Solving the Coronal Heating Problem Using LAPD Experiments on Alfvén Wave Damping

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Why is the Sun's corona nearly 200 times hotter than the underlying solar surface? This is one of the most important unsolved problems in astrophysics, dating back to when the temperature of the corona was first measured over 75 years ago. The Large Plasma Device (LAPD) located at the Basic Plasma Science Facility (BaPSF) at the University of California, Los Angeles, offers the key to solving this mystery.

1 Scientific Challenge

Wave-driven coronal heating models theorize that the corona is heated by the dissipation of low frequency Alfvén waves that are launched from lower layers of the Sun. The challenge for these models has been that such waves are not thought to dissipate over short enough distances, so that the energy is carried away by the waves, rather than heating the plasma. Recent observations, however, have shown that the waves do, in fact, damp at sufficiently low heights to heat the corona (e.g., Hahn & Savin 2013). Thus, solar observations have revealed a fundamental problem in basic plasma physics, namely, what causes the observed damping of low frequency Alfvén waves? We have proposed experiments at LAPD that will answer this question.

Because Alfvén waves have long been considered a potential coronal heating mechanism, numerous theories have proposed potential mechanisms by which the waves could be damped faster than that expected for simple mechanisms, such as from viscosity and resistivity. All the proposed damping processes rely on inhomogeneities to drive flows and currents at small length scales, at which the energy can be efficiently dissipated.

One class of proposed damping processes is based on Alfvén wave reflection followed by turbulent dissipation. Waves can be reflected when there is a gradient in the Alfvén speed along the magnetic field. Such a gradient may be caused by changes in the magnetic field strength or the plasma density. The outward-propagating and reflected waves interact, producing turbulence and driving wave energy to high wavenumbers where wave-particle interactions dissipate the energy. Experiments are needed to test theoretical predictions for the efficiency of Alfvén wave reflection and transmission efficiency from a parallel gradient.

Another class of possible damping processes is based on cross-field gradients. Many magnetohydrodynamic theories relevant to solar physics have focused on phase mixing. A cross field gradient in the Alfvén speed results in waves on neighboring field lines having different phase velocities. Waves propagating along these different field lines may be excited initially in-phase, but then become out-of-phase as they propagate. This drives eddies within the gradient layer, which increases the rate of viscous and resistive dissipation. The linear theory of phase mixing predicts too small of an enhancement to the damping rate to explain coronal heating. However, three-dimensional numerical models predict that phase mixing excites fast mode waves, which dissipate more efficiently leading to faster damping. Experimental measurements are needed to test these predictions.

Lastly, gradients along and across the magnetic field can combine to increase the dissipation rate. The actual effect has not been well studied theoretically. Linear analytic theories predict that variation along the field only moderates the phase mixing dissipation rate. In contrast, some numerical models find that the combination of gradients increases the dissipation rate by orders of magnitude. Empirical studies are a necessary guide for further theoretical developments.

2 Research Approach

LAPD (Gekelman et al. 1991) provides an excellent system in which to study these theories of wave damping. The device produces an ≈ 20 m long column of plasma in which the magnetic field and density can be controlled over a broad range. Alfvén waves can be launched through LAPD and the resulting three-dimensional wave magnetic fields and plasma properties measured with high temporal and spatial resolution. Experiments on Alfvén waves in other contexts have already been carried out and suitable diagnostics and antennas have been developed. In addition to the wave fields, diagnostics exist to measure the ion and electron temperatures and flows. Thus, we can directly monitor the energy balance of the plasma and the transfer of energy between the wave fields, thermal energy, and flows.

The above proposed basic plasma experiments are relevant to the solar corona. LAPD has the unique advantage for the proposed studies that the plasma can be set up in such a way that it is similar to a coronal plasma in terms of dimensionless ratios.

3 Impact

Experimental studies of these Alfvén wave damping processes would represent a fundamental advance in our understanding of basic plasma physics as well as contribute greatly to solving the coronal heating problem. LAPD provides a well characterized plasma, with high resolution diagnostics, and has a simple magnetic geometry so that direct theoretical calculations relevant to the experiment are tractable. Thus, definitive results can be expected.

These are novel experiments that will fill a significant gap in our understanding of plasma science. For example, although the reflection of Alfvén waves appears simple from a theoretical standpoint, no experiment has measured the efficiencies of Alfvén wave reflection and transmission through a simple gradient in the Alfvén speed. There have been measurements of wave reflection from metal plates or lattices of magnetic wells, which do generally support the theory of Alfvén wave reflection, but, as far as we can determine, the most theoretically direct case of measuring transmission and reflection as a function of the magnitude of the parallel gradient has not been performed. Such measurements would not only be important for plasma science, but also be directly relevant to the application of coronal heating. Measurements of the behavior of waves in gradients perpendicular to the magnetic field direction are also needed. Currently, the only relevant experiments have explored Alfvén wave propagation in the gradients that necessarily arise at the edge of plasma devices. Such measurements do not test theory in a systematic way. Instead, experiments with independently controlled gradients are needed. Finally, as mentioned above, theory has difficulty predicting the effect of a complex geometry with both parallel and perpendicular gradients. Experiments of such cases would guide the development of theory in this area.

References

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