Why is the corona hotter than it has any right to be?

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SHINE 2019 Student Day

Thanks to Steve Cranmer for some slides
Why the Sun is the way it is
The Sun is magnetically active
The Sun rotates differentially.
Rotation + plasma = magnetism
Magnetism + rotation = solar activity
That’s why the Sun is the way it is
Temperature Profile of the Solar Atmosphere

- Photosphere (top of the convection zone)
- Chromosphere (forest of complex structures)
- Corona (magnetic domination & heating conundrum)
Coronal Heating

- How do you achieve those temperatures?
- Step 1: Have energy
- Step 2: Move energy
- Step 3: Turn energy to heat
- Step 4: Retain heat
- Step 5: HOT
Step 1: Have energy

- The photosphere’s kinetic energy is enough by orders of magnitude
Photospheric granulation
Photospheric granulation
Step 2: Move energy

**“AC”**
- MHD waves

**“DC”**
- Field-line braiding → “nanoflares”

**“IR”**
- Emerging bipoles
- Jets?

“Taylor relaxation”
(twist wants to untwist, due to mag. tension)
Step 3: Turn energy to heat

- Turbulence

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Step 4: Retain heat

- Very hot
  - complete ionization
    - no blackbody radiation
      - very limited cooling

- Combined with low density, required heat isn’t too mind-boggling
Step 5: HOT
Step 1: Have energy
- The photosphere’s kinetic energy is enough by orders of magnitude

Step 2: Move energy
- “AC”
- MHD waves?
- “DC”
- Field-line braiding → “superflow”
- Emerging bipolar
- “IR”
- Jets?
- “Taylor relaxation”
  (twist wants to untwist,
due to mag. tension)

Step 3: Turn energy to heat
- Turbulence
  \[ \_(_\_\_)\_\_ \]

Step 4: Retain heat
- Very hot
  → complete ionization
  → no blackbody radiation
  → very limited cooling
- Combined with low density, required heat isn’t too mind-boggling
So what’s the “coronal heating problem”?

Table 1  MHD coronal heating theories: Efficiency scalings relative to the Poynting flux  

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So what’s the “coronal heating problem”?

- The theory side is fine
- All coronal heating models occur at small scales in thin plasmas
  - Really hard to see!
- It’s an observational problem
  - Can’t observe heating happening
  - Can’t measure or rule out models
So why is the corona hotter than it has any right to be?
Probably a bit of everything

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Let’s delve into “waves”
Bright points

- Magnetic field: 1000 Gauss
  - $1000 \times$ average solar field
  - $2000 \times$ average Earth field
- $\sim 100$ km across
Bright points are bases of flux tubes
Bright points motion is a suspected driver of coronal heating.
Goals

- Bright points are barely resolved in current observations
- DKIST will better resolve them
- Use DKIST-comparable simulations to
  - Learn what we can now
  - Prep for DKIST
- Also: Better understand bright point motion
Rempel’s MURaM Simulations
ROUGH Simulation

- Phenomenological
- Laminar (no turbulence!)
- Parameters control granulation directly
Observational Sources

- Granule Drift Velocities: Roudier et al. (2012)
- Vertical Velocities: Puschmann et al. (2005)
MURaM Bright Points

- Automatically identified and tracked
ROUGH “Bright Points”

- Passive tracers
  - Follow plasma flow
  - Move with downflow lanes
Bright Point Motion Spectrum

- **MURaM**
- **BPs**
- **ROUGH**
- **Passive Tracers**

Power spectrum (km$^2$ s$^{-2}$ Hz$^{-1}$)

Frequency (Hz)
Next frontier: measuring shape changes
SHINE 2019

Coronal Turbulence Driven from the Photosphere: Opportunities for DKIST

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The big picture

What’s a bright point?
Photographic bright points are small (~100 km) regions of concentrated (~10⁴) vertical magnetic flux. They appear in the image between granules on the solar surface (compare panel below) and are thought to be due to convection-driven effects.

Why care?

Connective cooling and/or flux tubes resonate in the bright point, exciting waves. These waves are believed to displace the corona and deposit energy—constraining coronal heating. The power spectrum of bright point motion provides insight into the waves launched and serves as an input to models of MHD wave propagation through the corona and heliosphere [1].

Flux tubes
Bright points are the bases (footpoints) of magnetic flux tubes reaching up to the corona, illustrated in red (right panel). These tubes carry gas pressure and drive waves. Waves propagate up the tube from the central churning of the tube base. At the photosphere, the tubes’ magnetic pressure overcomes gas pressure. This reduces the gas density and ionizes atoms, causing a drop in density. This makes the footpoint look like a bright point at the tube’s base, and is the easily observable feature of these flux tubes.

Beyond the flux, coronal waves propagate in lower-order waves which carry energy to the corona. DKIST will be the first telescope to study the relationship between the shape and size of bright points and the coronal structure. This could provide valuable information about the internal structure of bright points and the solar magnetic field.

What we’re working on

In past work [2], we compared the motions of bright points and bright points in two simulations, with a spatial resolution comparable to DKIST and similar corona conditions. MURAM is a module, 3D, MHD simulation of magnetic bright points. We developed a new simulation, called ROUGH. ROUGH is a phenomenological model that produces reasonable but turbulence-free simulations and allows direct control of granular properties.

ROUGH simulates bright points as passive tracers, or “rocks,” that slide in the plasma flow. They radially remain in and move with the convective flows, where the horizontal flows converge. In MURAM, we identified and tracked bright points. The models predict the evolution of bright points.

Results

We evaluated our results using two different methods: visual observation and numerical simulations. Our results showed that ROUGH tracks bright points well, with a correlation coefficient of 0.87, indicating a strong linear relationship. The bright points in ROUGH are more numerous and distributed over a larger area than in MURAM, suggesting that the model is better at capturing the complexity of the system.

A warning
We used numerical simulations to study the behavior of bright points. Our simulations showed that bright points tend to form in pairs and that the distance between them increases over time. However, our results may be biased due to the limitations of our numerical methods.

Acknowledgements
We thank Matthias Fender for providing the results of his MURAM simulations, and Mark Rent and Piyam Agrawal for their helpful discussions.

References
Summary

• Coronal heating uses magnetism to push heat against the thermal gradient
• The coronal heating problem is:
  – Theorists out of control
  – Insufficient observations
• DKIST will enable new observation