Shock Waves—at KU and beyond

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I walked into the main physics office in the fall of 1980 looking for work—teaching or research. At the time I was working for the phone company as a construction foreman (TPA later made use of this background) and was fed up and ready to go back to school (having earned enough to help support myself). Jack Davidson, then the chairman, suggested that I talk to Tom Armstrong who might be able to support me. I did so and wound up working on the Nasa Lewis contract doing PIC simulations of spacecraft charging phenomena. I wasn't directly working with TPA on this contract—Jake Enoch was my advisor—although I had an office in 55, the largely Space Physics domain.

The following spring I took my first Space Physics course from Tom Armstrong and enjoyed the course very much. Incidently, I also met my husband by taking this course. We later joked that 'a good place for meeting a spouse' should be added to the course description. After taking space physics and having lively discussions with the other grad students that summer and the following year I was hooked. Actually, I should not call these discussions, per se, since what I mostly did was listen! I found the spacecraft charging research interesting but not absorbing and more and more was leaning toward something more in the main line of space physics.

I talked with TPA about this and, as he was wont to do, he came up with an idea for a new direction for me to pursue. The direction was not new to TPA, he is particularly good at establishing lines of research which a string of students would work on. I was to be the third (but not the last) in a line of people working on collisionless shocks—preceeded by Gloria Chen and Rob Decker, followed by Joe Giacalone. As a start he suggested I accompany him to a conference on collisionless shocks. This was really a hardship tour—the conference was held at a resort in Napa Valley, California. I had a sister living in San Francisco and she generously lent us her car, which on a tight budget may have been part of the reason my trip could be financed. I met and/or saw a lot of the people in the field who I would later become familiar with, I soaked up the terminology, but I can't say I learned a lot of physics. I did, however, enjoy the afternoons we had off for wine tasting and the excellent dinner at the Domain Chandon (who make a very good and affordable champagne—though not on a grad student budget).

For my thesis I examined the energization of charged particles due to their interaction with traveling interplanetary shock waves. I made use of observed magnetic fields, plasma bulk density and velocity to establish ambient conditions. I then followed particles through a single complete interaction with a shock using a time reversed computer simulation. The initial velocities were calculated using detector look angles, *i.e.*, the range of energies and directions which the detector could measure. I assumed that all of these represented real particles. I further assumed a relationship between energy and particle number based on a power law. Since the particles were followed backward in time, I could predict the initial distribution for the range of the instrument (0.29–0.5 MeV). I was able to reproduce the essential observed features for most of the shocks I studied. In the course of this study I used data that TPA either had already (plasma data) or acquired (magnetic field data). I also used the time-honored TPA technique of particle trajectory following. A new twist was to determine the shock normal which was necessary in order to establish the geometry. I wrote several computer programs to do so (different methods) and this turned out to be one of the most useful exercises of my graduate years—I used these methods and programs over and over again.

Although TPA did not always appreciate my working habits—I tended to work a lot at home and go into 55 mostly in the evenings when it was slightly less crowded—he eventually came to accept my somewhat unorthodox hours and my hat collection. He frequently worked in the evenings so there was always some overlap. His hard work inspired others besides myself. I knew if I got stuck I could go in and talk it over and he would come up with an idea of something I could try. This worked very well and I progressed towards my degree. I think he may have got fed up with me (and a large number of the 55 inmates) one summer when I spent a large portion of my time managing the department softball team. But we had a winning season and I learned management skills so I think it was time well spent. TPA even accepted the title I chose for my thesis :"Gone With the Solar Wind, A Study of Protons Accelerated by Interplanetary Shocks"; albeit reluctantly.

All in all, by the time I got my PhD I knew something about spacecraft charging, quite a bit about energy gain at collisionless interplanetary shocks, and a fair bit about computer programming. I have used one of the shock normal programs to calculate the normal at bow shocks, at cometary shocks and am in the process of rewriting it for multi-ion shocks. I have also used the spacecraft charging code in a project for the European Space Agency—we extended the allowed geometries, added features such as a non self-consistent magnetic field, multiple dielectric materials, streaming ions and others. I have not actually redone my thesis many times but I have made use of much of my graduate work. This is a tribute to TPA in that the research he suggests is timely and useful.

There is one thing (at least) that I did not learn from TPA and that is an appreciation of instrument hardware. I was content to take data at its face value and use it. Fortunately, the laboratory I went to after graduate school was mainly involved in building detectors and I was able to make up this deficiency. The Mullard Space Science Laboratory in Holmbury St. Mary (which the residents think is the middle of nowhere—40 miles from London—they have never been to western Kansas), Nr. Dorking (this is *Near* Dorking, not *North* Dorking), England, is housed in an old manor home in a picturesque setting. You could imagine yourself in another age were it not for the high tech hardware and software being developed on the premises. Besides the work on KU extensions already mentioned, I re-calibrated the ion plasma instrument on AMPTE-UKS, worked on a data compression contract for ESA, did data analysis for the AMPTE-UKS and GIOTTO missions and was lastly involved with two new missions: MARS 94 and CLUSTER.

The Cluster Mission

Cluster is a fleet of four spacecraft that will study small-scale plasma structures (from a few to a few tens of ion Larmor radii) in three dimensions. It is a collaboration between the European Space Agency, ESA, and the U. S. National Aeronautical and Space Administration, NASA. Cluster will be operated in conjunction with Soho, a solar and heliospheric monitor. Additionally, the Institute of Space Research (IKI) of the Soviet Academy of Science, Moscow, intend to launch a multi-spacecraft mission at about the same time which will be operated in close collaboration with Cluster and Soho.

The Cluster mission is planned to last for two years with the four spacecraft flying in formation in a polar orbit (apogee: 22 R_E, perigee: 4 R_E, inclination: 90°, orbit period: 66 hours). The spacecraft will be spin stabilized with the spin axis normal to the ecliptic plane. The orbits will be phased so that the four spacecraft lie at the points of a tetrahedron. The spatial separation will be adjusted for different phases of the mission over a range of about 500 to 18000 km. All four spacecraft will have an on-board cold gas thruster system, so that the inter-spacecraft separations can be varied intentionally. The four spacecraft will follow basically the same highly eccentric orbit around the Earth, but their velocities will vary so that there will be a significant periodic variation around the orbit in the size and shape of the tetrahedron. Work is continuing to investigate suitable candidate tetrahedra for different parts of the mission.

There are eleven different investigations planned, one of which is the Plasma Electron and Current Experiment (PEACE) which is a European consortium based at the Mullard Space Science Laboratory. The first task of the electron instrument is to determine the moments of the electron distribution function and then to determine the nature and causes of energization, scattering and diffusion processes that modify the distributions, especially at plasma boundaries.

The sensor requirements are four-fold: a complete and uniform coverage of viewing direction, a wide dynamic range, a fast time resolution and an energy range which is extended to the lowest energies. The requirements are met with two sensors: the Low Energy Electron Analyser (LEEA) covering the energy range 0 eV to 1 keV and the High Energy Electron Analyzer (HEEA) from 10 eV to 30 keV. Both are hemispherical electrostatic analyzers of the top hat type with a field of view of 360° in a half spacecraft rotation for HEEA and a full rotation for LEEA.

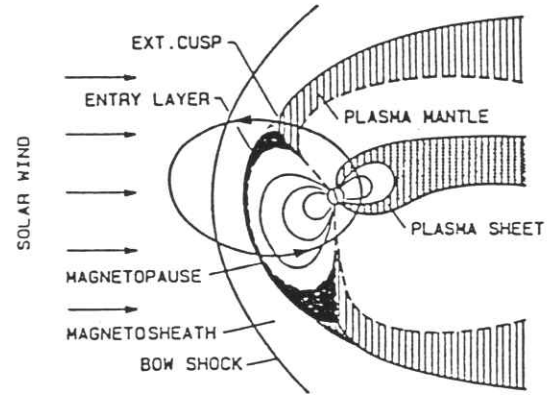

Figure 1: Cluster orbit in relation to the magnetosphere. The inter-spacecraft distances are $< 1R_E$.

Figure 1 shows the dayside orbit which will constitute about half of the mission (the other half being an orbit through the magnetotail). There will be two crossings of the bow shock in the 66 hour orbit, so telemetry allowing, there will be plenty of electron data. Frequently the lack of accurate measurements of electrons at energies less than 10 eV in the solar wind, and at the bow shock, has hindered interpretation of data from earlier missions where there are data gaps at these low energies. AMPTE-UKS and HELIOS measurements have indicated that the low energy population in the solar wind may not be Maxwellian as expected, and the AMPTE-UKS measurements at the bow shock suggest that this low energy population may behave differently from what is expected. Determination of the nature of the core population, and its behavior as it is transported through the bow shock and magnetopause will be a major objective of studies using measurements from the electron sensors.

The unique feature of Cluster is its three dimensional nature. Attempts have been made in the past to resolve the spatial/temporal ambiguity but with limited success. The International Sun Earth Explorer (ISEE) and the Active Magnetospheric Particle Tracer Explorer (AMPTE) missions used two spacecraft measurements along a common orbit. Both made important advances but only in a one-dimensional way along the orbit. If the underlying structure is planar than motion and vector gradient quantities can be determined. However, it is becoming increasingly clear that the structures are three dimensional and thus a group of 4 spacecraft in a non-planar configuration is necessary to resolve the ambiguities and determine the nature of the structure. Four spacecraft allow an unambiguous separation of spatial and temporal variations. This allows for a determination of current densities (from the curl of the magnetic field, $\mathbf{B}$), the vorticity of the flow (from curl $\mathbf{v}$, shear flows (from div **E**, and the momentum balance (from the divergence of the pressure and magnetic stress tensors).

It is important to know what the three-dimensional spatial structure of the shock surface is as well as how steady the structure is in time. These questions are particularly important for quasi-parallel shocks, where unsteadiness and spatial structure may be especially crucial. High time resolution, three-dimensional measurements of the electron distribution will help establish the macroscopic electrostatic potential structure of the shock, and determine how the transmitted core of the distribution is heated, thereby helping to identify the microscopic plasma instabilities which contribute to the shock dissipation parallel and perpendicular to the magnetic field.

My work in shocks is clearly not complete. Cluster may not be an end-all either but it is certainly a step in the right direction. I am looking forward to seeing those data sets!