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My dealings with the aurora borealis

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Two important decisions on my career path had the consequence that, after a quarter century of experimentation with barium plasma clouds, I was directing my research more and more towards physics of the auroral borealis. The combination of ground-based optical and radar observations and two national satellite missions were our means to deepen the understanding of the plasma physics background of the aurora, especially of discrete auroral arcs. Our contributions are put in perspective with the global research in this field by a quick run through the major steps in the exploration of the physics of the aurora. Although by the end of the 20th century all key ingredients for the understanding of auroral arcs were available, the present state leaves many open questions, foremost with respect to the true generators processes and the overall flow of momentum and energy. Some of these questions I tried to address during my retirement years.

KEYWORDS

career decisions, auroral plasma physics, brief auroral history, auroral generators, incomplete theories

1 Introduction

There are two interlinked goals for this Generation-to-Generation communications article. The first is that a career decision in the less challenging direction, based on the recognition of one's intellectual, physical, or other limitations, need not have negative effects on one's creativity and professional success. This applies to my way. It led more and more into the physics of the aurora borealis. As my second goal, I briefly review the development of this field during my professional life and conclude with some comments on the present state.

2 Recognize your limitations

Hardly any career has taken place without an event of luck and/or mentorship. This was so in my case. The lucky event was that I had been working on my thesis about the Van Allen Belt, when Germany decided to enter space research. A working group was formed to this end at the Max Planck Institute for Physics and Astrophysics in Munich in October 1961 under the direction of Reimar Lüst. It was almost natural that he invited the graduate student to join his group. The experiments with barium plasma clouds were quickly rewarded with fascinating optical phenomena, primarily in the auroral zone. That needed theoretical work and it turned out that I soon assumed the position of the house theoretician. On one of the first evenings of a rocket campaign in Ft. Churchill on the Hudson Bay, I experienced a fantastic auroral event, lying with my back on a rock and watching for at least half an hour the continuously moving and changing auroral arcs. I fell in love with the aurora borealis. Our work became very popular. For me it meant that I had to give presentations at conferences, was asked to join working groups of the European Space Research Organization, ESRO, and the German Ministry for Science and Technology (BMFT). For instance, I was the scientific German delegate to the Scientific Programme Board, SPB, ESRO, soon to mutate into ESA, and, from late 1972, (komma) member of the Launching Programme Advisory Committee, LPAC, ESRO's highest scientific advisory group. I sensed that the committee work and concomitant responsibilities would increase. At the same time, I directed rocket campaigns in Southern India, in Northern Sweden, and Greenland. Furthermore, in 1974 we had just begun to receive data from the dayside magnetopause taken by the ESRO satellite HEOS-2. We were at the frontiers of space physics. I searched myself and recognized it was difficult to do justice to these different tasks at the same time. I recognized my limitations in dealing with high-level management. Therefore, 1 day in late 1974 during an LPAC meeting, I declared my intention to resign from LPAC and soon after also from the SPB. That caused angry reactions from various sides and disappointment from my mentor Reimar Lüst. However, it set the course for my future. I had decided in favor of my own scientific work.

This work progressed well, in spite of some severe setbacks, like the crash of the Firewheel spacecraft in 1980. A few years later, we had reached our ultimate goal. Producing two artificial comets in the solar wind, we had opened a chapter of hitherto unknown plasma processes. Up to this point, my work had consisted of creating or exploiting opportunities for the application of the plasma cloud technique, and suddenly we noticed that we had largely exhausted its possibilities. What to do next? Already a few years before, I had taken over the leadership of a young group in infrared astronomy at our institute. I liked this new task and saw the possibility of a new frontier for myself. We had established a wonderful cooperation with a Dutch group on ESA's ISO (Infrared Space Observatory) mission and were planning a European infrared flying observatory, the Astroplane. Again, I examined myself. Was my education and technical knowhow sufficient to lead the IR group into a great future? The implicit answer was that I began to look for a promising young IR astronomer. I found him in the person of Reinhard Genzel in Berkeley working with Nobel Laureate Charley Townes. It soon proved that he did what I never would have been able to achieve, namely designing novel instrumentation for a most ambitious research program. The Nobel Prize in Physics of 2020 was a deserved recognition (Genzel, 2022).

3 Towards auroral physics

Until completion of the artificial comet experiments in 1985 (Haerendel et al., 1986; Valenzuela et al., 1986), I had had a wonderful career. As of 1972, I was director at MPE, had exciting work, and enjoyed a long-term support of my research by the Max Planck Society. The freedom I gained with my decision to step down from the high-level committees of ESRO/ESA, I devoted to a full engagement in our plasma clouds experiments and theoretical support. With our international sounding rocket campaigns in the auroral zone we had made some significant contributions to the physics of magnetosphere and aurora borealis, such as the penetration of a barium ion jet through the auroral acceleration region in Greenland in 1975 (Haerendel et al., 1976; Haerendel, 2019). In 1980, I conceived the fracture theory for embedded evening arcs (Haerendel, 1980). Until then our focus was on the application of the barium cloud technique with artificial comets and equatorial spread F being the main goals. When that was completed and the IR astronomy at MPE had been handed over to more competent hands, auroral research began to take the front seat for me.

In the late 1980s the opportunities arose with the participation in the Freja mission (Launch 1992) with Sweden (Lundin and Haerendel, 1993) and in the use of the incoherent radar technique with EISCAT (European Incoherent Scatter Radar). While the Freja mission produced many new insights into the nature of the primary auroral particles and their effects on the ionosphere (Lundin et al., 1994), a special topic could be addressed by EISCAT in combination with our highly developed imaging technique. Determination of plasma motions in the ionospheric F region with the first and tracking the motion of auroral arcs with the latter, we could prove the prediction of my fracture theory that embedded arcs have a proper motion with respect to the ambient plasma (Haerendel et al., 1993). This is essential for a continued energy supply out of the magnetic field stretched by magnetospheric convection to counter friction in the ionosphere. Many other insights into the structure of auroral arcs were obtained helping an increasing understanding of the physical processes behind. In the 1990s my attention was drawn more and more to the processes of the substorm onset and the energy entry into the magnetosphere. [The onset is the beginning. It is a matter of definition whether you call the entry simultaneous or subsequent, since entry is coupled with redistribution of the energy]. For an *in-situ* study of these processes, we had conceived and finally built the Equator-S spacecraft. It was a great pity that this mission ended abruptly in 1996, after 5 months of operation and just 2 months before the orbit had drifted into the midnight sector. Throughout the 1990s, my group and guests engaged in the data reduction and interpretation of the observed auroral phenomena and the theory.

4 Major steps in the development of auroral physics

The work of my group to auroral physics, of course, only represented scattered contributions to the worldwide research of the origin of the fascinating aurora borealis. When I was working on my thesis, I could observe already the first results of the impressive progress in auroral physics made by means of space flight. In 1960, Carl McIlwain (1960) had discovered nearly mono-energetic electrons above an auroral arc indicating electrostatic acceleration. Equally fast expanding ground-based research resulted in the recognition of what Syun-Ichi Akasofu had named the substorm (Akasofu, 1964), and Rolf Boström defined the global current system driving ionospheric convection (Boström, 1964). [Magnetospheric forces drive motions of the hot plasma which are coupled to the ionosphere by the global current systems.] The seventies were the time of great discoveries and setting the theoretical foundations. Already in 1972, Vasyliunas (1972) related the origin of the global currents to pressure gradients in the hot magnetospheric plasma. A most important finding was the inverted-V structure of the auroral electron spectrum, discovered by Frank and Ackerson (1971), and the accompanying interpretation as originating from U-shaped electrostatic potentials by Don Gurnett (1972). Hallinan and Davis (1970) had found that auroral rays were, in reality, moving curls indicating the presence of strong shear flows or transverse electric fields above an arc. This was experimentally proven by the employment of Langmuir double probes to measure electric fields and the identification of electrostatic U-shaped potentials by Mozer et al. (1977). At the same time theorists wondered about the processes able to sustain parallel electric fields. There were two widely different proposals, current driven anomalous resistivity by Kindel and Kennel (1971) and Papadopoulos (1977) and a current-voltage relationship derived by Knight (1973) on the basis of kinetic theory in presence of the mirror effect. [Repositioned and reformulated.] The latter theory was elaborated by Fridman and Lemaire (1980). Lyons (1980) used a field-parallel conductance on the basis of the Knight-relation in combination with the Pedersen conductivity to derive M-I coupling scales, not applicable to auroral arcs. Whereas the author (Haerendel 1980) proposed oblique propagating quasi-static Alfvén waves as energy suppliers to the auroral acceleration region, Goertz (1981) associated kinetic or inertial Alfvén waves with short-lived auroral structures. Realistic scales of auroral arcs followed from the Alfvén wave conductance coupled with the Knight conductance (Lysak 1985). Measurements of the Freja spacecraft (Lundin et al., 1994) showed that, instead of accelerating magnetospheric electrons, kinetic Alfvén waves deliver energy to the cool plasma of the topside ionosphere, accelerating electrons parallel to the magnetic field and the ions transversely. The functioning of this ionospheric erosion process has been studied by Chaston et al. (2006). The Fast (Fast Auroral SnapshoT) mission, launched in 1996 (Carlson et al., 1998), brought an unprecedented enrichment of the physics of auroral arcs. This pertained foremost to the micro-processes excited in the acceleration region, which, on the one hand, play a role in exchanging energy and momentum between the e. m. field and the charged particles, thus contributing to the field-parallel resistivity. On the other hand, they give rise to a host of wave fields serving as diagnostic tools. Further great progress coming from the FAST data applies to the downward currents. The data elucidated and underpinned the "pressure cooker" theory of Gorney et al. (1985).

I think that by the end of the 20th century the ingredients to understand discrete auroral arcs were available. What was needed was to identify the energy sources and respective mechanical forces that drive quasi-steady currents or waves thus transferring energy into the magnetic field. Waves may deliver their energy directly to auroral particles or by interaction with the cool plasma of the topside ionosphere. Quasi-stationary currents are set up by interaction of the driving forces with the frictional ionosphere thereby storing energy in the sheared magnetic field, from where it may be extracted in auroral acceleration regions. Apart from diffuse arcs owed to the precipitation of pitch-angle scattered electrons or ions, I maintain that all discrete aurora is caused by extracting energy from intermediately stored energy in terms of sheared magnetic field components. This is grossly different from the suspicion voiced in the early days of space research that anti-parallel magnetic field reconnection in the tail was a source of auroral arcs (Atkinson 1992). By contrast, the powerful energy conversion processes in the solar corona are generally attributed to reconnection processes. [The point lies in the contrast between sheared and anti-parallel field components]. At this point, I am asking: Why have so far only few of the striking auroral structures been explained along these lines? I will have a brief look at that in the next section.

5 What do we understand?

An impressive outcome of a workshop at the International Space Science Institute, ISSI, in Berne led by Dave Knudsen is the series of comprehensive review papers on auroral research (Knudsen et al., 2021). It is a great thesaurus for the state of the art but acknowledges also the many unsolved questions. In the spirit of the considerations at the end of the preceding section, I will look primarily into the reviews covering quiet discrete arcs, namely (Borovsky et al., 2020; Karlsson et al., 2020; Lysak et al., 2020). I will largely neglect the other eight reviews covering the wide range of other auroral phenomena, such as small-scale and mesoscale auroral forms, or dayside and subauroral auroral forms.

The review by Lysak et al. (2020) is largely devoted to understanding of the setup and maintenance of parallel electric fields or voltages in the presence of quasi-steady currents and propagating and reflected Alfvén waves. This is done with kinetic theory as well as with two-fluid descriptions. The relation between transverse and parallel electric fields is discussed in detail, whereas the potential role of anomalous resistivity finds little coverage. Other topics are the reflection of Alfvén waves, and the production of ion conical distributions, the connection of double layers with discontinuities in the plasma parameters, and the relation of density cavities and downward currents. All these topics are key issues in auroral physics and, apart from some subtleties, largely understood. There is, however, one shortcoming; they are treated in non-moving reference systems, which is typical for most of the literature on auroral arcs. Since the experiments of Wescott et al. (1975), it has been known that auroral arcs can have a proper motion with respect to the ambient plasma. It turns out that acceleration regions propagating with respect to the ambient plasma require new considerations of energy and momentum transport (Haerendel, 2021).

The review by Karlsson et al. (2020) presents the key scales of auroral arcs, widths, height distributions of the acceleration regions, potential distributions and relations to upward and downward currents. Much attention is directed to electrostatic potential structure and the current closure in the ionosphere. A special topic is the unipolar and multipolar nature of arcs, i.e., the absence or presence of return currents in the immediate neighborhood of an arc. It is connected with the spatial distribution of the energy supply. Also this review regards arcs as electrostatic entities. Proper motions are mentioned.

The essence of understanding auroral arcs is the identification of potential generator processes. Since at least discrete arcs seem to be related to acceleration by parallel electric fields embedded in upward field-aligned currents or in propagating Alfvén waves, the identification of the generator of these currents is necessary. This is the subject of the review of Borovsky et al. (2020). The authors distinguish between the classes of generators of high-latitude and low altitude arcs, meaning sources at magnetospheric outer interfaces or inside the magnetosphere, respectively. In the first class, there are plenty of ideas for the generation of Alfvén waves with small perpendicular scales, i.e., kinetic or inertial Alfvén waves. Owing to their parallel electric field component, they can accelerate electrons in flight, but only to limited energies. Conversion of the wave energy in the topside ionosphere, as suggested by the discoveries of the Freja mission (Lundin et al., 1994) is not mentioned. Quiet high-latitude arcs are attributed to the generation of transverse potentials at interfaces of plasmas with different thermodynamic properties. These potentials are meant to propagate along the magnetic field down to the ionosphere, where current closure and Pedersen conductivity are used to determine the local potential. The difference with the high-altitude potential leads to the electron acceleration. I have problems with these theories, because current closure in the ionosphere means momentum dumping, whereas the origin of this momentum remains obscure. This problem does not exist with the second class of generators, which are typically current generators, driven by pressure gradients. One example is the arcs embedded in the magnetospheric convection in the evening auroral oval. However, the review also considers static pressure gradients to be sources for the pre-midnight quiescent arcs without flows associated [e.g., (Stasiewicz, 1985)]. [The low pressure region was a cloud. I refrain from quoting details]. Again, these models lack identifications of the source of momentum. If flows are driven, they constitute voltage generators at first sight. However, they cannot sustain the arc for more than a few Alfvén wave reflection periods (Haerendel 2014) and must be maintained by pressure gradients. In case of embedded arcs, the momentum is supplied from the release of stored magnetic shear stresses. Another viable current generator is flow braking. While the merit of the review of Borovsky et al. (2020) is the extensive listing of potential auroral generators, it also raises many questions. In spite of the existence of many incomplete theories, very few auroral forms have been described in a way allowing quantitative evaluation and comparison with data. Why is that so? The information on any observed auroral form is incomplete. Therefore it needs focused and temporally better resolved observations, intuition, theory, and numerical modeling, which, as the authors write, "... encompass the entire auroral-arc region from the equatorial magnetosphere to the resistive ionosphere, ... ".

6 Conclusion

I return to the beginning of my story. Insights into my limitations had led to two decisions that may seem as downward steps on my career ladder. In some sense they were. Such decisions turn out to be unavoidable, whenever the self-examination is done honestly. Cheating may lead to unpleasant consequences. However, the process of self-examination may lead to sensing one's unexploited abilities and to take the path into a risky future, often with success. My case should be seen as rather atypical. What were the benefits for me? It left me in my established realm of competence, planning experiments, conceiving missions, participating personally in rocket and satellite campaigns, being deeply immersed in interpreting data, and providing theoretical support. It led my way inevitably into the fascinating auroral plasma physics and some ambitious projects. It continued to fill my meanwhile 18 years of retirement with the pleasure of addressing a few of the many unanswered questions. During this period, I was able to publish 25 theoretical or interpretative papers on the aurora as well as in solar physics as sole or first author and a few more as co-author only. Thus, from my entry into space research until today, I had a rich, often exciting, and certainly intellectually challenging life. More can be read on that in my professional autobiography: "My Life in Space Exploration," Springer Biographies, 2022.

Author contributions

The author confirms being the sole contributor of this work and has approved it for publication.

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