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What produces and what controls the spatial-temporal structuring of the magnetospheric chorus waves that create the pulsating aurora: An unsolved problem in need of new measurements

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In this Perspective article discussing solved and unsolved problems in space physics, the focus is on the unsolved problem of the spatial-temporal variability of the magnetospheric plasma waves that produce the spatial-temporal atmospheric luminosity of the pulsating aurora. In particular the outstanding issue of what causes the spatial-temporal variations of the chorus-wave intensities is highlighted: Two great unknowns are (1) how does it work and (2) what are the controlling factors. The point is made that the whistler-mode chorus waves that produce the pulsating aurora are the same chorus waves that energize the Earth's electron radiation belt. Hence, beyond not understanding the cause of pulsating aurora there is (1) a lack of understanding of the magnetosphere-ionosphere system behavior and (2) a lack of understanding of how the electron radiation belt is energized. It is noted that the pulsating aurora is perhaps the most-obvious example of an "emergent phenomena" in the magnetosphere-ionosphere-thermosphere system, and so perhaps the clearest indication that the magnetosphere-ionosphere-thermosphere system is a truly "complex system", not just a complicated system. Future needs for solving this unsolved problem are discussed: the most-critical need is argued to be gaining an ability to measure cold-electron structuring in the equatorial magnetosphere.

KEYWORDS
pulsating aurora, magnetosphere, ionosphere, system science, emergence, waveparticle interaction

1 Introduction: Pulsating aurora

Pulsating aurora are irregularly shaped patches of atmospheric illumination that blink between bright and dim phases caused by a cyclic modulation of the precipitation of electrons from the magnetosphere onto the upper atmosphere. Pulsating aurora cycle "on and off" on timescales typically of 2–20 s (Cresswell, 1972; Johnstone, 1978; Lessard, 2012; Partamies et al., 2017), with there also being higher-frequency temporal modulations to the optical emission (Kataoka et al., 2012). An interval of pulsating aurora can persist for hours (Jones et al., 2011) and can occupy a substantial region of local time and magnetic latitude (Bland et al., 2021). Pulsating aurora are predominant in the nightside (post-midnight) dipolar regions of the magnetosphere (Grono and Donovan, 2020; Bland et al., 2021) but they also appear on the dayside (Partamies et al., 2022a). The mechanisms underlying the workings of pulsating aurora have been a mystery for decades: some definite understanding has been gained but there are still important outstanding questions. Historical papers and reviews that focus on the pulsating aurora can be found in Omholt (1971), Cresswell (1972), Jones (1974), Oguti (1976), Royrvik and Davis, 1977; Johnstone (1978), Lessard (2012), and Nishimura et al., (2020).

In the nightside auroral zone, pulsating aurora are prevalent after a magnetospheric substorm has occurred (Cresswell, 1972; Oguti, 1976; Nemzek et al., 1995; Jones et al., 2011). The kinetic energies of the precipitating electrons giving rise to the atmospheric optical emission are typically in the keV range (McEwan et al., 1981; Sato et al., 2004; Miyoshi et al., 2015; Tesema et al., 2020a) but also extend up into the 100s of keV range (Ostgaard et al., 1998; Miyoshi et al., 2015; Turunen et al., 2016) and down into the sub-keV range (Liang et al., 2016). Pulsating aurora are also associated with relativistic-electron microbursts of precipitation (Miyoshi et al., 2020; Kawamura et al., 2021).

The pulsating aurora have a variety of shapes and sizes (Royrvik and Davis, 1977), with horizontal patch sizes of 20–50 km in the upper atmosphere being common (Partamies et al., 2019). The blink temporal sequences from one spatial patch to another are typically uncorrelated (Scourfield et al., 1972; Kosch and Scourfield, 1992). The lifetimes of individual blinking patches are on the order of 10s of min (e.g. Humberset et al., 2016; Partamies et al., 2019).

The pulsating aurora is an important source of energy deposition from the magnetosphere into the ionosphere and upper atmosphere (Bland et al., 2021; Tesema et al., 2022; Partamies et al., 2022b) and the higher-energy precipitating electrons of the pulsating aurora may be important for atmospheric chemistry (Tesema et al., 2020b, Tesema et al., 2022; Verronen et al., 2021).

Spacecraft measurements have shown that pulsating aurora are predominantly associated with the pitch-angle scattering of magnetospheric electrons by whistler-mode chorus waves in the magnetosphere (e.g. Nishimura et al., 2010, Nishimura et al., 2011a, Nishimura et al., 2011b; Li et al., 2012; Miyoshi et al., 2015; Ozaki et al., 2015, 2018; Kashara et al., 2018), although electrostatic electron-cyclotron-harmonic (ECH) waves can be involved (Liang et al., 2010; Fukizawa et al., 2018), as well as time-domain structures (Mozer et al., 2017). The turning on and off of the electron precipitation is associated with a temporal modulation of the wave amplitudes. The turning on and off of the waves to produce the turning on and off of electron precipitation has been the subject of many plasma-wave theories (e.g. Davidson, 1979, 1990; Demekhov and Trakhtengerts, 1994; Suszcynsky et al., 1997; Humberset et al., 2016). The involvement of lower-frequency compressional waves modulating the high-frequency waves is also possible (Li et al., 2011; Nishiyama et al., 2012; Jaynes et al., 2015).

Because the pulsating spatial patches of optical emission move with an approximate E-cross-B velocity (Scourfield et al., 1983; Yang et al., 2015, Yang et al., 2017), the spatial patterns of the aurora are believed to be associated with cold plasma structures in the magnetosphere or in the ionosphere (Oguti, 1976; Yamamoto, 1988; Grono et al., 2017; Liang et al., 2021). Because the pulsating aurora are associated with whistler-mode chorus waves, and whistler-mode chorus waves do not interact with ions, the spatial structuring is thought to be in cold electrons. (Cold ions could also be structured to ensure charge neutrality, and the cold-electron structuring probably also involves ion physics.) Spacecraft measurements have found evidence of magnetospheric ion-density variations associated with pulsating auroral patches (e.g. Nemzek et al., 1995; Nishimura et al., 2015) and Fukizawa et al., 2021 find evidence of electron-density variations in the ionosphere). Cold electrons, however, are very difficult to measure in the magnetosphere (cf. Delzanno et al., 2021; Maldonado et al., 2022).

Pulsating aurora are also associated with field-aligned currents (Oguti and Hayashi, 1984; Fujii et al., 1985; Gillies et al., 2015).

Some definitions of a "complex system" require that the system exhibits "emergence" (Anderson, 1977; Bar-Yam, 1997; Borovsky and Valdivia, 2018), which can be defined as: "Emergence is the phase when new organizations and functions arise from the interactions of smaller, less complicated entities" (Mobus and Kalton 2015). The spatial-temporal pulsating aurora is perhaps the best example of an emergent phenomenon in the Earth's magnetosphere-ionosphere-thermosphere system. Hence, the pulsating aurora is a clear signature that the magnetosphere-ionosphere-thermosphere is a true complex system, not just a complicated system.

Understanding the processes that give rise to pulsating aurora is not only important for understanding the aurora: the chorus waves that are exhibiting spatial-temporal intensity modulations are the chorus waves that accelerate radiation-belt electrons. These are the chorus waves that energize radiation-belt electrons (Meredith et al., 2003; Shprits et al., 2008), that pitch-angle scatter radiation-belt, substorm-injected, and plasma-sheet electrons (Glauert and Horne, 2005), and that produce microbursts of electron precipitation (Thorne et al., 2005; Saito et al., 2012) that change atmospheric chemistry (Clilverd et al., 2009; Turunen et al., 2016) and effect atmospheric electricity (Rodger et al., 2007; Borovsky, 2017). Understanding what produces and what controls the spatial-temporal structuring of these chorus waves is important for understanding the magnetospheric system, for understanding aurora, for understanding auroral effects on the atmosphere, and for understanding the evolution of the electron radiation belt. Understanding the magnetospheric physics of the pulsating aurora will bring the community one step closer to being able to use the optical aurora as window (TV screen) to monitoring magnetospheric physics (e.g. Akasofu, 1965; Mende, 2016).

2 Outstanding questions

Multiple outstanding questions can be posed about the pulsating aurora and the processes that create it.

(1) Is there a process that uplifts electrons (and ions) from the ionosphere to form spatial structures in the magnetosphere?
(2) What are the controlling factors (solar-wind parameters, geomagnetic time history, intensity of substorm-injected electrons, . . .) for this structuring?
(3) Why do the waves turn on and off in a patch?
(4) What controls the wave intensities?
(5) What is the role of wave combinations (chorus, ECH, . . .) and the patchy structure in the particle precipitation energy distribution?
(6) How are the field-aligned currents driven and how do they affect the ionosphere?
(7) How are microbursts related to pulsating aurora?
(8) Do pulsating-aurora processes have something to do with the origin of the cloak particle populations?

3 Discussion

If it was not for the optical aurora, would the magnetospheric-physics community have a clear understanding that the chorus waves in the magnetosphere are spatially patched and temporally modulating on local scales. Could it be that other magnetospheric plasma waves such as EMIC occur in spatial patches or are temporally modulated? Could it be that other magnetospheric waves have an outflow feedback with the ionosphere to create structuring? For other plasma waves we do not have the advantage of observing auroral optical emission associated with the wave activity in the magnetosphere. Should spatial-temporal patterns for these other wave activities be investigated?

The warm plasma cloak is seen co-located with the electron plasma sheet chiefly on the dawnside (Borovsky et al., 2013). The electron plasma sheet magnetically maps to the auroral zone in the atmosphere (Feldstein and Galperin, 1985, 1993; Galperin and Feldstein, 1996). During active times the cloak is most dense near the plasmapause (Borovsky et al., 2013) and at those active times the inner edge of the electron plasma sheet is close to the plasmapause (Schield and Frank 1970), mapping magnetically to the low-latitude portions of the auroral zone in the dipolar portions of the magnetosphere. An obvious question is: Does pulsating aurora have any connection to the origin of the cloak ion and electron populations? After all, the cloak ion and electron populations are seen in flux tubes that were recently pulsating-aurora flux tubes.

One might wonder if the pulsating-auroral structured cold electrons in the magnetosphere are on open or closed E-cross-B drift trajectories, and whether it matters. For pulsating aurora caused by an electron injection from a temporally isolated substorm the pulsating aurora is probably on closed drift trajectories and the magnetospheric electron structures will approximately corotate across the dayside magnetosphere from dawn to dusk. During sustained magnetospheric activity when periodic substorms are occurring the pulsating aurora is likely on open drift trajectories with the structured cold electrons advecting to the dayside magnetopause where they will be lost to the solar wind or to the low-latitude boundary layer.

Ionospheric-outflow physics is likely to be important to attaining a complete understand of the pulsating aurora. Three obvious questions for the outflows are: (1) What is the role of precipitating electrons? (2) What is the role of field-aligned currents? (3) What is the role of low-altitude plasma waves?

To calculate chorus-wave momentum and pitch-angle diffusion coefficients for the radiation-belt electrons, for substorm-injected electrons, and for plasma-sheet electrons one should think about whether one can simply use the time-averaged measured intensity of the chorus activity or whether you need to know something about the nature of the temporal on-off switching of the activity. What if, during the on-off cycle, there are phases where the chorus waves are nonlinear?

As mentioned in Section 1 pulsating aurora can involve a mix of plasma waves (e.g. chorus and ECH) and a mix of electron-precipitation energies. In the observing experience of the authors, it seems like some morphological versions of pulsating aurora (amorphous) are not related to equally energetic particle precipitation and thus, the wave-particle-interaction driving might be different. Because the structures from different-energy electrons are visually different and distinguishable (e.g.

Tesema et al., 2020a), this can be helpful in the TV-screen interpretation of aurora as a view of magnetospheric processes (e.g. Akasofu, 1965; Mende, 2016). It is also quite clear to the authors that patchy aurora (and patchy pulsating aurora) are so distinct that it will be possible to automatically detect them in the auroral image data with good success rate, which would then mean detecting energetic electron precipitation.

4 Future needs

How the pulsating aurora works and what factors control it are clearly unsolved problems in space physics. Because of the diverse potential impacts of the processes that drive pulsating aurora, important future work is needed.

The primary need is the ability to measure cold electrons in the nightside equatorial magnetosphere. Cold electrons are difficult to observe because electron particle detectors are blinded by the copious fluxes of low-energy spacecraft-generated photoelectrons and secondary electrons that are returning back to the spacecraft (Suszcynsky et al., 1997; Delzanno et al., 2021). It is desirable to measure ambient electrons that have sub-eV energies, whereas the populations of photoelectrons and secondary electrons have "temperatures" of several eV. Innovative methodologies to measure ambient cold magnetospheric electrons are being developed (e.g. Maldonado et al., 2022), but have not yet flown in space. The number density of cold electrons is already possible to measure, for example by combining a plasma-line measurement for the total electron density and an electrostatic-analyzer measurement for the hot-electron density. However, when the cold-electron density is low (as it is in the diffuse-aurora region beyond the plasmapause), detecting a plasma line may be difficult. It is emphasized here that the temperature and anisotropy of the cold electrons can be important for chorus-wave physics (e.g. Maxworth and Golkowski, 2017; Roytershteyn and Delzanno, 2021; Delzanno et al., 2021) and hence can be important for understanding the pulsating aurora. A capability to measure cold electrons (density, temperature, anisotropy) would permit studies of the creation and evolution of the electron structures and their controlling factors.

Another need is the ability to measure cold ions the equatorial magnetosphere, which is challenging but the challenges have been overcome in the past (Chappell, 1982; Fields et al., 1982). The evolution of pulsating-aurora cold-electron structures probably involves the physics of both electrons and ions.

In the meanwhile to improve the understanding of the pulsating-aurora structuring and to better plan future missions, the re-exploration of existing data sets would be wise. This could involve ion measurements from DE RIMS (e.g. Chappell, 1982) and could involve ion measurements exploiting spacecraft-wake effects on other missions (e.g. Engwall et al., 2009; Andre et al., 2021a, Andre et al., 2021b). And it could involve electron-density measurements from plasma-wave instruments (the plasma line), electric-field instruments (spacecraft potential), and sounders. Tying these existing measurements statistically to the occurrence of pulsating aurora could yield confirmation (or not) of assumptions and could clarify measurement parameters for future missions.

To understand the outflow physics of cold electrons and cold ions into the magnetosphere associated with pulsating aurora, high-quality low-altitude spacecraft observations of both electron and ion outflows are needed, particularly the cold, hot, secondary, and backscattered electron populations that may drive the outflows *via* ambipolar parallel electric fields. Simultaneously observing the populations of the electron-ion plasma "system" (e.g. Borovsky, 2021) will be uniquely helpful. Using these new measurements could solve problems about the physics and controlling factors of outflows related to pulsating-auroral processes.

Here again revisiting existing data sets of ion outflows (e.g. Andersson et al., 2005; Redmon et al., 2012; Fernandes et al., 2016), and using incoherent scatter radar (e.g. Wahlund et al., 1992; Godbole et al., 2022) would be wise. But note that the pulsating aurora may involve electron outflows without ion outflows, the cold outflowing electrons replacing precipitated hot electrons.

Kinetic modeling with realistic scalings of entire pulsating-aurora flux tubes from the ionosphere to the equator is needed to understand the interaction of electron precipitation into the atmosphere, electron and ion outflow from the ionosphere, plasma-sheet electrons, substorm-injected electrons, and plasma waves.

For use with present-day high-resolution optical data, the development of artificial-intelligence (AI) patch-detection tools could be very helpful to study the structural evolution of the pulsating aurora. Ultimately this needs to happen in conjugacy with the particle and waves measurements in space to properly reveal the causes and consequences.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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