

MCEN 55151 Get Wet: Sunspots, Solar Convection, Magnetic Fields

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ABSTRACT

In this report, I present photos taken of sunspots for MCEN 5151. The Sun is covered in convection cells, recycling hot plasma from within the so-called Convection Zone to replace relatively cooler plasma at the surface of the photosphere. Sunspots are formed when regions of solar convection are suppressed by sufficiently strong magnetic fields. This causes the plasma that is held at the surface to cool substantially, relative to the surrounding photosphere. We perceive these cooler areas as dark spots on the Sun, and with a solar filter and sufficiently powerful amateur camera lens, sunspots can be photographed.

Keywords: Flow Visualization, Solar Convection, Magnetohydrodynamics

INTRODUCTION

Figure 1 is my submission for Get Wet, produced for MCEN 5151, Flow Visualization, at the University of Colorado: Boulder under the supervision of Dr. Laura Sunberg. Our first assignment was an introduction to fluid dynamics, visualization, and photography techniques. A chance for the class to "get its feet wet", as it were.

A few weeks before I began working on the Get Wet assignment, a video from Anton Petrov, a science communicator on YouTube, caught my eye (Petrov, 2026). In it he discusses a host of new solar observations, but what blew me away were the images of the Sun taken by Kuridze et al. (2026) with 19km resolution. I could not get the images of the sunspots and convection cells out of my head, so I purchased a solar filter. If I could sufficiently resolve any surface effects or fluid behavior for the Sun, then that was to be my project submission. Fortunately, the end result is what you see in Figure 1, with clearly visible sunspots.

I choose here to visualize the lack of a flow. The surface of the Sun is constantly churning, turbulent convection that all life on Earth depends on. Sunspots form when conditions at the photosphere are such that convection is suppressed, and this parcel of plasma is unable to sink back into the photosphere as it cools. I wanted to highlight the momentary suppression of a flow that we all take for granted, and may not have realized could be treated as a fluid. I also sought impress upon the viewer the awesome magnificence of the Sun, presenting it as the long figure in an otherwise pitch black frame.

FLOW PHYSICS

0.1 Convection in the Sun

The standard solar model describes a self-gravitating ball of plasma, primarily ionized hydrogen and helium with trace amounts of heavier elements, supported by radiative pressure (Schumacher and Sreenivasan, 2020). Globally, this is approximated as hydrostatic equilibrium. Fusion of hydrogen into helium takes place almost entirely within approximately $r \leq 0.3R_{\odot}$, where gravitational pressure is the greatest (Miesch, 2005). From approximately $0.30R_{\odot} \leq r \leq 0.70R_{\odot}$ energy is transferred via radiation, with convection beginning at $r \geq 0.70R_{\odot}$, the so-called Convection Zone (CZ). There is evidence to suggest a brief interstitial period called the tachocline, which is typically neglected by the standard model (Schumacher and Sreenivasan, 2020). In the CZ the Sun begins to shift from nearly uniform rotation to differential rotation in the CZ (Miesch, 2005). The sheer at this boundary must be extraordinary, but that is beyond the scope of this report.



Figure 1. Photo taken of the Sun with several prominent sunspots.

In the CZ transport of energy becomes dominated by turbulent convection, the outer-most $0.01R_{\odot}$ of which comprises the photosphere (Schumacher and Sreenivasan, 2020). This is where energy that started as fusion at the core of the Sun is able to be broadcast into the Solar System. A parcel of plasma in the photosphere cools as energy is radiated, begins to darken, grow more dense, and sink into the CZ to be replaced by hot, bright, less dense plasma from deeper within the CZ. The resulting convection cells are sometimes called solar granules and can be seen in Figure 2.

A quantity of interest when discussing turbulence and convection is the Reynolds Number, given by:

$$\text{Re} = \frac{uL}{\nu} \quad (1)$$

Where u is the flow velocity of the fluid, L is a characteristic length scale, and ν is the dynamic viscosity. The Reynolds Number characterizes turbulent flow by comparing velocity to the fluid's ability to disperse and transfer velocity through viscous interaction. For $\text{Re} \ll 1$ a fluid is said to be dominated by viscosity.

Measurements of these properties of the photosphere is complicated, and simplified simulations are used to validate estimations by comparing computational fluid dynamics and magnetohydrodynamics simulations against observations (Spruit, 1973; Schumacher and Sreenivasan, 2020; Hayashi et al., 2026). Canonical values are presented by Miesch (2005) for large solar granules as $u \sim 100\text{m s}^{-1}$ $L \sim 200\text{Mm}$, and $\nu \sim 1\text{cm}^2 \text{s}^{-1}$ for the dynamic viscosity of fully ionized hydrogen plasma. Of course, these values vary across the surface of the photosphere, but using this approximation a reasonable approximation for the Reynold's Number at the top of the photosphere is:

$$\text{Re} \sim \frac{(100\text{m s}^{-1})(2 \cdot 10^8\text{m})}{0.01\text{cm}^2 \text{s}^{-1}} \sim 10^{14} \quad (2)$$

Thus we can say that the surface of the Sun is highly turbulent, with inertial forces due to convection dominating over viscosity.

Another quantity of interest is the Prandtl number, characterizing the ratio of momentum transfer to heat transfer. We treat the Prandtl number as:

$$\text{Pr} = \frac{\nu}{\alpha} \quad (3)$$

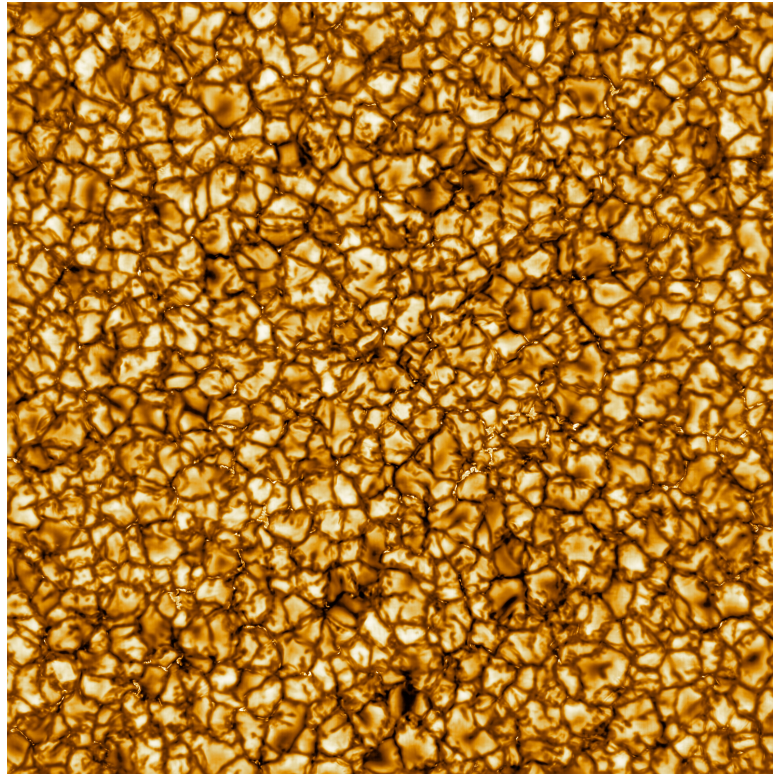


Figure 2. Image of Solar granules taken with the Daniel K. Inouye Solar Telescope funded by NSO/AURA/NSF. Licensed under CCA 4.0

Where α is the thermal diffusivity with values of $10^{5-7} \text{ cm s}^{-1}$ (Miesch, 2005). Using the same value for ν as above yields a Prandtl number of $10^{-6 \sim -4}$, indicating that diffusion in the photosphere is temperature dominated.

0.2 Sunspots as Regions of Suppressed Convection

So far, I have neglected to mention the Sun's magnetic field, which has been known to be associated with sunspots since Hale (1908) observed the Zeeman splitting¹ in and around sunspots. The solar dynamo is extremely complex, globally and locally, so to keep the discussion straightforward, I consider the magnetic field that runs longitudinally² through the CZ (Parker, 1995; Miesch, 2005). These longitudinal magnetic fields can be thought of as "flux tubes" that wrap around the Sun at a particular longitudes. The flux tubes will bend and twist dynamically with and within the Sun itself, driven by turbulent convection of hydrogen ions.

Active regions of the Sun have been observed to have longitudinal flux tubes with magnetic flux densities of 10 kG (Miesch, 2005). For comparison, the magnetic flux density of Earth's magnetic field density ranges from approximately 3 G to 6 G (Mandea and Purucker, 2005). The flux tubes themselves will buoyantly rise to the surface of the photosphere, where a part of the tube breaks through the surface of the Sun (Parker, 1995). In these regions where flux tubes have protruded vertically through the edge of the CZ, the magnetic force exerted on positively charged hydrogen atoms is sufficient to stop the convective process.

With a parcel of plasma effectively "trapped" at the surface of the photosphere, it radiates away energy, cooling by 1000 – 1900 K compared to inactive regions of the Sun (Solanki, 2003). These regions form the dark umbra of the sunspot, which are clearly visible in Figure 1 as black/brown dots at the center of the image, trailing down the to the 7 o'clock position. Towards the edge of the flux tube (and therefore the sunspot), the magnetic field becomes less coherent, and is less able to suppress convection (Chen et al.,

¹The Zeeman effect is the splitting of spectral lines under extreme magnetic fields.

²Also referred to as toroidal.

2017). This forms the penumbra, which can be seen faintly in Figure 1 around the black/brown dots. A higher magnification image of a sunspot can be found in Figure 3, where the umbra and penumbra can be clearly seen. In this way, the convective flow being suppressed is the dynamical process being visualized.

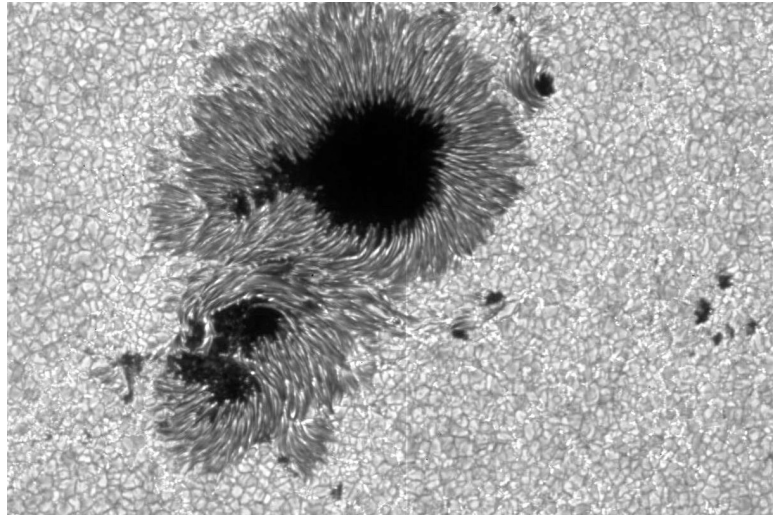


Figure 3. Image of a sunspot where the umbra and penumbra are distinguishable from the rest of the solar surface. Courtesy of NASA via the public domain.

VISUALIZATION TECHNIQUES AND PHOTOGRAPHIC SPECIFICATIONS

Visualization of the Sun is straightforward, but not without its challenges. In principle it was as simple as "point and shoot". In practice, Total Solar Irradiance is 1361 W m^{-2} before atmospheric attenuation (Prša et al., 2016), with a distance of $1.49 \cdot 10^{11} \text{ m}$. This is a tremendous amount of energy that can overwhelm optical sensors and an incredible distance requiring intense magnification.

My image was captured on a Nikon D3300 DSLR camera using a Nikkor 200-500mm telephoto lens, a 1.7x teleconverter, and universal solar filter of ISO 12312-2:2015(E). The final image used a shutter speed of $\frac{1}{125} \text{ s}$, ISO of 800, F-stop of $\frac{f}{9.5}$, and a final focal length of 440mm before the additional teleconverter magnification. The camera was placed on a tripod, and shutter release was controlled with a 10 s self-timer to ensure there was time to settle to stillness.

The image was edited in darktable³, an open source photography workflow application. The image before editing can be seen in Figure 4. The image was heavily cropped in darktable and the post-processing included suppressing the most of the reds and yellows via manipulation of the RGB curve in order to remove coronal flare. There was also slight manipulation of the exposure in order to bring the dim the solar disk slight such that the sunspots were more readily visible.

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³<https://www.darktable.org/>



Figure 4. Image taken of Sun for the Get Wet project, before editing in darktable.

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