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Physically-consistent Riemann solvers for accurate and robust MHD modelling with low plasma beta

The solar atmosphere hosts various physical phenomena driven by strong magnetic fields, but accurate and efficient MHD numerical modelling of such phenomena is challenging. Specifically, high accuracy typically requires low numerical dissipation, which may come with high computational costs and is prone to numerical oscillations. Conversely, efficiency demands sufficient robustness, which needs adequate numerical diffusion. These challenges must be addressed adequately in MHD models, such as the newly developed fully-implicit MHD global solar coronal model, COCONUT.

While COCONUT currently uses finite-volume discretisation and approximate Riemann solvers that are well-established for MHD simulations, their robustness is often challenged under strong magnetic fields or, more precisely, in low-beta plasma. One important reason is that magnetic energy becomes dominant compared to the much smaller thermal energy. Thus, even a small numerical discrepancy in magnetic energy may lead to negative thermal energy, causing the positivity-preservation problem, typically tackled by adding numerical diffusion. This issue, of course, also exists in other plasma MHD simulations.

Without adding numerical diffusion, we ensure physical consistency in HLL-type Riemann solvers, specifically the consistency between the numerically calculated magnetic field and magnetic energy, which is frequently broken in numerical solutions. The resulting Riemann solvers are more robust than their widely used counterparts, yet with less diffusive effects observed in fully implicit global coronal modelling. Additionally, we have discussed the positivity-preservation property of the proposed Riemann solvers and explained the reason behind their improved robustness.

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