5

JAMES A. VAN ALLEN*

Magnetospheric physics**

AUTHOR'S PREFACE

How did a Ph.D. in experimental nuclear physics become a planetary astronomer? Well, it wasn't simple! Here is my story.

During the early days of World War II, I helped develop the radio proximity fuze for gun-fired projectiles, working at the Applied Physics Laboratory of Johns Hopkins University. In November 1942, I was commissioned as a line officer in the U.S. Naval Reserve and was dispatched immediately to the South Pacific Fleet to foster the adoption of this innovative, "smart" anti-aircraft fuze. During the next three and a half years, I served a total of 17 months in two tours of duty on combatant ships and at ammunition depots in the South Pacific. In March 1946, now at the exalted rank of lieutenant commander, I was placed on inactive duty and returned as a civilian employee of the APL/JHU.

Then during the period 1946–1950, I developed and oversaw a program of high altitude research in cosmic rays, atmospheric ozone, solar UV spectroscopy, ionospheric currents, and photography of large regions of the Earth's surface. The work was supported by the U.S. Navy Bureau of Naval Ordnance. Our instruments were transported up to altitudes of 160 km by the U.S. Army Ordnance Department's post-World War II test flights of refurbished German V-2 rockets and by American Aerobee rockets. The latter were developed specifically for our investigations of physical phenomena in and above the Earth's atmosphere. Our original Aerobee and its successive upgrades were later adopted by many others. By 1988, over a thousand such vehicles had been flown for a wide variety of atmospheric, solar, astronomical and astrophysical investigations.

In January 1951, I returned to my Ph.D. alma mater as a professor of physics and head of the Department of Physics (later Physics and Astronomy) at the University of Iowa and, with the support of the Research Corporation and the U.S. Office of Naval Research (ONR), initiated and led a student-centered program of similar research using balloons and balloon launched rockets (rockoons) as vehicles. The rockoon technique provided a low cost method of transporting our instruments up to altitudes of 130 km. During the period 1952–1957, we conducted 109 rockoon flights, all from shipboard, over a large range of latitudes from Baffin Bay in the Arctic to the Ross Sea in Antarctica, under the sponsorship of the ONR and, during 1957, by the National Science Foundation as part of the 1957–1958 International Geophysical Year (IGY). Our principal results were a latitude survey of the intensity of the primary galactic cosmic rays, including the heavy nuclei therein, the discovery of X-rays from auroral electrons, and the measurement of ionospheric currents near the equator and at high latitudes.

Beginning in 1956, I participated as a member of several of the committees and panels planning U.S. participation in the IGY and, most importantly, the one on scientific uses of artificial satellites of the Earth. The realistic expectations for investigations with satellite-borne instruments were heavily dependent on the experience and aspirations of a small cadre of us veterans of research with high altitude rockets during the preceding decade.

Following the successful launch of Sputnik I by the U.S.S.R. on 4 October 1957, there was a fast-breaking effort in the United States to speed up our efforts to place artificial satellites in orbit, all within the context of the International Geophysical Year. As part of that response, the

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U.S. Army's proven four-stage Juno II vehicle was adapted for the first attempt rather than the previously planned Naval Research Laboratory's new Vanguard vehicle, still plagued by developmental problems.

A cosmic ray instrument developed by George Ludwig and me at the University of Iowa had been selected previously by the relevant IGY panel as one of four payloads slated for early flights on a Vanguard vehicle. Our instrument was essentially ready for flight in late autumn 1957. During the preceding several years, I had followed in detail the relative status of the Juno II and Vanguard vehicles and had decided that it would be wise to design our instrument so that it would be suitable for either. By virtue of this fact and our previously established place on the short list, the Iowa instrument was selected for the first Juno II attempt. We then worked with the Jet Propulsion Laboratory to integrate it into the overall payload for the flight.

The purpose of the investigation was to greatly extend our rocket measurements of cosmic ray intensity above the appreciable atmosphere as a function of latitude, longitude and altitude. Our adopted sensor for this purpose was a single Geiger-Mueller tube.

The Juno II, also known as Jupiter C, delivered the payload (then named Explorer I) into a durable, moderately eccentric orbit on 31 January 1958 (1 February GMT). Telemetered data during and immediately after the launch sequence showed that our instrument was operating properly in free flight. Short segments of real-time data (typically of 2 or 3 minutes duration) gradually flowed into our laboratory from the wide geographical distribution of receiving stations. Some segments showed about the expected cosmic ray counting rates. In others the apparent rate was zero, a physical impossibility for cosmic rays. For several weeks we puzzled over conceivable failure modes, but were much preoccupied by intense preparations for further launches. An upgraded instrument was carried on Explorer II, a Jupiter C launch failure on 5 March. Our third instrument also included Ludwig's magnetic tape recorder for recording data during a complete orbit and then, upon command from a ground station, playing back the record within about 6 seconds. Data were also to be transmitted in real-time. This payload was launched successfully by a Jupiter C on 26 March and called Explorer III. The very first full orbit playback that we received confirmed the existence of expected cosmic ray rates at low altitudes, but then showed rapidly increasing rates as the satellite moved to higher altitudes in its elliptical orbit, and then apparent rates of zero at the highest altitudes. This sequence was repeated in reverse as the satellite descended to lower altitudes. A further series of Explorer III tape playbacks gave repeated examples of similar results and established a coherent pattern. Meanwhile, Carl McIlwain demonstrated by a laboratory test of a similar detector system that the zero rates in Explorer I and Explorer III data were, almost certainly, caused by radiation intensity so great that the GM tube no longer yielded resolvable individual pulses but only a kind of noise level of pulses too small to trigger the counting circuit.

We then returned to the analysis of the real-time Explorer I records, which had much greater dynamic range, and we used a laboratory calibration of a similar system for apparent vs. true (i.e., assuming zero dead-time) counting rates to find true counting rates. The altitude dependence of counting rate was far too rapid and at far too high an altitude to be attributed to any form of electromagnetic radiation (e.g., X-rays or γ-rays) or to any form of corpuscular radiation on direct trajectories from a distant source.

I concluded that the observed "effect" must be attributed to energetic, electrically charged particles trapped mechanically in the Earth's external magnetic field. This was the essence of my "discovery" announcement of the existence of enormous intensities of geomagnetically trapped corpuscular radiation at a joint National Academy of Sciences/American Physical Society meeting in Washington, D.C. on 1 May 1958.

We were immediately given a go-ahead for conducting follow up investigations with detector systems of far greater dynamic range than that of Explorers I, II and III. We worked with the Army Ballistic Missile Agency in Huntsville, Alabama in building payloads for two further launches of upgraded Jupiter C vehicles. The first of these two launches on 26 July 1958 placed Explorer IV in a durable orbit at an inclination of 50° (up from the 33° of the orbits of Explorers I and III). The second attempt on 24 August 1958 was a vehicular failure.

Our multi-fold detector system on Explorer IV yielded immediate and massive confirmation of our earlier results and a substantial advance in particle identification. In addition, it provided the principal observations of artificial radiation belts composed of energetic electrons injected by the radiative decay of the fission products from a series of three high altitude nuclear bomb bursts, called Argus I, II and III. The latter body of observations was classified as secret until public release by the federal government in early 1959. During the following six months, we provided radiation detectors for "moon" shots by Pioneer II, Pioneer III and Pioneer IV. Pioneer III did not achieve escape velocity but reached an apogee of 17 Earth radii (radial) and yielded data during both outbound and inbound legs of its trajectory. These data, combined with the lower altitude data by similar detectors on Explorer IV, clearly established the existence of two major radiation belts, distinguished by the markedly different absorbtivity of the trapped particle population. The very penetrating radiation in the inner belt had been well characterized by Explorers I, III and IV. Meanwhile Sputnik III (May 1958) had provided information on an outer belt. But Pioneer III gave the first complete survey of the radial distribution of trapped particles and established the outer boundary of the trapping region.

Pioneer IV did achieve escape velocity and made a rather remote pass by the Moon as it continued into interplanetary space. Our radiation data from this one-way flight through the Earth's external magnetic field confirmed and extended the basic findings from Pioneer III and gave a generally concurrent determination of the outer boundary of trapping.

Our laboratory then conducted subsequent investigations on the "heavy" IGY satellite Explorer VII of the Army Ballistic Missile Agency and on a series of complete satellites designed, built and instrumented in our small university laboratory. During the period 1961–1974, our six Injun and Hawkeye satellites were placed in a variety of high inclination orbits and provided a wealth of pioneering data on auroral radiation, solar X-rays, VLF radio waves above the ionosphere, galactic cosmic rays, solar energetic particles, and the structure of both radiation belts.

Also during the 1960s and 1970s, we participated in a series of NASA missions, including the Orbiting Geophysical Observatories 1, 2, 3, 4 and 5, Explorers XII and XIV and Explorers 33, 34 and 35.

At one point in time, the University of Iowa had more space flights to its credit than the entire European Space Agency, including individual member states.

During the 1960s, the primary emphasis of the evolving U.S. national space program was on manned missions in low Earth orbit, in preparation of the Apollo manned missions to the Moon. A secondary emphasis was on exploratory (unmanned) missions to the inner planets Venus and Mars. There was a special interest in exploring Mars to establish whether or not the physical conditions on Mars were favorable for the development of some sort of biological activity there, as had been frequently speculated.

Our radiation instruments were carried on Mariner II, the first spacecraft to fly by Venus (1962); on Mariner IV, the first spacecraft to fly by Mars (1964); and Mariner V, the second spacecraft to fly by Venus (1965). We found that neither Mars nor Venus has radiation belts, and we contributed observations establishing significantly small upper limits on the magnitude of their magnetic moments.

As a member of both the Space Science Board of the National Academy of Sciences and NASA's Lunar and Planetary Mission Board, I led special advocacy committees for missions to Jupiter and the other giant gaseous planets Saturn, Uranus and Neptune. It was already known from radio-astronomical evidence that Jupiter had a large radiation belt of relativistic electrons, but there was no credible radio-astronomical evidence of radiation belts around Saturn, Uranus or Neptune.

Our advocacy group provided the scientific rationale for missions to the outer planets. In 1968, NASA adopted two missions designed to pass through the asteroid belt between the orbits of Mars and Jupiter and to pass by Jupiter at a heliocentric distance of 5 AU, beyond any previous missions. Management of the development of the spacecraft was undertaken by NASA's Ames Research Center. Our Iowa package of radiation detectors was one of several selected for these flights.

The missions of the two spacecraft, later named Pioneer 10 and Pioneer 11, were brilliantly successful. Pioneer 10 passed through the asteroid belt unscathed and made the first in situ investigation of Jupiter's huge and intense radiation belt and magnetosphere in November–December 1973. It continued outward in a solar-system escape trajectory. Pioneer 11 made the second and somewhat different passage through Jupiter's magnetosphere a year later. Following the success of Pioneer 10, and at the urging of the scientific investigators, Pioneer 11's encounter trajectory for Jupiter was chosen so that it led to a subsequent encounter with Saturn. Its close flight by Saturn occurred in August–September 1979. We discovered that Saturn is also a highly magnetized planet and has a large radiation belt and magnetosphere, though considerably smaller in magnitude and intensity of trapped particles than that of Jupiter.

There was an intense debate among the scientific investigators and officers of NASA on the best choice of the flight trajectory for Saturn. One ballistic option was a very close passage within the inner edge of Saturn's ring system. Another was an encounter that would lead Pioneer 11 to a subsequent encounter with Uranus. In the end, NASA selected a trajectory that would cross Saturn's ring plane at about the radial distance that was being considered for future Voyager 1 and Voyager 2 encounters, thereby calibrating the survival probability for those missions. After its Saturn encounter, Pioneer 11 also had solar system escape velocity.

Both Pioneers 10 and 11 continued to provide uniquely valuable data as they flew through the outer heliosphere, most notably on the properties of the solar wind and on the cosmic ray intensity over a long time span and over previously unexplored distances from the Sun. Because of a combination of technical limitations, the flow of useful data from Pioneer 11 terminated in January 1995 at a heliocentric radial distance of 42 AU.

As of mid-2000, after over 28 years of flight, Pioneer 10 continues to operate well. Valuable, though rather sparse, data on cosmic ray intensity are still being telemetered reliably from my radiation instrument on Pioneer 10, now at a heliocentric radial distance of over 75 AU (11,220,000,000 km), a truly heroic achievement for NASA's Deep Space Network of receiving stations. (The radiated power of the S/C transmitter is only 8 watts.) We are seeking the boundary of the heliosphere but our most recent data show that the cosmic ray intensity at 75 AU is still influenced by solar activity. Hence, that boundary lies beyond, possibly far beyond, 75 AU.

Meanwhile, my Iowa colleagues are serving as the principal investigators on the currently active missions of Dynamics Explorer I, Geotail, Cluster II, Voyagers 1 and 2, Galileo and Cassini, and they are developing instruments for future missions.

INTRODUCTION

Space science is an eclectic mixture of the traditional disciplines of astronomy, physics, chemistry, geology and biology. The commonalty of its observational component is (a) the use of rocket-propelled vehicles for the delivery of instruments into orbit about the Earth, to the Moon, and through the interplanetary medium to and beyond distant planets, comets and astroids; and (b) the use of radio telemetry as the primary method for transmitting data to terrestrial stations. In addition, physical samples of the solar wind, lunar surface material and meteoric dust have been collected and returned for laboratory study. The return of samples of cometary dust and Martian surface material is planned.

The term space physics designates the sub-field of space science that deals with certain classes of electromagnetic radiations of solar system origin, as well as with electric and magnetic fields, ionized gases (plasma), energetic electrons and energetic ions. The heritage of space physics is well represented by the great monographs of Chapman and Bartels (1940), Störmer (1955), Mitra (1952), and Alfvén (1950).

The modern epoch of space physics began in the late 1940s with the use of high altitude sounding rockets and now encompasses the research efforts of thousands of investigators throughout the civilized world. Sophisticated instruments of superb quality are being flown on all manner of automated, commandable spacecraft. The original data are, for the most part, descriptive of natural physical phenomena, whose interpretation engages a growing cadre of theorists and modelers. In addition, numerous artificial experiments are being conducted in space (Hultqvist and Fälthammar, 1990).

This chapter is a tutorial review of magnetospheric physics, with primary emphasis on the magnetic fields of planets and the energetic particles therein. Aside from this fresh introduction, it is a reproduction of the author's "Kuiper Prize Lecture: Electrons, Protons, and Planets," which was sponsored by the American Astronomical Society, published in the journal *Icarus* (**122**, 209–232, 1996) and reprinted in this volume with the copyright permission of the Academic Press. The relatively short bibliography comprises classical and recent monographs, reviews, major compilations of papers, and a few original papers, but does not cite scores of other original papers.

MAGNETISM OF PLANETARY BODIES

The interior of the Earth has an estimated temperature of several thousand degrees Kelvin, far above the Curie points of all known ferromagnetic substances, i.e., the temperatures above which they lose their ferromagnetic properties. Common evidence for such high temperatures is the flow of molten lava from volcanoes on land surfaces and on the floor of the ocean. Also the permanent magnetization of the cool outer crust is far too weak and fragmentary to be important on a global scale.

It is now almost universally accepted that the general magnetic field of the Earth must be attributed to electromagnetism or the flow of electrical currents in patterns resembling those of laboratory solenoids (Rikitaki, 1966). The consequent magnetic field may be complex because of the likely complexity of the causative current system. However, at distances large compared to the dimensions of the current system, such complexity disappears and the general magnetic field is that of a small current loop or equivalent point magnetic dipole of vector moment **M**. In general, **M** of a planetary body may be offset with respect to the geometric center of the body and tilted with respect to the body's rotational axis.

A first-order approximation to the Earth's external magnetic field is that of a point dipole of moment $M = 7.90 \times 10^{25}$ gauss cm^3 (0.304 gauss $R_\oplus^3$, where the equatorial radius of the Earth, 1.0 $R_\oplus$ = 6,378 km) located at the geometric center of the Earth and tilted by 11.5° to its rotational axis. The corresponding geomagnetic poles are at 78.5°N, 69.1°W; and 78.5°S, 110.9°E (epoch 1965). The vector moment **M** points southward.

An improved approximation is obtained by displacing the same vector moment **M**, as in the centered dipole model, by 450 km from the Earth's geometric center toward latitude 17°N and longitude 149°E. This is called the eccentric dipole model. The need for such an improved representation is evident in global charts of the scalar magnitude B as a function of latitude and longitude at zero altitude.

Contemporary measurements establish the secular variation of the Earth's magnetic field and paleomagnetic evidence records reversals of polarity at irregular intervals on a time scale of the order of 10^5–10^6 years (Akasofu and Chapman, 1972), thus testifying to the long-term instability of the internal current system.

Maintenance of the necessary system of electrical currents is attributed to a self-excited dynamo, according to the theory pioneered by Bullard and Elsasser. In this theory, it is visualized that any initial magnetic field, however small, is amplified by the convective flow of electrically conducting material (e.g., molten lava) through that field to induce electrical currents of such strength as to achieve a quasi-steady state between energy input and ohmic and viscous losses. Detailed theories of this effect are complex and have not reached the stage at which quantitative predictions can be made, even given the interior conditions of a planet. But it does appear that two properties of the planet are necessary: (a) an interior that is sufficiently hot to produce a fluid, electrically conducting fluid, and to drive convective flow of that fluid and (b) a rotational rate that is sufficiently rapid to guide the pattern of convective flow. Plausible values of electrical conductivity are derived from laboratory experiments

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