Dayside Aurora and Auroral Conjugacy

Xiaoyan Zhou¹, Athanasios Boudouridis, John P. Dombeck, Eric Donovan, David J. Knudsen, Kan Liou, Dag A. Lorentzen, Anthony Lui, Dirk Lummerzheim, Ching I. Meng, Joran I. Moen, Patrick T. Newell, Nikolai Ostgaard, George K. Parks, Robert Rankin, David G. Sibeck, James F. Spann, Robert J. Strangeway, Clare Watt, Yongliang Zhang ¹Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California

Overview

This white paper discusses the scientific significance of dayside and conjugate auroras. The dayside aurora and its variation have less ambiguity in the connection to their cause. Examples of such advantages are: 1) the timing of the shock-aurora trigger (i.e., the touchdown time of an interplanetary shock on the subsolar magnetopause) can be as accurate as from few seconds to few minutes; 2) the shock-aurora speed in the ionosphere can be compared with the shock speed in the solar wind. These features provide a unique opportunity to test the existing theories of auroral dynamics, and to establish one-to-one correlations between the auroral forms and particle precipitation mechanisms. Measurements of dayside and conjugate auroras can be achieved by conducting balloon campaigns in the Antarctica and by coordinating the balloon observations with simultaneous Arctic ground-based auroral imaging.

1. Science Background

The aurora provides a map of magnetospheric structure and dynamics and thus auroral images provide rich information about the global magnetosphere that cannot be obtained from in-situ observations alone. The physics of the dayside aurora is different in many ways from that of the nightside aurora because of dayside-nightside asymmetries of the magnetosphere and the ionosphere due to the presence of the solar wind and solar photon ionization. The insight provided by studying the dayside aurora is critical to determining the coupling between variability in the solar wind and the resulting geospace response.

One salient dayside auroral phenomenon occurs when interplanetary shocks or sudden increases in the solar wind ram pressure impinge on the subsolar magnetopause. As a consequence, the magnetospheric compression and magnetic reconnection are enhanced in the local noon sector. Auroras in the dayside auroral ionosphere from the oval to ~65° MLat light up within seconds to few minutes indicating causes of the aurora in the outer magnetosphere and/or on the magnetopause ~10 R_E away from the ionosphere (Craven et al., 1986; Sandhalt et al., 1994; Spann et al., 1998; Zhou and Tsurutani 1999; Vorobjev et al., 2001; Liou et al., 2002; Zhang et al., 2002; Hubert et al., 2003; Meurant et al., 2003,2004; Zhou et al., 2003; Fuselier et al., 2004; Zhou et al., 2009). The auroras then propagate antisunward along the oval at very high ionospheric speeds of ~6-11 km/s that match the corresponding shock speed in the solar wind. The aurora is found to be caused by both the electron and proton precipitation. The auroral brightness is related not only to the variation in the solar wind, but also the plasma precondition in the dayside magnetosphere.

There have been speculations as to the causes of the aurora, such as magnetic reconnection, wave-particle interaction and magnetic shearing, etc. However, since there is a lack of observations of the small-scale dayside auroral structure, we have little understanding of a one-to-one correlation between auroral forms and the particle precipitation mechanism. For example, theoretically, a fast release of magnetic shear stresses could establish field-aligned potential drops and convert the differential magnetic energy into kinetic energy of auroral particles (Haerendel 2007; 2008). But the theory is not tested by auroral observations and it is unclear what would be the resultant auroral color (i.e., the electron characteristic energy), auroral form and their variations. Another example is that it has been a long-time belief that dayside red arcs are the manifestation of the magnetic reconnection on the magnetopause (e.g., Moen et al., 1998; Sandhalt et al., 1998a,b; Chaston et al., 2005). The red oxygen OI¹D emission layer is mainly at ~250 km altitude and caused by soft electrons with the characteristic energy of few hundred eV. However, a 1-D MHD model showed that Alfven-wave accelerated electrons possess energies up to few keV (Chaston et al., 2002). On the dayside magnetopause the kinetic Alfven wave is very likely generated by the magnetic reconnection (Chaston et al., 2005).

It has been a long-term challenge to image the aurora from the ground under sunlit conditions (e.g., Ree et al., 2000). This is mainly due to substantial contamination by sunlight and the limited land area available for installing imagers near the auroral zone in both hemispheres. While ultra-violet remote sensing from space can measure dayside aurora, it does not resolve small-scale auroral structures and is contaminated by UV airglow. Consequently, we have little knowledge of dayside auroral small-scale structures (i.e., auroral forms), their variations, and their coupling to conjugate aurora. As a result, there are important unanswered questions regarding the coupling between the variable solar wind and the dayside magnetosphere and ionosphere and also questions about the basic phenomenology of small-scale dayside auroral structures.

2. Scientific Questions

These questions include:

- 1). What are the auroral particle precipitation mechanisms? The advantage of studying dayside auroras is that there is less ambiguity in identifying the solar wind and magnetospheric causes of the auroral particle precipitation. The touchdown time of an interplanetary shock on the subsolar magnetopause can be accurately identified up to few seconds few minutes; the auroral speed in the ionosphere matches that in the solar wind. These characteristics are unique opportunity to test various kinds of auroral mechanisms.
- 2). How do the dayside magnetosphere and ionosphere respond to solar wind variations in terms of auroral forms? (e.g. diffuse auroral patches and their expansion, auroral arcs/beams and their motion, the auroral response to abrupt solar wind pressure changes, jumps in IMF direction or stable but intense IMF such as in magnetic clouds.)

- 3). Are auroras (e.g., those seen during substorms, geomagnetic storms, and magnetospheric compression) hemispherically symmetric? The question covers the symmetry from small-scale structures (e.g., Sato et al., 1998) to global dynamics (e.g., Ostgaard et al., 2004; Laundal and Ostgaard, 2009). The answer can test many of current models and our understanding of geomagnetic disturbances. For example, do substorm onsets start in the auroral ionosphere (Kan and Sun, 1996) or in the magnetotail (Lui, 1991a,b; Baker et al., 2002)? The onset auroras in the two hemispheres are not necessarily conjugate for onsets in the ionosphere, but should be conjugate for those in the tail.
- 4). What signatures in conjugate dayside aurora can be used to diagnose reconnection and the response of the dayside magnetopause to IMF variations? What does this tell us about particle acceleration, magnetopause reconnection rates, and coupling of energy, mass and momentum from the solar wind?
- 5). What are the differences in the auroral emissions in sunlight and darkness? Are there unique signatures in the sunlight and what causes them? The answers will address the ionospheric conductivity effect and how it couples with the dayside and nightside magnetospheric dynamics.
- 6). What are the differences in auroral forms in dayside (~06-12-18 MLT) and nightside ionosphere (~08-00-16 MLT)? This question addresses the difference of the solar wind-magnetosphere-ionosphere interaction in the dayside and nightside geospace areas.

Identifying dayside auroral forms actually has broader applications beyond the above questions. It has been confirmed by the FAST and Cluster observations that ion conics occur along with the broadband VLF waves where soft electrons (with energy less than 1 keV) are seen to be highly field-aligned with the magnetic field (e.g., Chaston et al., 2005). Red auroral arcs are expected at the ionospheric footprints of the field lines. This connection between the red arcs and the ion conics implies that the red arc can be an indication of the oxygen ion outflow that is considered a very important, if not the most, ionospheric source of the ring current energetic ions. Could this indication only valid in the dayside/cusp or change case by case? Furthermore, since the dayside red arcs are caused by the magnetic reconnection (e.g., Chaston et al., 2005), there is a strong likelihood of the reconnection being the very responsibility of the oxygen ion outflow. This speculation is consistent with Strangeway et al.'s flow chart for the generation of ionospheric outflows (Strangeway et al., 2005) and is consistent with the fact that geomagnetic storms develop only when there is a long lasting southward IMF.

3. Technical Approach and the Feasibility

To answer such questions, the basic requirement is to image the aurora in relatively close distance (so auroral forms can be determined) in sunlight. If such measurements can be achieved, conjugate auroral images can be obtained by combining auroral images taken in sunlight (local summer) from Antarctic balloons with simultaneous Arctic ground-based auroral images taken in

darkness (local winter). Thus, the science questions lead to a technical challenge, i.e., how can we image aurora under sunlight? Seeking a feasible method has been a continuing effort (Chakrabarti, 1998; Rees et al., 2000; Pallamraju et al., 2004), which deserves a solution because of the science significance discussed above.

Atmospheric models predict that sky brightness decreases with increasing altitude and wavelength (Anderson et al., 1999; Liou, 2002). Based on these models and test observations, Zhou et al. (2007, 2008) have confirmed that the N_2^+ Meinel line emissions (~1100 nm), which gives the best signal noise ratio (SNR) in near-infrared, can be measured in sunlight at typical balloon altitudes (>35km) where signal to background ratios are adequate. Using a JPL built near-infrared (NIR) InGaAs camera (with a small focal plane array of 320 x 256 and a small FOV of 9°), the Meinel auroral emissions were detected during twilight when the sky brightness was similar to that of 35-40 km altitude during the highest solar elevation in the Antarctica.

Some of the images are shown in Figure 1. The aurora was detected on April 13, 2005 during evening twilight when the solar zenith angle, SZA, was $\sim 96^{\circ}$ (i.e., the sun was $\sim 6^{\circ}$ below the horizon). Corresponding AL was about -400 nT implying a medium level of auroral intensity. This test result confirmed the feasibility of measuring sunlit auroras from balloon. When the measurements in the Antarctica are coordinated with the existing ground-based all-sky imagers, conjugate auroras can be obtained.



Fig. 1. Auroras detected by the JPL InGaAs NIR camera from Poker Flat, Alaska. Images are shown in one second cadence chronologically from left to right, then down to the second row. Without applying any filter, the images were taken in evening twilight from 2116:23 to 2116:33 LT on April 13, 2005 when SZA was ~96°. Each image has had a sky background subtracted that was calculated from 40 images around the time of the image (Zhou et al., 2007, 2008). The sky background is mainly contributed by the OH airglow in 1400-1700 nm (Remick et al., 2001). Detailed discussions of the sky intensity can be found in Zhou et al. (2007, 2008).

Comparing to space mission, balloon flight for auroral observations is very cost effective with a total cost only ~\$2M including the balloon flight and the NIR camera system development. The JPL NIR InGaAs camera technology has a TRL 5-6 and possesses much better quality than commercial NIR cameras that only function well under high frame rate of ~100/s or higher. With current NASA balloon technology, flying at 35-40 km altitudes with a 1000 kg payload is routine.

The NASA balloon altitude record is ~50 km with ~200 kg payload. Driven by the Antarctic circumpolar winds, a balloon can maintain a trajectory around the geographic pole over several weeks. (Such an example of the balloon trajectory relative to the oval and the NIR camera's field-of-view is shown in Zhou et al., 2007.) The NIR camera system requires less than 10 kg weight and consumes ~30 W, which are suitable for the balloon flight and even a balloon piggyback flight.

4. Concluding Remarks

The 24th solar cycle started its ascending phase recently. Increasing solar and solar wind activity will more frequently light up intense auroral bursts. The Antarctic auroral campaign and its leverage with the ground-based all-sky imager arrays and with the Cluster and THEMIS satellite constellation will provide a unique opportunity for dayside and conjugate auroral investigations. (Note there certainly are opportunities to measure the nightside aurora in both hemispheres during a conjugate auroral campaign.) A broader coordination and collaboration with observations of riometer, X-ray, SuperDARN and other ionospheric measurements as well as theory/modeling will be strongly encouraged.

We highly recommend that the communities interested in the solar wind-magnetosphereionosphere interaction, high-latitude ionosphere, auroral dynamics, auroral conjugacy, auroral morphology and its magnetospheric causes, and auroral particle acceleration theory be given the opportunity to work jointly on measuring the dayside and conjugate aurora and on the auroral investigation.

The primary benefits of this task include: 1) an insight into the dayside geospace response to the varying solar wind; 2) one-to-one correlations between the auroral form and particle precipitation mechanism. Such correlations are helpful references for the nightside auroral activity; 3) the auroral conjugacy during the dayside reconnection, magnetosphere compression and magnetic shearing as well as during nightside auroral substorms; 4) a test of existing storm and substorm models and speculations; 5) a complementary method (that employs NIR camera for auroral emissions at ~1100 nm) to traditional visible and UV auroral remote sensing. Note that the characteristic energy of precipitated electrons alters with the auroral wavelength; and 6) a more complete knowledge of auroral micro-scale signatures along the global auroral zone.

References

Anderson, G.P., et al., *Proc.SPIE*, *Optics in Atmospheric Propagation and Adaptive Systems III*, 3666, 2-10, 1999.
Baker, D.N., et al., *Geophys. Res. Lett.*, 29, 2190, 10.1029/2002GL015539, 2002.
Chakrabarti, S., *J. Atmos. And Terr. Phys.*, 60, 1403, 1998.
Chaston, C. C., et al., Phys. Rev. Lett., 95, 065002, doi:10.1103/PhysRevLett.95.065002, 2005.
Chaston, C. C., et al., Geophys.Res.Lett., 29, 11, doi:10.1029/2001GL013842, 2002.
Craven, J. D., et al., in Solar Wind-Magnetosphere Coupling, edited by Y. Kamide and J. A. Slavin, pp. 367–380, Terra Sci., Tokyo, 1986.

Fuselier, S. A., et al., J. Geophys. Res., 109, A12227, doi:10.1029/2004JA010393, 2004.

Haerendel G., J. Geophys. Res., 112, A09214, doi:10.1029/2007JA012378, 2007

Haerendel G., J. Geophys. Res., 113, A07205, doi:10.1029/2007JA012947, 2008

Hubert, B., et al., Geophys. Res. Lett., 30(3), 1145, doi:10.1029/2002GL016464, 2003.

Kan, J. R., and W. Sun, J. Geophys. Res., 101, 27,271, 1996.

Laundal, K. M., and N. Ostgaard, Nature, 460, 491-493, doi:10.1038/nature08154, 2009.

Liou, K., et al., Geophys. Res. Lett., 29(16), 1771, doi:10.1029/2001GL014182, 2002.

Liou, K.N., Academic Press, San Diego, 2002.

Lui, A.T.Y., J. Geophys. Res., 96, 1849, 1991a.

Lui, A.T.Y., In Magnetospheric Substorms, Geophysical Monograph 64, Ed. J. Kan, et al., pp. 43, Washington, DC: AGU, 1991b.

Meurant, M., et al., Geophys. Res. Lett., 30(20), 2032, doi:10.1029/2003GL018017, 2003.

Meurant, M., et al., J. Geophys. Res., 109, A10210, doi:10.1029/2004JA010453, 2004.

Moen, J., et al., J. Geophys. Res., 103(A7), 14,855 - 14,863, doi:10.1029/97JA02877, 1998.

Ostgaard, N., et al., J. Geophys. Res., 109, A07204, doi:10.1029/2003JA010370, 2004.

Pallamraju D., et al., Geophys. Res. Lett., 31, L08807, doi:10.1029/2003GL019173, 2004.

Rees, D., et al., Geophys. Res. Lett., 27, 313–316, doi:10.1029/1999GL003696, 2000.

Remick, K. J., et al., J. Atmos. Sol.-Terr. Phys., 63, 295, 2001.

Sandholt, P. E., et al., J. Geophys. Res., 99, 17,323, 1994.

Sandholt, P. E., et al., J. Geophys. Res., 103(A10), 23,325, doi:10.1029/98JA02156, 1998a.

Sandholt, P., et al., J. Geophys. Res., 103(A9), 20,279–20,295, doi:10.1029/98JA01541, 1998b.

Sato, N., et al., J. Geophys. Res., 103, NO. A6, PAGES 11,641-11,652, JUNE 1, 1998.

Spann, J. F., et al., Geophys. Res. Lett., 25, 2577, 1998.

Strangeway, R.J., et al., J. Geophys. Res., 110, A03221, doi:10.1029/2004JA010829, 2005.

Vorobjev, V. G., et al., J. Geophys. Res., 106, 28,897, 2001.

Zhang, Y., et al., J. Geophys. Res., 107, 8001, doi:10.1029/2002JA009355, 2002.

Zhou, X.-Y., and B. T. Tsurutani, Geophys. Res. Lett., 26, 1097, 1999.

Zhou, X.-Y., et al., J. Geophys. Res., 108(A4), 8019, doi:10.1029/2002JA009701, 2003.

Zhou, X.-Y., et al., Geophys. Res. Lett., 34, L03105, doi:10.1029/2006GL028611, 2007.

Zhou, X.-Y., et al., J. Adv. Space Res., 42, 1676-1682, doi:10.1016/j.asr.2007.02.034, 2008.

Zhou, X-Y., et al., J. Geophys. Res., 114, A12216, doi:10.1029/2009JA014186, 2009.