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SCIENTIFIC BALLOONING IN THE 20TH CENTURY; A HISTORICAL PERSPECTIVE

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ABSTRACT

Hess discovered the cosmic rays in 1912. Using a manned balloon, he found the altitude variation of the radiation. After this discovery, many balloon experiments were performed to explore the most mysterious radiation coming from outside of the earth during the 1920's to the 1930's.
At the end of the 1940's, balloon systems were revolutionized by the use of new plastic films and telemetry systems. At almost the same time, highly sensitive nuclear emulsions were developed.
Balloon exposures of emulsions brought us new discoveries of the heavy primaries in cosmic rays. Extensive studies with nuclear emulsions discovered high-energy phenomena and new particles between the end of 1940's to the 1960's. At the same time, in various countries, experiments with more sophisticated electronic devices were begun together with ingenious work on balloon technology. Inventions were made in the areas of designing, manufacturing, materials, telemetry systems for balloons and long duration flight systems etc.
Several permanent launching stations were established in various countries in the 1960's
Here, I review the development of essential technologies in scientific ballooning, and their value in contributing to the growth of space physics. As the future prospect, I stress the point that scientific ballooning is indispensable and a most cost-effective way to explore space astrophysics and Earth science, in addition to the preparation of satellite and the space station experiments. Published by Elsevier Science Ltd on behalf of COSPAR.

INTRODUCTION

As is well known, Mongolfier successfully conducted the first hot air balloon flight in June 1783. The balloon was fabricated by linen lined with paper. According to the literature, the size was 750 m^3, and it attained an altitude of 1950 m. Shape of the balloon was almost spherical. A hydrogen-filled balloon was launched by Charles in Paris soon after in the same year. After these successes, manned balloons were developed for both hot air and hydrogen, mainly for pleasure. However, meteorological observations were attempted from the beginning, and balloons were used sometimes for military purposes. The early history of balloon activities is found in the reference (Pfotzer 1972).

Observations of solar spectroscopy were already tried in the 1870's at low altitude of several km by manned balloons, but systematic observations in astrophysics are started from the beginning of this century. This is more than 100 years after the first flights of Mongolfier and Charles. It opened the era of space science with balloon vehicles, in advance to the age of space science using rockets and satellites. The first epoch making event was the discovery of cosmic rays by HESS on board a balloon in 1912. His observations confirmed the increase of the radiation with altitude. Since then, cosmic-ray research has contributed significantly to the development of modern particle physics. Scientists spent considerable efforts to explore this mysterious radiation using mostly unmanned rubber balloons.

Manned balloons were also developed to explore the stratosphere. We can mention the pioneering flight performed by Picard, who used 14,000-m3 balloon to attain 16-km altitude in 1933. Manned balloons of the US and USSR, respectively, named Explorer and USSR, followed with sizes of 10,000 m^3 to 100,000 m^3, arriving at the highest altitudes of 15 to 22 km. It is also to be noted that the Japanese military developed balloon systems using the jet stream to bomb the US during the Second World War, in which concepts of super-pressure balloons were first proposed, investigated and tested.

According to my view, the highlights of cosmic-ray research using balloons before the 1940's were

- The discovery of the radiation peak of cosmic rays at an altitude of around 10 km detected by Pfotzer with triple coincidence of Geiger counters. This has been called the Pfotzer maximum, and it indicated that electro-magnetic showers were developed in the atmosphere by the cosmic rays (Pfotzer 1935).
- Continuous observations conducted by Bowen, Millikan, Neher and Pickering to identify the altitude variations at various latitudes at different occasions (Bowen et al. 1934, 1937, 1938, 1944).
- Shein, Jesse and Wollan, showed the evidence that main part of the primary cosmic rays are protons, and are not positrons. The positron primaries had been believed after the finding of Pfotzer maximum and of the east-west asymmetry by ground observations indicating that the primary cosmic rays are positively charged particles. (Shein et al., 1941).

After the Second World War, revolutionary advances in scientific ballooning followed the progress of the plastic films and telemetry technology. New balloons could carry heavy payloads of several tons, attaining an altitude of 30 to 40 km, and light payloads above 50 km.

Here I briefly review the essential technology and progress of scientific ballooning in the past 50 years. The efforts were first made in the US and later by various countries.

THE ERA OF PLASTIC BALLOONS (after 1947)

Following the suggestion by Picard, the University Minnesota group started to study to use plastic films for the balloon envelope, collaborating with Winzen under contract with the US NAVY. The project called "Skyhook" to observe unknown wind pattern at high altitudes. The first successful flight was achieved an altitude of 30 km with a payload of 32 kg in 1947. This was the first successful flight of the plastic balloon. The most significant feature of this plastic balloon was that it could stay at the same altitude, which was the most important for scientific observations. The conventional rubber balloons could not stay at a constant level of an altitude.

Then, the modern plastic balloons became important tools for space science, and various countries started to study extensively the balloon technologies. Scientific ballooning facilities were established first in the US, followed by France, India, Japan, Norway, Sweden, USSR and China in the 1960's to 1970's. Also active balloon flight groups started in Australia, Argentina, Brazil and Indonesia.

The Natural Shape Balloons

In order to design the proper shape of the zero pressure plastic balloon, Upton of the University Minnesota spent major efforts on the physics of balloons, and he proposed the Natural Shape of Balloon concept in the 1950's. The natural balloon shape has a feature that takes the stress off the film and transfers it to the load tapes. This relaxes the stress problem, compared with the conventional sphere and cone shaped balloons used prior to that time. This was the beginning of the modern design of plastic balloons. Later, Smally developed a detail treatment applicable to different balloon weights (Smalley, 1963). More sophisticated structural analyses have been made with extensive advanced computer calculations in various countries.

These efforts in the US were classified in the 1960's, and the mathematical treatment of the natural shape of the balloon was developed independently by using a variational method almost at the same time in Japan (Nishimura 1962). The concept was to find a shape of the minimum gravitational energy under the limited length from nadir to apex, which was restricted, by the length of load tapes. This derived the shape of weightless natural shape balloon of the heart type. It also derived the shape of water drop type with the constraint of minimum surface energy of the balloon envelope.

The relations of the various types of balloon shapes are categorized in figure 1. We see that the tetrahedron type has a shape similar to that of a heart type balloon, and the pumpkin balloon is the limiting case of high internal pressures of this type. The tetrahedron shape balloon was called Tetroon, and it was easy to manufacture, since it required only straight cuts and welding to construct the balloon from the flat films. Tetroons were widely used by the French group for small balloons since the 1960's.

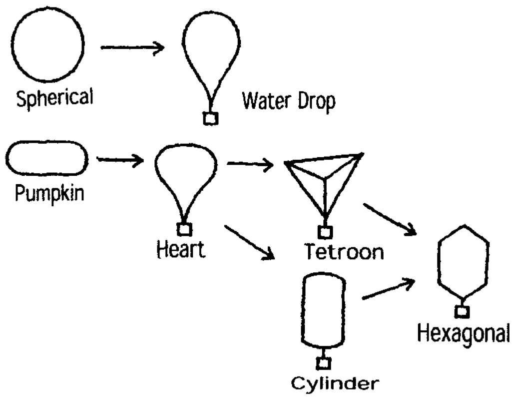


Fig. 1. Relation of Various Type of Balloons

Balloon Materials

Polyethylene film has a superior character as a balloon film, specifically its low brittleness temperature. In addition, the balloon is easily fabricated by heat sealing. Polyester, Nylon and other plastic materials have also been investigated, Those have normally higher ultimate strength, but their ultimate elongation is not large enough. In addition, they present some difficulties for seaming to manufacture the balloon. Recent investigations indicate that balloon failures seem to relate to the toughness of the film at low temperature in the stratosphere rather than the ultimate strength or elongation of the film itself, as naively suspected in the early stage. Toughness is the energy necessary to break the films. It is almost proportional to the breaking strength multiplied by the ultimate elongation (Said 1994).

It has been found that the film character is affected not only by the grade of the polyethylene itself, but it is also seriously influenced by the method of extrusion. Many efforts have been spent to produce polyethylene films suitable for balloon use. Winzen produced the so-called Strato-Film in the 1960's. It has the brittleness temperature of about -80^{0}C, and success rate of balloons made with this film proved almost 100%. However, in the 1980's, balloon failure rates increase by the demand of increasing the size of balloons and weights of payloads. NASA spent many efforts to improve this situation, including re-examination of the film characteristics and manufacturing as well as launching systems.

In .the 1980's, a new LLDPE (Linear Low Density Polyethylene) became available. It has a good character at low temperature. CNES has produced LLDPE films, and LLDPE was used in the Raven-produced Astro-E, and Winzen-produced new Strato Film 375. Films with similar characters were produced later in USSR, China, India and Japan. Those films have brittleness temperatures as low as nearly -100^{0}C. The success rate of balloons increased again to almost 100%, and the problem seems to be solved as far as zero-pressure balloons are concerned. Efforts have also been made to extrude extremely thin films of a few microns of polyethylene for high altitude balloons with light payloads in the US and Japan. Other films such as polyester, biaxially oriented-Nylon, EVAL (Ethylene-Vinyl-Alcohol) and a combination of these films are being widely investigated for super-pressure type balloons

Emulsion Experiments Stimulated the Scientific Ballooning

Soon after the flight success of the plastic balloon, they were used extensively to cosmic-ray research activities. I note especially the discovery of heavy components in primary cosmic rays (Freier et al, 1948). These were carried out with a cloud chamber and nuclear emulsions on board the balloons. The discoveries of heavy primaries such as Li, Be, B, C, N, O...Fe other than protons in cosmic rays made it possible to conduct further precise studies to explore the nature of cosmic rays, how and where they are accelerated and how they propagate in the Galaxy. Observations by balloons and satellites have continued those early investigations to the present time.

The sensitivity of nuclear emulsion was much improved at the end of the 1940's, and those detectors played an important role for the discovery of the new elementary particles of π and μ mesons in cosmic rays at mountain exposures. Nuclear emulsions are very suitable for balloon experiments, because they are relatively stable against temperature changes, and no electronic devices are required. Ilford developed the most sensitive nuclear emulsion G5, with the collaboration of the Bristol group headed by Powell at the end of the 1940's. The Bristol group had own small balloon manufacturing facility in their laboratory, and they carried out balloon flights by themselves. To achieve longer duration flights, they also conducted launchings at Sardinia Island in the Mediterranean Sea. They launched balloons with large size emulsion stacks, and they produced many findings on heavy primaries, high energy jets and new particles,

Their works stimulated other laboratories in the world in two ways. One was to promote the collaborative study of cosmic rays with emulsions exposed by the Bristol group. Another was to promote to fabricate the balloons in their individual laboratories. Stimulated by the Bristol activities, TIFR (Tata Institute of Fundamental Research) in India began to manufacture balloons and to develop its technology. India spent a lot of effort performing scientific observations, and finally the permanent facility in Hyderabad was established in 1969. They performed extensive pioneering works on cosmic rays and studies of gamma rays, X-rays and Infrared, while conducting also much international collaboration. They took advantage of their location near the equator, where the geomagnetic cut off energy of cosmic rays is the largest, which is important to reject the background due to low energy cosmic rays.

The cost of nuclear emulsions is rather expensive. Therefore, the size of the emulsion is limited. The Rochester group in the US proposed the concept of an emulsion chamber, which is a pile of metal plates sandwiched with thin nuclear emulsions. Their primary purpose is to study the target effects of high energy nuclear interactions in cosmic rays.

Japanese group paid attention on this low expense in preparing a large instrument with emulsions, and also found that an appropriate assembly is quite suitable for studying high-energy jets. They put the target layers at the upper part of the assembled stack and shower development layers underneath. They put a certain separation between the target and shower development layers which enable to observe individual shower development from πo mesons. Seventeen emulsion chambers of 25 cm x 20 cm x 25cm with this concept were prepared, and launched with 7 balloons in 1956 in Japan. The 5600 m^3 balloons were manufactured in Japan. This was the beginning of the systematic study of scientific ballooning in Japan. Later, huge emulsion chambers with sizes of 100 m^2 for mountain exposures were constructed with this concept. Large instruments with emulsions for balloon experiments such as JACEE (Japanese-American Cooperative Emulsion Experiment) and RUNJOB (Russia & Japan Collaboration) experiments became possible with the concept of the emulsion chamber.

In the US, Shein, University of Chicago, proposed to expose large emulsion stacks with an international collaboration. This program was called ICEF (International Collaborative Emulsion Flights). His plan was to prepare two large emulsion stacks of 60 cm x 45 cm x 30 cm, and share the analysis with laboratories around the world. Winzen prepared 10 Million Cubic Feet (almost 300,000 m^3) balloons, and those were launched in 1960 from an aircraft carrier in the Caribbean Sea, as shown in figure 1. The flights, however, were not quite successful. This was also the beginning of the epoch on modern large size balloon fabrication and launching. It is sad that Shein pasted during this campaign. Koshiba followed this project, and finally succeeded to expose the stack for 36 hrs from Brawley in California.

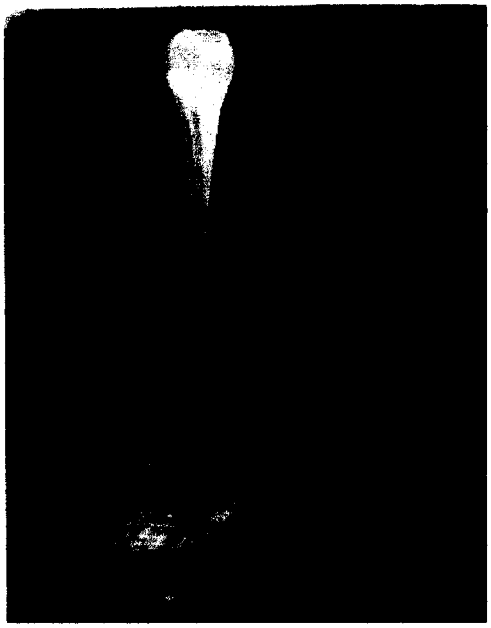


Fig. 2. Launching of 10 MCF Balloon from aircraft carrier for ICEF, 1960

LONG DURATION FLIGHT SYSTEMS

After the many scientific observations in the 1950's and 1960's, it was recognized that the longer duration observations are indispensable for performing the precise observations.

There are two problems that must be addressed to achieve long duration flights. One is balloon drift and the other is ballasting. The problem of balloon drift has been solved by satellite link of telemetry and by preparing recovery areas remote from the launching location.

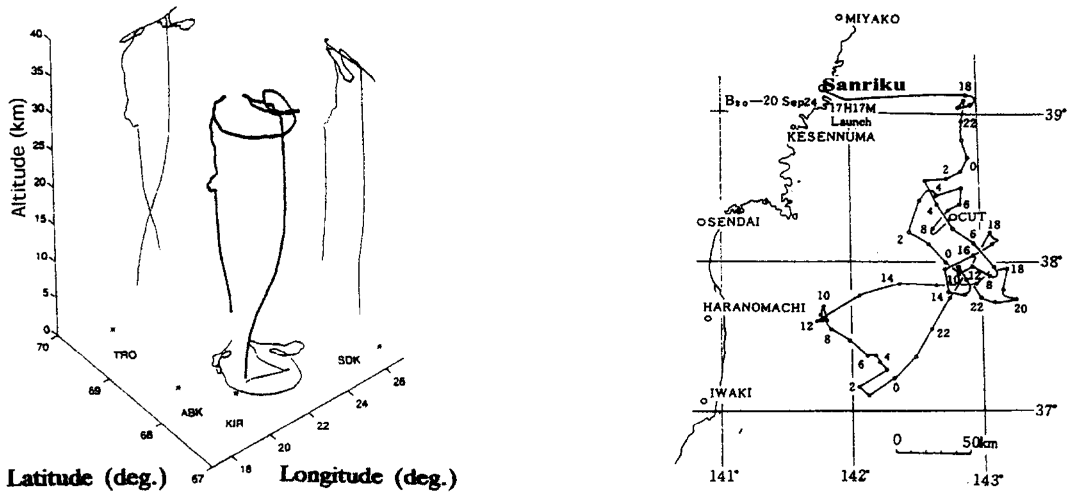
At mid latitudes, a balloon loses about 10% of its lift during the day to night excursion. We need to drop equivalent amount of ballast each day to maintain the altitude. After several days, all ballast is exhausted, and the flight terminates. This is the most serious problem for long duration flights. The US, France and Japan have extensively studied thermal analysis of the balloon behaviour.

To resolve this problem several systems have been proposed, such as:

- *Super-pressure balloons, Mongolfiere Infrarouge, Flights in Polar region etc.*

Turn-Around Period Flights

There were early attempts to make use of the stratospheric wind of turn-around period. This is the term used to represent the period when high altitude winds cease and a balloon can stay at almost the same location. Turn around periods appear at the end of spring and summer. The period lasts one week to 10 days, but precise prediction of when it will appear is difficult. During these periods, one can recover the payload near the launching station after flights of 2 to 3 days. CNES and Japanese groups reported very successful examples, which are shown in figure 3.



a) Observed by CNES at ESRANGE in 1997. b) Observed at Sanriku Balloon Center in 1975

Fig. 3. Examples of the trajectories during turnaround periods.

Transoceanic Flights and others

The next natural step was to extend the length of the balloon trajectories. One such effort is the "Boomerang Balloon" system used in Japan. A more efficient way is to provide the recovery area remote from the launching area. Such efforts include flights:

·*From Kamchatka to Volsk in USSR*

·*Trans Atlantic Flight (From Europe to US)*

·*Australia to South America*

·*From China to Russia*

·*From Japan to China*

·*ODISSEA: Trans Mediterranean flight from Sicily to Spain. (CNES)*

Those flights were started in the 1970s, and some of them are still operating now. They achieved extended duration of several days to 1 week. One of the most successful examples was the flight conducted by the USSR with the flight trajectories from Kamchatka to Volsk in 1999 shown in figure 4.

Fig. 4. Balloon Trajectories for RUNJOB from Kamchatka to Volsk in 1999

Mongolfiere Infrarouge

CNES has developed an ingenious system called Mongolfiere Infrarouge. This is essentially a hot air balloons, but the heat is supplied by infrared radiation from the surface of the earth. The upper part of the balloon is made of Aluminized films, and the lower part employs polyester films having rather strong absorption-bands in the Infrared radiation. In the daytime, the sunlight reflected by the upper part of the balloon. Part of the Infrared radiation from the earth is absorbed and reflected from the Aluminized films. The reflected infrared radiation is absorbed by the lower part of the balloon. The temperature inside the balloon becomes higher than the ambient atmospheric temperature. At the nighttime, the balloon loses several km in altitude, but it rises again the next day, which is suitable for studying the atmosphere at various altitudes.

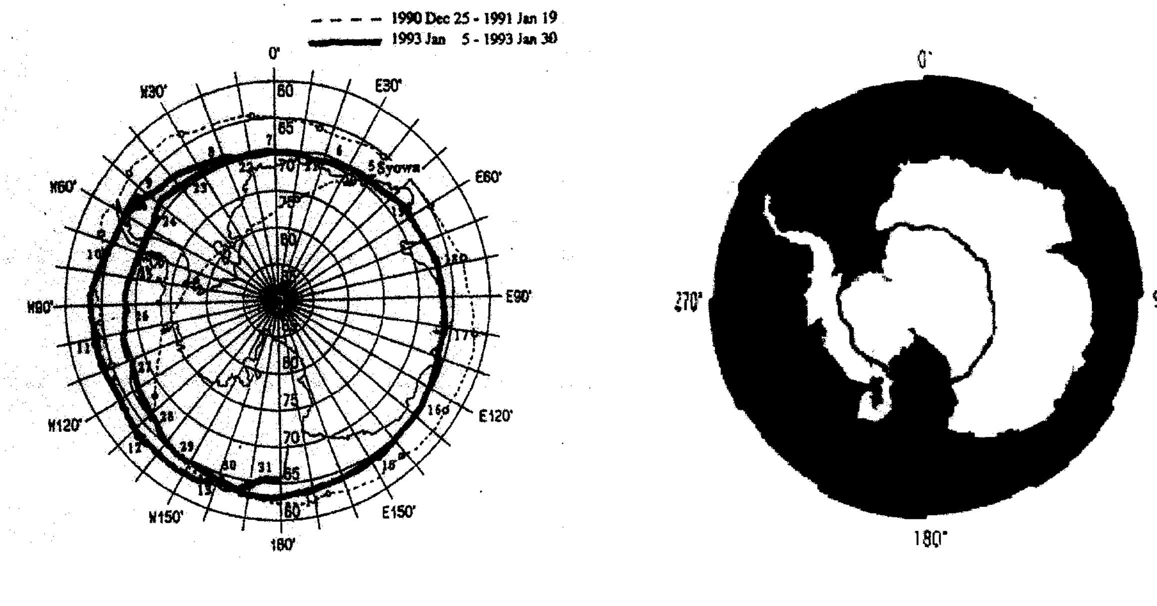
The flights have been successfully conducted, mainly in the Southern Hemisphere, since the 1970's, and improvements have continuously been carried out. The longest flight duration is reported as 69 days. Test flights have also been conducted in the north Polar Regions to observe vortex of the wind in this region.

Polar Flights

In Antarctica, there are no sunsets during the summer season, so the balloons do not experience day-night altitude excursions. This means that, at least in principle, ballasting is not needed for Polar flights. In addition to this, there is a circumpolar wind over Antarctica during the summer season. We can expect that the balloon trajectory is circumpolar, and the balloon will return to near the launching site after 2 to 3 weeks.

It is curious that nobody mentioned that we could use zero pressure balloons for long duration flights in Antarctica before we proposed and carried out a test flight in the 1980's. (Nishimura et al., 1985). We call this system a PPB (Polar Patrol Balloon). We launched the PPB from Syowa station ($69^0.00$'S, 35^035'E) of the National Polar Institute, Japan, and achieved 2 to 3 weeks' flights to complete a circumpolar flight. NASA started Antarctica flights at almost the similar time from McMurdo (~78^0S). In this case, the duration to complete a circumpolar flight is about 10 days. Following success of Antarctica flights, NASA has proceeded to conduct flights near the North Pole. The launching was performed from Fair Banks, Alaska, and recovery was from the northern part of Canada in 1998, taking more than 10 days.

The polar flights are the most efficient long duration system at this stage, and many observations have been performed. This includes the JACEE program, which has obtained the longest exposure of emulsion chambers to see the high-energy spectrum of cosmic rays. (In total about 30 days by 3 flights). One of the most successful investigations in Antarctic has been the Observation of Cosmic Microwave Background, which I will touch upon at the end of this paper.



a) Flights from Syowa station in 1990 b) Flight from McMurdo in 1998

Fig. 5. Examples of Trajectories in Antarctica Flights

Super-pressure Balloon

To achieve a long duration flight, super-pressure balloons have been investigated for many years, particularly in France and the US. The spherical balloon shape was first investigated. To withstand the strong internal pressure, polyester films (Mylar) were first selected as a balloon material. From the 1970's, those pressure balloons become practical to use, but the size was limited to about 7000 m^3. Larger size balloons were not successful. Other possible candidates of balloon materials, such as biaxially oriented nylon, combination of polyester film, and Spectra Scrim were extensively tested in the US.

CNES was the first to propose a pumpkin shaped balloon instead of a spherical shaped balloon. The idea is to relax the stress of the film by reducing the circumferencial stress through the use of strong load tapes attached from the Apex to Nadia. A 214 m^3 balloon was successfully tested at an altitude of 17 km for 143 days in 1978, but CNES did not extend this type of balloon to larger size.

Recently, Yajima proposed to reduce the stress of the films by using load tapes with appropriate length shorter than the film gores, in order to reduce the circumferencial radius of curvature of the film, and thereby reduce the circumferencial stress of the films (Yajima, 1998).

NASA is now planning ULDB (Ultra Long Duration Balloon) Flights with almost 600,000 m^3, super-pressure balloons, which can stay a few months at a constant level of high altitude. For this program, NASA selected a pumpkin-shaped balloon using the above concept together with many improvements of the balloon materials. Test flights have been going on, and the results are promising. It will be realized after a few years, with no doubt that it will open a new era of scientific ballooning in the next century.

Smith is going to make overview of this NASA program, Winker will report the history of Pumpkin balloons, and some details of recent achievements by NASA and other groups including Yajima will also be reported in this meeting, so I will not go into the details here.

SCIENCES IN BALLOON OBSERVATIONS

Reviewing the scientific ballooning history, we see steady development of the balloon technologies, and this opened new fields of scientific observations. Although the balloon history extends back for more than 200 years, the impact of balloon technology development has been enormous in this century for space science. The subjects covered by scientific ballooning during past 50 years are

· **Earth Science,**

Atmospheric chemistry, circulation, Aurora, Atmospheric Electricity and Magnetic field.

· **Astrophysics,**

Submillimeter, Infrared, UV and Optical Astronomy, High-energy X-rays, Gamma rays, Cosmic rays.

· **Planetary Science,** Planetary Balloons on the Venus.

· **Tests in advance** to verify the performance of payloads for satellites or the space station.

International collaborative efforts and campaigns have played important roles for these investigations.

In Earth science, large European international campaigns have continued at ESRANGE and Andoya, starting with the project SPARMO in the 1960's, and extending to SBALMO, SEASAME,.., THESEO, etc.
As an illustration, I list the sciences performed in the field of astrophysics by balloons in the past 50 years. Participation of each country is tentatively listed in the order of almost the location of their latitudes.

Table 1. List of Scientific Ballooning in Astrophysics (after 1950)

· **Infrared Observations** : European Countries, US, Indonesia, Japan, Australia, India....

· *Mapping in the Galaxy, CMB, CII line, Star formation region....*

Balloon Observations ⇨ Satellite (COBE), IRAS, ISO, IRTS...

· **UV, Optical Observations**: European, US, Japan, China....

· *Stratoscope* (1958)...

Balloon Observations ⇨ Space Telescope

· **High-energy X-rays:**, European, USSR, US, Brazil, Japan, India, China..

· *Discovery of Solar X-rays, Discovery of Hard X-rays from Crab Nebula.*

· *Detailed observation of Crab nebula, Cygnus X-1, Scox-1, HerX-1,SN1987A.....*

Balloon Observation ⇨ Satellite

· **Cosmic rays**: European Countries, US, USSR, Japan, Australia, India...

·*Composition* (Heavy Primaries, Isotopes, Electrons, Anti-matter...)

·*Spectrum*

·*High Energy Interaction*

Balloon Observations ⇨ Balloon Observations Effectively Continued

⇨ HEAO-C, Pioneer. Voyager, Ulysses, ACE,., Shuttle, Space Station

From this list, we recognize that scientific ballooning is a most effective way to explore space science and to open new fields of science by virtue of:

·*Cost effectiveness,*

·*Quick response,*

·*Recovery of Payloads*

·*Giving many chances to the scientists* .

In addition, demands for scientific ballooning are increasing to conduct demonstrations to prove the performance of expensive instruments to put on satellites and the space station.

To conclude this section, it is pity that I can not mention many excellent accomplishments in scientific ballooning during last 50 years in this limited report. I just mention the following items, as examples, to show the recent achievements of scientific ballooning programs in technology and science.

Some Recent Status

ULDB Program:

As mentioned above on the section of super-pressure balloons, NASA is now planning to perform a long duration flight that will last for a few months. If this is realized, there is no doubt it will open new era in scientific ballooning. This will be the most orthodox way to resolve the long-standing problems for the new balloon systems.

STRATECOLE:

CNES has a plan to trace many small spherical super-pressure balloons, floating for a few month at altitudes of 15 km between 50 ^{0}S and 70 ^{0}S to study the dynamics of the polar vortex and its relation to the ozone formation. CNES plans to launch 200 small super-pressure balloons in the near future.

PRONAOS Program:

PRONAOS is a large and precise Submillimeter IR telescope supported by CNES. The diameter of the mirror is 2 m and its pointing accuracy is 20" with a stability of 5". The observed wave range is 180 micron to 1.2 mm. It successfully detected cold interstellar molecular clouds and the Snyaev-Zeldvich effect for the 2.7 ^{0}K Cosmic Microwave Background.

BOOMERANG Observations:

This European-US collaboration made precise observations using long duration flights in Antarctica. The precise angular distribution was measured for the Cosmic Microwave background. After analyzing data, new results were found to support the uniform Universe model, which could not be achieved with the COBE satellite measurements.

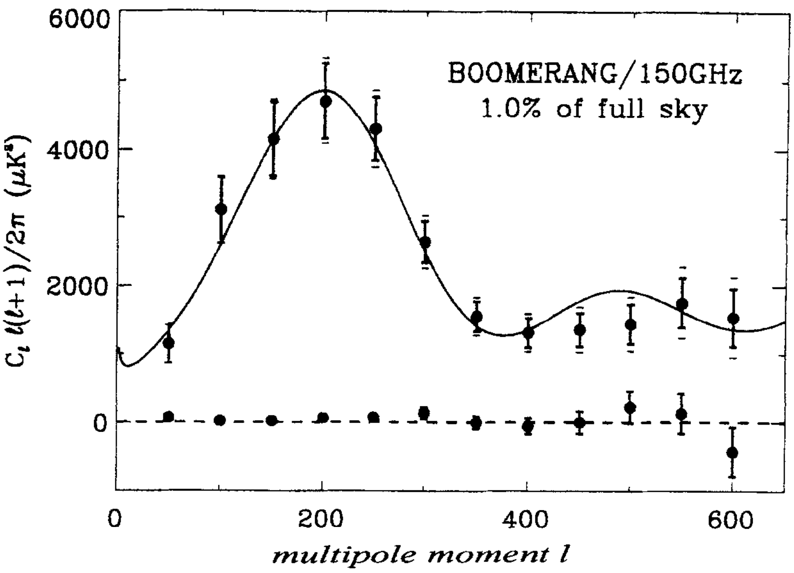


Fig. 6. Angular Power spectrum of CMB measured by BOOMERANG (http://www/orangecoffee.it)

Anti-Matter Search:

There are several fine super-conducting magnetic spectrometers such as BESS, IMAX, and Caprice, to observe anti-protons, He and other components, including isotopes in cosmic rays. BESS is collaboration between Japan and US scientists. The others are collaborations of US and European scientists. NASA has conducted the flights every year from Lynn Lake, Canada. Among these, BESS has the largest acceptance apertures of 0.3 m^2sr, and they have already detected more than 1000 anti-protons. There remains the possibility that some of the anti-protons are produced by the exotic phenomena such as the evaporation of primordial small black holes, but most of them are interpreted as being produced by cosmic rays while they are propagating inside the Galaxy.

SUMMARY

Reviewing the development of scientific ballooning over the past 50 years, balloon experiments have performed pioneering works in space science, and always balloon technological developments opened a new field. Some of the balloon investigations developed into satellite missions. A planetary balloon is going to open a new door and the role to verify the performance of more sophisticated instruments for satellites and space station experiments is now increasing. I have no doubt that the role of scientific ballooning will continue and be growing in the next century through development efforts of new balloon systems.

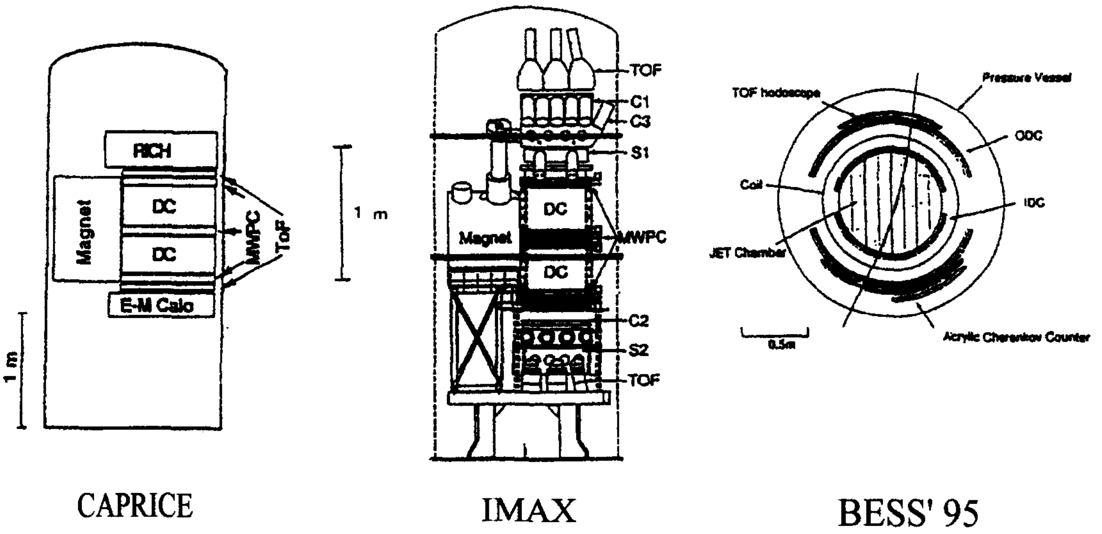


Fig. 7. Some Instruments of Super- Conducting Magnetic Spectrometer for Anti P, He observations

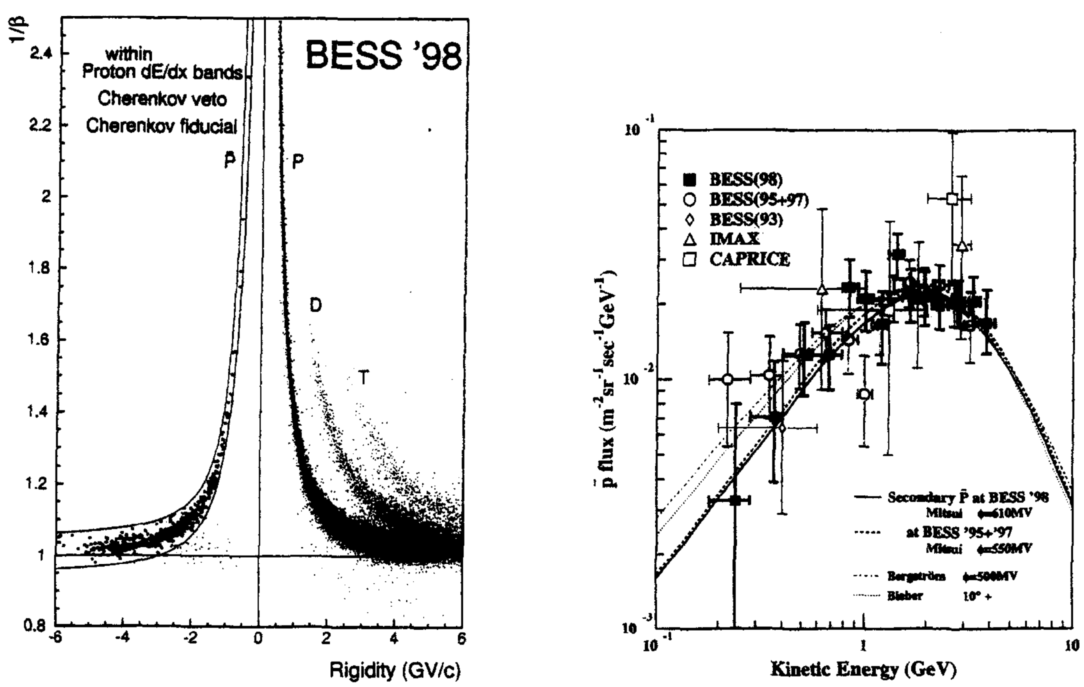


Fig. 8. Some of observed results by BESS Spectrometer

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