Studying and Simulating Magnetic Avalanches in the Solar Corona

Student: Mr A. P. K. Prokopyszyn
Supervisor: Prof A. W. Hood

School of Mathematics and Statistics, University of St Andrews, St Andrews, Fife, U.K.
Cormack Undergraduate Research Scholarship

Abstract

Over the last 25 years there have been a number of sophisticated computer models of the putative phenomenon known as the Solar Magnetic Avalanche. A magnetic avalanche is a cumulative process in which magnetic energy is released in a region of space, which in turn causes nearby magnetic field to release energy as well, and so on. Many of these simulations, while computationally cheap, rely on somewhat arbitrary rules to govern their behaviour. This year Professor Alan Hood of the University of St Andrews, led a paper (Hood et al., 2016) detailing the results of an MHD (magnetohydrodynamics) simulation grounded very firmly in physics. The downside of such an approach is the high computational demand of the simulation, meaning that the number of avalanches that could be investigated, was orders of magnitude below the number required to compare with previous *Cellular Automata* (see below) results and with actual solar observations. This summer project analyses the results of the aforementioned paper and tries to produce a simple simulation which is both based on physics and computationally cheap. A simulation that can achieve both of these aims would contribute to solving the "Coronal Heating Problem".

Cellular Automation Simulation

Starting in the early 90's Magnetic Avalanches have been simulated using *Cellular Automata* simulations. *Cellular automation* is a computing term and refers to a collection of "coloured" cells on a grid of specified shapes (see Figure 1) that evolves through a number of discrete time steps according to a set of rules based on the states of neighbouring cells. The simulation offered in Lu et al. (1993) can be seen as simulating a square table on which sand grains are dropped one at a time, leading to the build-up of a more or less conical pile. The sand pile steepens until its slope reaches a critical angle, beyond which further addition of sand rapidly leads to avalanches sweeping sand down the pile, so that the angle of the slope remains close to its critical value. When the sand pile reaches this state, it is in a state of Self-Organised Criticality.

Unfortunately, Cellular Automata simulations have yet to match observations in certain key aspects (Charbonneau et al., 2001). It is believed that if a simulation with less assumptions and arbitrary rules can be produced, then results observed in the corona can be reproduced.

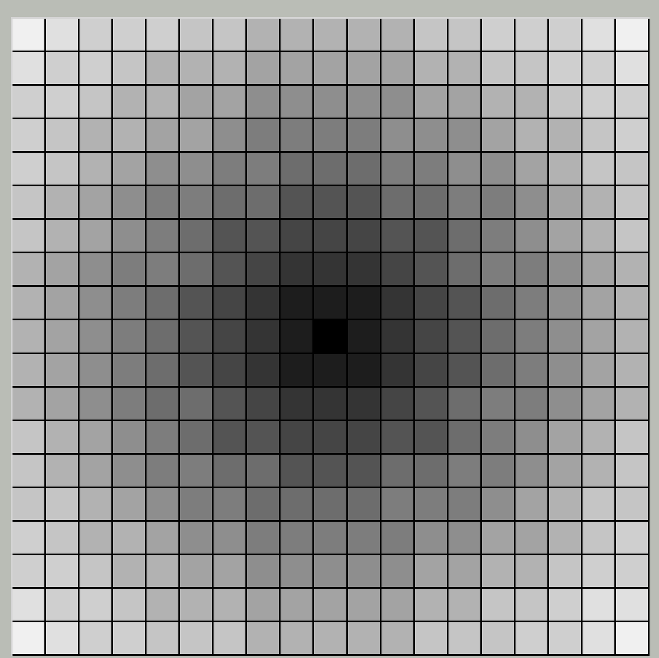

Figure 1: This figure shows an example of a lattice similar to the lattice used in Lu et al. (1993) that has reached a pix-elated conical pile and is also in a state of self-organised criticality. The darker the square, the stronger the field at that point.

Simulation Offered in Hood et al. (2016)

This year a simulation grounded firmly in solar physics with no arbitrary rules was offered in Hood et al. (2016). This simulation has an initial configuration of 23 flux tubes and these are illustrated in Figure 2. The centre node has been twisted so tightly that it is unstable, this is why it expands and triggers the avalanche. This simulation provides a phenomenal amount of detail, the drawback of this is the high computational demand. Only one avalanche could be carried out, which is orders of magnitude below the number required to reach self organised criticality.

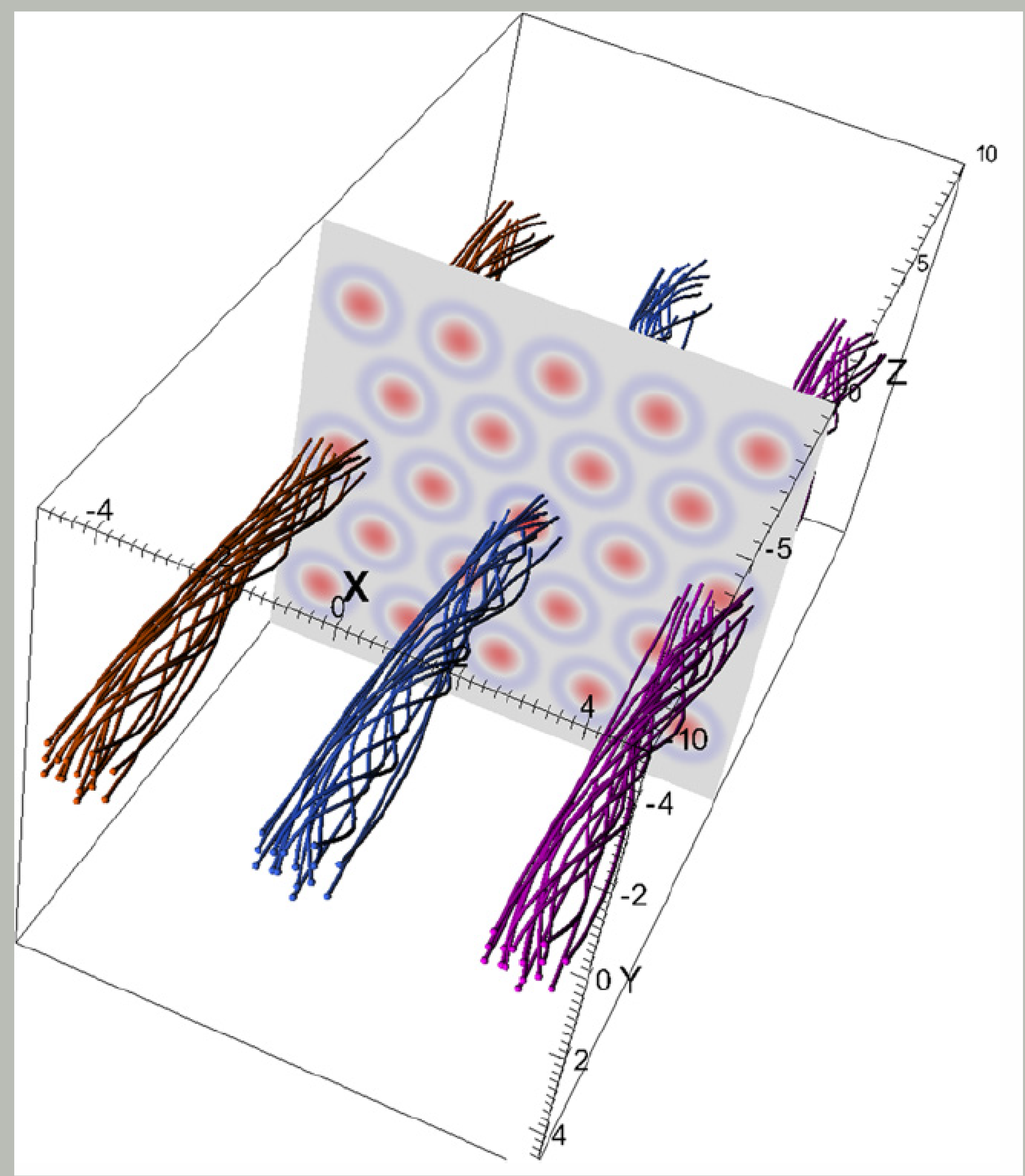

Figure 2: This figure was taken from Hood et al. (2016) and shows the initial configuration of all 23 nodes.

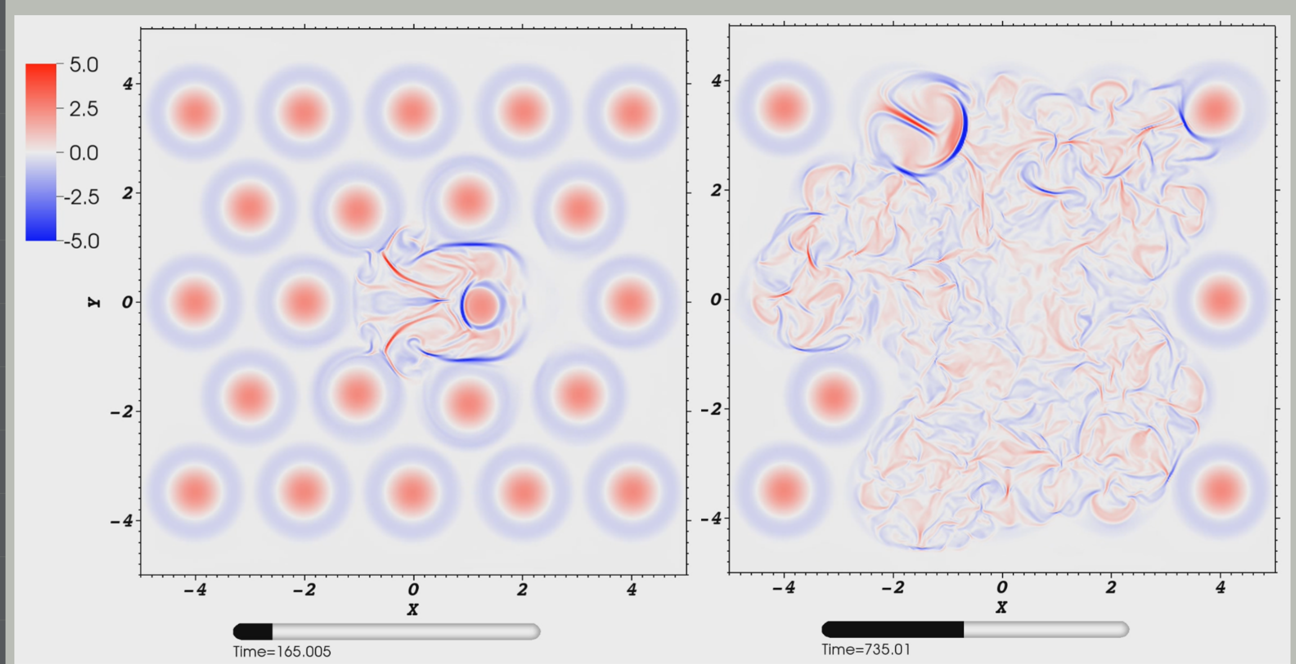

Figure 3: This figure was taken from Hood et al. (2016) and shows the simualtion in action. The more red a region is the more positive current there is, the more blue a region is the more negative the current in that region.

Simulation Offered in the Summer Project

The aim of this project was to find a compromise between the simulation offered in Lu et al. (1993) and Hood et al. (2016). More specifically, the aims were to produce a simulation that could: 1. Reproduce results of the simulation in Hood et al. (2016). 2. Be computationally cheap. 3. Have as few arbitrary rules as possible and instead be governed by rules grounded in solar physics.

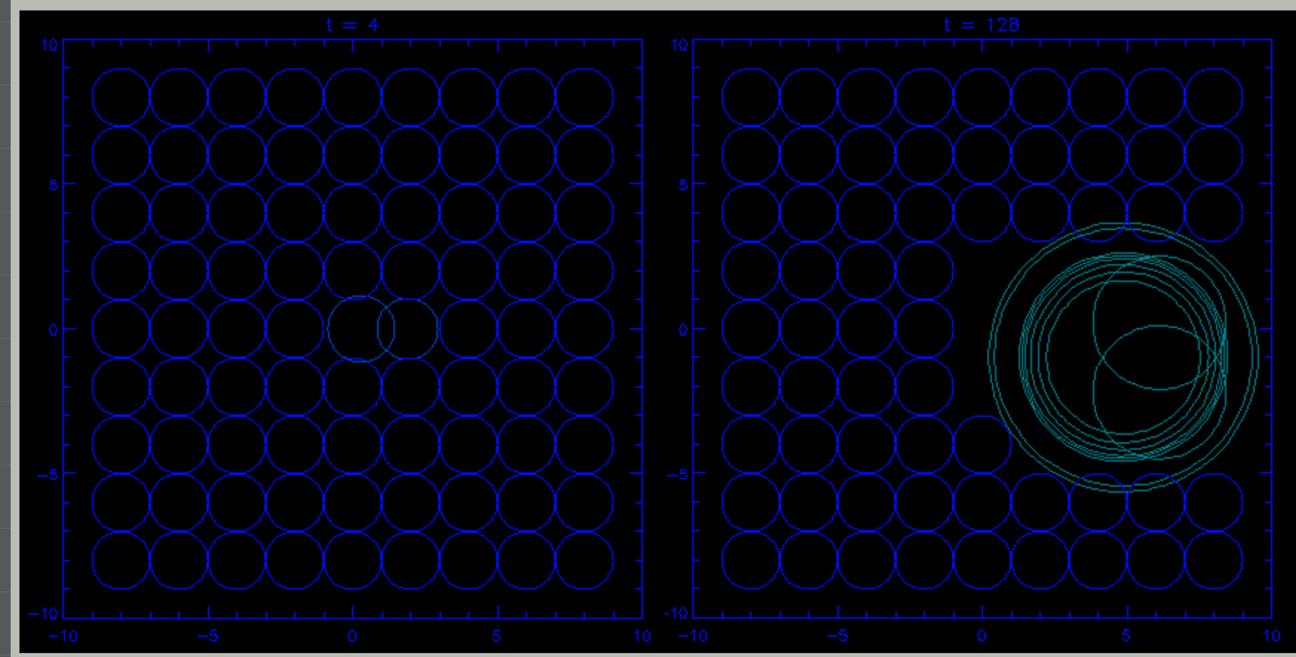

Figure 4: This figure shows two snapshots of the simulation created in the summer project at times t=4 and t=128. Each circle represents the cross section of a twisted flux tubes. The more green a node is the less twisted it is and the more blue a node is the more twisted it is.

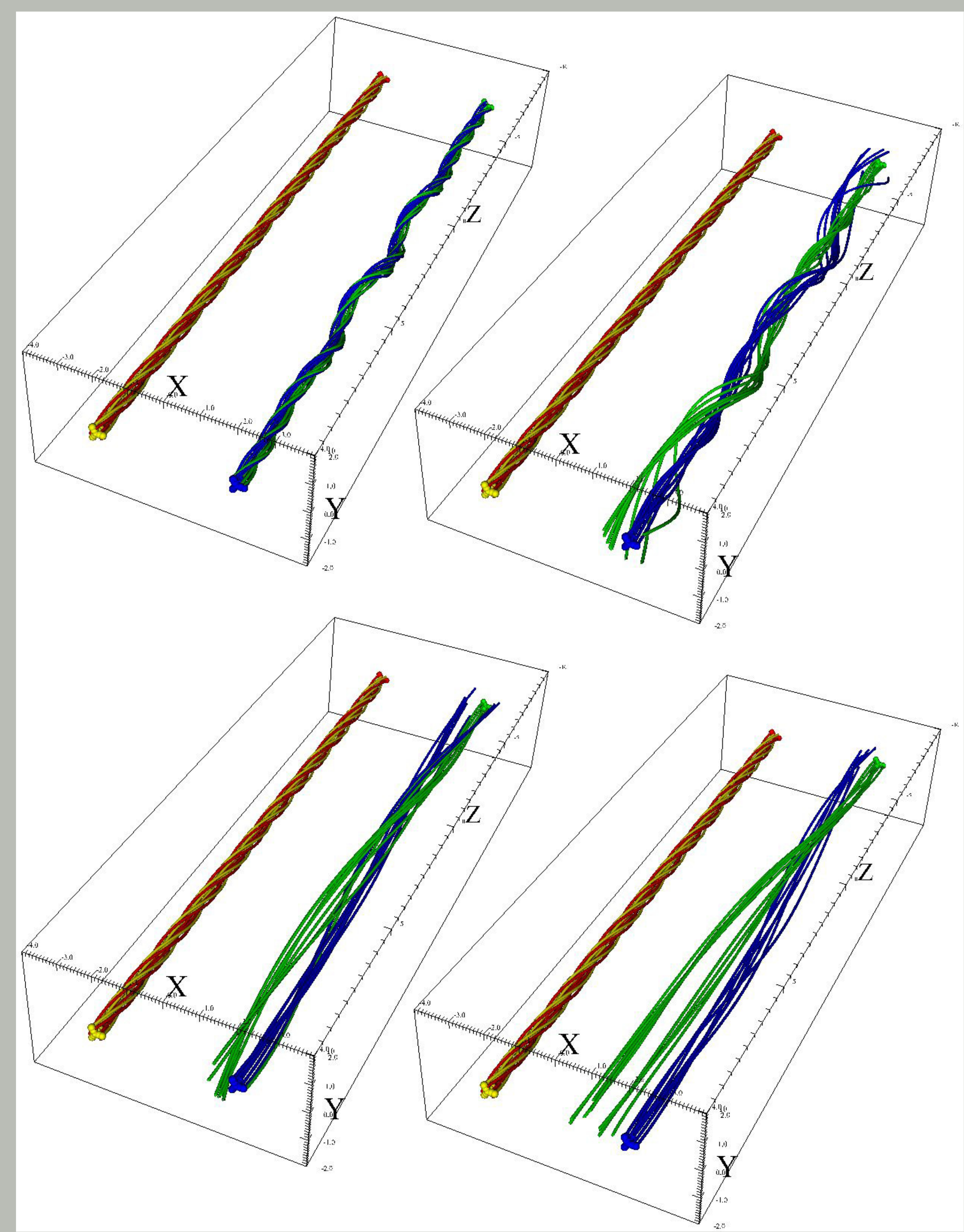

Figure 5: This Figure taken from Tam et al. (2015) illustrates two phenomena: unstable flux tubes and converging flux tubes. Figure 2 (a): (*top left*) $t = 60$ The flux tube on the left is stable while the one on the right is so tightly twisted that it is unstable. Figure 2 (b): (*top right*) $t = 80$ The unstable flux tube on the right is expanding. Figure 2 (c): (*bottom left*) $t = 160$ The two flux tubes are converging. Figure 2 (d): (*bottom right*) $t = 300$ The two flux tubes have finished converging and have now formed one larger less twisted flux tube.

Summer Project Simulation Continued

The simulation produced in this summer project, was produced after close examination of the simulation in Hood et al. (2016). There are two main phenomena the code simulates: first, is unstable flux tubes and the second is converging flux tubes, both of these are illustrated in Figure 5.

```
1  PROGRAM avalanche
2
3  aa=initial_conditions !set aa to its initial values
4
5  !first resolve unstable groups
6  DO i=1,n_g !iterate over all groups
7    ii=group_node_numbers !ii array gives node numbers of
8                          !all the nodes in group i
9    IF (SUM(λ_ii(:)) > λ_c) THEN !group is unstable
10     Λ_ii(:) = Λ_inew = Λ_ii(1) sqrt(1 - Λ_ii(1)^2/7) !assign group new values
11     ω_ii(:) = σ_1 ω_ii(1)
12     R_ii(:) = sqrt(ω_ii(1)/(π Λ_ii(1)))
13   END IF
14 END DO
15
16 !second resolve convergences between groups
17 DO i=1,n_g
18   DO j=i+1,n_g !iterate over all distinct group pairs
19     ii=group_node_numbers !gives nodes of group i
20     jj=group_node_numbers !gives nodes of group j
21     IF (SUM(λ_ii(:) + λ_ojj(:)) .OR. SUM(λ_jj(:) + λ_oii(:)) > λ_c) THEN
22       g_jj(:) = i !merge the two distinct groups into one
23       ii = [ii, jj] !concatenate ii with new nodes
24       Λ_ii(:) = (Λ_inew R_ii(1)^2 + Λ_jnew R_jj(1)^2)/(R_ii(1)^2 + R_jj(1)^2)
25       ω_ii(:) = σ_2 ω_ii(:)
26       ω_jj(:) = σ_2 ω_jj(:)
27       R_ii(:) = sqrt(ω_ii(1)/(π Λ_ii(1)))
28       X_ii(:) = X_ii(1) + (X_jj(1) - X_ii(1)) ω_jj(1)/ω_ii(1)/(1 + ω_jj(1)/ω_ii(1))
29     END IF
30   END DO
31 END DO
32
33 !third move nodes accordingly
34 DO i=1,n !iterate over all nodes
35   IF (|X_i - x_i| < |v_1|) THEN !move full amount
36     x_i = x_i + v_1
37   ELSE !move less than full velocity
38     x_i = X_i
39   END IF
40   IF (R_i - r_i < v_2) THEN !expand radius by full amount
41     r_i = r_i + v_2
42   ELSE !expand radius by less than full amount
43     r_i = R_i
44   END IF
45 END DO
46
47 !fourth check if avalanche has finished
48 IF (avalanche_finished) THEN
49   !start next iteration by adding new flux tubes to
50   !random coordinates centred on the origin
51 ELSE
52   !Go back to line 17
53 END IF
54
55 END PROGRAM avalanche
```

Coronal Heating Problem

The coronal heating problem relates to the question of why the temperature of the Sun's corona is millions of Kelvin higher than that of the surface. The average temperature of the upper boundary of the solar photosphere is 5785 K (Aschwanden, 2005). The average temperature of the corona, which is located above the photosphere, has a temperature exceeding 1,000,000 K (Aschwanden, 2005). The physical explanation for the high temperature in the solar corona remains one of the outstanding unsolved problems for solar physicists. It is widely accepted that the heating mechanism is closely linked to the strong magnetic field in the corona, however, the details are still uncertain. Perhaps, magnetic avalanches are the dominating heating mechanism?

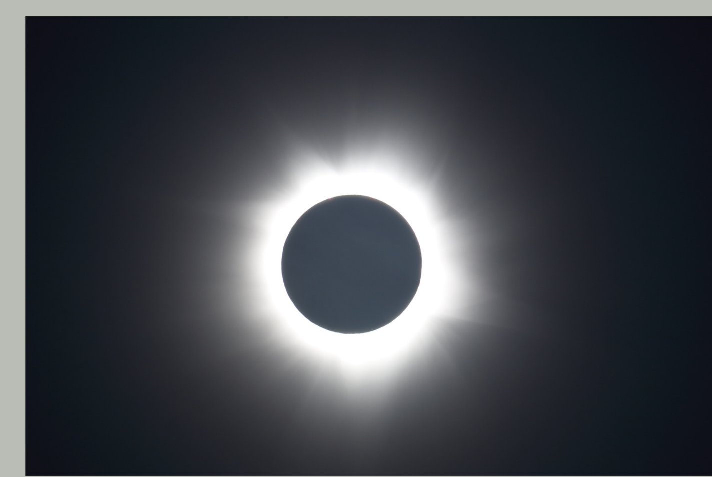

Figure 6:Total solar eclipse as seen from Mount Carbine, Queensland, November 13, 2012. The photosphere is covered however the corona can still be seen.

References

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apkp@st-andrews.ac.uk