GetWet

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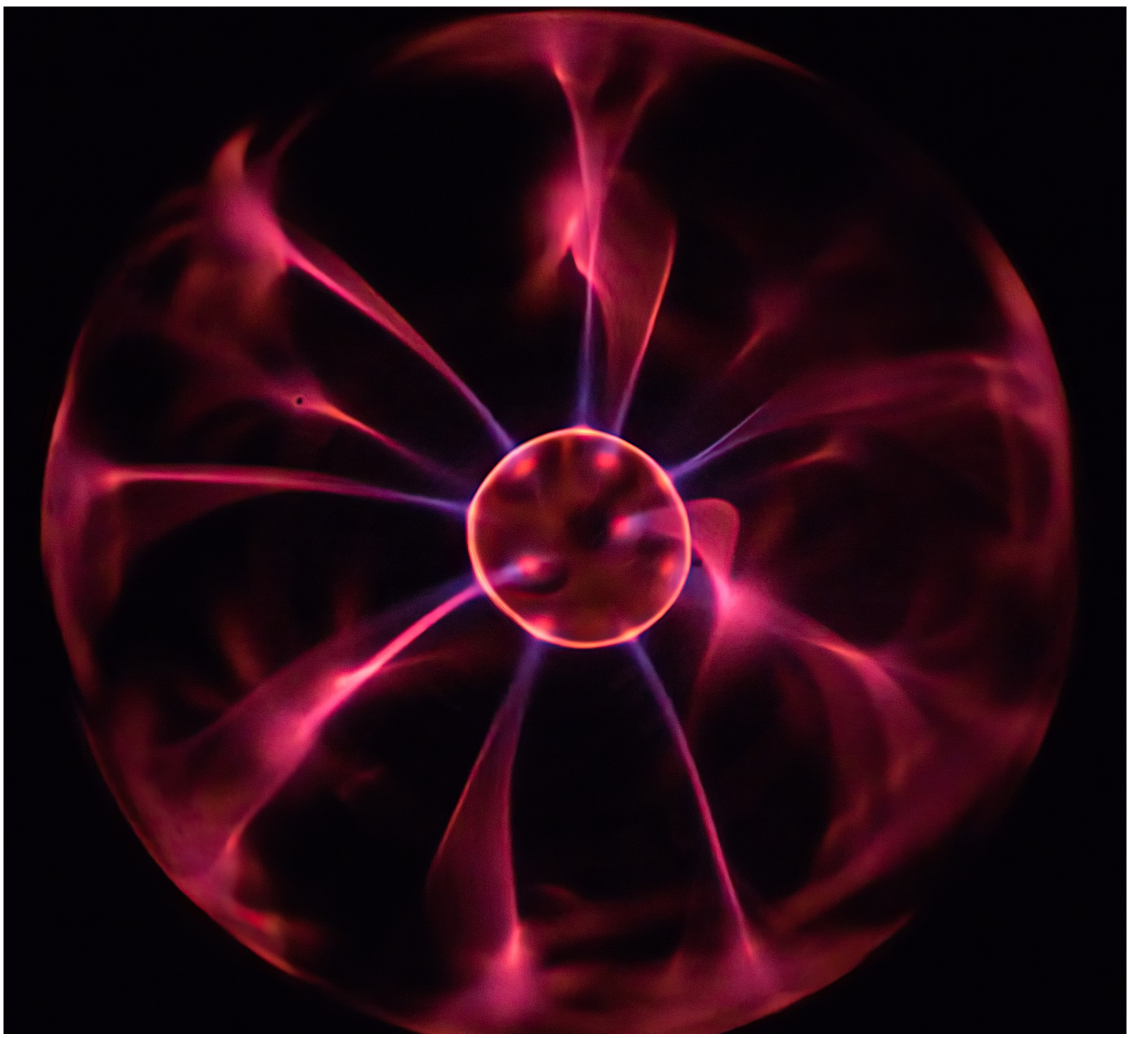

Figure 1: Final plasma globe image submission.

Abstract

The image captured above depicts a cold, weakly ionized plasma discharge confined to a glass sphere. This consumer-grade plasma globe replicates many of the same interesting physical phenomena found in laboratory plasmas and shows striking similarity to gas-discharge processes occurring in nature. Some familiar examples of matter in the plasma phase include: the Sun, stars, lightning, and the Aurora Borealis.[4]

I was inspired to take images of this plasma globe for our first project, *Get Wet*, for obvious reasons. These mysterious displays of energy seem to flow like a fluid in some environments, and in others, behave more sporadically. Further, I realized that this desktop plasma globe, framed correctly, would become my window into an interesting realm of physical phenomena that I have never had the pleasure of exploring. The project instantly became an intellectual crucible of plasma physics, optics, photography, and post-processing techniques.

Imaging Setup and Equipment

I used a Canon EOS R50 mirrorless camera with a Canon RF 50mm f/1.8 STM macro lens. The plasma globe was placed on a black desk with a black cardstock background in a dark basement at night. Initially, I photographed the plasma globe front-on, but this setup produced an unexpected circular light artifact, likely caused by internal reflections in the lens–sensor system and amplified by the globe's geometry. The artifact illustrates the sensitivity of camera positioning. The image below, shot in manual mode, at ISO 1000, f/4.5, and 1/25 s, shows the artifact as a thin white ellipse above the central electrode.[1].

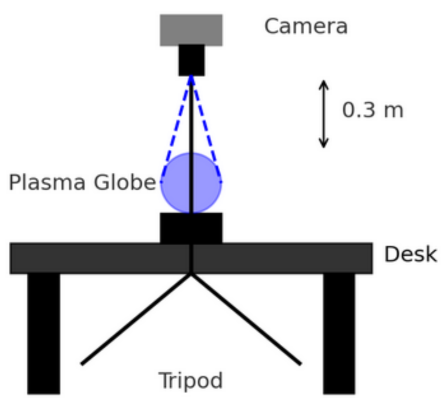

Figure 2: Imaging Setup for control of circular reflective artifact

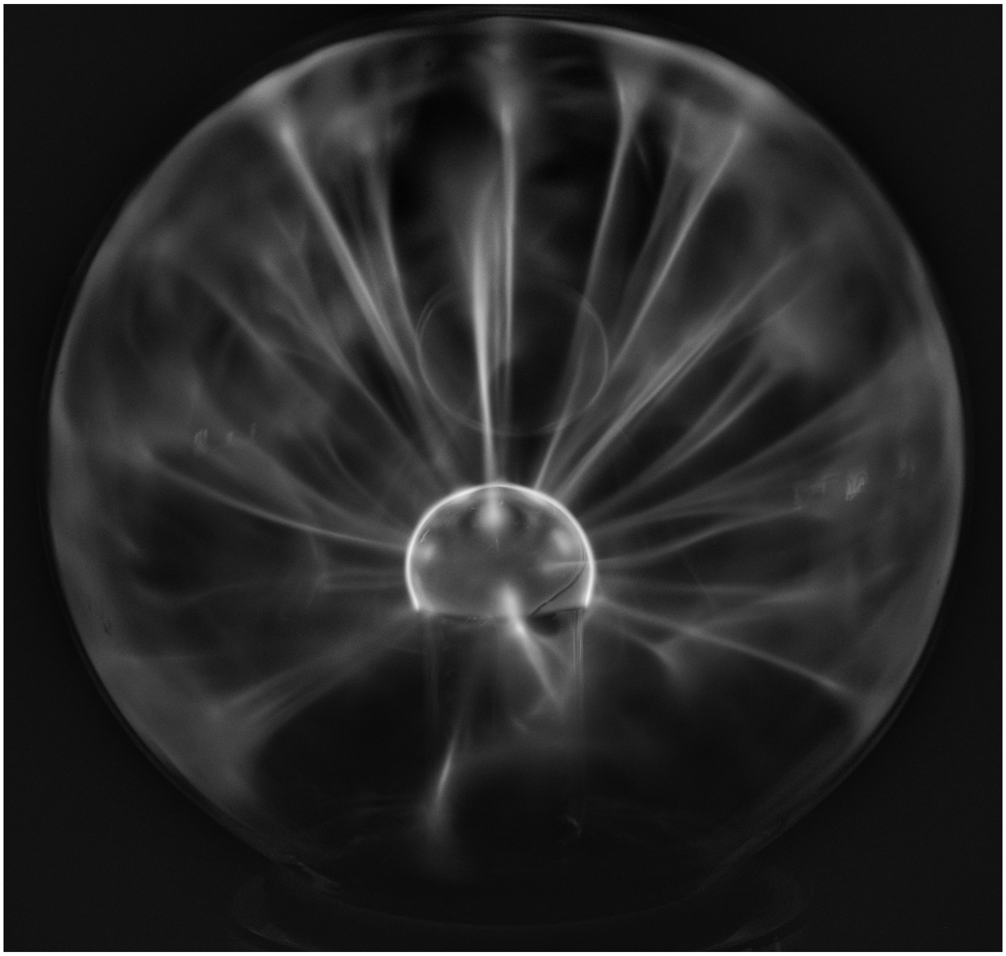

Figure 3: Manifestation of a circular reflective artifact while shot head on

Depth of Field Analysis

To analyze the optical physics, the Depth of Field (DOF) is estimated using:[1]

$$\text{DOF} = \frac{2Ncf^2d_0^2}{f^4 - N^2c^2d_0^2} \tag{1}$$

I began to explore different combinations of aperture, exposure time, shutter speed, and ISO. Manipulating these parameters allowed me to control depth of field, motion blur, and overall brightness directly. The process allowed for the opportunity to learn about the interrelated nature of these parameters. This resulted in a very shallow DOF of a few millimeters. The Canon "Fifty Nifty" RF 50mm macro lens has the following specifications to use in the DOF equation mentioned below: f=1.8 which can be thought of as the widest aperture achievable, APS-C sensor c=0.019mm, object's distance 0.30m.[1,7] After inserting these values into the DOF equation above, it is easy to see the DOF for this configuration is roughly a few millimeters, a shallow slice of sharpness at this distance to the subject. This relationship also explains the reason why I had to stop down to an aperature of f/8 for the final image.

Post Processing

Initial attempts using Darktable failed due to unresolved dependencies. I switched to Luminar Neo, which handled RAW files well. Luminar Neo's noise reduction and sharpening tools were prioritized, and minimal color editing was required, as the plasma filaments produced rich, visible wavelengths with pink-violet-purple hues.

Physical Phenomena

In our weakly ionized, RF-driven, unmagnetized discharge, the visually observed *instability* is the ionization-front (streamer) instability: avalanches satisfy the Raether–Meek criterion, form space-charge-enhanced streamer tips, and branch via Laplacian focusing. Dielectric surface-charge memory and RF modulation yield the characteristic flickering filaments.

Classical two-stream, drift-wave, and kinetic anisotropy instabilities from Chen's classification[5] are suppressed by high electron–neutral collisionality and the absence of a confining magnetic field. Thermal buoyancy of the heated neutral background biases filament paths but is secondary to the electrically driven streamer dynamics.

The degree of ionization is given by

$$\alpha = \frac{n_i}{n_i + n_n} \tag{2}$$

where n_i is the ion density and n_n is the neutral atom density. In this plasma globe, the bulk is approximately quasi-neutral ($n_i \approx n_e$), with most of the gas remaining neutral($\alpha \ll 1$)[3].

Following Piel [4], a plasma is defined as a quasi-neutral gas of charged and neutral particles which exhibits collective behavior. Quasi-neutrality implies that, on length scales larger than the Debye length, the densities of positive and negative charges balance such that $n_e \approx n_i$. Collective behavior arises because the long-range Coulomb forces couple particle motions to self-consistent electromagnetic fields, governed by Maxwell's equations.

Chen [5] proposes three practical criteria to test whether a gas can be considered a plasma:

1. **Plasma approximation.** There must be many charges per Debye sphere, i.e.

$$N_D = \frac{4}{3}\pi n_e \lambda_D^3 \gg 1, \qquad \lambda_D = \sqrt{\frac{\varepsilon_0 k_B T_e}{n_e e^2}}.$$

2. **Quasi-neutrality.** For scales $L \gg \lambda_D$, the electron and ion densities satisfy $n_e \approx n_i$, with departures confined to thin sheath regions near boundaries.

3. **Collective frequency dominance.** The electron plasma frequency,

$$\omega_{pe} = \sqrt{\frac{n_e e^2}{\varepsilon_0 m_e}},$$

should exceed the relevant collision frequency ν_{en} so that collective oscillations persist.

In the plasma globe, the fill pressure is typically near 1 Torr, corresponding to a neutral density of $n_n \sim 10^{22}$–$10^{23}\,\mathrm{m}^{-3}$ at room temperature. Because the plasma is weakly ionized, the degree of ionization equation becomes:

$$\alpha = \frac{n_i}{n_n + n_i} \approx \frac{n_e}{n_n}$$

A weakly ionized plasma's degree of ionization is very small, with typical values $\alpha \sim 10^{-6}$–10^{-5} for RF-driven glow discharges [6]. Taking $\alpha \sim 10^{-6}$, one finds $n_e \sim 10^{16}\,\text{m}^{-3}$. With an electron temperature of $T_e \sim 2$ eV, this yields a Debye length of $\lambda_D \approx 60\,\mu$m and a Debye number $N_D \sim 10^4$, comfortably satisfying the plasma approximation. The globe is therefore quasi-neutral in the bulk, with thin sheaths forming at the central electrode and along the glass wall.

The electron plasma frequency under these conditions is $\omega_{pe} \sim 10^{10}\,\text{s}^{-1}$, while the electron–neutral collision rate estimated from $\nu_{en} = n_n \sigma_m \bar{v}_e$ (with $\sigma_m \sim 3 \times 10^{-19}\,\text{m}^2$ and $\bar{v}_e \sim 10^6\,\text{m/s}$) is of order 10^9–$10^{10}\,\text{s}^{-1}$. Thus, ω_{pe} is only slightly greater than ν_{en}, meaning that collective oscillations exist but are heavily damped. This collisionality explains why Landau damping is not relevant here. Instead, the plasma dynamics are governed by electron–neutral collisions, RF energy input, and space-charge effects at streamer heads.[3]

The visually striking filaments observed in the globe are streamers: localized ionization fronts driven by strong electric fields at their tips. Streamer propagation is governed by the Raether–Meek avalanche criterion, space-charge field enhancement, and Laplacian focusing, leading to characteristic branching [4]. The RF drive supplies energy each cycle, while surface charge memory on the glass and collisional damping modulate the filaments, producing the flickering, dynamic appearance. Thermal buoyancy of the heated neutral gas biases streamer paths upward, but the dominant physics remains the electrically driven, weakly ionized streamer discharge.

In summary, the plasma globe operates in the regime of a cold, weakly ionized plasma: $\alpha \ll 1$, $N_D \gg 1$, quasi-neutral in the bulk, and collisional with $\omega_{pe} \gtrsim \nu_{en}$. Collective effects are present but strongly damped, sustained by the oscillating RF field. producing the filamentary discharge patterns characteristic of this device.[4,5,6]

Conclusion

This project demonstrated that even an inexpensive device can showcase the hierarchy of plasma phenomena: from Paschen's breakdown law and the Raether–Meek criterion governing avalanche-to-streamer transitions, to the role of dielectric charging, collisional damping, and thermal buoyancy in shaping filament behavior. The camera lens became not only a tool of visualization but also a diagnostic, capturing the fleeting geometry of space-charge–enhanced branches that are otherwise invisible to the eye. Ultimately, the plasma globe is both art and science: a demonstration of how complex non-equilibrium physics can manifest as striking visual beauty.

References

[1] Ray, Sidney F. *Applied Photographic Optics*. 3rd ed., Focal Press, 2002.

[2] Kingslake, Rudolf. *A History of the Photographic Lens*. Academic Press, 1989.

[3] Moisan, Michel, et al. "The Physics of Collisional Plasmas." *Plasma Sources Sci. Technol.*, 2006.

[4] Piel, Alexander. *Plasma Physics: An Introduction to Laboratory, Space, and Fusion Plasmas*. Springer, 2010.

[5] Chen, Francis F. *Introduction to Plasma Physics and Controlled Fusion*. 3rd ed., Springer, 2016.

[6] Lieberman, Michael A., and Alan J. Lichtenberg. *Principles of Plasma Discharges and Materials Processing.* 2nd ed., Wiley-Interscience, 2005..

[7] H. D. Young and R. A. Freedman, *University Physics with Modern Physics*, 15th ed., Pearson, 2019.

[8] OpenAI ChatGPT - 4o/5 w/ additional support for writing and technical checks provided by ChatGPT 2025.

Appendix

Avalanche growth and Raether–Meek threshold (worked example)

Setup and field model

Inner electrode radius $a = 0.5$ in $= 0.0127$ m, outer glass radius $b = 2.5$ in $= 0.0635$ m. Assume an RF peak amplitude $V_0 \approx 3$ kV. Approximating the discharge gap as a concentric spherical capacitor, the radial electric field is

$$E(r) \;\approx\; \frac{V_0\, ab}{(b-a)\, r^2} \qquad (a < r < b).$$

At a point $r = 0.015$ m (i.e., $\sim$2.3 mm outside the 1-inch electrode), this gives

$$E(r)\big|_{0.015\text{ m}} \approx 2.12\times 10^5 \text{ V/m} \;=\; 2.12\times 10^3 \text{ V/cm}.$$

With $p = 1$ Torr, the reduced field is

$$\frac{E}{p} \;\approx\; 2.12\times 10^3\, \frac{\text{V}}{\text{cm}\cdot\text{Torr}}.$$

Avalanche (Townsend) law

For a noble-gas-like mixture we take the common semi-empirical first Townsend form

$$\alpha \;=\; A\, p\, \exp\!\left(-\frac{B\, p}{E}\right),$$

with representative argon-like coefficients $A \approx 15$ cm^{-1}Torr^{-1}, $B \approx 180$ V$\,$(cm $\cdot$ Torr)$^{-1}$. At $E/p \approx 2.12\times 10^3$ V/(cm $\cdot$ Torr) and $p = 1$ Torr:

$$\alpha \;\approx\; 15\cdot 1\cdot \exp\!\left(-\frac{180}{2116}\right) \;\approx\; 13.8 \text{ cm}^{-1}.$$

(For a neon-like choice $A \approx 4.4$, $B \approx 110$, one gets $\alpha \approx 4.18$ cm^{-1}. The true Ar/Ne mix will lie between.)

The electron number along a short path d grows as

$$N(d) \;=\; N_0\, \exp\!\left(\int_0^d \alpha_{\text{eff}}(x)\, dx\right), \qquad \alpha_{\text{eff}} \equiv \alpha - \eta \text{ (with attachment } \eta \approx 0 \text{ for Ar/Ne)}.$$

Over a small region where E (hence α) is roughly constant, this is $N(d) = N_0\, e^{\alpha d}$.

Raether–Meek streamer threshold

The transition to a space-charge–dominated streamer occurs when the avalanche reaches

$$\int_0^d \alpha_{\text{eff}}(x)\, dx \;\simeq\; \ln N_{\text{crit}} \;\approx\; 18\text{–}20 \quad (\text{i.e., } N_{\text{crit}} \sim 10^8\text{–}10^9).$$

Using the local $\alpha \approx 13.8$ cm^{-1} estimate:

$$\boxed{d_{\text{crit}} \;\approx\; \frac{18}{\alpha} \;\approx\; \frac{18}{13.8} \;\approx\; 1.30 \text{ cm}, \quad d_{\text{crit}}(20) \approx 1.45 \text{ cm}}.$$

Interpretation for the globe

Near the inner electrode at $p\sim 1$ Torr, an electron avalanche needs of order 1–1.5 cm of high-field path to satisfy Raether–Meek locally; this is well within the several-centimeter gap to the glass, so avalanches can reach the streamer threshold and then self-propagate/branch as observed. Because $E(r) \propto r^{-2}$, $\alpha(r)$ decreases with radius; a more precise treatment integrates

$$\int_{r_0}^{r_1} A\, p\, \exp\left[-\frac{B\, p}{E(r)}\right] dr \ \gtrsim\ 18,$$

but the constant-α estimate above captures the correct centimeter-scale threshold.

Assumptions (i) Peak RF voltage $V_0 \approx 3$ kV; (ii) concentric-sphere field model; (iii) argon-like Townsend coefficients (neon-like values give a conservative lower α); (iv) negligible attachment in Ar/Ne; (v) local-constant α over millimeter–centimeter steps near the electrode.

Additional Images Captured During Flow Visualization

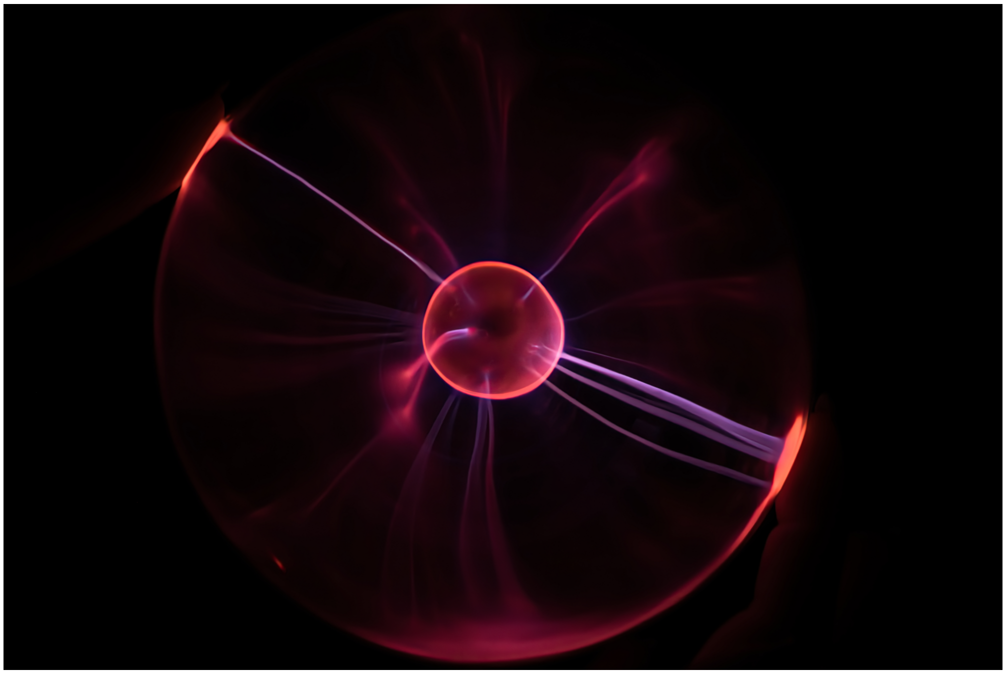

Figure 4: Capacitive coupling and discharge through fingertips

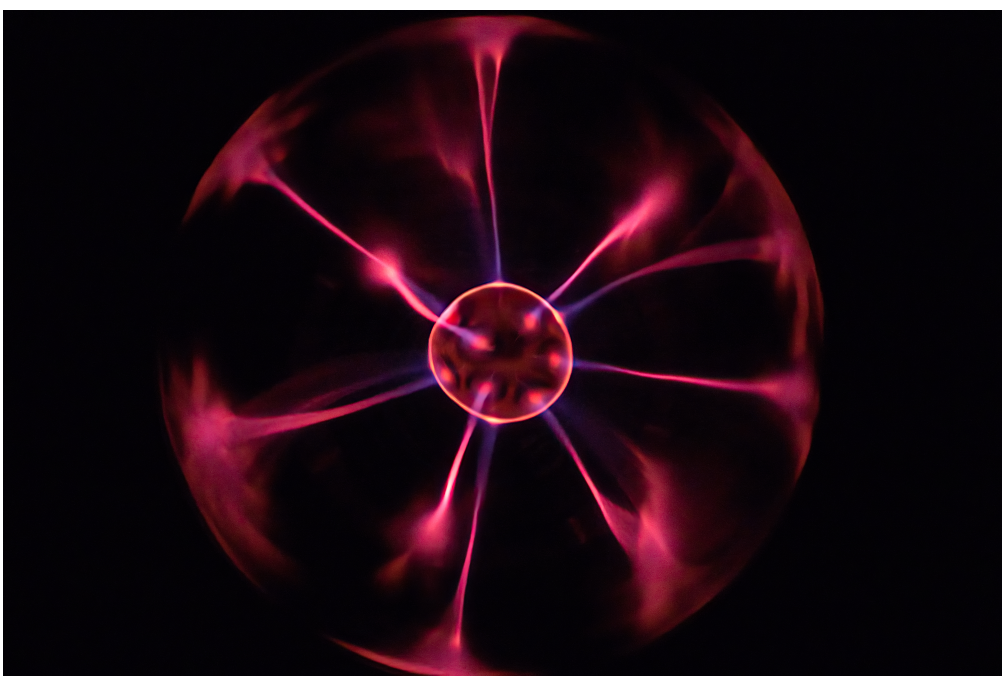

Figure 5: f/8, 1/40 s, ISO 10000

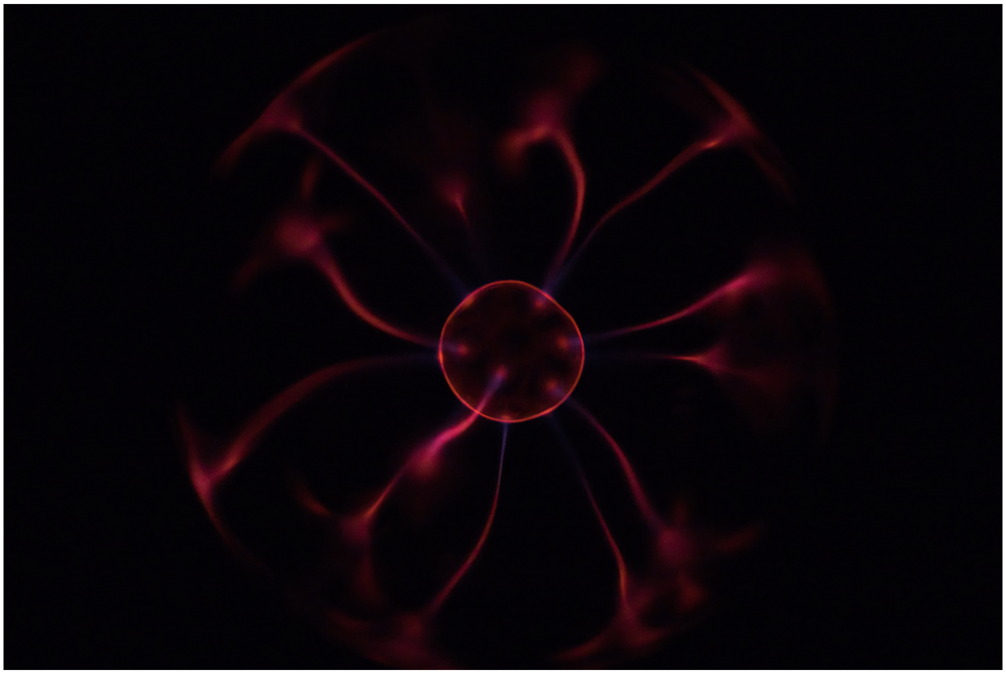

Figure 6: f/5.6, 1/320 s, ISO 16000

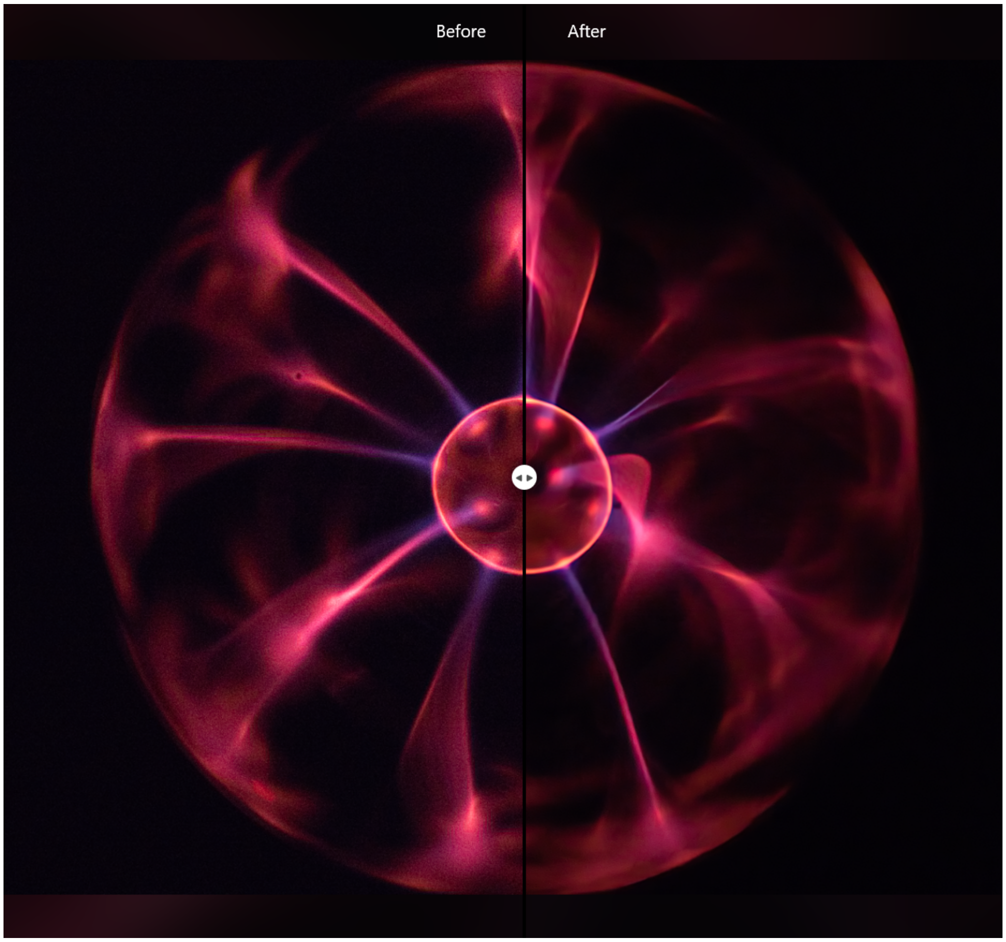

Figure 7: Before vs. After Post Processing Slice of Main Submission

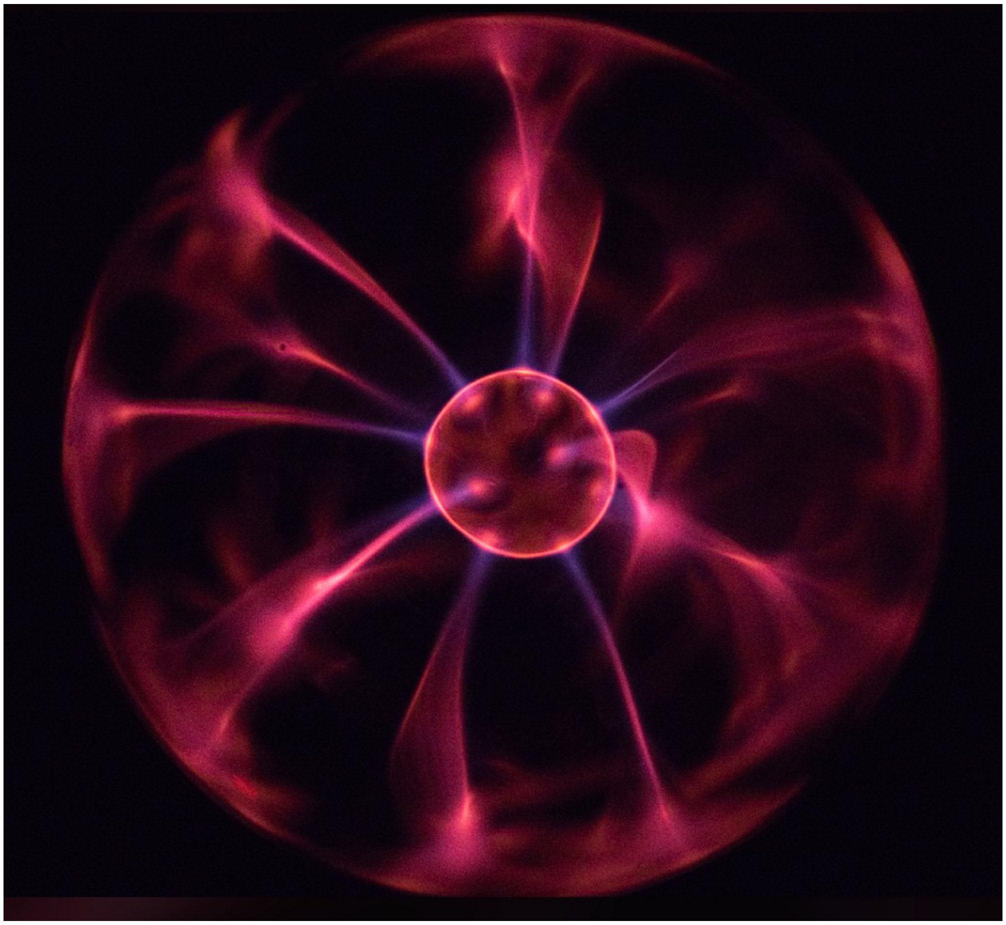

Figure 8: Raw Image of Main Submission