Particle acceleration in relativistic magnetic reconnection with strong inverse-Compton cooling in pair plasmas

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ABSTRACT
Particle-in-cell (PIC) simulations have shown that relativistic collisionless magnetic reconnection drives nonthermal particle acceleration (NTPA), potentially explaining high-energy (X-ray/γ-ray) synchrotron and/or inverse Compton (IC) radiation observed from various astrophysical sources. The radiation back-reaction force on radiating particles has been neglected in most of these simulations, even though radiative cooling considerably alters particle dynamics in many astrophysical environments where reconnection may be important. We present a radiative PIC study examining the effects of external IC cooling on the basic dynamics, NTPA, and radiative signatures of relativistic reconnection in pair plasmas. We find that, while the reconnection rate and overall dynamics are basically unchanged, IC cooling significantly influences NTPA: the particle spectra still show a hard power law (index $\gamma \geq -2$) as in nonradiative reconnection, but transition to a steeper power law that extends to a cooling-dependent cutoff. The steep power-law index fluctuates in time between roughly $-3$ and $-5$. The time-integrated photon spectra display corresponding power laws with indices $\approx -0.5$ and $\approx -1.1$, similar to those observed in hard X-ray spectra of accreting black holes.

Key words: acceleration of particles – accretion, accretion discs – magnetic reconnection – radiation mechanisms: general – X-rays: binaries – galaxies: jets

1 INTRODUCTION
Spectacular high-energy flares in various astrophysical sources are often believed to be powered by magnetic reconnection – a fundamental plasma process of rapid magnetic field reorganization accompanied by a violent release of magnetic energy and its conversion to plasma energy (e.g., Zweibel & Yamada 2009). In many systems, reconnection occurs in the relativistic regime, where magnetic energy density exceeds the total (including rest-mass) energy density of the plasma (Lyutikov & Uzdensky 2003; Lyubarsky 2005), generating relativistic flows, heating the plasma to relativistic temperatures, and driving ultrarelativistic nonthermal particle acceleration (NTPA) (Kagan et al. 2015). Due to its broad astrophysical relevance, relativistic reconnection has been studied extensively, including via particle-in-cell (PIC) simulations. So far, most of these studies have ignored any radiative aspects of reconnection. However, in many high-energy astrophysical environments, the radiation reaction (which we call radiaction for short) force on the particles can strongly affect the dynamics, energetics, NTPA, and radiative signatures of reconnection (Uzdensky 2016). The two main radiative processes in astrophysical reconnection are synchrotron emission (e.g., in pulsar magnetospheres, Lyubarsky 1996; Uzdensky & Spitkovsky 2014; Cerutti et al. 2016; Philippov & Spitkovsky 2018 and pulsar wind nebulae Uzdensky et al. 2011; Cerutti et al. 2013) and inverse-Compton (IC) scattering (e.g., in black-hole (BH) accretion disc coronae (ADCe) in X-ray Binaries (XRBs) and active galactic nuclei (AGN) Goodman & Uzdensky 2008; Beloborodov 2017, and also in AGN (e.g., blazar) jets). While several pioneering PIC studies have investigated reconnection with synchrotron cooling (Jaroschek & Hoshino 2009; Cerutti et al. 2013; Yuan et al. 2016), IC cooling effects on reconnection have not yet been explored.

Here we present the first systematic numerical study of relativistic collisionless reconnection with optically-thin external IC cooling due to an imposed soft radiation bath. In real systems, such as BH ADCe in the High-Soft (HS) state of XRBs, this radiation bath may be due to the soft thermal X-rays illuminating the corona from the underlying accretion disc. We use two PIC codes that incorporate the IC radiaction force, TRISTAN-MP and ZELTRON. To study how

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IC cooling affects reconnection and the resulting NTPA and radiation signatures, we conduct a set of simulations with varying radiation strengths, controlled by the intensity of radiation signatures, we conduct a set of simulations with IC cooling affects reconnection and the resulting NTPA and $\dot{\gamma}$.

**2 NUMERICAL SIMULATION SETUP**

We use a standard double-periodic box with two relativistic Harris pair-plasma current sheets (Kirk & Sijkemaansen 2003), plus a uniform background pair plasma of total ($e^-$ and $e^+$) density $n_b$ and temperature $T_b = 25 m_e c^2$, reflecting the ambient upstream conditions. The box dimensions are $L_x \times L_y (L_y = 2 L_x)$, with $x$ parallel to the reconnecting magnetic field $B_0$ and $y$ perpendicular to the current sheets; $z$ (not simulated) is the initial sheet current direction. All key parameters are described fully in Werner & Uzdensky (2017) and briefly in Table 1 in terms of $B_0$, $n_b$, and $T_b$. Reconnection is gently kick-started with a small (1 per cent) magnetic field perturbation as in Werner & Uzdensky (2017). We present results for $L_x/\sigma n_b = 320$, well in the large-system regime (Werner et al. 2016) where the high-energy cutoff of the particle spectrum no longer grows linearly with $L_x$.

Our codes TRISTAN-MP (Spitkovsky 2005) and ZELTRON (Cerutti et al. 2013) use standard PIC algorithms, explicitly evolving Maxwell’s equations on a grid with currents self-consistently calculated from particles moving via the Lorentz force. In addition, they include the back-reaction force on particles emitting IC radiation (Tamburini et al. 2010).

The IC drag force, felt by an electron or positron with velocity $\hat{v}_e$ and energy $\gamma m_e c^2$ as it upscatters photons from an isotropic radiation bath of energy density $U_{\nu B}$, is $f_{IC} = -(4/3) \pi \sigma_c e B_0^2 \gamma^2 \hat{v}_e$, where $\sigma_c = 8 \pi \pi^4/(3 m_e^2 c^6)$. Balancing $f_{IC}$ against the acceleration force of the reconnecting magnetic field $E = \beta_{rec} B_0$, and estimating $\beta_{rec} \sim 0.1$ for relativistic reconnection, yields the radial limit:

$$\gamma \lesssim \gamma_{\text{rad}} \equiv \sqrt{3(0.1) e B_0/(4 \pi \sigma_c U_{\nu B})}. \quad (1)$$

IC cooling, controlled by $U_{\nu B}$, is conveniently quantified by $\gamma_{\text{rad}}$, since $|f_{IC}| \approx 10 \beta_{rec} B_0 (\gamma/\gamma_{\text{rad}})^2$ for $|\beta| \approx 1$.

We ran seven simulations differing only in $U_{\nu B}$: $\gamma_{\text{rad}}/\sigma = 1, 2, 4, 6, 8, 16,$ and $\infty$ (no radiation) – a wide-ranging exploration, since $|f_{IC}| \sim \gamma_{\text{rad}}^2$. Stronger radiation, $\gamma_{\text{rad}} \ll \sigma$, would (for $\sigma_b = 100$) cool the upstream plasma before it reaches the current layer, causing the upstream parameters to vary in time and changing the nature of the problem.

**3 RESULTS**

**Reconnection Dynamics and Energetics.** Reconnection begins as the tearing instability breaks up the current layer into chains of magnetic islands (plasmoids) separated by magnetic X-points. Over time, plasmoids merge into larger ones, while secondary current sheets between them succumb to secondary tearing, yielding a hierarchical structure of X-points and plasmoids (Bhattacharjee et al. 2009; Uzdensky et al. 2010). This familiar picture remains largely unchanged by IC cooling: reconnection continues to perform its most basic function, converting magnetic field energy to particle kinetic energy, almost regardless of radiation; radiative cooling merely converts some of that particle energy to radiation.

Although IC cooling strongly affects particles that gain high energies during reconnection (cf. §3), it has little effect on the overall reconnection dynamics and energy conversion, which are apparently controlled by the lower-energy particles that emit negligible radiation (for $\gamma_{\text{rad}} \gtrsim \sigma$, see §2). Notably, as shown in Fig. 1(a), magnetic energy release proceeds nearly independently of IC cooling and we see no discernible effect of radiation on the reconnection rate, $\beta_{rec} \sim 0.15$. There is, however, a modest effect of radiation on magnetic dissipation: reconnection with strong radiation converts slightly more transverse magnetic energy to guide-field energy $B_y^2/8 \pi$. This is because increasing cooling reduces plasma pressure in plasmoids, leading to a stronger compression of the guide magnetic field in them.

Although reconnection converts magnetic to particle energy at essentially the same rate, strong radiative cooling ($\gamma_{\text{rad}} \lesssim 4 \sigma$) causes this energy to be promptly radiated away, maintaining the plasma kinetic magnetic energy $U_{\text{plasma}}$ at a nearly constant radiation-limited level (Fig. 1(b) shows the evolution of magnetic, plasma, and radiated energies for $\gamma_{\text{rad}} = \gamma_{\text{max}} = 100, 4 \sigma$). Therefore, in the strong cooling regime the IC luminosity reaches a universal value $dU_{\nu B}/dt \sim 0.1 U_{\nu B, \gamma_{\text{max}}}/(L_\gamma/c)$.

IC drag, which scales as $\gamma_{\text{rad}}^2$, is, however, a modest effect of IC cooling; reconnection continues to perform its most basic function, converting magnetic field energy to particle kinetic energy, almost regardless of radiation; radiative cooling merely converts some of that particle energy to radiation. 

Weaker cooling allows particles to reach higher energies before radiation balances the acceleration due to reconnection. In the limit of very weak cooling, particles are accelerated almost as without cooling, slowly radiating away energy long after exiting the reconnection region.

**Particle Acceleration.** Recent PIC simulations have clearly shown NTPA driven by relativistic reconnection. Reconnection accelerates a large fraction of particles to high energies $\gamma \gtrsim \sigma$, yielding nonthermal high-energy spectra characterized by a power-law index (slope) $p$ and a high-energy cutoff $\gamma_c$. IC drag, which scales as $\gamma^2$, can, however, suppress NTPA at highest energies.

With radiation, high-energy particle spectra $f(\gamma)$ vary more in time and display more complicated forms than the familiar single power law with a high-energy cutoff. To mea-
Magnetic reconnection with IC cooling

Figure 1. (a) The total and transverse magnetic energy $U_B(t)$ and $U_{B,xy}(t)$ versus time are nearly independent of radiative cooling strength (given by $\gamma_{rad}$), and, inset, the normalized reconnection rate is also independent of $\gamma_{rad}$. (b) For a strongly-cooled simulation, $\gamma_{rad} = 2\sigma$, the magnetic energy $U_B(t)$ is similar to weakly-cooled cases, as is the sum of particle $U_{plasma}$ and radiated $U_{rad}$ energies; being strongly-cooled, however, $U_{plasma}(t)$ quickly saturates, after which any particle energy gains are promptly radiated away. (c) The magnetic energy dissipated between 1 and $3L_x/c$ is independent of cooling strength; for weak cooling, it increases the plasma energy, while for strong cooling it is no sooner given to particles than it is radiated away. All energies are normalized to $U_B(t = 0)$.

sure spectral slopes and cutoffs, we calculated the local slope $p(\gamma) = -d \ln f/d \ln \gamma$ and then searched for the longest stretch over which $p(\gamma)$ varied within ±10 per cent; the next higher power-law stretch was also identified. We counted only power laws stretching over a factor of ≥2 in $\gamma$, and identified the power-law index $p$ as the median $p(\gamma)$. The high-energy cutoff $\gamma_\text{c}$ was defined by $f(\gamma_c) = e^{-\gamma_\text{c}^p}$, with $A\gamma^{-p}$ being the best fit for $f(\gamma)$ over the power-law stretch.

Fig. 2 displays the time evolution of $f(\gamma)$ as a function of radiation strength. In the nonradiative case, $\gamma_{rad} = \infty$ [see Fig. 2(a)], a hard power law develops with index $p_\text{c} \approx 1.9$ [we note that $p_\text{c}$ decreases with weaker guide field (Werner & Uzdensky 2017), e.g., $p_\text{c} \approx 1.6$ for $B_\text{gs} = 0.05B_0$] as in previous studies (e.g., Sironi & Spitkovsky 2014; Guo et al. 2014; Werner et al. 2016). However, as cooling strength increases ($\gamma_{rad}$ decreases), the high-energy spectrum falls off considerably faster. In Fig. 2(b) we show the evolution of $f(\gamma)$ for an illustrative intermediate-cooling case, $\gamma_{rad} = 8\sigma$, where we observe a double power-law distribution during the active stages of reconnection, $t \leq 3L_\text{c}/c$. The spectrum comprises the usual uncooled hard power law with index $p_\approx 1.9$ at energies $\gamma \lesssim 0.1\sigma$ and a variable high-energy soft/steep power-law segment with index $p_\approx 3$ [5] and a high-energy cutoff $\gamma_\text{c} \approx 8\sigma$. After reconnection ends at $t \approx 3L_\text{c}/c$, rapid cooling of high-energy particles shifts the spectral break $\gamma_\text{c}$ to lower energies. In the strong cooling regime, represented by $\gamma_{rad} \approx 2\sigma$ [Fig. 2(c)], the familiar high-energy cutoff $\gamma_\text{c}$ falls off and we observe only the soft/steep radiatively-cooled power law. Although the high-energy cutoff is essentially unchanged with $\gamma_{rad} = 8\sigma$, the steep-power-law index varies over time in approximately the same range between 3 and 5.

In Fig. 3(a) we present the time evolution of the power-law indices in all our simulations. Here, the weak cooling cases, $\gamma_{rad} = 16\sigma, \infty$, consistently show a single hard power law with index $p_\approx 1.9$. For $\gamma_{rad} = 16\sigma$, high-energy particles continue to cool after reconnection ends at $t \approx 3L_\text{c}/c$, and the power law steepens slightly as the high-energy cutoff decreases. For intermediate cooling, $\gamma_{rad} = 6, 8\sigma$, we initially observe formation of the same hard power law, but at time $t \approx 2L_\text{c}/c$ a second, steep and highly-variable high-energy power law develops, and for a significant period of time both power-laws are present. After reconnection ends, the low-energy hard power law disappears, while the soft power law systematically steepens. In the strong cooling cases, $\gamma_{rad} = 1, 2, 4\sigma$, the hard power law appears tenuously at the beginning of active reconnection, but is quickly replaced by the soft/steep power law which dominates for the remaining time. This plot clearly shows that, although they appear at different stages, both soft and hard power-law indices are independent of the cooling strength. In Fig. 3(c) we summarize this picture and show that the hard power-law index is $p_\approx 1.9$, and the soft power-law index falls in the range $3 < p_\approx 5$. Steady-state models for radiatively cooled broken power laws predict an increase of $p$ by 1. Reconnection-driven NTPA is non-steady, with bursts of efficient acceleration at X-points followed by cooling episodes when particles reside in plasmoids. Thus, the soft/steep power-law appears to reach a minimum slope of $p_{\text{min}} \approx 3 \approx p_\approx 1$ occasionally, but $p_\approx$ varies greatly in time, becoming much steeper than $p_\approx 1$ during uninterrupted cooling episodes.

In Fig. 3(b) we present temporal evolution of the spectral high-energy cutoffs $\gamma_\text{c}$ (when two power laws are present, we show $\gamma_\text{c}$ for both). Without cooling, $\gamma_{rad} = \infty$, the high-energy extent of the hard power law saturates with time around $\gamma_\text{c} \approx 10\sigma$. In the weak cooling case, $\gamma_{rad} = 16\sigma$, the cutoff is lower and slowly declines after active reconnection ends. For moderate cooling, $\gamma_{rad} = 6, 8\sigma$, the spectral break between the hard and soft power laws is even lower (and the hard power law disappears at $t \approx 3-4L_\text{c}/c$). However, $\gamma_\text{c}$ for the steep power law is around $\gamma_{rad}$ during the active phase. We see similar behaviour for strong cooling cases, $\gamma_{rad} \leq 2\sigma$, where only the soft/steep power law is present during the simulation. We summarize the dependence of $\gamma_\text{c}$ on $\gamma_{rad}$ in Fig. 3(c) and show that the cutoff of the soft/steep power law (when it exists, i.e., for $\gamma_{rad} \leq 6\sigma$) scales as $\gamma_{rad}$. The hard power law’s cutoff decreases with stronger cooling, until this power law disappears at $\gamma_{rad} \approx 6\sigma$.

Radiation. Fig. 4 presents IC radiation spectra $F(\gamma)$ integrated over the simulation time, i.e., over an entire reconnection flare. The power-law index of IC radiation emitted by particles with steady-state power-law index $p$ should be $\alpha_{IC} = (p - 1)/2$, consistent with our measurements $p_\approx 1.9$ and $\alpha_{IC} \approx 0.5$ for weak cooling, $\gamma_{rad} = 16\sigma$. For strong cooling ($\gamma_{rad} = 2\sigma$), the instantaneous particle and hence photon spectra vary greatly with time. However, periods with
harder spectra, $p_\ast(t) \approx p_{\ast,\min} \approx 3$, should dominate the overall high-energy emission, i.e., $\alpha_{\IC} \approx (p_{\ast,\min} - 1)/2 \approx 1$, in agreement with our measured value $\alpha_{\IC} \approx 1.1$.

**Code Comparison.** TRISTAN-3P and ZELTRON implement the same essential algorithms, including the IC radiation reaction (52), but also have minor differences, e.g., in charge-conserving current deposition, (Umeda et al. 2003) and (Esirkepov 2001). Despite their wide use in astrophysics, the two codes have not yet been systematically compared; fortunately, we find that they produce essentially identical results for radiative reconnection. Although noisy, the magnetic energy evolution matches closely over longer time scales. Crucial to our study of NTPA, the particle spectra are remarkably similar [Fig. 5(a)], agreeing very closely on spectral indices $p$ [Fig. 5(b)] and cutoffs $\gamma_c$ (not shown) for $\gamma_{\IC} = \infty$. For the strongly-radiative case $\gamma_{\IC} = 2\sigma$, stochastic time variation prevents precise comparison at any given time, but both codes yield variation within the same range.

**4 CONCLUSIONS**

We presented the first systematic numerical study of the effects of the IC radiation reaction (‘radiation’) on magnetic reconnection using first-principles PIC simulation. We found that, even in the strong cooling regime, basic reconnection and plasmoid dynamics, including the reconnection rate and magnetic energy dissipation, are robustly unchanged. However, IC cooling strongly affects NTPA and the particle energy spectrum. As a result of radiation, the high-energy spectrum has, in principle, two power laws: at lower energy, a hard slope as in nonradiative simulations ($p_h \approx 1.8$–2 for $\sigma_h = 100$ and $B_{\parallel 0} = B_0/4$), and a steeper slope $p_h \geq 3$ at higher energy. While the break $\gamma_{\IC}$ between power laws varies with $\gamma_{\IC}$ and time, the values of $p_h$ and $p_s$ are nearly independent of $\gamma_{\IC}$. When $\gamma_{\IC}$ is well above the reconnection-controlled cutoff (weak radiation, $\gamma_{\IC} \gtrsim 16\sigma$), only the hard power law appears. As radiation is increased, $\gamma_{\IC}$ de-
The IC spectra accordingly have two power-law slopes for $\gamma_{\text{rad}} = 2\sigma$ and $\gamma_{\text{rad}} = \infty$. For stronger radiation ($\gamma_{\text{rad}} \lesssim 4\sigma$), the uncooled hard power law is seen only at very early times. Reflecting the bursty nature of plasmoid-dominated reconnection, the steep power-law index $p_s$ fluctuates strongly, roughly within 3–5, but the hard power-law ($p_h$), built up over time, is much steadier. Thus, $p_s \gtrsim p_h + 1$, with equality expected for radiative steepening of a continuously injected power law $p_h$ subject to IC cooling, and inequality corresponding to further cooling between acceleration episodes. The IC spectra accordingly have two power laws with slopes of roughly $\alpha_{\text{IC}} \approx (p_h - 1)/2$ and $\alpha_{\text{IC}} \approx (p_s_{\text{min}} - 1)/2 \sim p_h/2$. Lowering the guide field (e.g., to $B_0 = 0.05B_0$) yields very similar results but slightly hardens all spectra, as expected (Werner & Uzdensky 2017).

The robust dichotomy of nonthermal spectra produced by reconnection with IC cooling has important implications for understanding radiative kinetic plasma processes in astrophysical systems like BH ADCe. The spectral indices of IC radiation from our simulations of strongly-cooled relativistic reconnection, $\alpha_{\text{IC}} \approx 1.1$, are close to $\alpha \approx 1.5$ observed in hard X-ray spectra (believed to come from IC scattering of soft disc photons by energetic coronal electrons) in HS and Steep Power Law XRB states, while $\alpha_{\text{IC}} \approx 0.5$ seen in weak-cooling simulations is similar to $\alpha \approx 0.7$ observed in the low-hard states (Remillard & McClintock 2006). In future work we will check whether our conclusions about NTPA and radiative signatures still hold in the presence of ions and pair production. We will also study effects of the Comptonization (e.g., secondary scatterings) on the escaping radiation. This will allow first-principles prediction of the IC spectrum of flares powered by magnetic reconnection.

REFERENCES

Beloborodov A. M., 2017, ApJ, 850, 141
Bhattacherjee A., Huang Y.-M., Yang H., Rogers B., 2009, Phys. Plasmas, 16, 112102
Cerutti B., Werner G. R., Uzdensky D. A., Begelman M. C., 2013, ApJ, 770, 147
Cerutti B., Philippov A. A., Spitkovsky A., 2016, MNRAS, 457, 2401
Esirkepov T. Z., 2001, Comput. Phys. Commun., 135, 144
Goodman J., Uzdensky D., 2008, ApJ, 688, 555
Guo F., Li H., Daughton W., Liu Y.-H., 2014, Phys. Rev. Lett., 113, 155005
Jaroschek C. H., Hoshino M., 2009, Phys. Rev. Lett., 103, 075002
Kagan D., Sironi L., Cerutti B., Giannios D., 2015, Space Sci. Rev., 191, 545
Kirk J. G., Skjæraasen O., 2003, ApJ, 591, 366
Lyubarsky Y. E., 1996, Ak A, 311, 172
Lyubarsky Y. E., 2005, MNRAS, 358, 113
Lyutikov M., Uzdensky D., 2003, ApJ, 589, 893
Philippov A. A., Spitkovsky A., 2018, ApJ, 855, 94
Remillard R. A., McClintock J. E., 2006, ARA&A, 44, 49
Sironi L., Spitkovsky A., 2014, ApJ Lett., 783, L21
Spitkovsky A., 2005, T. Bulik, B. Rudak, & G. Madejski (Melville, NY: AIP), 345
Tamburini M., Pogoraro F., Di Piazza A., Keitel C. H., Macchi A., 2010, New J. Phys., 12, 123005
Toomey J., et al., 2014, Comput. Sci. Eng., 16, 62
Umeda T., Omura Y., Tomimaga T., Matsumoto H., 2003, Comput. Phys. Commun., 156, 73
Uzdensky D. A., 2016, in Gonzalez W., Park R., eds, Astrophysics and Space Science Library Vol. 427, Magnetic Reconnection: Concepts and Applications. Springer-Verlag, p. 473
Uzdensky D. A., Spitkovsky A., 2014, ApJ, 780, 3
Uzdensky D. A., Loureiro N. F., Schekochihin A. A., 2010, Phys. Rev. Lett., 105, 235002
Uzdensky D. A., Cerutti B., Begelman M. C., 2011, ApJ Lett., 737, L40
Werner G. R., Uzdensky D. A., 2017, ApJ Lett., 843, L27
Werner G. R., Uzdensky D. A., Cerutti B., Nalewajko K., Begelman M. C., 2016, ApJ Lett., 816, L8
Yuan Y., Nalewajko K., Drake J., East W. E., Blandford R. D., 2016, ApJ, 828, 92
Zweibel E. G., Yamada M., 2009, ARA&A, 47, 291

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