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Stairway to Heaven: Multistage propagation of Waves from the Solar Interior to the Corona

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The Sun's outer atmosphere, the corona, is hot, very hot, typically over a million degrees Kelvin. And yet the visible solar surface, the photosphere, is only a few thousand degrees. In fact, it is so cool that the ionization fraction is as low as 0.01%. Between the two lies the chromosphere, rising up to 20,000 K across its 2000 km thickness, and the steep transition region (TR) of only a few hundred km across which the temperature rises by around two orders of magnitude. How is it possible that the atmosphere (chromosphere to corona) are so much hotter than the surface?

The chromospheric and coronal heating problems are amongst the oldest unsolved problems in astrophysics, but one thing is clear: the Sun's magnetism plays a central role. Both DC (flares and reconnection on many scales) and AC (waves) mechanisms are likely at play.

A decade ago, the view was that waves carry insufficient energy to heat the corona, largely because of damping in the chromosphere and reflection from the transition region (Klimchuk, Sol Phys 234, 41, 2006), and because observations showed insufficient Alfvénic coronal wave amplitudes (Tomczyk et al, Science 317, 1192, 2007). However, more recent observations from SDO/AIA (McIntosh et al, Nature 475, 477, 2011) have revealed an enormous reservoir of "hidden" Alfvénic wave energy unresolved by earlier studies associated with flux tubes, but consistent with the several-mHz-frequency chromospheric oscillations associated with spicules.

But which types of waves can traverse the many scaleheights between the photosphere and corona, and how? I will review the tortuous multi-level process by which waves leak from the solar interior to penetrate the TR reach the corona. Important processes include fast/slow mode conversion [1], and fast/Alfvén conversion [2], [3]. I will also discuss the role played by low ionization fraction in the chromosphere [4], [5].

References

[1] Schunker & Cally, MNRAS 372, 551, 2006
[2] Cally & Hansen, ApJ 738, 119, 2011
[3] Hansen & Cally ApJ 751, 31, 2012
[4] Cally & Khomenko, ApJ 814, 106, 2015
[5] Cally & Khomenko, ApJ 856, 20, 2018