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The magnetosphere as a plasma laboratory

INTRODUCTION

Most of the baryonic matter in the Universe is in the plasma state. This comes about when the temperature of the matter becomes so hot that the atoms spontaneously dissociate into positively charged ions and electrons. Because of charge conservation in this dissociation process, plasmas are usually quasineutral with equal numbers of negative and positive charges. In other words, the number densities, $n_{e,i}$, of the oppositely charged particles are equal, $n_e = Z_i n_i$, where the indices e, i indicate electrons and ions, and Z_i is the nuclear charge number. Since the overwhelming majority of baryonic matter is hydrogen, one usually has equal numbers of electrons and protons in the volume, $n_e = n_i$. Even when the fraction of the ionized component is small the ionized component shows a totally different behaviour than neutral matter. It is governed by the laws of electrodynamics and many particle theory rather than by gravitation. It is these interactions which lead to the particular properties of a plasma and distinguish it from other matter states.

Information about remote plasmas is obtained solely from the electromagnetic radiation that they emit. At temperatures on the order of eV ($1\,\mathrm{eV} = 1.6 \times 10^{-19}$ Joule corresponds to a temperature of $\sim 11\,000\,\mathrm{K}$) and much higher, this radiation is in the UV, X-ray, and radio wave ranges, the latter indicating the presence of magnetic fields. Of all this radiation, only long-wavelength radio waves can reach the surface of Earth, because all short wavelengths are absorbed by the atmosphere. The study of collisionless processes in plasmas in space thus became possible only after the advent of the space era. For astronomy, which had been previously restricted to the optical and long-wavelength radio wavebands, the space era opened up the areas of UV-, X-ray, Gamma-ray and Infrared Astronomy. However, from the point of view of physics, the greatest success in space exploration must be attributed to Space Plasma Physics. This domain profited directly from the possibility of *in situ* observation of the processes, the structure, and the particle and field distributions in the plasma environment of Earth. It discovered its richness and beauty and uncovered a wealth of new and unknown physical phenomena and processes which could not have been produced in the laboratory but are of utmost importance for the understanding of the properties of remote plasmas in astrophysics. Because, however, space plasma physics as a field of research does not, by its very nature, produce a multitude of nice pictures and photographs which please a broad public, the success of space plasma physics has been by far less spectacular than that of both groundbased and spacebound astronomy, where each technical progress literally opens up new vistas out into the Universe.

The plasma in near Earth space, which is the only one accessible to *in situ* measurements, is, with a few exceptions, invisible. The most spectacular of these exceptions is the Aurora. As it turns out, however, this phenomenon provides only a marginal indication of other much more violent processes taking place in the depths of near Earth space which would never have been discovered nor understood without direct access to these regions. One may easily conclude from this fact that many astrophysical observations are nothing but marginal indications of processes to which we have not the slightest access and which are hidden forever to our knowledge, forcing us into interpretations which may have little to do with what actually takes place out there.

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Rudolf A. Treumann and Manfred Scholer, The Century of Space Science, 1495–1528

In this respect, space plasma physics is of undeniable value. It provides the only possibility of testing models and processes which are believed to take place in plasma but cannot yet be directly measured. In fact, astrophysics has, probably more than any other science, benefited from the insights reached in space plasma physics. Many of its more successful models and descriptions are based on extensions and rescaling of the processes inferred from measurements in the plasma in near Earth space and in particular the Earth's magnetosphere, the easiest accessible part of all the cosmos.

To mention only one example, we refer to the very existence of Earth's magnetosphere (cf. Chapter 63). The possibility of a magnetosphere surrounding Earth and confining its magnetic field into a drop-like region was first suggested by T. Gold in 1949 as a theoretical idea lacking any experimental evidence and without any mathematical explication. It was picked up by the Russian plasma physics school at the end of the fifties, when it was already possible to perform measurements in space, using rockets and satellites. By the time when astrophysicists (Pacini 1967, Gold 1968, Goldreich and Julian 1969) made the first use of the notion of a magnetosphere in 1967–1969 in order to understand the physics of pulsars in analogy to Earth, the Earth's magnetosphere was already a well established and also, in its basic properties, a well understood fact.

The plasma in the magnetosphere and its closer environment constitutes an invaluable huge laboratory for the investigation of the processes taking place in a collisionless (or at the best weakly collisional) dilute warm plasma. This has been immediately recognized after the discovery of the magnetosphere. Thus most of the efforts to explore the processes taking place in the magnetospheric plasma are driven by two complementary intentions: the purely explorational wish to map and understand the space-time evolution of the near-Earth environment with the highest available precision and, at the same time, to use this environment in order to infer about the physical processes which take place in an extended dilute natural plasma. The former intention is the more geophysically and environmentally oriented one, which is of enormous importance in understanding the more extended human living space. The latter intention instead is entirely physically oriented and can be considered as the contribution of space physics to basic plasma research. These processes arise in the first place in the interaction between the high speed collisionless solar wind stream and the dipolar almost stationary geomagnetic field confined to the magnetosphere. They also arise in the dynamical mixing of plasma of solar wind origin with plasma of atmospheric origin. Thus the three main actors in the physical spectacle of space plasma physics are the solar wind, the geomagnetic field confined to the magnetosphere, and the electrically conducting upper layer of Earth's atmosphere, the ionosphere. With the solar wind, geomagnetic field and ionosphere at hand, one is in the fortunate position to monitor many processes to which we otherwise would not have any access.

In the present essay we review a number of the magnetospheric processes in the context of their history and their physical importance. When identifying such processes we have to be very selective. We therefore focus on only a few most obvious ones: the investigation of particle confinement in a magnetic mirror geometry as naturally given in the radiation belt dipolar geomagnetic field region, the formation of the Earth's bow shock wave, the surface of violent deceleration of the solar wind by the presence of Earth's magnetic field, on transport processes at the magnetospheric boundary, the magnetopause, on reconnection, on the generation of electric fields and particle acceleration, and on the most interesting processes of wave generation and radiation. Wherever possible, we also in passing attempt to point on the key historical events. However, as our historical knowledge and abilities are rather restricted we apologize for that the historical aspect will naturally fall short compared with the scientific description. Unfortunately, historical recollections by its main actors on these subjects are rather sparse. We refer the more historically interested reader to the article by Stern (1996) and references therein. Of interest in this respect are also the books by Van Allen (1983) and Kennel (1995), and an essay by Van Allen (1990). Additional historical information can be found in Gillmor and Spreiter (1997).

PLASMA CONFINEMENT: THE RADIATION BELTS

Historically, the phenomenon of plasma confinement in a magnetic mirror geometry was the first physical problem where space physics became aware of the existence of the magnetosphere.

The first few Russian spacecraft launched at the end of the fifties and in the early sixties of the twentieth century the first one, including the famous Sputnik I, launched on 4 October 1957 in honour of the fiftieth anniversary of the Bol'shevyk October Revolution (for a recollection of the shock on the American public and US administration and the immediate science-political activity following it see McDougall 1985), carried on board a few simple particle detectors which were sensitive to energies higher than a few 10 eV (or temperature of a few 100 000 K). One of us (R.T.) vividly remembers his feelings when, as a young high-school student during the autumn holidays in early October 1957, he saw the faint glimmering light of Sputnik I passing slowly and quietly over the dark late evening sky. No-one ever before had witnessed a man-made moon even as tiny as this one flying around Earth across the vast infinity of space. It was the sole privilege of our generation to be the first to visually experience and enjoy this demonstration and manifestation of the enormous achievements, dimensions and potentialities of human scientific and technological endeavour.

Very little was known at that time about the existence, density, particle flux and temperature of the plasma component in space. It was in fact widely believed that space was essentially empty, sometimes only crossed by high-energy cosmic rays, asteroids, quasi-regularly traversed by meteoric showers, occasionally by comets, and from time to time also by solar magnetic cloud ejections, which then caused strong geomagnetic storms the physics of which was largely unclear. Following the simple pioneering theory of Chapman and Ferraro, put forward nearly thirty years earlier in 1931, storms were boldly attributed to a brief compression of the geomagnetic field when one of these clouds, during its passage over Earth, transitionally compressed the geomagnetic field. The suddenness by which such storms begin did support this theory quite well, as did – in an entirely wrong interpretation – the long-lasting main phase of the storm, when the geomagnetic field on the Earth's surface falls below its undisturbed value, until it, finally, gradually recovers in the storm recovery phase. This undershoot of the field was, in its simplistic interpretation, attributed to an over-expanding geomagnetic field after the magnetic cloud had passed the Earth. One should note this disturbing and long prevailing lack of physical understanding of the storm mechanism and the even less well understood smaller sister of magnetic storms, the magnetic bay disturbance or, as it is called today, the *substorm*! The latter one was attributed solely to variations of currents flowing in the ionosphere. The only indication of space being filled continuously with plasma came from observation of comet tails, which are directed radially away from the Sun (Biermann 1951). This indication anticipated the solar wind.

Which instrument to put on a spacecraft depends on the expectation of what could be measured, and on the availability of instruments. The early Soviet spacecraft carried some low-energy particle traps. As it was known that space is continuously traversed by cosmic rays, the hope of the investigators was to measure *in situ* some of the lower energy cosmic rays which could not pass through the atmosphere, and possibly or occasionally some hypothetical medium energy solar particles, which, since the early theoretical endeavors of Störmer (1907), were thought to be responsible for the optical auroral emissions. They detected relatively strong charged particle fluxes at low altitudes and medium latitudes, the origin of which was difficult to explain (Gringauz *et al*. 1961, see also Lemaire and Gringauz 1998). The interpretation of these findings remained a mystery until the launch of the first tiny American satellite Explorer 1, of which a scale model mounted on its carrier could be lifted by its three principle experimenters, Wernher von Braun, James Van Allen, and William Pickering (Figure 1). Explorer 1 was carried into space in 1958 by one of von Braun's Army rockets "Juno", which was developed from the Second War German V2/V3 family also designed by von Braun.

Figure 1 William Pickering, James Van Allen, and Wernher von Braun (from left) proudly lifting a scale copy of the first U.S. satellite Explorer 1 and its launcher at a press conference after its successful launch into space by one of von Braun's Juno rockets a model of which is standing on the right of the table. (Courtesy, NASA, JPL photo, see also Murray 1990.)

Explorer 1 had on board just one single Geiger counter, which was provided in the last minute by James Van Allen and his collaborators, Carl McIlwain, Georg Ludwig and Ernest Ray, as the sole scientific instrument available at that time expected to work under space conditions (for a personal recollection of the history of Van Allen's contribution, see Van Allen 1996). Each time when the spacecraft passed a certain range of low magnetic latitudes at an altitude of a few hundred kilometers the counter fell into saturation. High particle flux had been detected permanently in those latitudes. It was Van Allen who immediately realized that these latitudes corresponded to a particular restricted range of dipolar geomagnetic field lines. The high particle flux detected here corresponded to particles that had been about permanently trapped in the dipolar geomagnetic field, a property of charged energetic particles that had been theoretically predicted long ago by H. Alfvén, E. Teller, T. Northrop and others, based on the theory of adiabatic motion of charged particles (cf. Northrop 1963). These regions were later called the Earth's Radiation Belts or *Van Allen Belts*, and are since publicly known as some regions which are biologically dangerous for astronauts to pass through. This is partially true, but the radiation belts are of danger in the first place for modern spacecraft like Hubble, Chandra, Rosat, SOHO and others because the high intensity of particle radiation can affect the highly sensitive instrumentation on board.

The origin of the radiation belts can be understood resulting from an interplay between the Earth's dense atmosphere and the flux of energetic galactic cosmic rays coming from the depths of the Universe and hitting the atmosphere. The collisions between the cosmic radiation and the atmosphere cause the cosmic ray albedo neutron decay. Neutrons, produced in the nuclear interaction between the cosmic rays and the nuclei of the atmosphere are reflected upward from the atmosphere. These free neutrons are unstable and decay into energetic protons and electrons which become trapped in the closed geomagnetic field configuration near the Earth, forming an inner and an outer radiation belt. The spectrum of the trapped protons typically decreases approximately inversely with energy from $\sim$1 MeV to $\sim$1 GeV. A third innermost belt is produced by the energetic interstellar ions of the anomalous cosmic ray component in our solar system. These ions have a high rigidity, ignore the geomagnetic field and penetrate deep into it. In collisions with the upper atmosphere they lead to ionization and become themselves stably trapped. Radiation belts have also been artificially generated during the enormous charged particle releases from atmospheric nuclear tests like the "Starfish" nuclear explosion in 1962. Sometimes similar injections of particles have been observed during very strong magnetic storms. Thus the origin of the radiation belts is well understood. However their persistent confinement, spatial structure and temporal variation requires explanation and provides an important and interesting exercise in plasma physics.

Plasma confinement is particularly important in fusion research, where a hot plasma with a temperature of $\sim 10^7$–10^8 K (or energy $\sim$1–10 keV) must be magnetically confined for a sufficiently long time in order to make possible the ignition and self-sustainment of the nuclear fusion reaction. At the high densities of a fusion plasma, these times are rather short and limited by collisions. At the low densities of the trapped particles in the Earth's (Van Allen) radiation belts, as these regions have been called, the trapping times can become very long, of the order of years, allowing for a detailed investigation of the injection and loss processes of trapped particles. Ideally, the particles can be trapped for infinitely long times because the trapped component does not experience any collisions. Thus the discovery of the radiation belts provided the immediate opportunity to study the properties of an ideally trapped plasma. This study led to a large number of hitherto unexpected results and to a deep understanding of the trapping process, one of the greatest successes in the early period of space science.

The early spacecraft carried instrumentation which was unable to distinguish between electrons and ions. Though it was clear that both kinds of particles could be trapped in the radiation belts, determination of the real distribution of electrons and ions in the belts had to wait until around 1975 for investigation and confirmation. At about that time, it was confirmed that protons above 100 keV energy populated one single large radiation belt, while the radiation belt electrons above 40 keV distributed themselves into two spatially separated belts, the inner and outer electron belts. The region between those two is called the *slot* of the radiation belts.

Pitch-angle diffusion

Stably trapped particles possess three adiabatic invariants: the magnetic moment, the bounce and the azimuthal drift invariant. Typical gyration times for electrons and protons

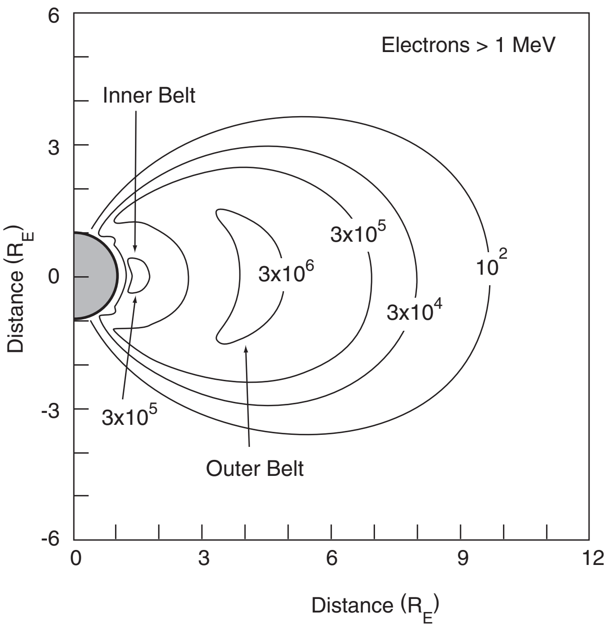

Figure 2 Spatial distribution of omnidirectional radiation belt electron flux (in units of electrons cm^{-2} s^{-1}) following the 1962 "Starfish" atmospheric nuclear test explosion. The flux distribution indicates the presence of an inner and an outer electron radiation belt. Constant flux contours follow the geomagnetic dipole field flux tubes. (After Walt 1994.)

Springer

http://www.springer.com/978-0-7923-7196-0

The Century of Space Science
Bleeker, J.A.; Geiss, J.; Huber, M. (Eds.)
2001, XLIX, 1846 p., Hardcover
ISBN: 978-0-7923-7196-0