Some Spacecraft I Have Known*

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INTRODUCTION

Spacecraft have personalities of their own. Some are attractive to look at; others look like an unsuccessful piece of cubist sculpture. Some are very demanding on the experimenter, while others are very easy to get on with. The great majority of them, I am pleased to say, work exceedingly well, and for a long time. It is a commonly observed phenomenon that equipment is much more reliable in space than in the laboratory. People seem to have a bad effect on space equipment.

Space research is carried out from satellites, rockets and from earth. In the following, I briefly touch on my experiences with each method. I also touch on that important problem "what do you do when your scientific interest seems to have dried up?". The short answer is "be thankful, a change is good for you".

THE CRUSADES OF SIR LAUNCH-A-LOT

My first direct involvement with satellites commenced in 1962, when NASA announced a series of spacecraft to be flown during the forthcoming International Quiet Sun Year (IQS Y). The primary goals of the missions were the measurement of the "baseline" properties of the interplanetary medium while the sun was very inactive. There was to be open competition for the space available on the spacecraft.

By today's standards, the spacecraft were minute. A grand total of 7 kilograms was available for all experiments; 5 watts of power; and typical data transmission rates of 16 bits per second (i.e. about 4 decimal digits per second). The spacecraft was to be "magnetically clean" and an absolute minimum of ferromagnetic materials was to be used in its construction. The fact that transistors, photomultipliers and many electronic devices used large quantities of a magnetic alloy was mercifully unknown to us at the time. We soon learned; the hard way.

My group proposed an experiment to measure the anisotropic characteristics of the "galactic" cosmic radiation that enters the solar system from elsewhere in the galaxy. The measurement was designed to yield the average properties of the interplanetary magnetic field in the solar system, and was therefore complementary to the direct measurements of the magnetic field and solar plasma (the "solar wind") that were to be made at the spacecraft. To our unending surprise, we were one of the six experiments chosen for the flights.

We realized that we had serious problems soon after we commenced the detailed design of the experiment. We had been given a weight allowance of 2.05 kilograms, while the smallest cosmic-ray detector we could build would weigh 1.60 kilograms leaving only 450 grams for electronics, power supplies, etc. It seemed quite impossible.

And then, as happens so often in science, a little luck came our way. Three kilometres away from my laboratory was the then relatively small company, Texas Instruments. I recruited one of their employees as my electronic engineer. And he said "why not use integrated circuits?". The first commercial production of ICs was still six months in the future, and none of my group had ever heard of such things. However, we obtained samples from the pilot production run (through the old boy network) and found they would do everything we wanted, with weight to spare!

Finding you can do it is one thing; being allowed to do it on a spacecraft is an entirely different matter. Reliability is of paramount importance, and proof of reliability is expensive. After an immense amount of paper work, argument and some vitriol, we were authorized to become the first experimenters to use ICs in an interplanetary spacecraft.

Pioneer VI was launched in December 1965. Within days our detector was telling us, in no uncertain terms, that the sun was far from quiet (Fig. 1). For more than 70% of the time, the galactic cosmic radiation was totally obscured by solar cosmic rays. Luck was with us again; the solar cosmic rays proved to be by far the more interesting of the two. We published eight papers on the solar cosmic-ray phenomena, versus a single rather lightweight one concerning the galactic radiation. It is interesting to ponder, however, that we would have been very unlikely to have been selected for the flight if we had proposed a solar cosmic-ray experiment.

Over the subsequent three years we built and flew experiments on six more spacecraft. While Pioneer VI was limited to measuring protons in the range 7.5-90 MeV, later experiments extended the proton range to include 1-8 MeV, and also measured relativistic electrons (i.e. E > 500 keV). In the later spacecraft the fluxes were measured from eight different directions, as against four directions in Pioneer VI. Each improvement was a response to the desire to look at the physics of the interplanetary region at different scales. For example, measurements of the 100,10 and 1 MeV proton fluxes indicated the degree of "roughness" of the interplanetary magnetic field over distances

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of the order of $1.9 \times 10^{-9}$, $6 \times 10^{-4}$ and $6.4 \times 10^{-6}$ astronomical unit (AU; the distance from the sun to the earth).

Five years, seven spacecraft and over a hundred solar flares gave us an entirely new understanding of the manner in which cosmic rays flow under the influence of the interplanetary magnetic field. This understanding is illustrated by Figure 2. The first cosmic rays reach the satellite by travelling along the lines of force of the solar system field (Fig. 3). This is understandable through simple orbit theory applied to a charged particle in a well-behaved magnetic field.

By the end of the first day, however, the maximum flux of cosmic rays is no longer parallel to the interplanetary magnetic vector. It is parallel to the direction of flow of the solar wind. The solar cosmic rays have been scattered by small kinks in the interplanetary field and move, en masse, as if attached to the moving solar wind. They are "surf-riding" out of the solar system with the radially expanding solar wind.

After several more days, the maximum flux of solar radiation is from a direction at right angles to the interplanetary magnetic field. By now, most of the cosmic rays generated in the original solar flare have ridden the wind to

Fig. 1. The upper graph shows the arrival of low-energy cosmic rays from a solar flare that occurred early on 30 December 1965. The flux of non-solar cosmic rays remained essentially constant until 2 January 1966, when the magnetohydrodynamic shock wave generated by the flare reached the spacecraft. (From McCracken et al., 1967)

Fig. 2. Summarizing the behaviour of the cosmic-ray flow vector as a function of time, subsequent to a solar flare on 30 March 1969. (From McCracken et al., 1971)

Fig. 3. Summarizing the nature of the interplanetary magnetic field, and the manner in which a low-energy cosmic ray travels from the sun to the spacecraft by spiralling along the surface of a magnetic tube of force. (From McCracken, 1969)
points well outside the orbit of earth. Some of these particles are scattered into orbits that cause them to spiral back along the interplanetary lines of force towards the sun. It can be shown that this implies that the flux will be a maximum at right angles to the magnetic induction vector. It all seems simple and quite straightforward now, but the sun had to give us many hints before we, and our theoretical colleagues, could tell us how obvious it all is.

**NEW FIELDS**

While we were preparing Pioneer VI for the Quiet Sun Year, a new field of astronomy was being born. My former boss at the Massachusetts Institute of Technology, Bruno Rossi, confounded the theoreticians when he and his colleagues observed X-rays coming from near the centre of the galaxy. A repeat performance of the radio astronomy story seemed an exciting possibility.

Rossi's pioneering discovery was made by detecting 2-8 keV X-rays. These are rapidly absorbed in the atmosphere, and must therefore be measured either from a rocket or a satellite. However, the absorption length of X-rays rapidly increases with energy, and simple calculations showed that 30 keV X-rays might be observable using an instrument carried to about 40,000 metres on a high-altitude balloon.

At the time (1963), we were preparing to fly a balloon version of our Pioneer experiment from Hyderabad, India, as a contribution to the International Quiet Sun Year. We therefore decided, on very short notice, to include an X-ray astronomy "hitchhiker" in our balloon experiment. Despite its extreme simplicity, it detected a strong X-ray source in the constellation Cygnus. It showed that extreme X-ray spectra extended to high energies, making the mechanism of origin seem even more remarkable.

At this time I was preparing to return to Australia in 1966, and was actively seeking a research activity that could be carried out at home. The Woomera rocket range; the balloon-launching base at Mildura; the galactic centre being in the southern sky; and the success in India made X-ray astronomy the obvious choice.

The first problem was to gain access to rocket flights from Woomera. While over 200 "Skylark" rockets had been flown as part of the 50-50 British-Australian joint project, no Australian experiment had ever been accepted for flight. Therefore, together with Geoff Fenton of the University of Tasmania, I approached the British authority responsible for the scientific programme at Woomera. At that time Australians still had "British" passports and in jest we pointed this out, saying we wanted to apply to fly as British, not Australians. The British thought it was a huge joke, and we were accepted. And so it was that the first Australian experiment flew out of Woomera on the 244th Skylark launch as part of the joint programme.

Lady luck was particularly kind to us this time. Predictably, we discovered several new X-ray sources (Fig. 4) because we could see the 40% of the celestial sphere that is invisible from the northern hemisphere. Our two flights also provided a much more important result, however. The intensity of one of the new sources in the southern sky decreased substantially in the period between the flights. Six weeks later it was invisible. We had positive proof that X-ray stars vary in intensity. This set distinct limits on the nature of X-ray stars. It paved the way for the postulation of such exotic source mechanisms as gravitational accretion of mass onto white dwarfs and, later, black holes.

**DOWN TO EARTH**

By the end of the 1960s, the prospects for conducting significant space research in Australia were very dim indeed. The Skylark programme was being discontinued from Woomera. In the USA, space research was increasingly "experiment by committee". I decided it was time to change my research interests again.

I therefore sought an area of research that was closely aligned to the industrial and political aspirations of Australia. The history of astronomy in the 18th century; chemistry in 19th-century Germany; and space research in the USSR and USA indicated the wisdom of such an alignment.
At the time, the nickel boom was suffering its terminal series of convulsions. It had become clear that the exploration technology developed for recently glaciated countries (e.g. Canada and Sweden) had failed miserably in regions of old, thick, saline soils. Development of a technology tailored to the Australian environment was clearly necessary. The Commonwealth Scientific and Industrial Research Organization (CSIRO) decided to enter this area of research, and I was lucky to be offered a job with them. This required supreme courage on their part; I knew absolutely nothing about minerals exploration.

The subsequent decade has emphasized the virtue of a scientist changing his research interests several times during his professional life. Being unencumbered by the dead hand of convention, and possessing several very unconventional skills, my colleagues have made a number of significant advances in response to the challenge presented by the Australian environment. In particular, the technology and mental attitudes of space research have proven to be important tools in meeting this challenge. The only real problem has been the very human one of communication; without a common background, serious misunderstanding can occur between the practitioner and the researcher. But that is another story!

To illustrate the application of a "space research" mentality to minerals exploration, I cite a single example of recent work that is now of major practical importance in Australia, and which is providing Australia with a significant international reputation.

In the late 1960s, NASA, in collaboration with the US Geological Survey, began building a satellite to provide "photographs" of the earth which could aid the management of resources. These satellites became known as the Landsat series. A group of Australian scientists proposed a series of experiments involving Landsat, which were accepted by NASA.

The subsequent history of Landsat in Australia is extremely illuminating. It demonstrates, yet again, the danger inherent in uncritical transfer of technology from one country to another.

The Landsat images available in 1972-73 were found to offer very little that Australia didn't know already. The imported technology had been tried, and had been found wanting. Industry, and the research community, rapidly lost interest in the product.

Then Andy Green in my laboratory made an extremely important discovery. He showed that much of the detail being transmitted by the spacecraft was never reaching the Australian user. The processing and copying procedures that were right for many parts of the world were wrong for Australia. From space, Australia is a very bright continent, and inadequate allowance was being made for this. The resulting images of Australia were noisy and of low contrast.

Green therefore went back to the digital data that were originally transmitted by the spacecraft. He and his co-workers developed computer techniques that yielded a greatly improved Landsat product. But was the improved product of any practical use?

In the first place, it was clear that Landsat's role would be to augment existing data sources, and that the satellite data would probably assist in some applications, but not in others. It was also clear that some of Landsat's advantages would be in areas involving commercial secrecy, such as crop prediction and mineral exploration. Preliminary investigations made it clear that it would be virtually impossible to gain access to the data of most interest to us in this regard. Further, our resources were inadequate for investigating enough separate applications to reach a statistically significant result.

We solved this problem of assessing the product by involving Australian industry in the research. Through the Australian Mineral Industries Research Association, we set up eight "characteristic regions" in which to conduct our joint investigations. The nine companies involved contributed their own large-scale geological maps, etc., and provided assistance during data collection on the ground.

In addition, however, we knew the companies would then use the technology they were gaining in the project on exploration prospects that were too sensitive for discussion with us. We knew that their success in these preliminary investigations would determine whether their Boards would endorse routine use of the technology in the future. These would be the real tests of practical usefulness of the new techniques.

Our joint experiment with industry has now been running for three years. We have all the conventional results of such scientific work: numerous papers; demand to speak overseas; many international visitors. These tell us nothing about the original question, "how useful is Landsat"? No one is about to tell us if Landsat helped them find a new orebody; or how much time and money it saved. But we can observe certain phenomena. Thus quite a few mining companies are now setting up equipment similar to ours, which will give them greater accessibility to the Landsat data as well as improved confidentiality. Each installation costs no less than $100,000. Sales of our computer-enhanced imagery have increased fourfold each year since 1977, and are now estimated to run in excess of $300,000 p.a. Many companies now have "Landsat specialists", and job advertisements specify "experience with Landsat". We conclude with confidence that the mining industry finds Landsat to be very useful indeed.

CONCLUSION

It has been a marvellous experience to participate in the "space research" era from the very beginning. A whole host of new discoveries have been made, and it has been immensely stimulating to contribute to the radical changes in scientific knowledge that have ensued. Luck, hard work, a little guile, a willingness to gamble and an open
mind seem to be the main ingredients that have led to success. I suspect it is so in all fields of science.

After ten busy years, it has been an invigorating experience to apply myself to the problems concerned with the Australian part of spaceship earth. I have found "space" skills to be highly relevant. I venture to say that two of our most successful projects would not have succeeded without our knowledge of space skills. The sales that have resulted from these projects amount to in excess of $750,000 p.a. already; the total benefit to the Australian economy exceeds this by a factor of 10.

It is well to recall that many Australians regard space research as a "waste of the American taxpayers' money". They are probably totally unaware of the role space research has played in providing Australia with an excellent international telephone service, more accurate weather predictions, and improved exploration for minerals (to name three). I see space research as a further example of the symbiotic relationship between the pursuit of knowledge and the derivation of practical benefits. To pursue one of these and ignore the other will be to the long-term disadvantage of all mankind, since it will kill both the intellectual, and the practical outworkings of science.

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