Magnetic field amplification at planetary and astrophysical high Mach-number shocks

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It is widely accepted that supernova remnant (SNR) shocks are responsible for the production of the Galactic cosmic ray (CR) component. Here we propose a new mechanism of magnetic field amplification in SNR shocks, which might modify the classical diffusive shock acceleration (DSA) mechanism of CR acceleration.

There are various possible mechanisms for magnetic field amplification at supernova remnant (SNR) shocks on scales larger than the shock width, e.g., cosmic-ray driven nonresonant modes, fluid vorticity downstream of the shock seeded by upstream density inhomogeneities, cosmic ray pressure driven magnetic field amplification, etc. However, magnetic field is also can be enhanced on much smaller scales. Indeed, Cassini's in-situ measurements that magnetic field can be amplified even by a factor of 50 at the Saturn's bow shock, which is characterized similar propagation velocities and Mach number compared to SNR shocks.

Here we use a set of large-scale Particle-In-Cell (PIC) simulations of non-relativistic perpendicular shocks in the high Mach number regime to clarify this issue. These shocks are Weibel mediated. We present evidence that the magnetic field is amplified at the shock transition by the Weibel instability which due to folding of the magnetic field by the Weibel modes whose wave vector is perpendicular to the relative velocity of shock-reflected and incoming upstream ions. The magnetic field strength strongly correlates with the Alfvénic Mach number and can be estimated as: $B_{sh}/B_0 \approx 2\sqrt{M_A}$.

Both simulation results and analytical calculations of the Weibel instability growth rate demonstrate that magnetic field amplification level depends exclusively on Alfvénic Mach number of the shock and other shock parameters, such as the shock velocity, the artificial ion-to-electron mass ratio, the upstream plasma beta, have no influence (or very minor) on magnetic field amplification and PIC simulation results can be directly compared with in-situ measurements. As a result, PIC simulation results match very well Cassini's in-situ measurements at $M_A \geq 10$.

Within our successfully fitted model, the momenta of injected particles become Mach number dependent, $p_{\mathrm{inj}} \propto \sqrt{M_A}$. This result is fundamentally important because it may modify the injection of particles into DSA and change our understanding of the underlying physics.