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Balloons for scientific research: The international scene

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Scientific ballooning has,over the last 30 to 40 years, led to many important discoveries and it continues to be relevant and important in the present era of space platforms. The advantages of using balloons for scientific research are enumerated. A brief review of the major achievements from scientific ballooning in several fields, such as atmospheric chemistry, atmospheric circulation, submillimeter and infrared astronomy, ultraviolet and optical astronomy, X-ray and gamma-ray astronomy, cosmic rays and cosmic dust, is presented. The unique advantages of balloon platforms and their role as precursors of extended missions with space platforms are described. Finally, the future needs of scientific ballooning for making it a more effective tool are highlighted.

1 Introduction

The Symposium on "Thirty Years of Scientific Ballooning in India" provided an ideal opportunity to re-evaluate scientific ballooning from an international viewpoint. Ballooning has made major advances over the past 30 years in its technical capabilities, such as altitude, duration, payload weight, and reliability, and as a result numerous and important scientific discoveries have been achieved. But in an era of high altitude airborne platforms and satellites, is ballooning still relevant? Is the scientific rationale for high altitude balloon research still valid? Do advantages still exist for doing research from balloons? What are the future needs of scientific ballooning? In this paper we will review the original objectives of scientific ballooning, its achievements over the past 30 years, and discuss what are its future directions. The following two previous US reviews of scientific ballooning will be referenced frequently: "*The use of balloons for physics and astronomy*" (Ref. 1), and "*National needs for scientific ballooning*" (Ref. 2). Activities of NASA in the field of ballooning in recent times and future expectations have been reviewed by Jones[3,4].

2 Scientific rationale

Scientists have used high altitude balloon-borne platforms for over a century to achieve two important objectives: (1) to study directly, with *in situ* measurements, the structure, composition, and chemistry of the earth's atmosphere, and (2) to detect electromagnetic radiation from submillimeter to gamma-ray wavelengths, high energy particles (cosmic rays), and particulates from extraterrestrial sources that cannot penetrate the earth's lower atmosphere. For the first purpose the balloon platform provides unique capabilities, and in the second case offers numerous advantages for certain classes of experiments when compared to airborne and space platforms.

The advantages of using balloons for scientific research are numerous. New experiments can be developed in relatively short lead-times for relatively low costs compared to spacecraft, and balloons provide a greater availability of flight opportunities. Ballooning has been invaluable in the training of graduate students, permitting them to witness and take an active part in the development of a scientific programme from conception to observations and publication of results, all within a time span of a few years. Finally, the balloon platform permits the development, test, and evaluation of new scientific instruments that will later be flown in space.

3 Scientific achievements

The unique and important contributions balloon-borne instruments have made to a wide variety of scientific areas are impressive. In this section we will briefly present a sample of the more important achievements.

3.1 Atmospheric chemistry

One of the most important contributions of scientific ballooning has been the *in situ* studies of the perturbation of the stratospheric ozone layer by human activity, including the effects of fluorocarbons, chemical fertilizers, high flying aircrafts, and rockets, and the studies of the climatic effects of increases in atmospheric carbon dioxide resulting from the burning of fossil fuels. These measurements have shown that the radicals important in ozone-destroying catalytic reactions (ClO, NO, NO_2) are present in the atmosphere. Simultaneous measurements of these species by a large number of experiments have been used to test the predictions of theoretical models. Balloon-borne observations have also been used to validate data obtained from the Space Shuttle and other spacecrafts, as well as to provide correlative data needed for the interpretation of the space observations. Detection of minor but important constituents, such as HO_2, H_2O_2, HBr, and HOCl, has also been made primarily from balloon-borne experiments.

3.2 Atmospheric circulation

Balloons are capable of long duration flight paths at constant altitude. This feature has been used as a means of determining tropospheric wind velocities along the balloon trajectory, and a large number of such small balloons have been used to determine the atmospheric circulation patterns at high altitudes.

3.3 Submillimeter and infrared wave astronomy

In this spectral region, balloon-borne telescopes have permitted the photometry and spectroscopy of the cosmic diffuse radiation, high angular resolution large-area mapping of the galactic centre and extended sources in our galaxy, and atomic and molecular spectroscopy of important interstellar lines.

The bulk of the energy of the 3 K cosmic background radiation, the electromagnetic remnant of the "big bang" explosion of the Universe, resides in the submillimeter spectral band. Prior to the recent cosmic background explorer (COBE) measurements, balloon-borne instruments had determined the shape of the spectrum, measured the large scale angular distribution, detected the dipole moment of the radiation pattern, and measured the small scale (approximately 1 degree) anisotropy of the radiation, testing theoretical models of the early Universe.

In the study of the structure of our Galaxy and the interstellar medium, balloon-borne submillimeter observations have mapped portions of the Galaxy in the C II emission line, which is important for determining the cooling properties of molecular clouds, measured dust properties in the Galaxy from continuum emission spectra, and mapped the distribution of cold molecular clouds.

At infrared wavelengths, balloon-borne observations have discovered and mapped the intense infrared emission from the galactic centre and its surrounding region and produced major contributions to our understanding in many areas of astrophysics, including the structure and evolution of our Galaxy, the star formation and evolution in molecular clouds, the structure and evolution of H II regions, the structure of the solar atmosphere, and the nature of the outer planets.

3.4 Ultraviolet and optical astronomy

At wavelengths greater than 1900 Å, ultraviolet astronomical observations can be made from balloon-borne platforms. This research has concentrated primarily on high resolution stellar spectroscopy, and has included the study of mass loss from O and B stars, large velocity mass outflows from Be and shell stars, structure of stellar chromospheres in late-type giant and supergiant stars, and properties of the interstellar gas, including velocity structure and composition. Wide-field imaging of galaxies, galactic H II regions and blue galactic halo stars has also been achieved.

In 1958 Project Stratoscope, a balloon-borne optical telescope obtained the highest resolution photographs of the solar photosphere, which resulted in improved understanding of solar granulation.

3.5 High-energy X-ray astrophysics

The first observations of hard X-ray emission from solar flares were made from balloon-borne telescopes and these observations provided the first direct evidence for non-thermal solar acceleration of electrons.

Early observations of the Crab Nebula showed that the X-ray continuum radiation was non-thermal in origin and later lunar occultation observations were used to obtain the first localized measurements, with sub-arc-min resolution, of the extent of the nebular X-ray emission relative to the central pulsar. These results helped develop a model for the translation of the pulsar's rotational energy into relativistic electrons radiating in the nebula. Other results include the detection of the diffuse cosmic X-ray background radiation above 20 keV, observation of longer variability in Cygnus X-1, observation of the first flare from a cosmic X-ray source, Sco X-1, discovery of the first slowly rotating X-ray pulsar, GX 1 + 4, first evidence for cyclotron X-ray emission in a pulsar, Her X-1, and detection of hard X-rays from the Coma cluster of galaxies.

Hard X-ray astronomy is an area of research where balloon-borne observations contributed very significantly to the early development of the field.

3.6 Gamma-ray astronomy

In the energy region between 0.1 MeV and 30 MeV, where the study of nuclear astrophysics is important, balloon-borne gamma-ray telescopes have also contributed significantly to the development of high energy astrophysics. Gamma-ray spectrometric observations first detected positron annihilation radiation from the galactic centre region; the source recently identified as 1E1740.7-2942 by the USSR Granat satellite. One of the recent major discoveries by balloon-borne gamma-ray spectrometers has been the detection of radioactive cobalt in the debris from Supernova 1987A. Gamma-ray lines from supernovae give direct evidence for the production of newly synthesized elements. Evidence for the galactic origin of cosmic gamma-ray bursts was obtained with balloon-borne telescopes, as was the first detection and evidence for variability of extragalactic sources, the discovery of pulsed gamma-ray emission from two supernova remnants: the Crab Nebula pulsar and the Vela pulsar, and the confirmation of excess radiation between 1 and 10 MeV in the diffuse cosmic gamma-ray background radiation. Detection and spectrometry of solar-flare gamma-ray bursts have been important in understanding the acceleration of high energy particles in solar flares.

At energies above 30 MeV balloon-borne detectors verified the presence of galactic gamma-ray emission and the importance of cosmic-ray interstellar matter collisions in producing this emission via the decay of neutral pions produced in the interactions.

3.7 Cosmic rays

Cosmic-ray observations on balloons have had a long and distinguished history, going back to 1910. These experiments have led to the identification of almost every individual component of cosmic rays, and still remain an important tool of research. Recent accomplishments have also included high precision observation of elemental composition of cosmic-ray nuclei, measurements of the spectra of the individual components of cosmic-ray nuclei, and advances toward measurement of isotopic composition. Earlier high energy electrons and positrons were detected in the primary cosmic radiation and their intensity and spectra were measured. Antiprotons and antinuclei in the primary cosmic radiation were also discovered with balloon-borne instruments. Balloon-borne experiments have contributed significantly to our understanding of the origin and nature of the sources of cosmic rays, as well as their acceleration, production, and propagation in our Galaxy.

3.8 Cosmic dust

Interplanetary dust is of considerable importance because it may have originated in comets. Collection of cosmic dust particles via stratospheric balloon and aircraft experiments is a means of obtaining cometary matter for laboratory analyses and remains the only method of obtaining such samples. Stratospheric flights are necessary to rise above the high concentrations of terrestrial particulates in the troposphere. Balloon-borne experiments were the first to collect genuine stratospheric particles in the 10 μm size region. Hundreds of extraterrestrial particles have been collected with NASA's U-2 aircraft using techniques developed by balloon-borne experiments. Such observations are capable of providing further insight into the processes that formed cometary bodies.

4 Importance of balloon-borne observations in the space era

Although spacecrafts provide an even greater opportunity to make long duration observations above the atmosphere, space flight opportunities have been very limited, take many years (sometimes more than 10 years) from acceptance to flight, and are expensive. Except for the Space Shuttle, payload weight has been very limited, and shuttle experiments have become very rare, if not impossible.

Balloon-borne experiments still provide a means of rapid response to targets of opportunity. An excellent example is the recent and very successful scientific balloon expedition to Australia to observe the Supernova 1987A at X-ray and gamma-ray wavelengths. Compared to space experiments, the cost of balloon-borne experiments is very low and greater opportunity for flight is available. The rapid development of long duration balloon flights will provide for longer observing times. Balloon reliability has improved to such a degree that heavy payloads, particularly cosmic ray experiments such as the cryogenic magnetic spectrometer, large infrared telescopes, and multiple atmospheric chemistry experiments, are easily flown. This is particularly important as access to the Shuttle and Space Station disappears.

However, one of the most important aspects of scientific ballooning in the space age has been the development and testing of spaceflight instrumentation. For example, many of the instruments on the COBE satellite were first developed, tested, and used for observations on balloon-borne platforms.

Ballooning has also provided an excellent training ground for space operations. On infrared and submillimeter astronomy spacecraft, a very large fraction of the investigators were also investigators on balloon-borne telescopes. This is also true for X-ray and gamma-ray astronomy, as well as cosmic ray astrophysics space experiments. Scientific ballooning also provides an ideal training ground for graduate students, and provides an opportunity for strengthening the interactions between university community, and space scientists and engineers. There is no doubt that scientific ballooning is here to stay for the indefinite future and that it will provide excellent opportunities for new and important scientific discoveries, development of new instrumentation, and be an excellent training ground for space scientists.

5 Future needs of scientific ballooning

The future needs of scientific ballooning as viewed from the present are the same as they were 25 years ago. It seems scientists are never satisfied. These needs are: (1) extended flight duration from a few days to a few weeks; (2) an increase in the number of flights; (3) capability to launch balloons regularly over a range of latitudes (including Antarctica); (4) capability to launch heavier and more complex scientific payloads; (5) improved wide bandwidth communication links between the payload and the ground station; and (6) higher float altitudes.

References

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