Particle Acceleration in Binary Star Winds†

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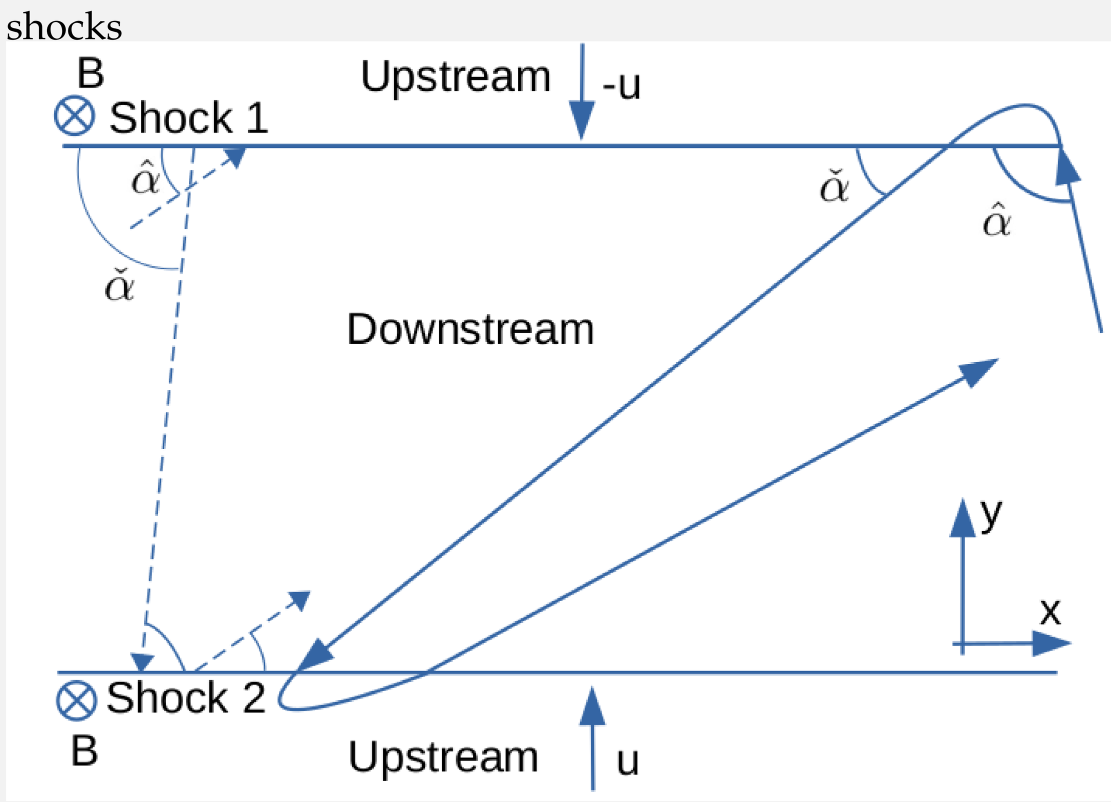
Abstract / Methods

Abstract A shock wave propagating perpendicularly to an ambient magnetic field accelerates particles considerably faster than in the parallel propagation regime. However, the perpendicular acceleration stops after the shock overruns a circular particle orbit. At the same time, it may continue in flows resulting from supersonically colliding plasmas that are bound by a pair of perpendicular shocks. Although the double-shock acceleration mechanism, which we consider in detail, is not advantageous for thermal particles, pre-energized particles may avoid the premature end of acceleration. We argue that if their gyroradius exceeds the dominant turbulence scale between the shocks, these particles might traverse the intershock space repeatedly before being carried away by the shocked plasma. Moreover, entering the space between the shocks of similar velocities $u_1 \approx u_2 \approx c$, such particles start bouncing between the shocks at a fixed angle $\approx 35.3°$ to the shock surface. Their drift along the shock fronts is slow, $V_d \sim |u_2 - u_1| \ll c$, so that it will take $N \sim Lc/|u_2 - u_1| d \gg 1$ bounces before they escape the accelerator. (Here L is the size of the shocks and d is the gap between them.) Since these particles more than ten-fold their energy per cycle (two consecutive bounces), we invoke other possible losses that can limit the acceleration. They include drifts due to rippled shocks, nonparallel mutual orientation of the upstream magnetic fields, and radiative losses [1].

Approach to the Problem We approach the particle acceleration in a double-shock system by constructing an *iterated map*. It starts from the particle relativistic factor γ and its two incidence angles relative to the shock plane and magnetic field direction before hitting one of the shocks, as shown in Fig.1.

Iterated Map of the Ingress to Egress angle $\hat{\alpha} \mapsto \check{\alpha}$. Presentation in Closed Parametric Form. Fixed Points of the Map

Fig.1: Ingress-Egress Angles of a Particle bouncing between two shocks



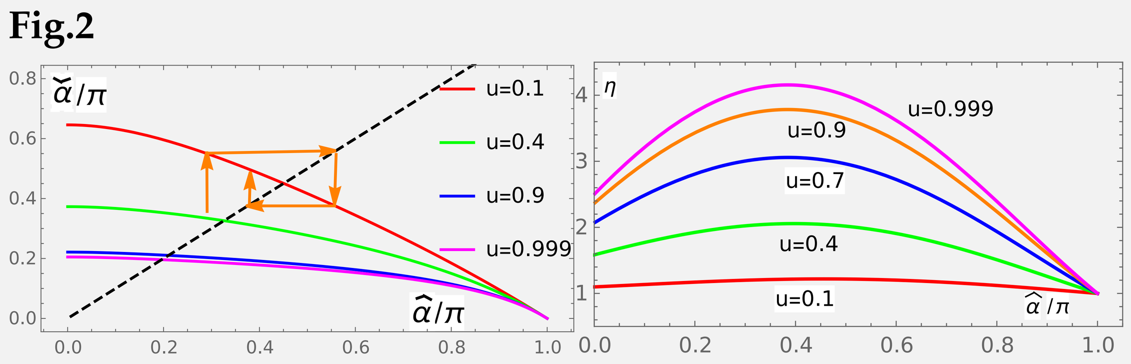
$$\hat{\alpha} = \cos^{-1}\left\{-\frac{\sin\left[\cos^{-1}(u\tau\csc\tau) - \tau\right]\sqrt{1-u^2}}{1 - u\cos\left[\cos^{-1}(u\tau\csc\tau) - \tau\right]}\right\} \quad (1)$$

$$\check{\alpha} = \cos^{-1}\left\{\frac{\sin\left[\cos^{-1}(u\tau\csc\tau) + \tau\right]\sqrt{1-u^2}}{1 - u\cos\left[\cos^{-1}(u\tau\csc\tau) + \tau\right]}\right\}$$

$$\eta \approx \frac{1 - u\cos\left[\cos^{-1}(u\tau\csc\tau) + \tau\right]}{1 - u\cos\left[\cos^{-1}(u\tau\csc\tau) - \tau\right]} \quad (2)$$

Eqs.(1-2) parametrically relate the particle egress angle and energy gain after one shock encounter to the particle ingress angle (use parameter τ, -one half of the upstream rotation phase). Shown in Fig.2 is the $\hat{\alpha} \mapsto \check{\alpha}$ map (left panel) along with the dependence of the energy gain $\eta \equiv \check{\gamma}/\hat{\gamma}$ upon $\hat{\alpha}$ for different shock velocities (right panel). The arrows show the iterations of the map, as they follow the particle bouncing between the shocks. These iterations converge to a single Fixed Point (FP) for which $\check{\alpha} = \hat{\alpha}$, shown with dashed line in Fig.1

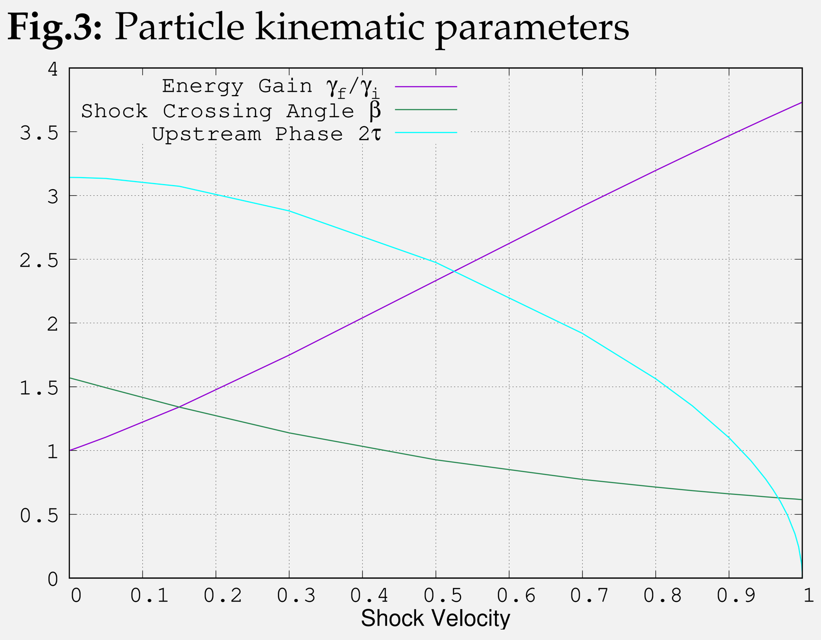
Fig.2



Lossless particles gain momentum each time they visit upstream media because of the motional electric field. Hence, the particle trajectory never returns to the same point in the phase space, which means that there are no FPs in the usual sense. Nevertheless, the map of angular variables reaches an FP, when $p_\parallel/p \to 0$.

Properties of Iterated Map Particle Energy Gain Deterministic Escape from the Shocks for $u_1 \neq u_2$

Fig.3: Particle kinematic parameters



Upstream rotation phase, 2τ, and the energy gained after each upstream excursion are shown for a steady state (fixed point of the iterated map).

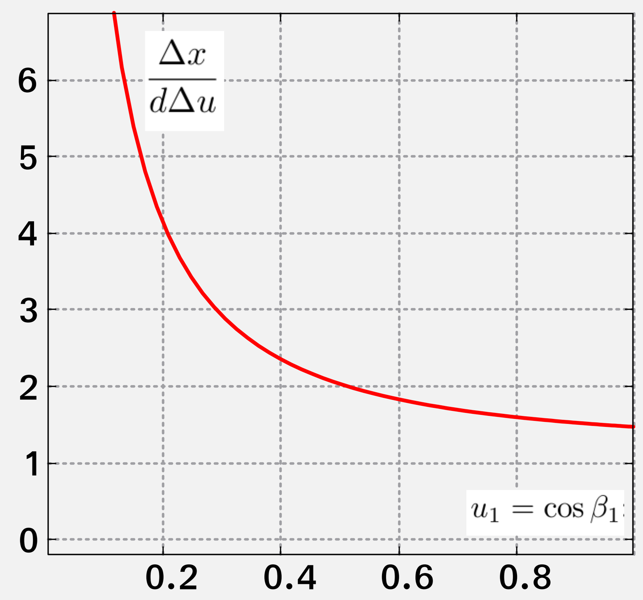
- Orbits may drift along the shock surface, which occurs, e.g., when the shock velocities are not equal, or shock(s) is (are) corrugated, or else, magnetic fields upstream the shocks are misaligned
- If $u_1 \neq u_2$, particles escape along the shock front with a constant speed

The particle escape rate can be characterized by a normalized displacement per cycle (two consecutive particle-shock collisions)

$$\Delta x/d \approx \cot\check{\alpha}_1 - \cot\hat{\alpha}_1,$$

where d is the gap between the shocks. This quantity is proportional to a (small) difference between the shock speeds, $\Delta u = u_1 - u_2 \ll 1$.

Fig.4: Particle escape rate vs the speed of one of two shocks, $u_1 \approx u_2$.



Stochasticity Particle Trapping and Lévy Flights Stochastic Escape from Shocks

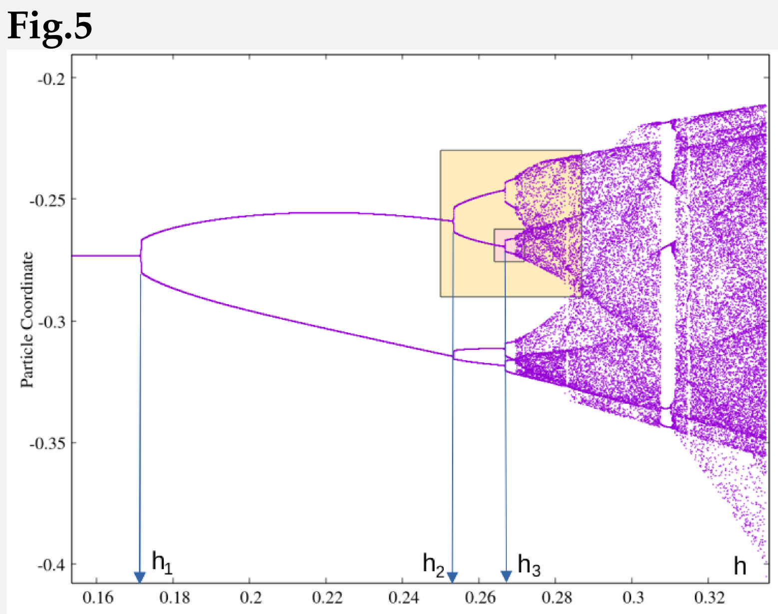
To illustrate the onset of stochasticity in particle dynamics, we impose a sinusoidal perturbation on the surface of one of the shocks:

$$d(x) = 1 + \frac{h}{k}\sin(kx), \quad (3)$$

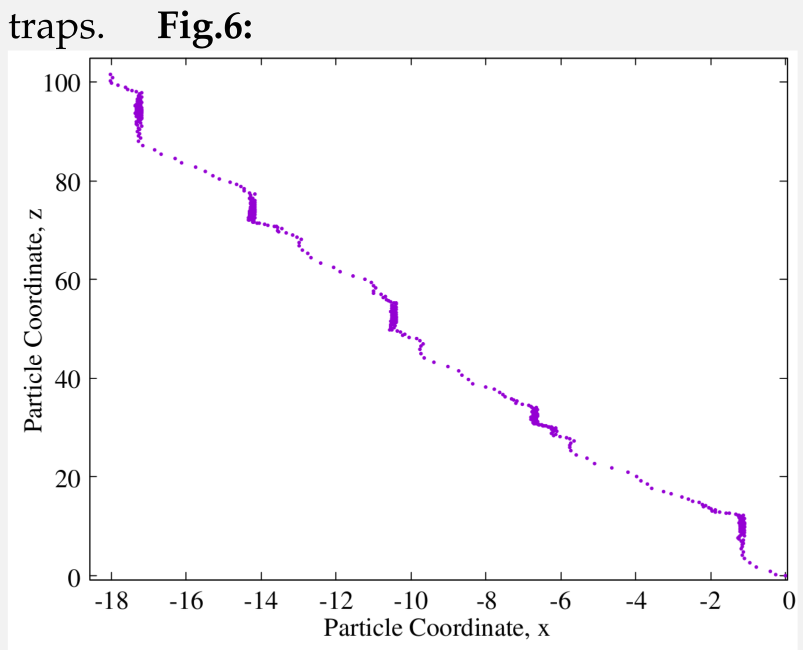
where h is an amplitude- and k - a wavenumber of corrugation. If we assume that the lower shock coincides with the plane $y = 0$, then $d(x)$ is the y- coordinate of the local position of the upper shock.

- While crossing the intershock space, particles incur energy losses that allow for a **genuine FP** of the iterated map. Lorentz factor: $1/\gamma \mapsto 1/\gamma + 1/\gamma_c$, where γ_c is an energy cut-off associated with the losses.
- With growing corrugation h the FP becomes unstable and the period doubling bifurcation sequence starts:
- Nested boxes show similar bifurcation pattern with universal properties (well known from dynamical chaos theory)
- Similar effects produce noncolliniear magnetic fields upstream of the shocks

Fig.5



Particle random walk on the shock surface (fractional kinetics): Lévy flights interspersed by traps. **Fig.6:**



Summary and Discussion References

We have studied a particle acceleration mechanism that operates in a double-shock system formed in colliding plasma flows. The acceleration is powered by upstream flows of the shocks that bound the shocked plasma layer. High energy particles bounce between these flows until they are convected with the shocked plasma or otherwise escape the accelerator. Our main findings are as follows:

1. For $u \to c$, the energy gain factor per collision with each shock is ≈ 3.73 for an equilibrium ingress angle, $\alpha = \alpha_{eq} \approx 35.3°$, and reaches a higher value, ≈ 4.15, for an optimum angle, $\alpha_{opt} \simeq \alpha_{eq}$ [1].
2. If the shock configuration is not ideal, particles may drift along the shock front and ultimately escape. We have considered the following three mechanisms of escape:

(a) *Unequal shock speeds*

(b) *Shock corrugation*

(c) *Nonparallel magnetic fields upstream*

We conclude, that the most efficient and sustainable acceleration occurs between relativistic shocks of the same speed with parallel magnetic fields upstream.

Given the substantial acceleration rates of relativistic shocks within extended systems, it becomes apparent that the upper limit on maximum energy is predominantly constrained by energy losses, as opposed to particle escape. Consequently, a concentration of particles near the energy cut-off, dictated by these losses, is virtually inevitable. This insight provides a solution to the challenge posed by the expected hardened spectra in the context of Ultra High Energy Cosmic Rays (UHECR). The double shock system seems to exhibit a more favorable comparison with AGN (Active Galactic Nuclei) jets in this context [2].

Recent detection at very high energies have triggered renewed interest to double-shock accelerators; see, for instance, the massive star binary η Car or the gamma-ray binary LS 5039.

References

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[2] Malkov, M. A., 2023. In S. Takayuki, ed., *ICRC Proc. https://pos.sissa.it/444/1556/pdf.*

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