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Title page "Coronal heating problem and binary reconnection":

- Hello everyone, welcome to my presentation. Today I will be discussing the coronal heating problem, and the strength of this model. We will first motivate the coronal heating problem with a bit of history and context and then move onto the binary reconnection theory. Then we discuss the tests we are undergoing to test the strength of this model as a solution for the coronal heating problem.

Frame 1 - Coronal heating problem

- It was discovered by Grotrian in 1939 after an analysis of the sun's coronal features that the temperatures of the solar corona can be anywhere from 2x10^6K to 10x10^6, i.e. 10 mega kelvin. This in stark contrast to the estimated and confirmed 5800K at the surface of the sun.
- With the absence of an obvious heating mechanism, this appears to be a clear contradiction to the second law of thermodynamics. So upon discovery, the problem has been begging for an answer: how does this drastic increase in temperature occur in such a short distance.
- The theory of wave propagation has been suggested in the instance for where there are open magnetic field line structures, but we focus on the latter, magnetic reconnection, which is better believed to be a solution for the higher rate of heating required in regions where we have closed magnetic loops.
- See the picture on the next frame for an illustration of what this looks like in the sun.

Frame 2 - Image of sun with closed and magnetic field lines.

- Observed the closed loop structures, and the open magnetic field lines going to infinity. It is these closed structures where we believe magnetic reconnection to be the best solution to the coronal heating problem.

Frame 3 - Magnetic reconnection

- Let us first motivate magnetic reconnection. The term magnetic reconnection refers to the changing in topology of field lines - field lines going in opposite directions break and reconnect with each other.
- Mathematically, after manipulating Ohm's law, we can show that 2D reconnection occurs if this relationship for the non-ideal term is satisfied but u has a singularity. Reconnection occurs where this singularity occurs. 3D reconnection occurs under the more general condition: if this relationship isn't held. Determining where exactly the reconnection requires further in depth analysis, but this isn't discussed here.
- The notion of breaking and connecting of field lines motivates the discussion of topology of magnetic field lines really nicely. Alfvén's theorem, or the frozen-in-flux theorem suggest the flux is "frozen" into the plasma, so as the plasma moves, so does the flux. This implies the conservation of topology of the magnetic field structures.

Frame 4 - Helicity

- A topological invariant of particular interest is helicity. We see why later, but let us first give a definition.
- We use the divergence-free property of magnetic fields to write it as the curl of a vector potential A. We then define helicity as a measure of the twisting, kinking and linking of magnetic field lines with itself and the fields around it. It is the sum of these parts: self-helicity (the twisting a flux tube with itself), and mutual helicity (the twisting relative to the flux tubes around it).
- Whilst helicity is conserved throughout the plasma generally, there are parts where we have momentary violation of this condition. It is here that field lines will try to untwist themselves and, following the laws of thermodynamics, reduce their energy and arrive at a lower energy configuration.

Frame 5 - Energy and heating

- It is the stored energy in the twisted and tangled field lines that is released in this process of reconnection. This energy can be converted into thermal energy and heats the solar corona.

- There are five different ways that reconnection can lead to heating of solar corona which have all been researched really well. However, in the active field regions, separator reconnection (which is what is says on the tin! Reconnection at separators arising from the global field structure) has been dominant in the conversation. However, the theory we discuss, binary reconnection was proposed as a potential alternative.

Frame 6 - Binary reconnection:
- Proposed by Eric Priest and others in 2003, binary reconnection is offered as a way magnetic reconnection could account for the heating in the closed magnetic field regions in the surface of the sun. Put simply, in the frame of reference of one magnetic fragment, the motion of its pair is relevant: it may rotate and twist the field lines in one of two ways: either through internal rotation or rotation around the axis of the larger source (see figure).
- This was suggested as an alternative to separator reconnection as its a lower order process: binary reconnection is the lowest order interaction (interaction between a pair), whereas separator reconnection is often as a result as result of topologies produced by three or four of these fragments.
- A key point: this relies on the idea that the flux between these two fragments in question are 100% connected to each other, otherwise reconnection effects from other fragments become relevant.
- We find that the model is accurate in producing the right numbers in the right regions, and so if the model is well grounded enough to be used across most of the surface of the sun, we have a strong candidate for an answer.

Frame 7 - Figure
- As aforementioned, figure a shows the reconnection of field lines (look at numbers!) occurring due to the rotation of the source in reference frame of the larger one. Observed the build up of field lines! This is helicity.
- Figure b shows reconnection as a result of internal twist of flux tube.

Let us construct a model for binary reconnection to test whether the key assumption holds.

Frame 8 - Model
- We simplify magnetic fragments down to particles which each follow a Brownian motion, random walks.
- We constrain them to a box by implementing periodic boundary conditions, describe how when particles leave they're chucked back in on the other side. This reduces the complexity of the model and the need to calculate to infinity,
- We can approximate the distribution of magnetic flux between sources by counting the number of field lines coming/going from/to any sources. To do so, we pick random field line starting positions close to a particle and use numerical methods to integrate the equation for field lines and then see where our initial field line position ends up. When they get within epsilon to another source, we say that at least part of the flux goes between these sources.

Frame 9 - Model continued.
- The heating rate in Priest's paper is calculated under the assumption there is a net zero flux in the configuration, so we must all account for this. This is typical for regions that aren't the northern or southern hemisphere.
- We have added functionality for fragments to behave as they would in practice: they may break down or just simply coalesce and have a joint polarity.
- Observe the figure. We can see how field lines leave from particle 0 in particular. Upon inspection, one would reasonably assume that most of the flux would go to particle 8 in particle. We found 86% of the field lines did, the rest going to 4.

Frame 10 - Testing the assumption
- So what can we do with this model?
- Several questions we can ask: how many sources are actually binary reconnected to another source at any given time. Model is not suitable if this isn't true.
- How does the binary reconnection of a source and sink that appear together, as happens in the solar surface, hold and change under evolution.
- The time evolution of flux distribution of a single particle.

- We have been running and continue to run these tests! Our initial testing shows promise, in particularly asking the first question: there tends to be a healthy population of pairs of sources that are binary reconnected. However, we continue to undergo further testing to confirm our observations and allow us to use the binary reconnection theory with full confidence.

Frame 11 - Limitations

- Whilst our model is a decent illustration of the physics in the solar magnetic carpet, it is still heavy limited. There is no accounting for the effect of helicity in the motion the magnetic particles, which we have seen can hinder/slow down movement.
- Further, we have approximated the magnetic field lines using periodic boundary conditions.
- We have not used this model to get a heating rate, we are yet to see if they hold using the motions that will incur.

We can extend our model by accounting for models where there is a net flux, which tends to be the case in the hemispheres of the sun. Further, we can use the motion from the underlying physics instead of a Brownian motion to see how motion alters when there is physics. However, as we speak we continue to run tests and collect our results in preparation for the larger conversation: is binary reconnection a suitable model for the coronal heating problem.

Thank you all! Please fire away with any questions