Aurora Visualization using Fluid Dynamics

DH2323 Computer Graphics and Interaction | Final project
Ksenia Biazruchanka | 0050523-T068 | kseniabi@ug.kth.se
KTH Royal Institute of Technology
https://github.com/kseniabez/aurora-fluid-simulation

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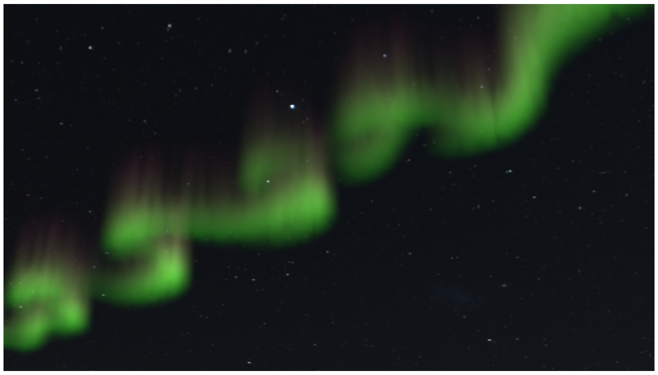

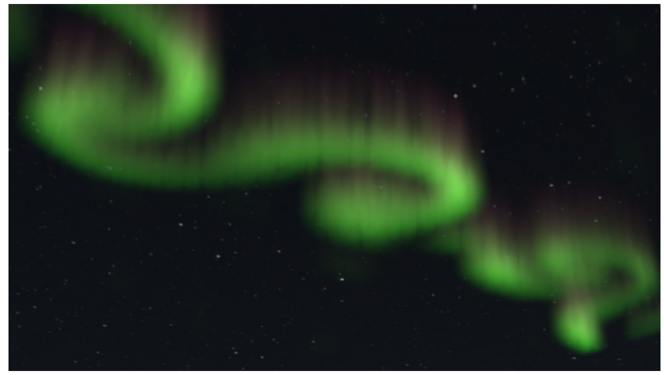

Abstract :

The aurora borealis, or northern lights, is a striking natural phenomenon caused by interactions between charged solar particles and Earth's magnetosphere. This project introduces a method for simulating the shape and motion of auroral spirals using a 2D fluid solver based on the Kelvin–Helmholtz instability. The approach aims to produce visually realistic auroral dynamics.

Keywords: aurora borealis, northern lights, fluid simulation, auroral spirals, computer graphics

1 Introduction

The Aurora Borealis, or northern lights, is a striking natural phenomenon caused by the interaction between charged solar particles and Earth's magnetic field. These interactions excite atmospheric gases, producing shimmering light patterns in the polar skies. Among the many shapes auroras can take, auroral arcs with embedded folds and spirals are particularly dynamic and visually complex.

1.1 Motivation

This project focuses on simulating auroral arcs that exhibit folds and spirals—structures believed to form due to localized instabilities in the ionosphere. Those instabilities can be qualitatively described using Kelvin-Helmholtz instability. The simulation draws inspiration from fluid dynamics to reproduce this flowing, organic behavior.

1.2 Research Question

Can a 2D fluid simulation be used to realistically visualize the formation and motion of auroral arcs with folds and spirals?

1.3 Project Objectives

The goals of this project are:

- To simulate the dynamic motion of auroral arcs with embedded folds and spirals using 2D fluid dynamics.
- To produce visually realistic and aesthetically pleasing auroral animations.

2 Related Work

Auroras appear in a wide variety of shapes and sizes, making it challenging to develop simulations that are both visually and physically accurate. As a result, relatively few studies have focused on creating realistic, dynamic visualizations of auroral phenomena.

Baranoski et al. [1] were among the first to propose a physically-based model to perform 3D visual simulations of auroral dynamics. This model takes into account the physical parameters and processes directly associated with plasma flow.

In a subsequent study, Baranoski et al. [2] introduced a simulation framework grounded in physical models of high-energy electron interactions with atmospheric particles. This allowed for time-varying visualizations of auroral emissions.

Lawlor and Genetti [8] developed a real-time rendering system for auroral displays leveraging modern GPU capabilities. Their approach combined an efficient atmospheric scattering model with a GPU-friendly simulation of auroral curtains. The aural sheets shapes were generated using fluid dynamics and random perturbations applied to sinusoidal base curves.

Ishikawa et al. [5] presented a data-driven method for reconstructing the 3D structure of auroras from observational datasets. Their work focused on large-scale visualizations, capturing the movement and evolution of entire auroral sheets across the sky.

3 Aurora Dynamics

3.1 The Aurora Phenomenon

Auroras are natural light displays that occur in the polar regions, most commonly referred to as the Northern Lights (Aurora Borealis) in the northern hemisphere and the Southern Lights (Aurora Australis) in the southern hemisphere. These displays are caused by the interaction between charged particles from the solar wind and the Earth's magnetic field.

As these charged particles are funneled along geomagnetic field lines toward the poles, they collide with atoms and molecules in the upper atmosphere, releasing energy in the form of visible light. Auroras manifest in a wide variety of shapes and motions, from diffuse glows to sharply defined rays and dynamic structures.

Among the most captivating of these are spiraling forms that exhibit fluid-like motion. These complex patterns, often evolving fast in space and time, are the primary focus of this project. Our goal is to simulate auroral spirals along the auroral curve in a visually and physically probable manner.

3.2 Auroral Sheet

The *auroral sheet* refers to the large, curtain-like structure of auroral emissions aligned roughly with geomagnetic latitude lines. These sheets can span hundreds of kilometers in length, appearing to drape across the sky from east to west.

Auroral sheets often appear to exhibit wave-like motion. According to Hallinan [4], such sheets can be effectively modeled by boundaries defined through sin waveforms. These sinusoidal distortions are thought to arise from instabilities or perturbations in the ionosphere, which modulate the spatial distribution of precipitating electrons.

Figure 1 shows examples of the auroral sheet, which exhibit wave-like shape.

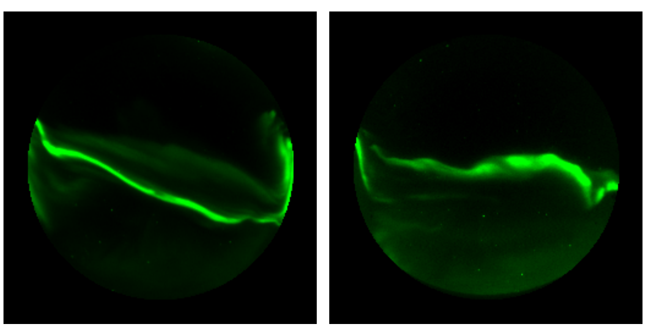

Figure 1. Examples of wave-like auroral sheets from the Oslo Aurora THEMIS (OATH) dataset [7].

3.3 Auroral Folds and Spirals

Auroral folds and spirals, shown in Figure 2, are distinctive auroral forms, that emerge from localized disturbances within the auroral sheets. Spirals are often characterized for their rotational, vortex-like geometry. Folds are often described as rippling or twisted curtains and may form just before or alongside spirals. These structures are caused by instabilities and often appear where strong, field-aligned currents are present.

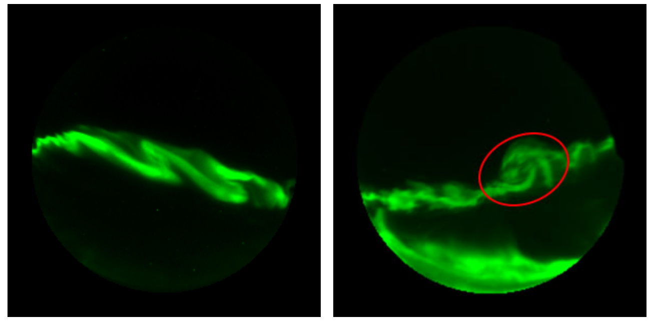

Figure 2. Examples of auroral folds(left) and spirals(right) from the Oslo Aurora THEMIS (OATH) dataset [7].

One physical mechanism that can lead to the formation of folds and spiral is a localized perturbation in the auroral current sheet. As described by Hallinan [4]. The process can be summarized as follows:

- In Figure 3a, a small current enhancement at $x = 0$ produces a localized circular magnetic field.
- In the region where x is slightly less than zero (Figure 3c), The sheet is distorted into that portion of the shear field which is directed in the +x direction. Similarly, at x somewhat greater than zero the relevant field lines have x components directed in the -x direction.
- The central deformation intensifies (Figure 3c), forming a fold.
- Eventually, this leads to the formation of a spiral structure (Figure 3d).

The process may repeat nearby, forming a sequence of folds and spirals, which is often observed in real life. Although Figure 3 presents a simplified schematic, it captures the qualitative behavior observed in real events.

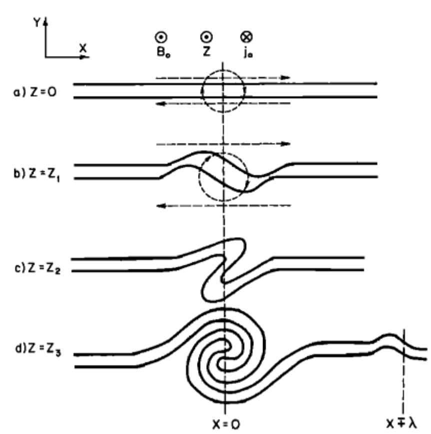

Figure 3. Schematic of spiral formation in the auroral current sheet due to a localized current perturbation (adapted from Hallinan, 1976 [4]).

A series of images in Figure 4 illustrates actual auroral spirals at different stages of their formation and evolution.

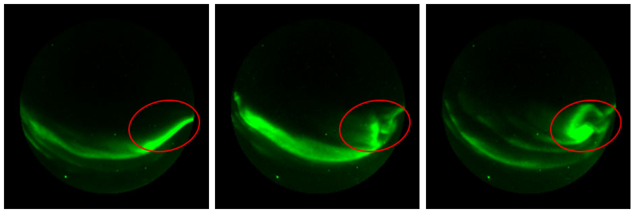

Figure 4. Stages in the formation of an auroral spiral from the Oslo Aurora THEMIS (OATH) dataset [7].

According to Hallinan [4], the formations of the spirals can be qualitivaly described using Kelvin-Helmholts instability caused by plasma flow.

3.4 KHI Instability and Relation to Fluid Dynamics

The Kelvin–Helmholtz instability (KHI) is a fluid dynamic phenomenon that arises at the interface of two fluids with different velocities, leading to the formation of vortex-like structures. First described by Helmholtz and Kelvin over a century ago, this instability has since been applied to various fields, including plasma physics [9, 6], therefore they became relevant in auroral dynamics.

In the case of auroras, these plasma instabilities can develop within the auroral current sheet. The interaction between the solar wind's charged particles and the Earth's magnetic field induces a shear in the plasma flow along geomagnetic field lines. This shear is analogous to the velocity difference observed between two layers of fluid in classical fluid dynamics. As a result, the interface between different plasma regions can become unstable, giving rise to vortex-like structures, including spirals.

Figure 5. Image of Northern Lights by Tiffany Hinkley from Alberta Aurora Chasers facebook group.

It is important to note that auroras appear in different shapes and structures, due to their high variability. And KHI cannot be applied to describe all of them. Figure 5 shows a picture of aurora phenomena where we can see periodic perturbations similar to those caused by KHI.

4 Methods

4.1 Fluid Simulation

The fluid solver employs a finite volume method combined with an Eulerian grid approach to solve the compressible Euler equations. These equations express the conservation of mass, momentum, and energy in an ideal fluid, formulated as:

$$\frac{\partial}{\partial t}\mathbf{U} + \nabla \cdot \mathbf{F}(\mathbf{U}) = 0$$

where $\mathbf{U} = \begin{pmatrix}\rho & \rho v_x & \rho v_y & \rho e\end{pmatrix}^T$ represents the conservative variables(ρ - mass density, ρv_x, ρv_y - momentum density, ρe - energy density), and $\mathbf{F}(\mathbf{U})$ denotes the flux function. The finite volume method ensures conservation by integrating these equations over control volumes and applying the divergence theorem to convert volume integrals into surface integrals [11].

The fluid is discretized into a grid of small cells of size $\Delta x \times \Delta x$. The cells exchange the conservative qualities described above through fluxes, thus preserving their total sum. Once the solution is obtained, the update from timestep n to $n+1$ is performed using the finite volume method. The conservative variables $\mathbf{U}^n_{i,j}$ at each cell (i, j) are updated based on the numerical fluxes across the cell interfaces:

$$\mathbf{U}^{n+1}_{i,j} = \mathbf{U}^n_{i,j} - \frac{\Delta t}{\Delta x}\left(\hat{F}^x_{i+1/2,j} - \hat{F}^x_{i-1/2,j}\right) - \frac{\Delta t}{\Delta y}\left(\hat{F}^y_{i,j+1/2} - \hat{F}^y_{i,j-1/2}\right)$$

where $\hat{F}^x$ and $\hat{F}^y$ represent the numerical fluxes in the x- and y-directions, respectively. These fluxes are computed using an approximate Riemann solver, such as the Rusanov flux:

$$\hat{F} = \frac{1}{2}\left(F_L + F_R\right) - \frac{c_{\max}}{2}\left(u_R - u_L\right)$$

where F_L and F_R are the fluxes on the left and right sides of the interface, respectively, and $c_{\max}$ is the maximum signal speed [10].

The simulation was done in python.

4.2 Kelvin–Helmholtz Instability (KHI)

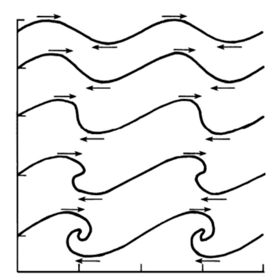

Figure 6. Schematic representation of KHI. Formations of folds and spirals (Courtesy of J. S. Turner, Buoyancy Effects in Fluids, 1973).

To simulate the swirling, layered motions characteristic of auroral curtains, the fluid was initialized with a velocity shear across a horizontal sheet. This setup naturally evolves into a Kelvin–Helmholtz instability (KHI), where small perturbations at the interface grow over time into rolling vortex structures. These structures closely resemble the folds and waves observed in aurora borealis phenomena, making KHI a fitting mechanism for simulating such natural motion [3].

To trigger the Kelvin–Helmholtz instability (KHI), the entire auroral sheet was initialized with a density and velocity configuration as illustrated in Figure 7. The thickness of the shear layer is predefined. Inside this layer, the fluid density is set to $\rho = 1$, while the surrounding regions are set to $\rho = 0$. (In practice, values between 1 and 2 are used to avoid numerical instability, but for visualization, these are linearly mapped to the $[0, 1]$ range, where 0 corresponds to black and 1 to white.)

A horizontal velocity shear is established by assigning a positive v_x inside the shear layer and a negative v_x outside. At the top and bottom boundaries of the shear region—where the auroral fold ends—small random vertical velocity perturbations v_y are introduced to cause the instability.

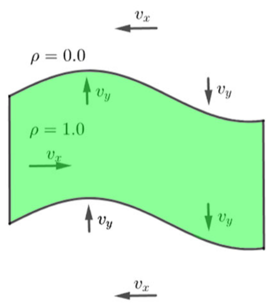

Figure 7. Schematic representation of auroral sheet initialization (Graphics by me).

4.3 Rendering in Blender

After simulating the 2D fluid motion, the resulting density and velocity fields were exported as a sequence of frames and imported into Blender. The 2D simulation was visualized as a vertical curtain by mapping fluid density to an emission shader. This approach enhanced the otherwise "flat" visualizations, adding depth and making the auroral structures more recognizable.

As illustrated in Figure 8, the rendering workflow in Blender involved a series of node-based effects. The simulation frame was used as a base input. A noise texture was layered on top to generate vertical streaks, mimicking the nature of real auroras. A vertical gradient texture was added to simulate the fading glow with altitude. Finally, a green-to-red color ramp was applied to emulate the natural auroral color transition. These layers were composited and mapped onto a vertical volumetric mesh, resulting in a convincing 3D rendering of the auroral curtain.

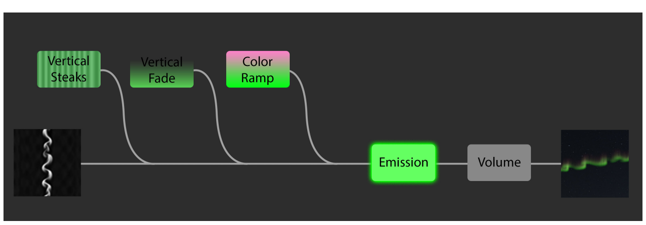

Figure 8. Aurora rendering workflow in Blender. (Graphics by the author.)

5 Results

I present the results of the 2D fluid simulations alongside their corresponding visualizations in Blender. The goal was to evaluate whether the simulations achieve a realistic appearance.

Figure 9 shows three representative frames from the simulation and visualization. The first column presents the raw 2D fluid simulation output. The second column shows the Blender render from the same viewpoint from the same camera angle, as the fluid simulation output. The third column shows the same frame rendered from a different camera angle, offering a more recognizable and visually compelling view of the swirling aurora-like motion.

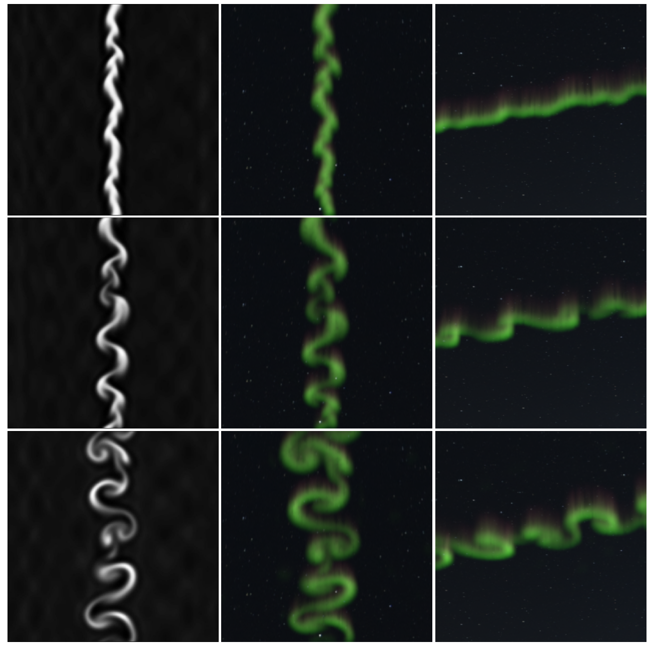

Figure 9. Frames from resulting fluid simulation (left), rendered aurora from the same angle(center), rendered aurora from different angle (right).

The full animation video is available on the development blog of the project: kseniabez.github.io/projects/aurora-simulation/.

6 Discussion

The results demonstrate that simulating a 2D velocity shear using the compressible Euler equations can produce visually convincing auroral-like structures when appropriately visualized. The emergence of the Kelvin–Helmholtz instability (KHI) generated layered, swirling features that qualitatively resemble the folds and swirls observed in real auroral curtains. This suggests that, at least from a visual and artistic standpoint, KHI provides a plausible mechanism for approximating auroral dynamics in animation.

Nevertheless, the simulation makes several simplifying assumptions that limit its physical accuracy. Real auroras are driven by complex magnetospheric interactions involving charged particles, magnetic fields, and altitude-dependent emission spectra—none of which are captured in this model. Additionally, the simulation focuses solely on the folded, curtain-like morphology and does not attempt to replicate other auroral forms, such as diffuse or patchy auroras, which lack such structures.

Given these limitations, the model should be understood as a qualitative and visual approximation rather than a faithful physical representation of aurora dynamics.

7 Conclusion

In this work, I presented a 2D compressible fluid simulation based on the finite volume method, designed to recreate the swirling, layered motion observed in natural auroral phenomena. By introducing a velocity shear at the fluid interface, the system developed a Kelvin–Helmholtz instability, which produced realistic vortex structures. These structures were visualized using Blender, where the fluid density field was mapped to an emission shader to simulate glowing auroral curtains.

The results demonstrate that even a relatively simple 2D fluid model can produce visually compelling dynamic aurora.

7.1 Future Work

Future work could explore the incorporation of additional physical phenomena relevant to auroral dynamics, such as magnetic field influences and charged particle interactions. In particular, introducing actual astronomical data, to replicate the phenomenon and gain deeper understanding into its formation.

This project focused primarily on animating the auroral shape through a 2D fluid animation, while the vertical curtain rendering was done for visualization purposes only. A natural extension would involve investigating the physical mechanisms behind auroral curtain formation, including the vertical structure and altitude-dependent variations. A more scientifically grounded coloring model—accounting for emission variations at different altitudes and driven by astronomical data—would also improve realism.

Another promising direction is refining the simulation-to-visualization pipeline. Currently, the process involves hardcoded animation parameters and manual export/import between the tools. Deeper integration with Blender—through scripting or real-time data exchange—could make the the workflow easier and make the system more accessible to artists, educators, and researchers without a technical background.

Acknowledgements

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References

[1] Gladimir V. G. Baranoski et al. *Simulating the dynamics of the dancing lights.* Tech. rep. CS-2002-16. University of Waterloo, School of Computer Science, Apr. 2002.

[2] Gladimir V. G. Baranoski et al. “Simulating the aurora”. In: *Journal of Visualization and Computer Animation* 14.1 (2003), pp. 43–59. doi: 10.1002/vis.304. url: https://onlinelibrary.wiley.com/doi/abs/10.1002/vis.304.

[3] P. G. Drazin. *Introduction to Hydrodynamic Stability.* ISBN 978-0-521-81068-4. Cambridge: Cambridge University Press, 2002.

[4] T. J. Hallinan. “Auroral Spirals 2. Theory”. In: *Journal of Geophysical Research* 81.22 (Aug. 1976), pp. 3959–3967. doi: 10.1029/JA081i022p03959.

[5] Tomokazu Ishikawa et al. “Modeling of Aurora Borealis Using the Observed Data”. In: *Proceedings of the 19th Spring Conference on Computer Graphics (SCCG).* 2011, pp. 35–42. doi: 10.1145/2461217.2461220. url: https://dl.acm.org/doi/10.1145/2461217.2461220.

[6] G. Joyce and D. Montgomery. “Nonlinear Kelvin–Helmholtz instability in magnetized plasmas”. In: *Journal of Plasma Physics* (1973).

[7] Hannes Nickisch. University of Oslo Lasse B. N. Clausen. *Oslo Aurora THEMIS (OATH) Dataset.* 2018. url: https://doi.org/10.1029/2018JA025274.

[8] Orion Sky Lawlor and Jon Genetti. “Interactive Volume Rendering Aurora on the GPU”. In: *Journal of WSCG* 19.1–3 (2011), pp. 25–32. url: https://www.cs.uaf.edu/~olawlor/2011/aurora_WSCG_2011.pdf.

[9] R. H. Levy and R. W. Hockney. “Space-charge phenomena in magnetized plasmas”. In: *Physics of Fluids* (1968).

[10] V. V. Rusanov. “Calculation of Interaction of Nonlinear Waves in a Viscous Fluid”. In: *Journal of Computational Mathematics and Mathematical Physics* 1.5 (1961), pp. 267–279.

[11] E. F. Toro. *Riemann Solvers and Numerical Methods for Fluid Dynamics.* ISBN 978-3-540-63156-1. Berlin: Springer-Verlag, 1997.