Ultra High Energy Cosmic Ray Puzzle and the Plasma Wakefield Acceleration

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Magnetowave induced plasma wakefield acceleration (MPWA) in a relativistic astrophysical outflow has been proposed as a viable mechanism for the acceleration of cosmic particles to ultra high energies. Here we present simulation results that demonstrate the viability of this mechanism. We invoke the high frequency and high speed whistler mode for the driving pulse. The plasma wakefield so induced validates precisely the theoretical prediction. This mechanism is shown capable of accelerating charged particles to ZeV energies in Active Galactic Nuclei (AGN).

1 Introduction

The origin of ultra high energy cosmic rays (UHECR) is an intriguing question in astrophysics. Theories categorized as either “top-down” or “bottom-up” scenarios are proposed to answer this question. Each scenario faces its own theoretical and observational challenges\textsuperscript{1}. Since the observations from HiRes\textsuperscript{2} and Auger\textsuperscript{3} confirm the Greisen-Zatsepin-Kuz’min (GZK) suppression of the cosmic ray flux\textsuperscript{4}, the need for top-down exotic models is reduced. Hence the challenge to find a viable “bottom up” mechanism for accelerating UHECR becomes more acute.

Shocks, unipolar inductors and magnetic flares are the three most potent, observed, “conventional” accelerators that can be extended to account for \( \sim \text{ZeV} (= 10^{21}\text{eV}) \) energy cosmic rays\textsuperscript{5}. Radio jet termination shocks and gamma ray bursts (GRB) have been invoked as sites for the shock acceleration, while dormant galactic center black holes and magnetars have been proposed as sites for the unipolar inductor acceleration and the flare acceleration, respectively. Each of these models, however, presents problems\textsuperscript{5}. Evidently, novel acceleration mechanisms that can avoid the difficulties faced by these conventional models should not be overlooked.

Plasma wakefield accelerators\textsuperscript{6,7} are known to possess two salient features: (1) The energy
gain per unit distance does not depend (inversely) on the particle’s instantaneous energy; (2) The acceleration is linear. These features are essential for a good acceleration efficiency. Although high-intensity, ultra-short photon or particle beam pulses that excite the laboratory plasma wakefields are not available in the astrophysical setting, large amplitude plasma wakefields can instead be excited by the astrophysically abundant plasma “magnetowaves”\(^8\). Protons can be accelerated beyond \(\text{ZeV}\) energy by riding on such wakefields. This attractive concept has never been validated through self-consistent computer simulations. In this presentation, we report our simulation that confirm this concept\(^9\). We also discuss this acceleration mechanism in AGN.

2 Wakefield Excited by the Magnetowave: Theory and Simulation

To ensure the linear acceleration, we consider wave modes propagating parallel to the external magnetic field. In this case, the eigenmodes are circularly polarized with dispersion relations given by\(^11\)

\[
\omega^2 = k^2 c^2 + \frac{\omega_{ip}^2}{1 \pm \omega c/\omega} + \frac{\omega_p^2}{1 \mp \omega c/\omega},
\]

(1)

where the upper (lower) signs denote the right-hand (left-hand) circularly polarized waves, the subscript \(i\) denotes the ion species, \(\omega_p\) and \(\omega_c\) are the electron plasma frequency and the electron cyclotron frequency respectively. The right-hand polarized, low frequency solution is called the whistler wave which propagates at a phase velocity less than the speed of light. For a sufficiently strong magnetic field such that \(\omega_c \gg \omega_p\), the dispersion of the whistler mode becomes more linear over a wider range of wavenumbers with phase velocity approaching the speed of light (see Fig.1). In this regime the traveling wave pulses can maintain their shape over macroscopic distance, a condition desirable for plasma wakefield acceleration.

![Figure 1: (a) Frequency and (b) phase velocity versus wavenumber for different magnetic fields. The vertical solid line is the mean value of the pulse wavenumber chosen for the PIC simulation, and the dashed lines its range.](image)

The whistler wave packet induces a ponderomotive force along the external magnetic field direction\(^11\). For convenience, this direction is taken to be along the \(+z\) axis. The ponderomotive force leads to the plasma wakefield \(E_z\) which, in the co-moving coordinate \(\zeta \equiv z - v_g t\), reads:

\[
E_z(\zeta) = -\frac{ek_pE_w^2}{m_e\omega(\omega - \omega_c)} \left[ 1 + \frac{k v_g \omega_c}{\omega(\omega - \omega_c)} \right] \chi(\zeta),
\]

(2)

where \(k_p = \omega_p/v_g\) and the form factor \(\chi(\zeta)\) is given by

\[
\chi(\zeta) = \frac{k_p}{2E_w^2} \int_{-\infty}^{\infty} d\zeta' E_w^2(\zeta') \cos[k_p(\zeta - \zeta')],
\]

(3)
with $E_{w}(\zeta)$ the field strength of the whistler wave packet and $E_{W}$ its maximum value. Assuming the driving pulse frequency is centered around $\omega$ and its group velocity $v_{g} = d\omega/dk \approx \omega/k$, the maximum wakefield attainable behind the driving pulse is found to be

$$E_{z}^{\text{max}} = \chi \frac{k^{2}c^{2}}{(\omega - \omega_{c})^{2}} a_{0}^{2} E_{wb},$$

(4)

for a Gaussian driving pulse $E_{W}(\zeta) = E_{W} \exp(-\zeta^{2}/2\sigma^{2})$ with $\chi = \sqrt{\pi}k_{p}\sigma \exp(-k_{p}^{2}\sigma^{2}/4)/2$, $a_{0} \equiv eE_{W}/m_{e}c\omega$ the “strength parameter” of the driving pulse, and $E_{wb} \equiv m_{e}c\omega_{p}/e$ the “wave-breaking” field. We note that Eq. (2) was derived under the non-relativistic approximation for the electron motion in the plasma. The relativistic generalization of this equation deserves further studies.

We have conducted computer simulations to study the MPWA process driven by a Gaussian driving whistler pulse described above. Our simulation model integrates the relativistic Newton-Lorentz equations of motion in the self-consistent electric and magnetic fields determined by the solution to Maxwell’s equations. We used a wavepacket with Gaussian width $\sigma = 80\Delta/\sqrt{2}$, where $\Delta$ is the cell size taken to be unity, and the wavenumber $k = 2\pi/60\Delta$. The physical parameters $\omega_{c}/\omega_{p} = 6$, $m_{i}/m_{e} = 2000$ and electron collisionless skin depth $c/\omega_{p} = 30\Delta$ were taken in the simulations. Other numerical parameters used are: total number of cells in the $z$-direction, $L_{z} = 8192\Delta = 273c/\omega_{p}$, average number of particles per cell was 10, and the time step $\omega_{p}\Delta t = 0.1$. The fields were normalized by $(1/30)E_{wb}$.

We set the maximum amplitude $E_{w} = 10$, which gives the strength parameter $a_{0} = eE_{w}/m_{e}c\omega = 0.11$. The pulse was initialized at $z_{0} = 500\Delta = 16.66c/\omega_{p}$. To avoid spurious effects, we gradually ramped up the driving pulse amplitude until $t = 100\omega_{p}^{-1}$, during which the plasma feedback to the driving pulse was ignored. After this time, the driving pulse-plasma interaction was tracked self-consistently. As the dispersion relation in this regime is not perfectly linear, there was a gradual spread of the pulse width. Thus $\chi$ and $E_{w}$ of the driving pulse decrease accordingly. As a result, the maximum wakefield amplitude, $E_{z}^{\text{max}}$, declined in time. Even so, it agrees very well with the theoretical value of $E_{z}^{\text{max}} \sim 0.266(1/30)E_{wb}$. Fig. 2 is a snapshot of $E_{x}$ and $E_{z}$ at $t = 230\omega_{p}^{-1}$. We note that while the driving pulse continues to disperse, the wakefield remains extremely coherent.

![Figure 2: A snapshot of the plasma wakefield, $E_{z}$ (in black), induced by the whistler pulse, $E_{x}$ (in gray).](image)

3 MPWA Production of UHECR in AGN

The MPWA production of UHECR can be effective in AGN. Typically, the jet from an AGN extends a very long distance with negligible diverging angle. For an AGN with the central black
hole mass $\sim 10^8 M_\odot$, it is reasonable to assume $n_{\text{AGN}} \sim 10^{10} \text{cm}^{-3}$ and $B_{\text{AGN}} \sim 10^4 \text{ G}$ in the core. If we further assume that the AGN luminosity approaches the Eddington limit ($\sim 10^{46} \text{ erg/s}$) and that the AGN jet size is comparable to the Schwarzschild radius of the central black hole, then we find that $a_0 \sim \sqrt{10^9 \eta}$ and $E_{\text{wb}} \sim 10^5 \text{ V/cm}$ with $\eta$ the fraction of total energy imparted into the magnetowave modes. Since the frequency of magnetowave in this case lies in the radio wave region, we assume that the observed AGN radio wave luminosity is the result of total mode-conversion from the magnetoshocks at the same frequency. This then gives $\eta \sim (10^{-3} - 10^{-4})$ and consequently $E_{\text{max}} \sim \mathcal{O}(10^5) \text{ eV/cm}$ from Eq. 4. Hence the acceleration distance to achieve $E \sim \mathcal{O}(10^{21}) \text{ eV}$ is about 10 pc, which is a tiny fraction of the typical AGN jet length.

4 Summary

Through PIC simulations, we have confirmed the concept of plasma wakefield excited by a magnetowave in the magnetized plasma. We have demonstrated how such a wakefield may accelerate particles to ZeV energies in AGN. As a first step, we investigated MPWA in the parallel-field configuration. Since both poloidal and toroidal field components are inevitable in astro-jets, we will further investigate plasma wakefield excitation and acceleration under the cross-field configuration. Besides, we have limited our discussions in the linear regime $a_0 \ll 1$, which is applicable to AGN. However, in other astrophysical settings, such as GRB, the magnetowave could be much stronger such that $a_0 \gg 1$. We will investigate plasma wakefield generations in this regime and therefore explore the MWPA production of UHECR in other powerful astrophysical sites.

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