Nonthermal particle acceleration by magnetic pumping in pulsating plasmas

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High-energy particles are an important component of many space and astrophysical plasmas, often exhibiting energy spectra with extended power-law tails. The origin of nonthermal particles is debated and several processes have been proposed to explain their acceleration. In this context, a key parameter is the ratio of the thermal pressure P to the magnetic pressure $B^2/8\pi$, the plasma beta $\beta = 8\pi P/B^2$. In plasmas with $\beta \ll 1$, like the solar corona, the interstellar medium, astrophysical jets of compact objects, free energy is mainly stored in magnetic fluctuations and processes such as magnetic reconnection and turbulence can produce nonthermal particle distributions by dissipating magnetic energy. Conversely, thermal energy is the main source of free energy in plasmas with $\beta \gg 1$. High-β plasmas are often embedded in large-scale compressible flows, including planetary magnetosheaths, undergoing periodic compression and expansion driven by the variable solar wind activity; accretion disks of compact objects where gravity, radiation pressure and convective motions compress and expand the plasma; the intracluster medium of galaxy clusters, subject to turbulent compressible and shearing motions. Compressing and expanding a plasma cyclically would increase and decrease its energy periodically, without any net heating. However, in collisionless plasmas compression and expansion also induces the development of temperature anisotropies that make the plasma unstable, causing the development of electromagnetic instabilities that pitch-angle scatter particles, making the cycles irreversible and causing net heating. This process is known as magnetic pumping (MP).

In our work, we introduce a new "pulsating box" framework to simulate plasmas subject to an external force that is compressing and expanding the system periodically. Compression–expansion cycles produce temperature anisotropy that triggers the cyclic development and alternation of mirror and firehose instabilities. These instabilities quickly grow and pitch-angle scatter plasma particles, limiting the growth of the temperature anisotropy and making compression–expansion cycles irreversible. As a consequence, plasma particles are continuously energized and steadily accelerated to ultra-relativistic energies by MP.

We find that particle acceleration induced by MP produces nonthermal energy spectra with extended power-law tails. The spectra we observe are consistent with kappa distributions with a high-energy cutoff imposed by the Hillas limit, occurring when particle gyroradii become comparable to the system size, implying that particles are no longer accelerated by electromagnetic fields. The development of these kappa distributions is consistent with a generalized maximum entropy (GME) principle based on the concept of "Casimir momenta", representing a generalization of the Boltzmann–Gibbs entropy. Our GME model allows us to calculate the kappa index of particle distributions as a function of the injected energy, and we find excellent agreement between our model and numerical simulations.

Our results are potentially relevant in understanding the formation of nonthermal particle distributions in space and astrophysical plasmas.