Freedom, Research and Serendipity: The Joy of Discovery

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When asked to write this article, I wondered from where to start and what to write: in chronological order or by research domains? I decided to focus on how fun it is to do science, on the importance of freedom and serendipity, and to only mention subjects close to radio science.

I grew up among books, in the heart of the Paris Latin quarter, into a family that valued education and knowledge. When I was a small girl, my father – a land surveyor – sometimes took me to his office in Paris city hall, and lent me a small part of his desk, covered with maps, squares, and pencils, and a mechanical calculating machine operated by turning a handle that I could not touch. I loved Jules Verne's books, my heroes were explorers of the world, and some teachers despised me because I harassed them with questions they could not answer.

Understanding the world meant studying physics and/or biology. At the end of my studies at École Normale Supérieure, when I had to choose a PhD subject, an exceptional opportunity arose: Jean-Louis Steinberg had created a laboratory of space radio astronomy in the Observatory in Meudon (Figure 1), and was assembling a team of young physicists and engineers. Located at the edge of a forest, the Observatory in Meudon was (and still is) a wonderful and magical place, with old remains dating from Louis XIV, buildings and instruments scattered among meadows where wild orchids spring up, and a pond full of huge carp seeming nearly as old as the buildings.

Figure 1. Meudon Observatory in Winter

There started my professional career.

In the 1970s, May 1968 was close by, with the freedom brought about by those events, and French space research was in its infancy, as well as the Centre National d'Études Spatiales. My PhD subject was very exciting. I would be responsible of a mission involving three small rocket launches in the ionosphere, to solve an interesting space radio-astronomy problem. Space environments are ionized, except for the close vicinity of planets protected

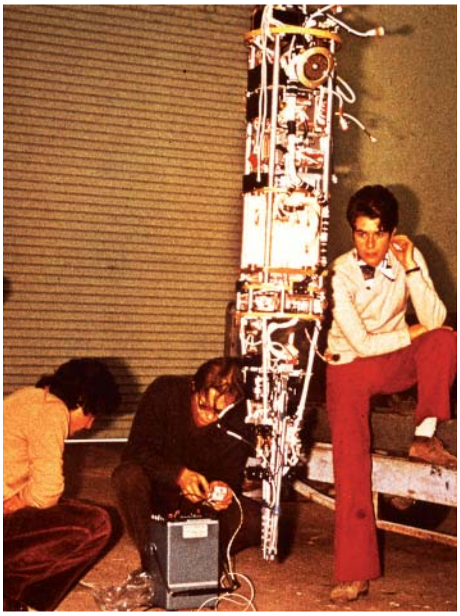

Figure 2. Tests on the payload at CEL in 1970 (l-r: P. Tilloles, R. Manning, and N. M.-V.).

Figure 3. Our office at CEL (l-r: N. M.-V. and P. Tilloles).

Figure 4. The Dragon rocket with the payload EIDI 1 on its launch pad (22/10/1970, photo C.E.L.).

by their dense atmospheres. Spaceborne electric antennas are thus immersed in plasmas. How are their measurements affected at frequencies close to the plasma resonances? This question had been tackled by some pioneers, such as Keith Balmain (who was to participate in my thesis jury), but many questions still remained and no data were available.

French rockets were then launched from the "Centre d'Essais des Landes" (CEL), a military base close to Biscarosse beach. We worked there to test the instruments (Figure 2), waiting for suitable launch conditions. We were young, having much fun, and the boss (me) was a 24-year-old female scientist. We got about by bicycle, and our office was littered with a mess of electric material, papers covered with figures, and even comics (Figure 3). The military did not like it!

When space science was in its infancy, a PhD thesis based on a space mission (Figure 4) required doing almost everything, from instrument testing to plasma-physics calculations: - marvelous school to learn space science. I had the luck of having a boss, Jean-Louis Steinberg, who gave me entire freedom... even when he did not agree with me.

These small experiments (EIDI), which measured the impedance of electric antennas in the ionosphere, would, after many peripeties, lead to a novel technique to measure plasma properties in space, and even to detect dust grains. However, we did not yet know that.

After my thesis, I began to explore several domains outside my research area. I had joined the French Centre National de la Recherche Scientifique (CNRS). They rightly wanted me to provide a research program, and were very angry when I refused to do so, since I had not yet found a suitable subject. Fortunately, my boss backed me up, asking them to let me be free. I then applied to a CNRS Biology course for physicists. Extrasolar planets had not yet been discovered, and the organizers did not understand why a young researcher in space radio astronomy wished to study biology, so they rebutted me.

I then fumbled into my PhD studies. Since Nyquist's theorem tells us that the electric noise measured by an antenna is related to its electrical resistance via the

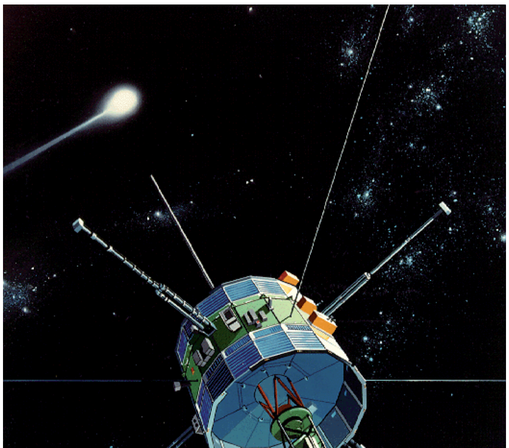

Figure 5. The spacecraft ISEE-3, later renamed to ICE.

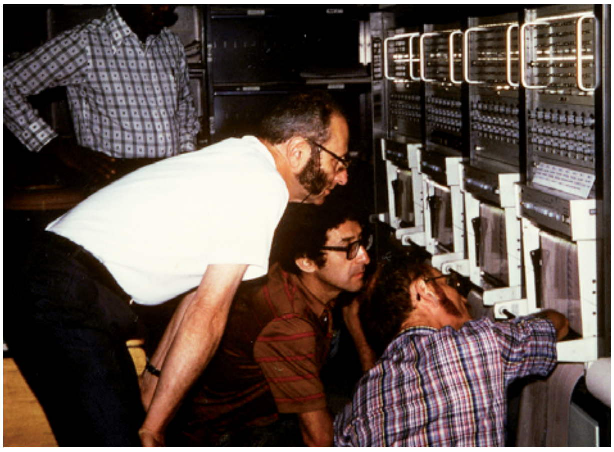

Figure 6. J. L. Steinberg, J. Fainberg, and R. Knoll looking at the first data at NASA/JSFC (8/13/1978, © S. Hoang).

Figure 7. (l-r) S. Hoang, C. Perche, N. M.-V., and P. Couturier showing their results on the day after the encounter (September 1985, NASA/GSFC).

temperature of the surrounding blackbody, one should measure in the interplanetary medium a weak, but detectable, noise produced by the quasi-thermal motion of the plasma electrons around the antenna, which should reveal the local electron density and temperature. In other words, an electric antenna connected to a sensitive radio receiver could serve as an *in-situ* plasma particle detector! I calculated the spectral density that should be measured in the solar wind and submitted this prediction to the *Journal of Geophysical Research*. Unfortunately, the journal rejected the paper, on the grounds that such a noise had never been measured before, and that anyway the theory was too simple to be applicable in the solar wind; the reviewer suggested that I should instead submit my manuscript to a purely theoretical journal.

Then, luck intervened.

The International Sun-Earth Explorer-3 (ISEE-3, Figure 5) had been launched a few days after the submission of my paper, and was orbiting in the interplanetary medium around the L1 Earth-Sun Lagrangian point. It carried the most-sensitive radio receiver ever flown, the data from which were becoming available. Furthermore, the investigators (Figure 6) were just discovering a weak "mysterious" radio emission, the spectrum of which turned out to agree in amplitude and shape with my predictions! This agreement prompted the immediate acceptance of the manuscript, which provided also a basic alternative explanation for observations previously interpreted as "new" emissions due to plasma instabilities.

In the beginning, this paper was badly received. Theoreticians did not like it because the early 1980s were the great epoch of plasma instabilities. Showing that emissions previously interpreted in this way were instead due to an effect as trivial as quasi-thermal noise was a crime of lèse-majesté, even though this explanation followed *Ockham's razor* prescription that "pluralitas non estponenda sine necessitate." Experimenters did not like it either, because this novel technique of measuring *in situ* plasma properties via analysis of a noise spectrum contradicted the current paradigm that plasma detection by wave instruments should require "active" sounding. Furthermore, this simple "passive" technique could be a serious challenger in the hard battle for instrument selection on future space missions.

However, luck struck again. Halley's comet was returning soon, and space agencies were in a hurry to prepare exploring missions. The Halley's armada included the European Space Agency's Giotto, two probes built by the Soviet Union, and two Japanese probes. For once, the US would not take the lead! However, the NASA engineers discovered that they could change the trajectory of the spacecraft ISEE-3, then renamed International Cometary Explorer (ICE), to make it encounter the plasma tail of comet Giacobini-Zinner near its 1985 perihelion, one year before the armada encounter with comet Halley. This gave us an opportunity to measure *in situ* the comet's plasma properties with the inboard radio experiment via the new method of quasi-thermal noise spectroscopy (QTN), if two conditions were met.

Figure 8. Bob Stone and J. L. Steinberg, ISEE-3/ ICE radio instrument PIs (© S. Hoang).

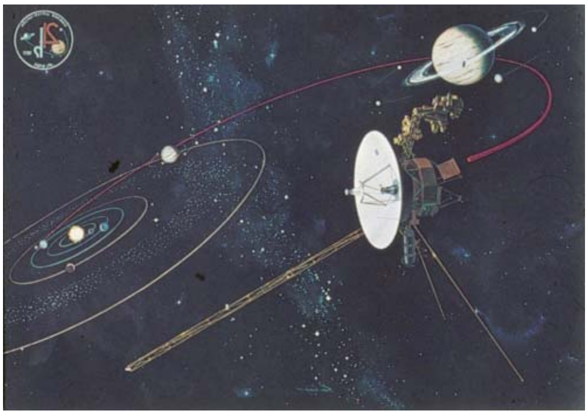

Figure 9. The mission Voyager (only Voyager 2 explored the planets Uranus and Neptune).

Figure10. The strawman payload of the space agencies (adapted from Meyer-Vernet et al., *J. Geophys. Res.*, 2017, drawing by F. Meyer).

First, the comet should not be too dusty, so that the fragile 0.2-mm radius electric antennas would not be broken by dust impacts. Second, the ambient plasma Debye length should be smaller than the 45-m antenna length, for this latter length to exceed the involved (Langmuir) wavelengths. Luckily, the comet was not very dusty and the plasma tail was dense and cold, so that both conditions happened to be met.

Our small team worked night and day in the stimulating environment of NASA Goddard Space Flight Center (GSFC), and produced the first and only measurement of the electron properties in a comet's plasma tail (Figure 7).

The radio experiment that its designers (Figure 8) had originally planned for solar-burst radio mapping thus had turned out to also be an efficient plasma *in situ* detector.

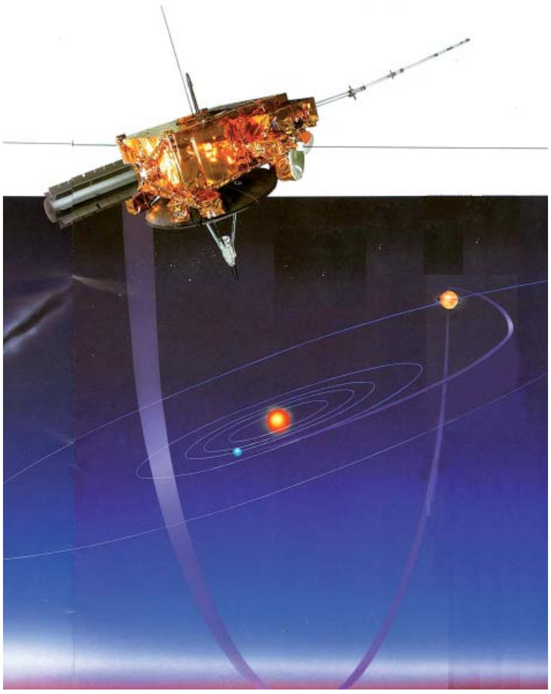

Figure 11. An artist's view of Ulysses exploring the solar wind in three dimensions (ESA).

In contrast, the dedicated plasma detector did not work well, because the comet's tail properties were outside the range for which the instrument had been built. At the hotel near GSFC, we happened to have a discussion with an American journalist who was surprised that being a woman with two children, I could lead the QTN team. She did not believe me when I explained that my husband was taking care of them in my absence, and that this behavior was common in France.

A few years before the comet saga, another event extended the range of *in situ* detections with radio receivers. The twin Voyager spacecraft, maybe the greatest space mission of the 20th century, carried a Planetary Radio Astronomy experiment (Figure 9). At Saturn's ring plane crossing in 1980, this instrument measured an intense power spectrum, decreasing with frequency as f^{-4}. Where did it come from? The Voyager's did not carry dust detectors, but the plasma-wave instrument, operating at lower frequencies than the radio instrument, simultaneously measured an f^{-2} power spectrum, whereas its waveform receiver detected electric pulses due to the charges produced by the vaporization of dust grains impacting the spacecraft. The radio-receiver measuring frequency exceeded the inverse of the pulse rise time, itself much smaller than the relaxation time. This meant that the voltage pulses should have an f^{-2} Fourier transform, which explained the observed f^{-4}

Figure 12. The Ulysses radio receiver.

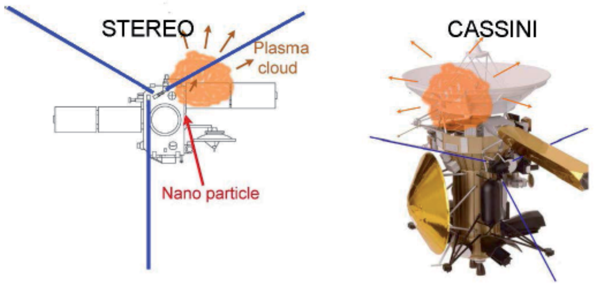

Figure 13. The principle of in situ dust detection with a radio instrument on STEREO and Cassini (electric antennas shown in blue, and impact plasma cloud shown in orange).

power spectrum. On the other hand, the plasma instrument, working at frequencies intermediate between the inverse of the rise and decay times, should see roughly step-like pulses, which explained the f^{-2} power spectrum. In this way, the electric antennas measured the dilute E and G rings of Saturn onboard, respectively, Voyager 1 and 2. We performed similar detections in 1986 and 1989 when Voyager 2 crossed the dilute rings of the planets Uranus and Neptune.

These results proved that long electric antennas onboard spacecraft (Figure 10), the radio receivers of which are generally designed to measure electromagnetic waves from distant sources, could be efficient *in situ* detectors for both plasma and dust. This paved the way to *in situ* measurements of plasmas and dust in various media – such as comets, planets, and the solar wind – onboard numerous spacecraft carrying radio instruments.

October 6, 1990, saw the launch of Ulysses, the outcome of thirty years of international engineering and science efforts to send a spacecraft where no probe had ever flown. Exploring the heliosphere outside the ecliptic plane was proposed as early as 1959 by a few visionary scientists, but only in the 1970s did the idea appear technically feasible by using Jupiter's gravity assist (Figure 11). The American and European space agencies then proposed the International Solar Polar Mission, a package of two spacecraft that were to be launched in 1983 and sweep towards opposite sides of the ecliptic plane, in order to achieve a stereoscopic view of the solar wind. Unfortunately, technical and financial difficulties led NASA to cancel the US spacecraft, transforming the mission into a single spacecraft built by ESA, carrying European and US instruments, to be launched by the Space Shuttle. In late 1983, the project had still to wait because the Shuttle was not ready. 1986 saw a catastrophic event: the Space Shuttle Challenger blew up, a few months before the planned launch, further delaying the mission.

Ulysses carried ten sophisticated instruments, and its three-dimensional exploration of the solar wind changed our view of the heliosphere. I had the chance to work on the results of the Unified Radio And Plasma Wave Experiment with a team of colleagues and friends at Meudon and NASA/GSFC, while leading brilliant PhD students. The radio receiver built at Meudon, despite its old technology (Figure 12) due to the numerous launch delays, worked perfectly well during the 18 years of the mission. Among many results, it produced routine solar-wind electron measurements with the new QTN technique.

Jupiter's encounter enabled Ulysses to explore the plasma torus of the satellite Io, and to measure the electron properties in this medium, therefore extending the technique to magnetized plasmas. This work showed that electric antennas in space do not always behave as expected. Electric fields are generally deduced by dividing the voltage by the antenna length, since short antennas measure a voltage proportional to their electric length and respond best to electric fields along their length. However, although the antenna was electromagnetically short, the power was not maximum when the electric field was oriented along its length. This was because the antenna measured (electrostatic) Bernstein waves, of wavelength close to the electron gyroradius, much smaller than the electromagnetic wavelength, so that the antenna was not short for these waves. These measurements also illustrated the non-Maxwellian nature of plasmas and its important consequences: a change of paradigm pioneered by Jack Scudder in another context.

Electric antennas also served to discover nanodust accelerated by the solar wind. This is a science detective story and a notable example of serendipity. This was also a striking performance of radio science, since this *in situ* detection was made with two spacecraft, STEREO and Cassini (Figure 13), carrying different wave receivers, whereas dedicated dust detectors had not seen such solar-wind particles, which were unknown when the instruments had been built.

The story began when the wave instrument on STEREO (S/WAVES) measured voltage pulses with an intense and variable power spectrum close to f^{-4}, similar to the radio-dust measurements made by Voyager in planetary rings nearly thirty years before. However, these measurements raised a big problem. The amplitude of the pulses suggested micro dust, but the pulse rate implied a dust flux exceeding the known values by four orders of magnitude, since the spacecraft was at 1 AU, far from any planet or comet.

The solution emerged at an ISSI International Team on "Dust-Plasma Interactions," led by Ingrid Mann. She showed me her recent paper, suggesting that the solar wind carried nanodust, the large charge-to-mass ratio of which enabled the nanodust particles to be accelerated by the Lorentz force up to roughly the solar-wind speed. This work brought about the missing piece of the puzzle. Indeed, the electric charge released by vaporization and ionization of dust grains impacting a spacecraft increases with speed much faster than their kinetic energy. A nanodust

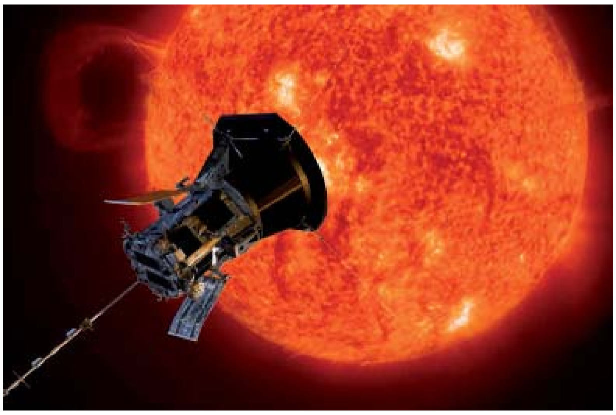

Figure 14. Parker Solar Probe (artist concept, credit: NASA/Johns Hopkins APL/Steve Gribben).

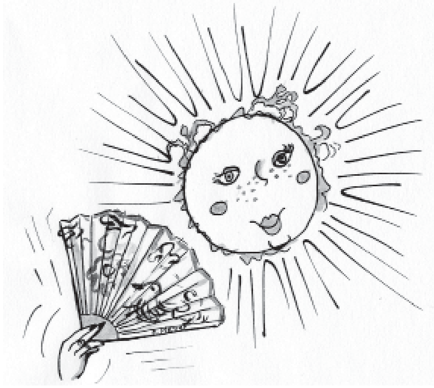

Figure 15. How does the solar wind blow? (*Basics of the Solar Wind*, Cambridge University Press 2007, drawing by F. Meyer).

impacting at solar-wind speed hence releases a similar charge as a micron-sized grain impacting at Keplerian speed. The impacts could thus be nanodust, which should solve the impact-rate problem, since their flux was expected to exceed that of microdust by several orders of magnitude; we then submitted a paper on these results. However, this was not the end of the story, since the original paper was rejected on the grounds that dedicated dust detectors had not previously observed these particles in the solar wind, and that radio instruments were not expected to be good enough to detect such dust in space.

To answer this objection, we then looked at the data of the radio receiver (Radio and Plasma Wave Science) on the spacecraft Cassini close to Jupiter, at times when the dedicated dust detector had detected fast nanodust ejected from Jupiter. We found nanodust signals at similar times with a similar rate as found by the dust detectors, proving that radio instruments were indeed capable of detecting nanodust, contrary to claims of the contrary. The final confirmation came from the Cassini radio data during the spacecraft cruise phase between 1 AU and 5 AU in the solar wind. Nanodust were there, with a variable flux compatible with both that found on STEREO at 1 AU and the theoretical simulations, and decreasing with distance as expected.

The performance of a radio receiver at the ports of an electric antenna for measuring *in situ* plasma particles and dust played an important part in the selection of the FIELDS instrument on the Parker Solar Probe mission (Figure 14). This was to carry electric antennas but no dedicated dust detector. It will approach the sun up to 9.5 solar radii in 2025, in order to understand the solar corona and the origin of the solar wind (Figure 15).

However, this is another story.

Figure 16. Some participants in the "Rencontres de l'Observatoire" at Meudon in January 2000 ("Physics of Space: Growth Points and Problems," Astrophys. Space Sci., 277, 381, 2001).

Figure 17. During a mini-symposium at the Solar-Terrestrial Centre of Excellence (l-r: E. N. Parker, J. Lemaire, and N. M.-V., Brussels, June 2009).

I will not mention a number of studies in other domains of physics and astronomy, but I wish to evoke the importance of friends and colleagues and of the international dimension of research: working together on projects and problems, laughing, exchanging ideas, learning new subjects, understanding surprising data, fighting together to make people change paradigms and accept new ideas or measurement techniques. Many people of diverse languages and cultures have influenced me (Figure 16), either personally or through their writings.

For example, the Ulysses data raised a number of new problems and were a strong encouragement to study the physics of weakly collisional plasmas, the importance of not being Maxwellian and the limitations of fluid models, in particular in the solar wind. I then had the great opportunity to meet a pioneer of kinetic solar-wind models, Joseph Lemaire, and to be involved in lively disputes between him and Eugene Parker on the importance of the electrons in accelerating the solar wind: another example of the difficulties in changing paradigms (Figure 17).

Juggling with spacecraft, planets, plasmas, and dust, while learning new subjects, is so rewarding that I always had (and still have) much fun in doing research (Figure 18). During my career I never had the impression of working, partly thanks to the support and warm environment of my laboratory, the LESIA (Observatoire de Paris, Meudon). Starting as a group focused on space radio astronomy, it now covers a wide spectrum of subjects, from solar physics to planetology, stars, galaxies, extrasolar planets, and high-resolution optical techniques with applications from astronomy to biomedicine. I am also now working part-time on the subject I wanted to address many years ago: physical biology and applications to the prospects of life on other planets. Such freedom and independence of fashion is unfortunately more and more difficult to achieve nowadays, because most institutions do not like free spirits (Figure 19).

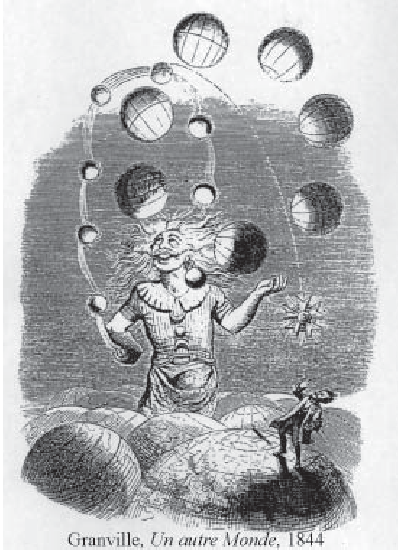

Figure 18. From "Un Autre Monde" (Granville, 1844)

> Theologians have their bells to ring: physicists have their laughter.
> (Bertolt Brecht in *Life of Galileo*, translated by John Willett, New York, Arcade Publishers)

Figure 19. N. M.-V. in the Observatory in Meudon.