has not occured for decades.

1. The nature of comets

What kind of bodies in the skies are comets and to which parts of the observed astronomical families do they belong? Until today about 1000 different comets have been observed, and every year 5 to 10 new comets are detected.

It is not surprising, therefore, that throughout history the unpredictable appearance of comets has been puzzling mankind and created fear in the hearts of the observers. A comet was regarded an omen, normally presaging disastrous events. Many people shared Aristotle's view that the appearance of a comet signaled adversity or drought.

Reports on the appearances of comets reach back many centuries before Christ. These early records come almost exclusively from China, Japan and Korea. There exists also a Babylonian description interpreted as a reference to the comet of 1140 B.C.

The question was whether comets were celestial objects or phenomena of the atmosphere. The Babylonians and also at first the Greeks were of the opinion that comets were cosmic bodies, like planets. But these ideas changed with Aristotle who ruled out the planetary nature of comets. According to his philosophy comets belonged to the sublunar sphere, being the product of meteorological processes in our atmosphere.

Around the time of Christ's birth, Seneca the Roman, Emperor Nero's teacher, wrote: "Some day there will arise a man who will demonstrate in what regions of the heavens comets take their way; why they journey so far apart from the other planets, what their size, their nature."

About 1600 years later, the time was ripe for those men to work out the comet's rightful place in the heaven. Tycho Brahe, generally considered to be the greatest astronomer of his days, made the decisive observation by determining the parallax of the comet of 1577. He showed that the distance of this comet was considerably greater than the distance from the Earth to the Moon. Although he was not able to determine the orbit of the comet, these objects could no longer be placed in sublunar atmospheric space. Since that time comets have been acknowledged as real objects in the solar system.

But still there remained the question of their orbit. Although Kepler was so successful in determining the orbits of the planets, he was wrong in his belief that comets moved along straight lines, but with irregular speed.

Isaac Newton and Edmund Halley, the latter having been eclipsed in History by the more famous Newton, made the final step in describing and calculating the orbits of comets. It was Halley who encouraged the retiring Newton to publish the principles of gravitation he had developed after years of thought, supposedly inspired by the legendary falling apple. Newton recognised that gravity on Earth represented the same law of force as that affecting the motion of planets around the Sun. Halley edited the manuscript and financed the publication in 1687 of Newton's great book, "The Mathematical Principles of Natural Philosophy". But in applying Newton's laws of gravitation in correctly predicting the return of a comet, Halley went an important step further. It turned out to be the first direct confirmation of Newton's theories.

Halley compared the orbits of 24 comets on the basis of observations. He was able to show that these bodies are moving in elliptical orbits like the planets, although some were very elongated, hardly distinguishable from parabolas. From his comparisons he detected that the orbit of the comet 1682 was almost identical with those of earlier years (1607 and 1531). Convinced that these three visits had been made by the same comet, he predicted that it would return in 1759. He knew he would not live to see if his calculations proved to be correct. But he expressed the hope that "candid posterity will not refuse to acknowledge that this was first discovered by an Englishman". Indeed on Christmas night in 1759, almost 17 years after Halley's death, the comet was seen again just as Halley had predicted. This comet now carries his name.

No other comet has been observed over such a long period of time. From the time this comet was mentioned for the first time - by the Chinese in the year 240 B.C. - it has been seen at each periodic visit. The missing record of an observation in the year 164 B.C. has most likely been found just recently on a Babylonian table with cuneiform characters. In 12 B.C. Halley's comet appeared over Rome and was said to have presaged the death of Agrippa. In 66 A.D. it was seen over the city of Jerusalem before the city was destroyed. It appeared again in 451 during the Battle of Chalons when the Roman General Aetius defeated Attila the Hun, and it appeared in 1066 during the Battle of Hastings and was blamed for the defeat of King Harold's armies by

William the Conqueror. Also when it returned in 1910, comet Halley caused considerable public concern - especially when it was known that the Earth was actually to pass through the comet's tail. Some worried people went to great lenghts to avoid being harmed by the poisonous cyanogen gas of which the tail was composed.

The English astronomer Halley was thus able to show that comets move around the Sun in an elliptical orbit and therefore belong to our planetary system. However, until 35 years ago it was still an open question as to where to place comets in the solar system and how they originated. Remarkable was the fact that the cometary orbits were not in a plane around the Sun like planetary orbits, but were distributed in a sphere around the Sun.

2. The orbits of comets and their origin

In 1950 the Dutch astronomer Jan Oort analysed 19 cometary orbits, which had very elongated ellipses and orbital periods of more than 30 000 years. The cometary orbits had been very accurately determined. Oort's analysis showed that the majority of these comets come from regions situated in the outermost part of our solar system. These regions extend from about 30 000 AU to about 50 000 AU (50 000 AU correspond to 0.8 light years - the distance to the second star, Proxima Centauri, is 4.3 light years). Oort concluded from the analysis of cometary orbits that a cloud of comets must exist in this region.

In the meantime the use of electronic computers had made it possible to analyse a much greater number of cometary orbits, as well as to determine their orbits with greater accuracy. These calculations have confirmed the ideas of Oort. The cloud contains roughly 1012 comets with a total mass of 1028 g or about the mass of the planet Earth.

This comet cloud came into being, together with the planets and our own Sun, some four-and-a-half thousand million years ago, through contraction and condensation from an interstellar cloud. The greater part of these comets have since then been far away from the Sun, and because of the very low temperatures out there have remained practically unchanged as if they were in an astronomical deep-freeze. Consequently, the material in a comet could be representative of the very earliest condensations in our solar system, and observations of its physical and chemical properties could yield information about what the solar system was like in its early stage.

But how does a comet from this cloud come close to the Sun, so that it can be observed from the Earth ? The most likely explanation is that a star streaking past the solar system from time to time throws comets in this cloud out of their usual circular orbit into an elliptical one. This elliptical orbit could then be affected so strongly by the large planets, and a comet comes so near to the Sun, that it finally becomes visible. It can be estimated that about once every two million years other stars come close enough to our solar system for their gravitational force to have a detectable effect on the comet cloud.

3. The physical and chemical properties of comets

So what are comets? The observer on Earth sees a brilliantly shining object, which as its gets closer to the Sun shows the tail that is a characteristic of comets. It was supposed that the brilliance comes from a temporary atmosphere surrounding a solid nucleus. From the Earth, it was impossible to observe this nucleus directly, and one only had clues; in particular it has been possible for only the past few years to receive radar signals from comets, suggesting that they had a radius of about 1 km.

From the observations of the outer envelope the American astronomer, Fred Whipple, arrived at the theory that the core was a dirty snowball, i.e. a conglomerate of ice and dirt. With a density of about 1 g/m3 and a diameter of a few kilometres, a core like this would have a mass of 1015 to 1018 g, so that the total mass of all the 1012 comets comes to only about the order of magnitude of the Earth's mass.

If one of these nuclei - of the kind postulated by Fred Whipple approaches the Sun, gas is given off by its surface as it heats up. This gas pulls off with its particles of dust, and this builds up a constantly expanding atmosphere, a coma, which can reach dimensions of 10 000 to 100 000 km. The ratio of gas to dust varies from one comet to another, and depends on the distance from the Sun; it can range from ten times more gas than dust to equal proportions. Gas emission begins to develop at about the distance of Jupiter (5 AU) with the lighter gases (such as carbon monoxide). At the distance of Mars, water vapour can also be observed.

As the comet gets closer to the Sun, a tail develops from the core, always pointed away from the Sun. Until the early 1950s there was no theoretical understanding of the observations of comet tails. The German astrophysicist Ludwig Biermann found the answer to this puzzle in the early fifties. A striking fact was that many comets build up not just one, but two tails. One tail consists of particles of dust that are accelerated by the pressure of sunlight and hence blown away in the opposite direction from the Sun. What was unclear was how the very much smaller gas particles are accelerated, and how the very much longer tails of gas, which sometimes stretch for more than 100 million km, come about. It was Biermann who, from the existence of this electrically-charged tail of gas and the high velocities noted in it (more than 100 km/see), concluded that this phenomenon could be caused only by a corpuscular radiation from the Sun. Ludwig Biermann thus worked out the theory that a continuous stream of particles must be emitted from the Sun - a wind. This stream of particles was indeed found, in the early 1960s, by the first of the interplanetary space probes, and since then it has been known as the solar wind.

The solar wind is responsible for the comet's ionized tail, and the force it exerts on the gas particles is far stronger than the radiation pressure on the dust particles. Because of this, the dust tails are curved, and do not have the velocities we find in the almost straight, long tails of gas.

4. Artificial cometary tails – Experiments in Space

In 1957 and 1958 the Russians and the Americans launched the first artificial satellites. Very soon also space probes had been started fwith measuring instruments to probe the space where the planets and comets are moving. As Biermann had predicted the existence of the solar wind could be proven and its strength for the first time could be measured. But how did solar wind interact with the cometary tails? So far this was not possible to observe directly. Also at that time it seems not feasible to send a space probe to a comet to carry out measurements in the neighberhoud of a comet in particular within a cometary tail.

For this reason in the Max Planck Instiute for extraterrestrial Physics the idea was developed to create an artificial cometary tail in space in order to study its interaction with the solar wind.

It would of course have been ideal if it had been possible to inject into Space the same atoms or molecules that had been found in the comet tails. First estimates showed, however, that several tons of carbon monoxide would be needed to produce in Space a cloud of CO^+ visible from the Earth. Since there was no hope of having a rocket to carry such a heavy payload, this idea had to be abandoned. On the other hand the element barium was very well suited to the purpose: a few grams of barium would be enough to make a visible cloud, it would be rapidly ionized by sunlight, and the barium ions could - when eluminated by the Sun - be observed from the Earth.

Since at that time there were however only small high-altitude sounding rockets available, we chose to use the upper atmosphere for this experiment, at a highs of between 200 and 250 km. After varaious at first unsuccessful experiments in 1962 and 1963, we released the first barium cloud into the ionosphere above the Algerian Sahara in November 1964.

Though the starting point for the barium cloud experiments was our interest in comet physics, this new method has been and still is used for quite different scientific purposes by numerous groups in other countries, for studying the Earth's upper atmosphere. Using barium clouds it is possible to visualize the lines of force in the Earth's magnetic field, just as we make lines of magnetic force visible here on Earth by using iron filings. The observation of barium clouds allowed for the first time reliable measurements of electrical fields and of features of the plasma high up in the Earth's atmosphere. Outside the Earth's atmosphere, but still within its magnetosphere, we carried out only two barium-cloud experiments in the 1960s, using the ESA satellite HEOS and a big Scout rocket made available by the NASA. But it was still not possible to reach interplanetary Space and, consequently, the solar wind.

Finally Gerhard Haerendel and his group at the Max-PlanckInstitute in Garching were able to achieve the original aim of the Barium cloud technique. On 27 December 1984, and on 18 July 1985, two Barium clouds were created in the solar wind outside the Earth's magnetosphere at a distance of 17.2 RE and 18.6 R~.

The opportunity for these experiments arose with the implementation of the AMPTE (Active Magnetospheric Particle Tracer Explorer) mission of the USA, West Germany and the United Kingdom. Although the prime aim of the mission was the long-range tracing of the transport of ions from the solar wind into the magnetosphere and further redistribution therein it was ideally suited for the study of the initial interaction of the injected plasma with the ambient medium. To this end, a set of plasma and field diagnostic instruments was installed on the German Ion Release Module (IRM) which carried the Barium and Lithium release containers. Furthermore, a subsatellite developed in the United Kingdom (UKS) was injected into nearly the same orbit as the IRM in order to provide another probe for the plasma and field perturbations created during the release experiments. In addition to the in-situ diagnostics, optical observations from the Earth contribute valuable information about the dynamics of the solar wind interaction with the seeded plasma. 2 kg of Barium were released each time and one was able to observe the interaction of the artificial cloud with the solar wind and the surrounding magnetic field. These measurements can be compared now with the observations in the near neighbourhood of Comet Halley from the spacecraft sent to Comet Halley.

5. The preparation of the space missions to Halley's comet and the spacecrafts

Four space agencies - the Intercosmos of the USSR Academy of Sciences, the Japanese Institute of Space and Astronautical Science (ISAS), the National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA) - sent spacecraft to Halley's Comet or have been involved with Halley observations from space during the comet's present apparition. Intercosmos launched Vega-1 and Vega-2, ISAS launched Sakigake and Suisei, and ESA launched Giotto, while NASA was able to redirect a spacecraft that was formerly known as the International Sun-Earth Explorer ISEE-3 and was now renamed International Cometary Explorer ICE.

The encounter spacecraft complemented each other in flyby distance, ranging from 600 km to 7 million km, and comet heliocentric distances at the times of encounter ranging from 0.79 to 0.89 AU. The encounters all took place in March 1986, because Halley crossed the ecliptic plane on 10 March and the launch energy required was minimised if the encounter spacecraft could stay close to the ecliptic. The relative flyby speeds, i.e. the speeds in the comet's frame of reference, were all very high. Unfortunately, due to Halley's retrograde orbit, only fast flyby missions were possible.

The whole programmes of the different space agencies were coordinated by an Inter-Agency Consultative Group (IACG) which was formed in 1981 and has met since then very regularly.

Comet Halley was chosen for a number of good reasons:

1. Compared to most of the other comets, the data of its orbit were very well known. ~

2. The energy requirements for the spacecraft to reach Comet Halley were relatively low.

3. Although Comet Halley often approached the Sun, its dust and gas production rate can be compared with those of "new" comets.

4. Last but not least it was its name and the role it played in History.

The Italian painter Giotto di Bondone saw Halley in 1301 and was so impressed by its appearance that he incorporated it a few years later as the "Star of Bethlehem" in one of the frescoes in the Scrovegni chapel in Padua. The painting shows details of the comet's coma and the tail not unlike the drawings made in the 19th century by scientists. This is why ESA has given the name "Giotto" to its comet mission to Halley.
The scientific objectives for the missions had been the following:

1. To measure the production of the dust and the gases, the size and the shape of the dust particles as well as to define the chemical and isotopic mixing of the gas and dust particles,

2. To investigate the physical processes and chemical reactions in the surroundings of the comet as well as the interaction of the comet with the solar wind plasma, and

3. to discover the nucleus and, if it really exists, to take photos of it with a resolution of up to 50 metres.

The scientific experiments on the various spacecraft complemented and supported each other.

The Giotto spacecraft is spin-stabilized, with a nominal spin period of 4 sec. Its diameter is 1.86 m, and the height from the tip of the tripod to the bottom adaptor ring is 2.85 m. At launch Giotto weighed 960 kg.

6. The Giotto mission

After five years' development work and a great many tests, Giotto was launched on schedule from Kourou in French Guiana on 2 July 1985, by the European Ariane rocket. Its flight was to last nine months. Giotto was put into its orbit so accurately that any course corrections would be needed only a couple of days before the flyby. During its flight, all the instruments were switched on and tested several times.

The nine months of the flight were full of tension for everyone concerned, and were not entirely free of worries. The least of our worries was that Halley's Comet would suddenly disappear. But I shall not easily forget the early morning of 24 January when I was woken with the news that radio contact with Giotto had been lost. As this was exactly the date on which the American Voyager probe was to fly by the planet Uranus, we did not for a while have the big American reflector telescopes immediately available for sending radio commands to Giotto. At two o'clock the following morning I was relieved to hear at last, from California, that contact with Giotto had been reestablished.

At long last everything was ready for the moment when Giotto was to fly by the core of Halley's Comet, at 3 minutes past midnight on 14 March. It was planned that Giotto would fly by at a distance of 500 kilometres, plus 40 km, on the Sun side of the Comet's nucleus. Final corrections were to be made on 9, 11 and 12 March. To make these we however needed exact data on the Comet's orbit; the normal astronomical observations made from the ground were inadequate. Because of this, there had long before been an international sharing-out of the work with the Intercosmos and NASA as agreed in the Inter-Agency Consultative Group.

The two Russian probes Vega 1 and 2, which flew by Halley on 6 and 9 March 1986 at a distance of 8890 to 8030 kilometres, pinpointed the exact position of the Comet, and the data was then passed from the Russian control centre in Moscow to the European control centre at Darmstadt. For this one needed however also to know the exact position of the two Russian probes, which could not be determined by the Russians but only with the help of the big American antennas. In this way, finally, Halley's position was plotted to within 40 kilometres. This showed that after almost nine months' flight and travelling 4.44 million kilometres Giotto would, if no course corrections were made from the ground, pass the Comet at a distance of about 800 kilometres, plus or minus 20 km.

Opinions differed among the experimenters as to how near Giotto should come to the Comet, and they argued about this closest distance up to 24 hours before the event. The camera team, especially, wanted to get no closer than 1000 km, while most of the other experimenters wanted 500 kilometres. They were prepared to take the risk of the probe being totally destroyed by the impact of dust particles, despite its protective shield. In the end, all concerned agreed on a distance of 540 kilometres. Ground control consequently made a slight course correction, 24 hours before the planned time of flyby. The probe was by then 140 million kilometres away from the Earth, and a radio signal needed about 8 minutes to travel this distance.

During the night of 13 to 14 March this stage was reached, after the first comet particles had already been recorded on 12 March at a distance of rather more than 7 million kilometres from the core. The experimenters were able to follow the instrument data being received at Darmstadt in real time, and these were released to the public a few minutes later. All the experiments worked without a hitch. The distance actually reached from the Comet's core was 605 kilometers.

Though Giotto was meant to fly by very close to the Comet's core, it was expected that it would survive. Between eight and sixteen seconds before the closest encounter Giotto was struck by a relatively large dust particle, which made the probe rock. Because of this the antenna was no longer pointing exactly at the Earth, and radio contact was suddenly lost. Such an eventuality had however been foreseen by the engineers, and they had built nutation dampers into Giotto; 32 minutes later these had reduced the spacecraft's nutating movements enough for the variation in antenna pointing to once more be within 1 degree of the required direction, and radio contact was restored.

The two Japanese spacecraft had a flyby distance of 151 000 km on 8 March and of 7 million km on 11 March, the American Explorer ICE a distance of about 28 million km on 25 March.

Decisive for the success of the space mission was the camera, developed by the Max Planck Institute for Aeronomie in Germany. The quality of the camera had been even better than the expectation. The passing velocity of Giotto with respect to the nucleus of comet Halley was 250.000 km/h. The camera had to take pictures from such a fast moving object. One comparison could demonstrate the performance of the camera: One would be able to photograph a pilot in an airplane that passing at a distance of 160 m with sound velocity or equal to 1.200 km/h with a resolution of 4 mm.

For the first time the nucleus of a comet could be photographed. Its surface as well as its size and shape could be observed and measured. As the theory prodicted, he is comparable to a dirty snowball and he is one of the darkest bodies in the solar system. The pictures show a lenghty, not spherical nucleus, comparible to a potatoe. The long axis has a length of about 15 km, while the smaller one between 7 to 10 km. The surface is irregular and shows spherical structures, quite comparable to craters, valleys and hills. Beside these pictures the other measuring instruments like mass spectrographs and dust counters have given very important results about the nature of this comet.

Giotto suffered some damages during the fly-by due to the impact of dust particles. After the encounter the instruments were checked, all worked perfectly with the exeption of the camera, which apparently was damaged by the dust impact. It was possible to retarget Giotto to return to the neighbourhood of the earth on July 1990. Using an Earth gravity assist it could be redirected towards another comet, namely to comet Grigg-Skjellerup. On June 10th 1992 Giotto passed his 2nd comet in a distance of about 200 km and again interesting and important results were received on the earth. At this time Giotto was at a distance of 314 million km and from the earth had travelled about 64 billion km. But Giotto still has enough fuel and therefore its orbit had been redirected again that it come near to the earth in the year 1999. Then it will be waked up from its hibernation, the instruments will be checked again and Giotto might be redirected to another comet.

But let me return to the start to comet Hale-Bopp: Also his observations have given us new explanations about comets. But while comet Halley will return after 76 years in the neighbourhood of the sun and therefore could be observed again this will take much longer for comet Hale-Bopp. When Hale-Bopp passed the nearest point of the sun it had lost every second about 100 t of material. But even with this *blood-latting* he has sufficient material to show up a dozen of times at least. But its next visite will occure in 2 380 years, that means at the end of the 44th century.