Laboratory study of collisionless coupling between explosive debris plasma and magnetized ambient plasma

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The explosive expansion of a localized plasma cloud into a relatively tenuous, magnetized, ambient plasma characterizes a variety of astrophysical and space phenomena. In these rarified environments, collisionless electromagnetic processes rather than Coulomb collisions typically mediate the transfer of momentum and energy from the expanding “debris” plasma to the surrounding ambient plasma. In an effort to better understand the detailed physics of collisionless coupling mechanisms, complement in situ measurements of space phenomena, and provide validation of previous computational and theoretical work, the present research jointly utilizes the Large Plasma Device and the Raptor laser facility at the University of California, Los Angeles to study the super-Alfvénic, quasi-perpendicular expansion of laser-produced carbon (C) and hydrogen (H) debris plasma through preformed, magnetized helium (He) ambient plasma via a variety of diagnostics, including emission spectroscopy, wavelength-filtered imaging, and a magnetic flux probe. Doppler shifts detected in a He1⁺ ion spectral line indicate that the ambient ions initially accelerate transverse to both the debris plasma flow and the background magnetic field. A qualitative analysis in the framework of a “hybrid” plasma model (kinetic ions and inertia-less fluid electrons) demonstrates that the ambient ion trajectories are consistent with the large-scale laminar electric field expected to develop due to the expanding debris. In particular, the transverse ambient ion motion provides direct evidence of Larmor coupling, a collisionless momentum exchange mechanism that has received extensive theoretical and numerical investigation. In order to quantitatively evaluate the observed Doppler shifts, a custom simulation utilizing a detailed model of the laser-produced debris plasma evolution calculates the laminar electric field and computes the initial response of a distribution of ambient test ions. A synthetic Doppler-shifted spectrum constructed from the simulated test ion velocities excellently reproduces the experimental measurements, verifying that the observed ambient ion motion corresponds to collisionless coupling through the laminar electric field. Published by AIP Publishing. [http://dx.doi.org/10.1063/1.4995480]

I. INTRODUCTION

A ubiquitous category of astrophysical and space phenomena is characterized by the rapid expansion or relative motion of a localized plasma cloud through a relatively tenuous, magnetized, ambient plasma. Examples include the expansion of stellar material through the surrounding interstellar medium in supernova remnants,1 the formation of cometary plasma tails due to the solar wind,2 the interaction of interplanetary coronal mass ejections with the Earth’s magnetosphere,3 ionospheric nuclear detonations,4 and artificial magnetospheric gas releases.5 In these rarified environments, the Coulomb collisional mean free paths $\lambda$ generally exceed the system sizes $D$ by many orders of magnitude ($\lambda/D \gg 1$), signifying that the explosive “debris” plasma exchanges momentum and energy with the surrounding ambient plasma via collisionless, collective, electromagnetic effects. In addition, the relative motion of the debris cloud across the magnetic field produces electric polarization fields between the magnetically confined electrons and the relatively free-streaming ions, resulting in $\vec{E} \times \vec{B}$ drift electron currents that expel the magnetic field within the cloud volume (the diamagnetic cavity) and enhance it at the cloud edge (the magnetic compression).6 The general evolution in the reference frame of the magnetized ambient plasma is thus a deceleration of the debris cloud as it couples to the ambient plasma via collisionless processes and deforms the magnetic field.

The collisionless processes that transfer momentum and energy between the debris and ambient plasmas can be broadly categorized as either turbulent or laminar. Turbulent coupling occurs when instabilities driven by the relative counter-streaming of different populations (e.g., debris and ambient ions) give rise to an anomalous viscosity, causing momentum exchange or plasma heating. A variety of candidate instabilities5,7 exist, each with unique anomalous...
“collision” frequencies and onset conditions that are sensitive to plasma parameters and the direction of propagation with respect to the magnetic field. However, theoretical and numerical studies have demonstrated that certain instabilities associated with counter-streaming across the magnetic field (in particular, the magnetized ion-ion instability\(^8\) and the modified two-stream instability\(^9\)) do not provide effective coupling in the parameter regime representative of many space and astrophysical environments, where the debris expansion speed \(v_{e,0}\) exceeds the ambient plasma Alfvén speed \(v_A\) (Alfvénic Mach number \(M_A \equiv v_{e,0}/v_A > 1\)) and the magnetic pressure \(B^2/8\pi\) dominates over the electron thermal pressure \(p_e\) (electron beta \(\beta_e \equiv 8\pi p_e/B^2 < 1\)).

Laminar coupling, the second category of collisionless processes, corresponds to ion acceleration via large-scale polarization and induction electric fields that arise as the debris expands through the magnetized background. Analysis in the framework of a “hybrid” plasma model, which treats the various ion species kinetically and the electrons as a single charge-neutralizing inertia-less fluid, demonstrates that the strongest laminar debris fields generally develop for quasi-perpendicular debris expansions, particularly at the magnetic compression front and diamagnetic cavity edge. Moreover, in the super-Alfvénic \((M_A > 1)\), magnetic pressure dominated \((\beta_e \ll 1)\) limit, simple scaling arguments\(^10\) show that the laminar electric field points transverse to both the direction of debris propagation and the magnetic field. The laminar interaction in this limit, termed Larmor coupling, characteristically involves an initially transverse acceleration of the ambient ions, which subsequently gyrate into the original direction of debris propagation within a time interval on the order of the ambient ion gyro-period. Larmor coupling has received extensive theoretical and numerical investigation,\(^11,12\) particularly in the context of ionospheric nuclear detonations\(^13,14\) and cosmic magnetized collisionless shocks.\(^15-17\)

Despite the substantial theoretical and computational efforts to understand laminar coupling between super-Alfvénic plasma explosions and surrounding magnetized plasmas, experimental verification remains limited. In part, this is due to the numerous challenges associated with observations and \textit{in situ} measurements of space and astrophysical phenomena, including inaccessibility, irreproducibility, and extraordinarily large system sizes. These issues have motivated properly scaled laboratory experiments capable of reproducing the key coupling physics despite orders of magnitude differences in spatial and temporal scales. Over the last several decades, a number of such experiments have achieved significant progress by combining explosive, laser-produced debris plasmas with preformed, magnetized ambient plasmas.\(^18\) Utilizing this configuration, recent investigations have successfully driven magnetized collisionless shocks into the ambient plasma\(^19-21\) and measured the electrostatic field structure associated with the explosive debris plasma cloud,\(^22,23\) providing indirect evidence of the collisionless debris-ambient interaction. However, none of these efforts examined the ion dynamics in sufficient detail to directly verify collisionless coupling through the laminar electric field structure proposed by the previous theoretical and numerical studies.

In addition to laboratory studies involving laser-produced plasmas, the AMPTE (Active Magnetospheric Particle Tracer Explorers) mission, which provided \textit{in situ} observations of the collisionless interaction between an artificial, photo-ionized barium plasma cloud and the streaming, magnetized hydrogen plasma of the solar wind, deserves special mention.\(^24-28\) One of the mission’s most significant findings was the unanticipated displacement of the barium ion “comet head” (and an oppositely directed deflection of the streaming hydrogen ions) transverse to both the solar wind flow and the interplanetary magnetic field, defying the conventional expectation that the barium ions would simply move downwind.\(^29\) Subsequent theoretical and computational efforts\(^30-32\) to interpret the observations assessed the role of the laminar electric field in detail, with one study\(^30\) explicitly attributing the transverse deflection to Larmor coupling. Prior to the present work, the AMPTE mission arguably constituted the only direct experimental evidence of collisionless momentum and energy exchange through the laminar electric field.

In an effort to better understand the physics of laminar collisionless coupling, compliment \textit{in situ} measurements of space phenomena, and provide validation of previous computational and theoretical work, this paper reports the laboratory investigation of the super-Alfvénic, quasi-perpendicular expansion of laser-produced carbon (C) and hydrogen (H) debris plasma through preformed, magnetized helium (He) ambient plasma, utilizing a unique experimental platform at the University of California, Los Angeles (UCLA). Emission spectroscopy, wavelength-filtered imaging, and a magnetic flux probe diagnose the debris-ambient interaction. The key result, first reported in a recent publication\(^33\) by the same authors and considerably expounded upon in the present paper, is the direct observation of laminar collisionless coupling through Doppler shifts in a He\(^{+}\) ion spectral line, which indicates ambient ion motion in response to the laser-produced debris along a trajectory qualitatively consistent with the hybrid model laminar electric field. Specifically, directed ambient ion acceleration along the axis perpendicular to both the debris flow and the background magnetic field demonstrates that the transverse component of the laminar electric field (associated with Larmor coupling) contributes significantly. In the subsequent analysis, a custom simulation utilizing a detailed model of the laser-produced debris plasma evolution calculates the laminar electric field and computes the initial response of a distribution of ambient test ions. A synthetic Doppler-shifted spectrum constructed from the simulated test ion velocities excellently reproduces the experimental measurements, quantitatively verifying that the observed ambient ion velocity distribution develops due to acceleration through the laminar electric field.

Section II begins by outlining the basic concepts and mathematical framework of laminar collisionless coupling in the context of the hybrid plasma model. Section III describes the experimental platform, diagnostics, and parameters. Section IV reports the key features of the debris-ambient interaction discerned from the experimental data, emphasizing the He\(^{+}\) ion motion deduced from Doppler shifts and the qualitative consistency of the observations with Larmor
coupling. Section V develops a custom simulation of the initial ambient ion response to the laser-produced debris and compares the simulation results to the experimental data, quantitatively confirming that the spectroscopic measurements indicate laminar collisionless coupling. Section VI concludes the paper.

II. THEORETICAL BACKGROUND

As outlined in the introduction, the collisionless ($\lambda/D \gg 1$), super-Alfvénic ($M_A > 1$), magnetic pressure dominated ($\beta_e \ll 1$) parameter regime of many space and astrophysical environments indicates that neither Coulomb collisions nor instabilities effectively transfer momentum and energy between quasi-perpendicular debris plasma explosions and surrounding magnetized plasmas. Consequently, laminar electric fields provide the dominant coupling mechanism. The present section therefore considers only the basic concepts and mathematical framework of laminar collisionless coupling and assumes that resistivity due to both collisions and anomalous turbulent effects is negligible.

A. General expression for the laminar electric field

Laminar collisionless coupling can be understood in the framework of a hybrid plasma model,34 which treats the various ion species kinetically and the electrons as a charge-neutralizing fluid. As the first step, it is useful to derive the general structure of the electric field. The evolution of the electron fluid follows from the momentum equation

$$m_e n_e \frac{d\vec{v}_e}{dt} = -\vec{\nabla} p_e - e n_e \left( \vec{E} + \frac{\vec{v}_e}{c} \times \vec{B} \right), \tag{1}$$

where $m_e$, $n_e$, $\vec{v}_e$, $p_e$, and $e$ are the electron mass, density, fluid velocity, isotropic thermal pressure, and charge, respectively; $\vec{E}$ and $\vec{B}$ are the electric and magnetic fields; and $c$ is the speed of light. On time scales relevant to significant momentum and energy transfer among the ions, the electrons respond almost instantaneously due to their negligible mass, such that transient behavior can be ignored. Thus, a good approximation to Eq. (1) is the inertia-less electron limit $m_e \to 0$, which allows for a solution to the laminar electric field:

$$\vec{E} = -\frac{1}{en_e} \vec{\nabla} p_e - \frac{\vec{v}_e}{c} \times \vec{B}. \tag{2}$$

It is useful to recast Eq. (2) in terms of the charge numbers $Z_i$, densities $n_i$, and velocities $\vec{v}_i$ of the various ion species. Neglecting the displacement current corresponding to transient high-frequency components of the electric field (i.e., the Darwin limit), Ampere’s Law reads

$$\vec{\nabla} \times \vec{B} = \frac{4\pi}{c} \left( \sum_i Z_i n_i \vec{v}_i - e n_e \vec{v}_e \right), \tag{3}$$

where the sum is taken over all ion species. Furthermore, as the system evolves, quasi-neutrality dictates that the electrons continually redistribute themselves to locally match the total charge density of all the ion species, such that

$$n_e \approx \sum_i Z_i n_i. \tag{4}$$

Rearranging Eq. (3) to solve for the electron velocity $\vec{v}_e$ and substituting Eq. (4) for the electron density $n_e$ yield

$$\vec{v}_e = \frac{\sum_i Z_i n_i \vec{v}_i}{\sum_i Z_i n_i} - \frac{c \vec{\nabla} \times \vec{B}}{4\pi e \sum_i Z_i n_i}. \tag{5}$$

Substitution of Eqs. (4) and (5) into Eq. (2) then produces the following expression for the laminar electric field:

$$\vec{E} = -\frac{\vec{\nabla} p_e}{e \sum_i Z_i n_i} - \frac{\vec{B} \times (\vec{\nabla} \times \vec{B})}{4\pi e \sum_i Z_i n_i} - \frac{\sum_i Z_i n_i \vec{v}_i \times \vec{B}}{c \sum_i Z_i n_i}. \tag{6}$$

It is straightforward to demonstrate that the ratio of the first term to the second term of Eq. (6) scales as $\beta_e \equiv 8\pi p_e / B^2$. Moreover, the third term becomes dominant at sufficiently large ion velocities quasi-perpendicular to the magnetic field. Thus, in magnetic pressure dominated environments ($\beta_e \ll 1$) containing fast cross-field ion motion, the first term is negligible with respect to the second and third terms, and a good approximation to the laminar electric field becomes

$$\vec{E} \approx -\frac{\vec{B} \times (\vec{\nabla} \times \vec{B})}{4\pi e \sum_i Z_i n_i} - \frac{\sum_i Z_i n_i \vec{v}_i \times \vec{B}}{c \sum_i Z_i n_i}. \tag{7}$$

Equation (7) yields the self-consistent electric field structure in terms of the ion parameters $Z_i$, $n_i$, and $\vec{v}_i$ and the magnetic field profile $\vec{B}$, indicating that an electric field must exist in regions containing spatially non-uniform magnetic fields (first term) and cross-field ion currents (second term). It is important to note, however, that this expression does not provide any insight into the physical mechanisms that cause the electric field to develop.

B. Laminar electric field of an expanding debris plasma

In order to examine the laminar electric field structure corresponding to the specific case of a debris plasma expanding into a magnetized ambient plasma, it is useful to perform a qualitative analysis of such a configuration and compare the predictions to Eq. (7). For simplicity, a spherically symmetric debris plasma shell of ion density $n_d$, ion charge number $Z_d$, and ion mass $m_d$ is assumed to expand radially at initial speed $v_{i0}$ into a homogeneous ambient plasma of ion density $n_a$, ion charge number $Z_a$, and ion mass $m_a$. The ambient plasma is initially stationary and magnetized by a uniform magnetic field of magnitude $B_{0z}$, assumed to point in the $-z$ direction.

Figure 1 schematically illustrates the resulting electric and magnetic fields in the central plane perpendicular to the background magnetic field (the “blow-off plane”). In the initial phase of debris expansion (at times much earlier than a
debris ion gyro-period but later than an electron gyro-period, the effectively free-streaming debris ions outrun the magnetically confined debris electrons, generating a radially inward polarization electric field ($\mathbf{E}_r$... in Fig. 1) that keeps the electrons and ions together and maintains quasi-neutrality. This electric field drives the debris electrons into an azimuthal $\mathbf{E} \times \mathbf{B}$ drift ($\mathbf{v}_r$...), producing a diamagnetic current in the debris shell that lowers the magnetic field magnitude ($|B_z| < B_0$) within the volume bound by the current layer (the diamagnetic cavity) and increases the field magnitude ($|B_z| > B_0$) just ahead of the current layer (the magnetic compression). A sufficiently strong diamagnetic current results in full expulsion of the magnetic field within the cavity ($|B_z| = 0$). As the debris shell expands, the time-changing magnetic field associated with the growing diamagnetic cavity and propagating magnetic compression produces an induction electric field ahead of the cavity edge, in accordance with the Maxwell-Faraday equation. In addition, the tendency of the $\mathbf{v} \times \mathbf{B}$ Lorentz force to deflect the moving debris ions and electrons into opposite directions sets up a transverse polarization electric field within the shell. In combination, these two effects result in a “clockwise” azimuthal electric field ($\mathbf{E}_\phi$) in regions outside of the cavity. The azimuthal electric field initially drives swept-over ambient electrons into a radially outward $\mathbf{E} \times \mathbf{B}$ drift, resulting in a radially outward polarization electric field ($\mathbf{E}_r$...) that maintains quasi-neutrality. This radial electric field then sends the ambient electrons into an oppositely directed azimuthal $\mathbf{E} \times \mathbf{B}$ drift ($\mathbf{v}_r$...), constituting a second, anti-diamagnetic current layer ahead of the cavity that further enhances the magnetic field magnitude within the compression region.\(^{35}\)

In summary, the electric field during the initial phase of debris expansion consists of radially inward, radially outward, and “clockwise” azimuthal contributions that maintain quasi-neutrality and self-consistently drive $\mathbf{E} \times \mathbf{B}$ drift electron currents that account for the compression and cavity characterizing the magnetic field profile.

Examination of each term of Eq. (7) yields an electric field structure consistent with the analysis of Fig. 1. The vector portion of the first term can be re-expressed via the identity

$$\mathbf{B} \times (\nabla \times \mathbf{B}) = \frac{1}{2} \nabla B^2 - (\mathbf{B} \cdot \nabla) \mathbf{B},$$

where $\nabla B^2$ represents magnetic pressure gradients and $(\mathbf{B} \cdot \nabla) \mathbf{B}$ corresponds to magnetic tension. In the blow-off plane, symmetry generally requires that the distorted magnetic field points in the same direction as the initial background magnetic field,\(^{36}\) implying that only the $z$ component ($B_z$) is non-vanishing. Furthermore, in typical distorted field profiles, gradients perpendicular to the field lines are much larger than gradients along the field lines. Under these assumptions, the magnetic tension contribution is negligible and Eq. (8) simplifies to

$$\mathbf{B} \times (\nabla \times \mathbf{B}) \approx B_z \nabla \mathbf{B}_z,$$

where $\nabla \mathbf{B}$ represents the gradient in the blow-off plane. The first term of Eq. (7) thus becomes

$$E_1 = -\frac{B_z \nabla \mathbf{B}_z}{4\pi e (Z_d n_d + Z_a n_a)},$$

representing an electric field that points in the direction of decreasing $|B_z|$. For a spherically symmetric expansion, $B_z \nabla \mathbf{B}_z = B_z (\partial B_z/\partial \rho) \hat{\rho}$, where $\rho$ represents the radial unit vector in the blow-off plane. $E_1$ thus points radially outward at the magnetic compression front (where $B_z < 0$ and $\partial B_z/\partial \rho > 0$) and radially inward at the diamagnetic cavity edge (where $B_z < 0$ and $\partial B_z/\partial \rho < 0$). As shown in Fig. 1, this is consistent with the qualitatively inferred electric fields $\mathbf{E}_r$... and $\mathbf{E}_z$... The second term of Eq. (7) also simplifies considerably in the blow-off plane. During the initial phase of debris expansion, the radial debris ion velocity $v_{r0}$ is everywhere perpendicular to the magnetic field $B_z$ and the ambient ions are stationary, such that

$$E_2 = \frac{Z_d n_d e v_{r0} B_z}{c(Z_d n_d + Z_a n_a)} \hat{\phi},$$

where $\hat{\phi}$ corresponds to the azimuthal unit vector. Since $B_z < 0$, $E_2$ points in the $-\hat{\phi}$ direction, consistent with the qualitatively inferred “clockwise” azimuthal electric field $\mathbf{E}_\phi$ shown in Fig. 1. The total laminar electric field in the blow-off plane is the sum of $\mathbf{E}_1$ [Eq. (10)] and $\mathbf{E}_2$ [Eq. (11)]

$$\mathbf{E} \approx -\frac{B_z \nabla \mathbf{B}_z}{4\pi e (Z_d n_d + Z_a n_a)} + \frac{Z_d n_d e v_{r0} B_z}{c(Z_d n_d + Z_a n_a)} \hat{\phi}.$$  

Equation (12) yields a reasonable approximation provided that the debris ion expansion velocity is predominantly radial and the ambient ion current density is negligible with respect to the debris ion current density (i.e., $Z_d n_d |v_{r0}|/Z_a n_a |v_a| \gg 1$).

C. Coupling to the ambient ions

As the debris shell expands through the ambient plasma, the laminar electric field acts to accelerate the initially
stationary ambient ions and decelerate the debris ions, resulting in collisionless momentum and energy exchange between the two species. In accordance with the hybrid model approach, the kinetic response of the ions follows from the Lorentz force, such that the equations of motion for the debris and ambient ions are given by $d\vec{v}_d/dt = (Z_d e/m_d) (\vec{E} + \vec{v}_d \times \vec{B}/c)$ and $d\vec{v}_a/dt = (Z_a e/m_a) (\vec{E} + \vec{v}_a \times \vec{B}/c)$, respectively. During the initial phase of debris expansion in the blow-off plane (i.e., at times much earlier than a debris or ambient ion gyro-period, $t \ll t_a, t_c$, the debris ion velocity is negligibly radial ($\vec{v}_d \approx v_{\phi} \hat{\rho}$), the ambient ion velocity is negligible ($\vec{v}_a \approx 0$), the magnetic field is represented by a characteristic profile containing a cavity and compression ($\vec{B} = B_z \hat{z}$), and the electric field $\vec{E}$ is approximated via Eq. (12). Performing these substitutions into the equations of motion and setting $B_z \vec{\nabla} \cdot B_z = B_z (\partial B_z/\partial \rho) \hat{\rho}$ in Eq. (12) under the assumption of spherical symmetry, the initial accelerations of the debris and ambient ions in the blow-off plane are thus given by

$$\left. \frac{d\vec{v}_d}{dt} \right|_{t \ll t_a, t_c} \approx -\Omega_d \left[ \frac{c (\partial B_z/\partial \rho)}{4\pi e (Z_d n_d + Z_a n_a)} \right] \hat{\rho} - \Omega_d \left[ \frac{1 + Z_a n_a}{Z_d n_d} \right] \left( \frac{v_{\phi 0}}{v_0} \right) \hat{\phi},$$

(13)

$$\left. \frac{d\vec{v}_a}{dt} \right|_{t \ll t_a, t_c} \approx -\Omega_a \left[ \frac{c (\partial B_z/\partial \rho)}{4\pi e (Z_d n_d + Z_a n_a)} \right] \hat{\rho} + \Omega_a \left[ \frac{1 + Z_d n_d}{Z_a n_a} \right] \left( \frac{v_{\phi 0}}{v_0} \right) \hat{\phi},$$

(14)

where $\Omega_d \equiv (Z_d e B_d)/(m_d c)$ and $\Omega_a \equiv (Z_a e B_a)/(m_a c)$ are the signed debris and ambient ion gyro-frequencies. Equations (13) and (14) indicate that the debris and ambient ions accelerate both radially and azimuthally. The debris ions, primarily localized at the diamagnetic cavity edge (where $B_z < 0$ and $\partial B_z/\partial \rho < 0$), experience a negative radial acceleration [first term of Eq. (13)] that slows their outward expansion, consistent with the radially inward electric field contribution in that region. Simultaneously, the debris ions accelerate in the positive azimuthal direction [second term of Eq. (13)] due to deflection by the $\vec{v} \times \vec{B}$ Lorentz force, which exceeds the oppositely directed force exerted by the negative azimuthal electric field component. By comparison, the initially stationary ambient ions swept up by the propagating magnetic compression front (where $B_z < 0$ and $\partial B_z/\partial \rho > 0$) experience a positive radial acceleration [first term of Eq. (14)], in accordance with the local radially outward electric field component. In addition, ambient ions within the debris shell (where $Z_d n_d \neq 0$) accelerate in the negative azimuthal direction [second term of Eq. (14)] due to the azimuthal electric field contribution.

More insights into the initial ambient ion response can be deduced by considering the relative magnitudes of the azimuthal and radial acceleration components in Eq. (14). Under the experimentally motivated assumption that the characteristic length scale of significant magnetic field gradients is on the order of the ambient ion inertial length $d_a \equiv c \sqrt{(m_a/4\pi e^2 Z_a^2 n_a)}$, the spatial derivative in the radial term can be expressed as $\partial B_z/\partial \rho = 2 B_0 d_a$, where $\alpha$ is a dimensionless number of order unity. The ratio $R_{\phi, \rho}$ of the azimuthal term to the radial term in Eq. (14) thus evaluates to

$$R_{\phi, \rho} \approx \alpha^{-1} \left( \frac{Z_d n_d}{Z_a n_a} \right) M_A,$$

(15)

where $M_A \equiv v_{\phi 0}/v_0$ defines the Alfvénic Mach number in terms of the ambient plasma Alfvén speed $v_0 = B_0/\sqrt{4\pi e n_m \mu_0}$. Many explosive space and astrophysical phenomena are characterized by highly super-Alfvénic ($M_A \gg 1$) or dense debris ($Z_d n_d/Z_a n_a \gg 1$) conditions. In the AMPTE barium releases, for instance, values of $M_A \approx 4$ and $Z_d n_d/Z_a n_a \sim 10^2$ were typical. In such environments, the ratio $R_{\phi, \rho} \gg 1$, indicating that the initial ambient ion response is dominated by an azimuthal acceleration [second term of Eq. (14)]. Laminar collisionless coupling in this regime, termed Larmor coupling, is schematically illustrated in Fig. 2. As a consequence of the predominantly azimuthal electric field, stationary ambient ions within the debris shell experience an initial acceleration in the $-\hat{\phi}$ direction, transverse to both the radial debris velocity $v_{\phi 0}$ and the magnetic field $B_z \hat{z}$. As the ambient ions acquire a velocity, the $\vec{v} \times \vec{B}$ Lorentz force “rotates” them into the original direction of debris expansion within a time interval on the order of the ambient ion gyro-period. If debris expansion persists along $\hat{\rho}$, the electric field continues to point in $-\hat{\phi}$ and ambient ions confined within the debris shell follow a cycloid-like path with an outward guiding center drift (an $\vec{E} \times \vec{B}$ drift-like trajectory). On the other hand, if the debris expansion stops or the ambient ions stream ahead of the debris shell, the ambient ion motion will resemble simple gyration. In either one of these scenarios, a population of ambient ions initially accelerated in $-\hat{\phi}$ must eventually redirect to $+\hat{\phi}$ at some distance farther along $\hat{\rho}$ that is on the order of the ambient ion gyro-radius.

![Fig. 2. Schematic illustration of the ambient ion response in the highly super-Alfvénic ($M_A \gg 1$) or dense debris ($Z_d n_d/Z_a n_a \gg 1$) regime (i.e., Larmor coupling), shown in the central plane perpendicular to the background magnetic field (the blow-off plane). Stationary ambient ions overrun by the debris shell are initially accelerated along the direction of the azimuthal electric field, transverse to both the debris expansion velocity and the magnetic field. As the ambient ions acquire a velocity, the $\vec{v} \times \vec{B}$ Lorentz force “rotates” them into the original direction of debris expansion. Provided that the ambient ions do not stream ahead of the radially expanding debris shell and continue to experience the azimuthal electric field, their trajectory resembles a radially outward $\vec{E} \times \vec{B}$ drift cycloid.](image-url)
From the azimuthal terms of Eqs. (13) and (14), it is clear that the effectiveness of Larmor coupling depends critically on the ratio of the debris and ambient ion charge densities. In the limit of high debris charge density \(Z_d \rho_{d} > Z_a \rho_{a} \gg 1\), the azimuthal acceleration of the debris ions vanishes, while the azimuthal acceleration of the ambient ions is maximized. In this limit, the force exerted on the debris ions by the azimuthal electric field perfectly balances the \(\mathbf{v} \times \mathbf{B}\) Lorentz force, and the debris ions do not deflect from their radial trajectory. Meanwhile, the initially stationary ambient ions experience a strong force from the same azimuthal electric field, generally resulting in effective coupling to the ambient plasma. Conversely, in the limit of low debris charge density \(Z_d \rho_{d} < Z_a \rho_{a} < 1\), the azimuthal acceleration of the debris ions is maximized, while the azimuthal acceleration of the ambient ions vanishes. In this limit, the azimuthal electric field is negligible. The debris ions thus deflect from their initially radial trajectory due to the \(\mathbf{v} \times \mathbf{B}\) Lorentz force, while the ambient ions do not move, such that negligible coupling occurs. In a typical configuration, where \(Z_d \rho_{d}/Z_a \rho_{a} > 1\) is satisfied initially and the debris density drops as the debris plasma expands, the transition from strong to poor Larmor coupling occurs when \(Z_d \rho_{d}/Z_a \rho_{a} \sim 1\). For a spherical expansion, this corresponds to a characteristic length scale known as the equal-charge radius \(R_{Z} \equiv (3Z_d \rho_{d}/4\pi Z_a \rho_{a})^{(1/3)}\), expressed in terms of the total number of debris ions \(N_d\) and the initial ambient plasma density \(\rho_{a}\).\(^{11,12}\)

### III. THE EXPERIMENT

To investigate the interaction between the explosive debris plasma and the magnetized ambient plasma in a reproducible laboratory setting, the present work utilizes a unique experimental platform at UCLA that combines two facilities. The first facility, the Large Plasma Device (LAPD),\(^{38}\) creates a well-characterized, current-free, steady-state (10 ms), highly reproducible (1 Hz), and large plasma column (18 m length, \(\sim 1\) m diameter) via cathode-anode discharge using a variety of gas fills (typically He, H, Ne, and Ar). Magnetic coils along the length of the machine generate a configurable axial magnetic field (200–1800 G) that magnetizes and radially confines the plasma. The second facility, the kJ-class Raptor laser,\(^{39}\) delivers an energetic pulse (1053 nm, \(5–25\) ns, \(>200\) J) once every 45 min onto the surface of a solid target (typically C or C\(_2\)H\(_4\)) embedded within the preformed ambient plasma of the LAPD, producing explosive debris plasma via ablation. Various diagnostics utilize LAPD’s access ports to monitor the debris-ambient interaction.

The configuration of the present experiment is schematically illustrated in Fig. 3. To understand the setup, it is useful to first define a right-handed coordinate system. The horizontal dimension across the diameter of the LAPD defines the \(x\)-axis, the vertical direction defines the \(y\)-axis, and the long, axial dimension defines the \(z\)-axis. The location of the target center closest to where the laser impinges on the target surface establishes the origin \((x, y, z) = (0, 0, 0)\) cm, and the time at which the laser pulse first irradiates the target sets the initial time \(t = 0\) ns. In this coordinate system, the central axis of the LAPD corresponds to \((x, y) = (30, 0)\) cm, the blow-off axis (the primary axis of debris expansion) corresponds to \((y, z) = (0, 0)\) cm, and the blow-off plane (the \(xy\) plane containing the target) is defined by \(z = 0\) cm. In the blow-off plane, the Cartesian LAPD coordinates transform into the cylindrical coordinates utilized in Sec. II via the standard relations \(\rho = \sqrt{x^2 + y^2}\), \(\phi = \arctan(y/x)\), \(\rho = \bar{x} \cos \phi + \bar{y} \sin \phi\), and \(\bar{z} = \bar{x} \sin \phi + \bar{y} \cos \phi\).

In this experiment, the LAPD generates a steady-state He plasma via an 8 ms long discharge of a single, high-emissivity lanthanum hexaboride (LaB\(_6\)) cathode located at one end of the machine. In the blow-off plane at \(z = 0\) cm, LAPD’s magnetic coils produce a field of 710 G directed in \(-\bar{z}\), radially confining the plasma. The resulting magnetized plasma column, roughly aligned to the central axis of the LAPD at \((x, y) = (30, 0)\) cm, has a peak electron density of \(7.2 \times 10^{12} \text{ cm}^{-3}\), a peak electron temperature of 4.3 eV, an estimated He\(^{1+}\) ion temperature of \(\approx 0.5\) eV, and a diameter of \(\approx 20\) cm at the density FWHM (see Fig. 4 for a detailed density profile of the ambient plasma column). A long, rectangular, high-density polyethylene (C\(_2\)H\(_4\)) target is submerged into the LAPD at an offset from the central axis, and the target surface normal is oriented in the \(+\bar{z}\) direction. The Raptor laser, operating at 150 + 20 J per 5 ns pulse, is focused onto the target surface at position \((x, y, z) = (0.6, 0, 0)\) cm and at an angle of \(30^\circ\) to the surface normal through a 1.8 m focal length lens, resulting in a spot diameter of 1.5 mm and an intensity of 1.7 \(\pm 0.3\) TW/cm\(^2\). The laser pulse irradiates the target 7.5 ms after the start of the LaB\(_6\) cathode discharge, rapidly ejecting electrons and various fractions of all the ion charge states (C\(_{1+}\) – C\(_{6+}\) and H\(_{1+}\)) from the surface. In the resulting multi-charge state debris plasma, ions of a higher charge-to-mass ratio acquire faster average expansion speeds.\(^{40}\) Moreover, initial pressure anisotropies drive the plasma to expand primarily along the target surface normal independent of the laser angle of incidence.\(^{41}\) The present target orientation thus ensures that the debris expands primarily in the \(+\bar{x}\) direction and along the blow-off axis at \((y, z) = (0, 0)\) cm, quasi-perpendicular to the magnetic field and through the maximal volume of the ambient plasma. Due to the target offset from the central axis, the debris expands through a region of neutral He gas before reaching the ambient plasma column [see Fig. 3(b)]. The target is moved up or down between every laser shot to provide a fresh, flat surface for ablation. Table I summarizes the key experimental parameters.

Three primary diagnostics are utilized in this experiment. First, a custom-built spectroscopic fiber probe is fixed at \((y, z) = (30, 0)\) cm and freely moves along \(x\) via a motorized 1D drive [see Fig. 3(c)]. The probe is oriented to collect line-integrated light emission along \(\bar{y}\), perpendicular to both the background magnetic field and the primary blow-off direction. A 75 mm focal length lens at the probe’s collection end projects an image from the blow-off axis onto a linear array of 20 200–\(\mu\)m fused silica optical fibers. The linear array is oriented such that the imaged field of view spans \(\approx 0.1\) cm along \(x\) and \(\approx 1.5\) cm along \(\bar{z}\). However, the collected signal also contains defocused contributions along the entire line of sight. The fibers are coupled through a 100 \(\mu\)m...
slit into a 0.75 m SPEX spectrometer containing a 3600 g/mm UV holographic grating. The spectrum is centered on the He\(^{1+}\) ion 468.6 nm line and projected onto a Princeton Instruments (PI) MAX 4 intensified charge coupled device (ICCD) camera, yielding a spectral resolution of $\approx 0.02$ nm. Light emission collected during laser shots is time-integrated for 500 ns at various delays after the laser pulse, while emission collected from the unperturbed ambient plasma is time-integrated for 2 ns and averaged over as many as 25 cathode discharges. Calibration of the spectrometer, as well as a measurement of the instrumental broadening function, is accomplished via an Oriel pencil-style xenon (Xe) calibration lamp.

Second, a custom magnetic flux (or “B-dot”) probe\(^{42}\) consisting of 5 differentially wound single-axis cores spaced at 1 cm increments is fixed along the blow-off axis at $(y,z) = (0,0)$ cm and freely moves along $x$ via a motorized 1D

<table>
<thead>
<tr>
<th>Laser energy</th>
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<td>Laser intensity on target</td>
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<td>Debris plasma species</td>
<td>C and H</td>
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<td>Ambient plasma species</td>
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<td>Ambient plasma diameter (FWHM)</td>
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<td>Ambient peak electron density</td>
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<tr>
<td>Ambient peak electron temperature</td>
<td>4.3 eV</td>
</tr>
<tr>
<td>Ambient He(^{1+}) ion temperature</td>
<td>$\leq 0.5$ eV</td>
</tr>
</tbody>
</table>
drive [see Fig. 3(c)]. The probe is oriented to measure the rate of change of the z component of the magnetic field \(\frac{dB_z}{dt}\), and the signals are sent through custom-built 150 MHz differential amplifiers and coupled into a 1.25 GHz, 10-bit digital acquisition system (DAQ). The measurements from each core are then numerically integrated, thus yielding \(B_z\) as a function of time at 5 consecutive positions from a single laser shot.

Third, a wavelength-filtered PIMAX 4 ICCD camera mounted at an LAPD port window collects light reflected off of an aluminum mirror at \(z \approx 500\) cm (not shown in Fig. 3), yielding fast planar imaging of the blow-off plane at \(z = 0\) cm with a field of view of \(\approx 60\) cm along \(x\) and \(\approx 60\) cm along \(y\). In the resulting images, the preformed plasma column of the LAPD appears roughly in the center, the target falls near the left edge, and the magnetic field points into the page. Two different wavelength filters are utilized in order to selectively image particular ion species. The first filter, centered at 500 nm with a 10 nm bandwidth, is tilted slightly with respect to the optical axis in order to isolate \(\text{C}^4\) ions in the debris plasma via the 494.4 nm spectral line [e.g., the image of Fig. 3(b)]. The second filter, centered at 468.6 nm with a 1 nm bandwidth, isolates \(\text{He}^{1+}\) ions in the ambient plasma via the 468.6 nm spectral line [e.g., the image of Fig. 3(e)]. Light emission collected during laser shots is time-integrated for 30 ns at various delays after the laser pulse.

In addition to the three primary diagnostics, a Langmuir probe (not shown in Fig. 3) is fixed one port downfield from the target in the plane \(z = -32\) cm and freely moves along both \(x\) and \(y\) via a motorized 2D drive. In the absence of explosive laser-produced debris, the Langmuir probe measurements yield profiles of the ambient plasma electron density and temperature in the plane perpendicular to the magnetic field, from which the peak electron density and temperature values stated in Table I, as well as the FWHM density contour shown in Fig. 3(b), are extracted. Figure 4 shows the electron density profile of the ambient plasma column. The peak value of \(7.2 \times 10^{15} \text{ cm}^{-3}\) occurs at \((x, y) = (32, 6)\) cm, somewhat offset from the central axis of the LAPD.

IV. KEY RESULTS

Diagnostics monitoring the explosive expansion of the laser-produced C and H debris plasma through the preformed, magnetized He ambient plasma of the LAPD yield two principal observations. First, wavelength-filtered imaging reveals an orders-of-magnitude intensification in the \(\text{He}^{1+}\) ion fluorescence as the debris expands through the ambient plasma column, indicative of energetic electrons that excite ground-state \(\text{He}^{1+}\) ions. A comparison of the filtered images to the measured magnetic field profile shows a spatial correspondence between the fluorescence boundary and the magnetic compression, suggesting that the energetic electrons are supplied by the characteristic diamagnetic and anti-diamagnetic \(\vec{E} \times \vec{B}\) drift electron currents (see Fig. 1). Second, and of prime significance in the context of this work, emission spectroscopy sampling the intensified population of \(\text{He}^{1+}\) ions detects large Doppler shifts in the 468.6 nm spectral line, indicating ambient ion acceleration in response to the expanding debris cloud. A qualitative analysis demonstrates that the ambient ions accelerate along a trajectory consistent with the transverse component of the theoretically expected laminar electric field (the second term of Eq. (12)), providing direct evidence of Larmor coupling.

A. Ambient ion intensification

Wavelength-filtered imaging reveals a considerable intensification of the He ambient plasma self-emission in response to the explosive debris. Figure 5 compares images of \(\text{C}^4+\) debris ions and \(\text{He}^{1+}\) ambient ions collected via emission of the 494.4 nm and 468.6 nm spectral lines, respectively, at \(t = 500\) ns, \(t = 750\) ns, and \(t = 1000\) ns. Due to the highly energized initial state of the debris plasma, the \(\text{C}^4+\) ions fluoresce intensely as they expand primarily along the blow-off axis, revealing flute-like structures at the leading edge. However, the \(\text{He}^{1+}\) ions remain virtually undetectable in the short (30 ns) exposures until the leading edge of the \(\text{C}^4+\) ions sweeps through the ambient plasma, substantially increasing the \(\text{He}^{1+}\) 468.6 nm fluorescence in its wake.

Figure 6 more clearly demonstrates the correspondence of the \(\text{C}^4+\) leading edge to the intensified \(\text{He}^{1+}\) region by comparing normalized intensity profiles of \(\text{C}^4+\) and \(\text{He}^{1+}\) along the blow-off axis from the images of Fig. 5. The profiles are superimposed on a line-out of the unperturbed ambient electron density of Fig. 4. In terms of half-maximums, the line-outs at \(t = 500\) ns reveal that \(\text{He}^{1+}\) intensification initially develops between \(x \approx 20\) cm and \(x \approx 25\) cm, where the leading edge of \(\text{C}^4+\) first penetrates the He plasma column after crossing a region of neutral gas fill. As the debris continues to expand through the ambient plasma, the \(\text{He}^{1+}\) fluorescence boundary trails the \(\text{C}^4+\) leading edge and the volume of intensified \(\text{He}^{1+}\) grows. By \(t = 750\) ns, the leading edges of both the \(\text{C}^4+\) and \(\text{He}^{1+}\) profiles reach \(x \approx 30\) cm, and by \(t = 1000\) ns, they reach \(x \approx 35\) cm. Figure 6 also compares the intensity line-outs to the spatial profiles of the magnetic field \(z\) component, measured along the blow-off axis via the magnetic flux probe. At \(t = 500\) ns, the characteristic magnetic compression resulting from the quasi-perpendicular debris plasma expansion (see Fig. 1) becomes apparent at the edge of the measured region at \(x \approx 25\) cm, where the field magnitude increases above the background value of \(B_0 = 710\) G. The compression continues to propagate along the blow-off axis, and by \(t = 750\) ns, the maximum reaches \(x \approx 33\) cm. By \(t = 1000\) ns, the maximum reaches \(x \approx 36\) cm and the trailing diamagnetic cavity edge becomes more fully apparent. The comparison reveals that the leading edges (at half-maximum) of the \(\text{C}^4+\) and \(\text{He}^{1+}\) emission profiles approximately correspond to the peak magnetic compression. The small maximum compression ratio of \(\left| B_z \right| / B_0 \approx 1.5\) and the absence of significant ramp steepening in the magnetic field profile indicate that a magnetized collisionless shock does not form. Comparison to a recent LAPD experiment\(^{19–21}\) that produced a collisionless shock and examination of related hybrid code simulations of shock formation\(^{22}\) suggest that insufficient ambient plasma density explains the absence of a shock in the present experiment.
Energetic electrons explain the observed ambient ion intensification. The emission of the He$^{+}$ 468.6 nm spectral line requires a population of He$^{+}$ ions to spontaneously transition from energy levels with principal quantum number $n = 4$ to $n = 3$. Intensified fluorescence therefore requires a significant increase in the $n = 4$ population. A detailed collisional-radiative analysis utilizing the code PrismSPECT$^{44}$ shows that the primary mechanism populating $n = 4$ in the ambient plasma is excitation from the predominant ground state $n = 1$ via collisions with free electrons, which must have a kinetic energy of at least 51 eV in order to overcome the energy difference between the two levels.$^{45}$ Intensification thus necessitates an increase in the population of free electrons with energies $\geq 51$ eV. The spatial correspondence of the ambient ion fluorescence boundary and the magnetic compression (as shown in Fig. 6) suggests that the energetic electrons are supplied by the diamagnetic and anti-diamagnetic $\mathbf{E} \times \mathbf{B}$ drift electron currents that cause the characteristic magnetic field deformation, although verification of this requires quantitative analysis outside the scope of the present study.

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FIG. 6. Normalized intensity profiles of C$^{4+}$ (solid red line) and He$^{+}$ (dashed blue line) along the blow-off axis from the images of Fig. 5, superimposed on a line-out of the unperturbed ambient electron density (gray fill) of Fig. 4. The profiles are compared to the magnetic field $z$ component, also measured along the blow-off axis. The leading edges of the C$^{4+}$ and He$^{+}$ emission profiles (at half-maximum) spatially correspond to each other and to the peak magnetic compression.
B. Ambient ion acceleration

The key result of this work follows from emission spectroscopy sampling the excited population of He\(^{1+}\) ions, which yields large Doppler shifts in the He\(^{1+}\): 468.6 nm spectral line and thus directly indicates ambient ion acceleration in response to the expanding debris cloud. The previously described ambient ion intensification has a highly beneficial consequence, as it allows for significantly better time resolution in the spectroscopic measurements. In fact, with the present apparatus, the intensified plasma yields sufficient signal-to-noise ratios with integration times of only 500 ns, a vast improvement over the \(\sim 1\) ms exposures required in the unperturbed ambient plasma. This allows for sub-gyro-period temporal resolution, a crucial aspect of the measurements to unperturbed ambient plasma. This allows for sub-gyro-period temporal resolution.

FIG. 7. (a) Normalized wavelength profiles of the He\(^{1+}\): 468.6 nm line measured with (solid red line) and without (dashed blue line) the debris plasma at \(x = 30\) cm, time-integrated between \(t = 500\) ns and \(t = 1000\) ns. (b) Wavelength profiles at \(x = 45\) cm, time-integrated between \(t = 4000\) ns and \(t = 4500\) ns. (c) Illustration of initial He\(^{1+}\) ion acceleration due to the transverse, azimuthal component of the laminar electric field \(E_{\perp}\), the second term of Eq. (12) towards the fiber probe, resulting in the Doppler blue shift detected in (a). (d) Illustration of the subsequent He\(^{1+}\) ion gyration in the magnetic field, resulting in the Doppler red shift detected in (b).
the electrons cool rapidly[37] and densities drop to values comparable to the ambient plasma (see Sec. V). Thus, the debris-ambient interaction satisfies the magnetic pressure dominated condition ($\beta_r \ll 1$). The Coulomb collisional mean free paths are estimated from the standard expressions.$^{46}$ For a $C^{+4}$ debris test ion streaming at $v_{\text{ab}} \approx 600$ km/s through the He ambient plasma at the peak density value $n_a \approx 7.2 \times 10^{12}$ cm$^{-3}$, both the $C^{+4}$ ion - He$^{1+}$ ion collisional mean free path of $\lambda_{\text{iv}} \sim 10$ km and the $C^{+4}$ ion - ambient electron collisional mean free path of $\lambda_{\text{ie}} \sim 10$ m significantly exceed the system size of $D \approx 50$ cm, yielding $\lambda_{\text{iv}}/D \sim 10^5$ and $\lambda_{\text{ie}}/D \sim 10^2$. Thus, at the length scales relevant to the experiment, the debris-ambient interaction is collisionless ($\lambda_{\text{iv}}/D \gg 1$). Finally, the debris-ambient ion charge density ratio $Z_{\text{gnd}}/Z_{\text{nab}}$ is estimated by utilizing empirical scaling laws$^{37,48}$ and previous experimental results,$^{37}$ which predict that the laser parameters in the present experiment result in $N_i \approx 2 \times 10^{17}$ total ablated debris ions with $C^{+4}$ ($Z_d = 4$) as the dominant charge state. Assuming that the debris ions expand spherically from the irradiated point on the target for an order-of-magnitude estimate, the debris ion charge density ranges from $Z_{\text{gnd}}n_d \sim 10^{15}$ cm$^{-3}$ at the target surface to $Z_{\text{gnd}}n_d \sim 10^{13}$ cm$^{-3}$ near the ambient plasma column center. Meanwhile, the Langmuir probe measurements of Fig. 4 indicate that the predominant He$^{1+}$ ion charge state ($Z_a = 1$) in the ambient plasma ranges from $Z_{\text{nab}}n_a < 10^{17}$ cm$^{-3}$ at the target surface to $Z_{\text{nab}}n_a \sim 10^{15}$ cm$^{-3}$ in the column center. Therefore, the initial coupling phase satisfies $Z_{\text{gnd}}Z_{\text{nab}} \gg 1$, and the ratio becomes increasingly large closer to the target surface. Table II summarizes the key parameters characterizing the regime of the experiment. In the super-Alfvénic ($M_A > 1$), magnetic pressure dominated ($\beta_r \ll 1$), collisionless ($\lambda_{\text{iv}}/D \gg 1$) regime of the present experiment, the laminar coupling process detailed in Sec. II dictates the ambient ion response. Thus, under the assumption that various ion charge states comprising the laser-produced debris plasma expand radially through initially stationary ambient ions, Eq. (12) gives the laminar electric field structure in the blow-off plane at $z = 0$ cm. Moreover, the satisfied condition $Z_{\text{gnd}}Z_{\text{nab}} \approx 1$ indicates that the azimuthal electric field component associated with Larmor coupling [i.e., the second term of Eq. (12)] should contribute significantly to the initial ambient ion acceleration, in accordance with Eq. (15). It now becomes evident that the detected Doppler shifts qualitatively correspond to Larmor coupling to the He$^{1+}$ ions. The radial debris ion expansion velocity $v_{\text{ab}} \hat{y}$ through the magnetic field $B \hat{z}$ (with $B_z < 0$) requires an electric field contribution directed in $-\phi$, equivalent to $-\hat{y}$ along the blow-off axis at $(y, z) = (0, 0)$ cm. As illustrated in Fig. 7(c), when the debris cloud enters the ambient plasma column, this azimuthal electric field initially accelerates excited He$^{1+}$ ions located near the blow-off axis primarily in the $-y$ direction and towards the fiber probe, producing the blue shift in Fig. 7(a). As shown in Fig. 7(d), the $\vec{v} \times \vec{B}$ Lorentz force subsequently “rotates” the accelerated He$^{1+}$ ions into the $+y$ direction over a distance on the order of the directed gyro-radius ($\approx 10$ cm for He$^{1+}$ ions with a speed of 160 km/s in the background magnetic field $B_0 = 710$ G), consistent with the red shift measured farther from the target and later in time in Fig. 7(b). Doppler spectroscopy thus directly demonstrates He$^{1+}$ ion acceleration transverse to both the direction of debris flow and the magnetic field, and the inferred trajectory is qualitatively consistent with the Larmor coupling process illustrated in Fig. 2.

V. ANALYSIS

The predominantly blue-shifted spectral profile of Fig. 7(a) provides qualitative evidence that the azimuthal component of the laminar electric field associated with Larmor coupling [i.e., the second term of Eq. (12)] participates in the initial acceleration of ambient He$^{1+}$ ions. However, the simplified interpretation in terms of Fig. 7(c) does not account for the spatially and temporally integrated nature of the spectroscopic measurement or the complex He$^{1+}$ ion trajectories resulting from the spatial and temporal dependence of the electric and magnetic fields, both of which contribute to the atypical He$^{1+}$ ion velocity distribution represented by the Doppler-broadened spectrum. Moreover, the interpretation fails to explain the presence of a small red shift in Fig. 7(a). In order to quantitatively evaluate whether the profile of Fig. 7(a) is indeed consistent with He$^{1+}$ ion acceleration via the theoretically expected laminar electric field, a computational approach is employed. Specifically, the response of a distribution of He$^{1+}$ test ions to the explosive laser-produced debris plasma is simulated via the Lorentz force $m_d \vec{v}_{\text{a}}/dt = Z_e e (\vec{E} + \vec{v}_{\text{a}}/c \times \vec{B})$, where the electric field $\vec{E}$ is evaluated numerically, the magnetic field $\vec{B}$ is extrapolated from the spatially and temporally resolved magnetic flux probe measurements, and $\vec{v}_{\text{a}}, m_d, Z_d = 1$ are the velocity, mass, and charge number of each He$^{1+}$ test ion. Selective sampling of the simulated test ion velocities then yields a synthetic Doppler-broadened profile of the He$^{1+}$ 468.6 nm line that is compared to the spectroscopic measurement.

It is important to recall that the debris expansion in the present experiment is only marginally super-Alfvénic with $M_A \approx 2$. Moreover, the debris and ambient ion charge densities are comparable at the position and time of the measurement of Fig. 7(a), such that $Z_{\text{gnd}}/Z_{\text{nab}} \sim 1$. As detailed in Sec. II [in particular, Eq. (15)], the initial ambient ion response in this marginal regime cannot be understood through Larmor coupling alone. In this section, we will therefore be necessary to consider both the azimuthal Larmor term and the radially-like magnetic pressure gradient term of the laminar electric field in order to fully model the observed spectrum of Fig. 7(a). At the end of the analysis, it will be clear that both terms contribute significantly to the ambient ion motion, but

| TABLE II. Key parameters characterizing the regime of the experiment. |
|-----------------|-----------------|
| System size ($D$) | 50 cm            |
| Debris plasma expansion speed ($v_{\text{ab}}$) | 600 km/s        |
| Ambient plasma Alfvén speed ($v_A$) | 290 km/s        |
| Alfvén Mach number ($M_A$) | 2                |
| Ambient plasma electron beta ($\beta_r$) | 0.0025           |
| Debris ion - ambient ion collisions ($\lambda_{\text{iv}}/D$) | $\sim 10^5$      |
| Debris ion - ambient elec. collisions ($\lambda_{\text{ie}}/D$) | $\sim 10^2$      |
| Ion charge density ratio ($Z_{\text{gnd}}/Z_{\text{nab}}$) | $\approx 1$      |
the Larmor term is ultimately responsible for the predominant blue shift in the measured profile.

A. Derivation of the computational model

The present simulation assumes a radial, ballistic debris ion expansion and negligible ambient ion current density. This provides a reasonable approximation during the spectroscopic measurement of Fig. 7(a) ($t = 500–1000$ ns), when debris-ambient coupling first begins. However, this assumption necessarily breaks down later in time as the debris ions decelerate and deflect from their radial trajectories while the ambient ions acquire non-negligible velocities [Eq. (14)]. Since the computational model developed here becomes invalid once significant coupling takes place, it is only compared to the earliest measured spectrum of Fig. 7(a). As detailed in Sec. II, Eq. (12) yields the laminar electric field structure in the blow-off plane ($z = 0$ cm) under the given assumptions. However, the expression must be modified slightly to account for the multiple ion charge states in the laser-produced debris plasma, such that

$$E \approx -\frac{B_x \phi + B_z}{4\pi e} \left( \sum_d Z_{d\alpha} n_d v_{d\alpha} B_z \right) + \frac{\sum_d Z_{d\alpha} n_d v_{d\alpha} B_z}{c \left( \sum_d Z_{d\alpha} n_d + Z_{d\alpha} n_d \right)} \hat{\phi},$$

(16)

where the sums are taken over all the debris ion species and only a single ambient ion charge state is assumed. The electric field in the blow-off plane is generally a function of the radial distance $\rho = \sqrt{x^2 + y^2}$ from the laser-irradiated point on the target, the angle $\phi = \arctan(y/x)$ with respect to the blow-off axis, and the time $t$. An explicit numerical evaluation of $E(\rho, \phi, t)$ via Eq. (16) thus requires the spatially and temporally dependent expansion speeds $v_{d\alpha}(\rho, \phi, t)$ and densities $n_d(\rho, \phi, t)$ of the various debris ion species, as well as the ambient ion density $n_\alpha(\rho, \phi, t)$ and the magnetic field $B_z(\rho, \phi, t)$. Reasonable models for these parameters are briefly derived here. A more detailed description is available elsewhere.

1. Debris ion expansion speeds

In accordance with the assumption of a radial, ballistic debris ion expansion, the speed $v_{d\alpha}(\rho, \phi, t)$ simply follows from time of flight. Thus, for every debris ion species

$$v_{d\alpha}(\rho, \phi, t) = \frac{\rho}{t}.\quad (17)$$

2. Debris ion densities

A reasonable estimate of the debris ion densities $n_d(\rho, \phi, t)$ requires detailed spatiotemporal knowledge of the expanding laser-produced plasma. In order to accurately model the complex composition and expansion geometry of the debris, which consists of a mixture of various charge states ($C^{1+} - C^{6+}$ and $H^{1+})$ with velocity distributions segmented by charge-to-mass ratios, the experimentally validated radiation-hydrodynamics code HELIOS is utilized in combination with wavelength-filtered imaging of the debris cloud. Given the laser configuration of Table I and the target material equation of state as input, HELIOS computes the population fractions and initial velocity distributions of all the ion charge states. The output indicates that the debris ion velocity distributions along the blow-off axis are well-approximated by drifting Maxwellians of the form

$$f_d(v) = C \exp \left[ -\frac{(v - V_d)^2}{2\sigma_d^2} \right],\quad (18)$$

where $V_d$ is the mean drift speed that increases with the ion charge number, $\sigma_d$ is the standard deviation corresponding to the spread in the distribution, and $C$ is an arbitrary normalization constant. Table III summarizes the HELIOS results.

Wavelength-filtered imaging of the debris cloud motivates a simple model of the expansion geometry, which is then combined with the HELIOS-predicted Maxwellian velocity distributions of Eq. (18) in order to derive the densities $n_d(\rho, \phi, t)$ of each debris ion charge state. Figure 8 shows $C^{4+}$ ions imaged in the blow-off plane via the 494.4 nm spectral line at $t = 625$ nm, $t = 750$ ns, and $t = 875$ ns. The images utilize the experimental setup of Fig. 3 but without the generation of the He ambient plasma column, thus showing debris expansion only into the magnetized vacuum of the LAPD. The expansion geometry follows from the $C^{4+}$ fluorescence boundary in the blow-off plane, well-represented by a heuristic “teardrop” function

$$\rho_d(\phi, t) = \rho_{d0}(t) \exp(-|\phi|/\phi_0) \cos \phi,\quad (19)$$

where $-\pi/2 \leq |\phi| \leq \pi/2$. In Eq. (19), $\rho_d$ represents the distance from the laser-irradiated point on the target to the fluorescence boundary in the blow-off plane, $\phi$ is the angle with respect to the blow-off axis, $\rho_{d0}$ is the time-dependent

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<th>Ion</th>
<th>$C^{1+}$</th>
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</tr>
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<td>$\sigma_d$</td>
<td>0.100</td>
<td>0.253</td>
<td>0.355</td>
<td>1.734</td>
<td>1.979</td>
<td>1.071</td>
</tr>
<tr>
<td>$C_d$</td>
<td>$1.225 \times 10^{-3}$</td>
<td>$1.722 \times 10^{-4}$</td>
<td>$9.171 \times 10^{-5}$</td>
<td>$1.195 \times 10^{-6}$</td>
<td>$1.027 \times 10^{-8}$</td>
<td>$1.668 \times 10^{-8}$</td>
</tr>
</tbody>
</table>
maximum extent of the fluorescence along the blow-off axis, and \( \phi_0 \) is a free parameter that varies the teardrop shape. A qualitative best fit of Eq. (19) is obtained at \( \phi_0 = 1.5 \) rad and superimposed on the images of Fig. 8. As the cusp position represented by \( \rho_\phi \) moves along the blow-off axis, Eq. (19) continues to provide a consistently good fit at the optimal fixed value of \( \phi_0 \). To model the three-dimensional expansion of the debris cloud, the ions are assumed to expand into the symmetric volume swept by rotating the teardrop outline of Fig. 8 about the blow-off axis.

Together, the drifting Maxwellian velocity distributions along the blow-off axis [Eq. (18)] and the teardrop expansion geometry [Eq. (19)] motivate the debris ion density function

\[
n_d(\rho, \phi, t) = \frac{C_d}{\rho^3} \exp \left[ -\frac{\left( \rho - \bar{v}_d t \exp(-|\phi|/\phi_0) \cos \phi \right)^2}{2 \sigma_d^2 \rho^2} \right],
\]

where \( C_d \) represents an integration constant normalized to the total number of ions within each charge state. As expected for radial, ballistic ions with a Maxwellian velocity distribution, the derived density profile of Eq. (20) is characterized by a radially drifting and widening Gaussian with a \( 1/\rho^3 \) amplitude decay resulting from the three-dimensional expansion. Moreover, the average drift speed \( \bar{v}_d \) is modulated via the angular dependence of Eq. (19) to take into account the observed teardrop geometry. The numerical evaluation of Eq. (20) for each debris ion charge state \( C^{+} + C^{+} \) utilizes the HELIOS-computed parameters given in Table III. \( \text{He}^{+} \) ions, which do not effectively transfer momentum and energy to the ambient plasma due to their relatively low mass and extremely high speeds, are ignored.52

3. Ambient ion density

The present computational model assumes that the ambient plasma only contains \( \text{He}^{+} \) ions (\( Z_a = 1 \)). By quasi-neutrality, the measured electron density profile \( n_{e,\text{meas}}(\rho, \phi) \) of Fig. 4 also represents the \( \text{He}^{+} \) ion density profile in the unperturbed ambient plasma. Invoking the approximation that the explosive debris has not significantly disturbed the ambient density profile by the start time of the spectroscopic measurement in Fig. 7(a), the ambient ion density profile \( n_a(\rho, \phi, t) \) is thus estimated via

\[
n_a(\rho, \phi, t) \simeq n_{e,\text{meas}}(\rho, \phi).
\]

4. Magnetic field z component

As previously concluded from Fig. 6, line-outs along the blow-off axis reveal a spatial correspondence between the \( C^{+} \) ion fluorescence boundary and the peak magnetic compression. Moreover, as deduced from Fig. 8, the \( C^{+} \) ion expansion geometry in the blow-off plane can be represented by the heuristic teardrop function of Eq. (19). This suggests that the profile of the peak compression throughout the blow-off plane also follows the teardrop shape. The model for the magnetic field \( z \)-component \( B_z(\rho, \phi, t) \) is thus derived by extrapolating spatiotemporal magnetic flux probe measurements \( B_{z,\text{meas}}(x, t) \) from the blow-off axis along the teardrop contours of Eq. (19), such that

\[
B_z(\rho, \phi, t) = B_{z,\text{meas}}(x, t), \quad x \equiv \frac{\rho}{\exp(-|\phi|/\phi_0) \cos \phi}.
\]

Substitution of the modeled debris ion speeds \( v_{d}(\rho, \phi, t) \) from Eq. (17), the debris ion densities \( n_d(\rho, \phi, t) \) from Eq. (20), the ambient ion density \( n_a(\rho, \phi, t) \) from Eq. (21), and magnetic field \( z \)-component \( B_z(\rho, \phi, t) \) from Eq. (22) into Eq. (16) yields the spatially and temporally dependent laminar electric field \( \vec{E}(\rho, \phi, t) \). The response of a distribution of \( N = 10^4 \) \( \text{He}^{+} \) test ions in the blow-off plane, initialized to match the measured density profile of Fig. 4 and the estimated ambient ion temperature of \( \lesssim 0.5 \) eV, is then simulated via the Lorentz force

\[
\frac{d\vec{r}_a(t)}{dt} = \frac{d^2\vec{r}_a(t)}{dt^2} = \frac{Ze_{\text{e}}}{m_a} \left[ \vec{E}(\vec{r}_a(t), t) + \vec{v}_a(t)/c \times \vec{H}(\vec{r}_a(t), t) \right].
\]

In Eq. (23), the time-dependent coordinates \( \vec{r}_a(t) = (\rho_a(t), \phi_a(t)) \) and velocities \( \vec{v}_a(t) \) of each test ion are evolved via
the local electric and magnetic fields \( \vec{E}(\vec{r}, t) = \vec{E}(\rho, \phi, t) \) and \( \vec{B}(\vec{r}, t) = \vec{B}(\rho, \phi, t) \) from Eqs. (16) and (22), the charge number \( Z_a = 1 \), and \( m_a \) represents the atomic mass of He. Because the Lorentz force in the blow-off plane does not have a \( z \) component and the initial ambient ion velocities are negligible, motion along the \( z \)-axis is ignored. The 0.8 ns time resolution of the magnetic flux probe measurements sets the time step of the simulation.

### B. Results of the simulation

Equation (16) and the HELIOS parameters of Table III allow for a numerical evaluation of the laminar electric field \( \vec{E}(\rho, \phi, t) \) in the blow-off plane (\( z = 0 \) cm). Figure 9 illustrates the evolution of \( \vec{E}(\rho, \phi, t) \) at various times between \( t = 375 \) ns and \( t = 1000 \) ns. The electric field vectors are superimposed on color contours of the magnetic field \( \vec{B}(\rho, \phi, t) \), extrapolated from magnetic flux probe measurements via Eq. (22). During this time interval, electric field magnitudes of \( 10^2 \)–\( 10^3 \) V/cm are typical. At \( t = 375 \) ns, the fastest debris ion charge states (primarily \( C_6^+ \)) stream through the central region of the ambient plasma column. Because these ions outrun the magnetic compression and pass through a region of uniform magnetic field (where \( B_z \vec{\nabla} \cdot \vec{B}_z = 0 \)), the first term of Eq. (16) vanishes. However, in accordance with the second term of Eq. (16) associated with Larmor coupling, debris ion motion across the magnetic field (with \( B_z < 0 \)) requires a “clockwise” azimuthal field structure. By \( t = 625 \) ns, the magnetic compression front reaches the ambient plasma column center, and the associated spatial gradients (\( B_z \vec{\nabla} \cdot \vec{B}_z \neq 0 \)) contribute a radial-like outward electric field due to the first term of Eq. (16), in addition to the “clockwise” azimuthal contribution associated with the second term. At the compression front, the vector sum of the azimuthal and radial-like contributions results in a complex, asymmetric electric field structure (see Fig. 11 for details). By \( t = 1000 \) ns, the diamagnetic cavity reaches the ambient plasma center and the electric field is dominated by a radial-like inward contribution at the cavity edge due to the first term of Eq. (16). It is worth noting that the numerically evaluated electric field structure is consistent with the theoretical considerations of Sec. II and Fig. 1. Specifically, the radial-like inward contribution at the cavity edge drives the diamagnetic \( \vec{E} \times \vec{B} \) drift electron current that expels the magnetic field and forms the cavity, while the radial-like outward contribution at the compression front drives the anti-diamagnetic electron current that reinforces the compression.

Utilizing the spatially and temporally dependent electric and magnetic fields shown in Fig. 9, the response of a distribution of \( \text{He}^{1+} \) test ions in the blow-off plane is simulated via the Lorentz force of Eq. (23). Figure 10 illustrates the evolution of the test ions at various times between \( t = 375 \) ns and \( t = 1000 \) ns, superimposed on color contours of the
magnetic field $z$ component $B_z(\rho, \phi, t)$ [Eq. (22)] and tear-drop contours corresponding to the peak density position of each debris ion charge state [Eq. (20)]. Because the plotted time interval corresponds to only about one-quarter of an ambient ion gyro-period ($T_{\text{g}} \approx 4000$ ns for $B_0 = 710$ G), the test ion motion is dominated by the initial electric field impulse, such that gyration due to the $\vec{v} \times \vec{B}$ magnetic force is not yet apparent. Between $t = 625$ ns and $t = 1000$ ns, the test ions in the vicinity of the propagating magnetic compression experience acceleration due to both the first (radial-like) and second (azimuthal) terms of the electric field of Eq. (16) (see Fig. 11 for details). By $t = 1000$ ns, the test ions in the lower half of the blow-off plane ($y < 0$) develop large velocity components in the $-\hat{y}$ direction, while those in the upper half ($y > 0$) acquire relatively small velocities in the $+\hat{y}$ direction, as evidenced by the asymmetric displacement.

In order to understand the cause of the asymmetric test ion displacement in Fig. 10, it is necessary to examine the structure of the laminar electric field in further detail. Figure 11 compares the simulated He$^{1+}$ test ion response at $t = 750$ ns to the electric field vectors evaluated at two sample locations via Eq. (16). The two sample positions are within the magnetic compression front, with one slightly above ($y > 0$) and the other slightly below ($y < 0$) the blow-off axis. As illustrated in Figs. 11(b) and 11(c), the vector sum of the first (radial-like) and second (azimuthal) terms of
Eq. (16) results in an asymmetric net electric field structure. Specifically, because typical magnitudes of the first term (≈300 V/cm at the sampled positions) exceed those of the second term (≈150 V/cm), the net electric field is characterized by a large component in the $-\hat{y}$ direction in the lower half of the blow-off plane ($y < 0$) and a relatively small component in the $+\hat{y}$ direction in the upper half ($y > 0$). When this net electric field acts on the test ions, it produces the asymmetric test ion distribution shown in Fig. 11(a).

Selective sampling of the simulated He$^{1+}$ test ions now allows for the construction of a synthetic Doppler-broadened profile of the He$^{1+}$ 468.6 nm line, which is compared to the spectroscopic measurement of Fig. 7(a). To mimic the configuration of the spectroscopic fiber probe, the velocity $y$ component of test ions located within the fiber probe field of view shown in Fig. 11(a) are sampled over the measurement time interval between $t = 500$ ns and $t = 1000$ ns. Because the fiber probe is predominantly sensitive to the intensified He$^{1+}$ ion population, only the "excited" subset of test ions [also shown in Fig. 11(a)] contributes to the synthetic velocity distribution and spectrum. Recalling the correspondence between the He$^{1+}$ ion intensified emission boundary and the magnetic compression observed in Fig. 6, this excited subset is selected by choosing only the test ions within the spatial region bound by the magnetic compression front in the blow-off plane. Each excited test ion contributes equally to the synthetic spectrum, implicitly invoking the assumption that the electron density profile of Fig. 7(a) is uniform in space and constant in time within the region bounded by the magnetic compression front. Figure 12(a) shows the resulting velocity distribution of the excited test ions within the fiber probe field of view, confirming that the asymmetrically structured laminar electric field [illustrated in Figs. 11(b) and 11(c)] accelerates test ions in the lower half of the blow-off plane to large velocities in the $-\hat{y}$ direction (magnitudes up to $\approx 250$ km/s) and those in the upper half to comparatively small velocities in the $+\hat{y}$ direction (up to $\approx 100$ km/s). The use of the standard Doppler relation $v_y = c\Delta \lambda / \lambda_c$ and convolution with instrumental and fine structure broadening converts the test ion velocity distribution into the synthetic wavelength spectrum of the He$^{1+}$ 468.6 nm line shown in Fig. 12(b). The simulated spectrum excellently matches the measured profile of Fig. 7(a), reproducing the asymmetric broadening, the predominant blue shift, and the small red shift.

The strong agreement between the measured and synthetic spectra shown in Fig. 12(b) confirms that the experimentally observed He$^{1+}$ ion response is quantitatively consistent with the laminar collisionless coupling process detailed in Sec. II. More specifically, the test ion analysis demonstrates that the key features of the spectroscopic measurement of Fig. 7(a) ultimately result from the asymmetric net electric field structure [illustrated in Figs. 11(b) and 11(c)], which accelerates some ambient ions to large speeds towards the fiber probe (producing a predominant blue shift) and other ambient ions to comparatively small speeds away from the fiber probe (producing a small red shift). While both the first (radial-like) term associated with magnetic field gradients and the second (azimuthal) term associated with Larmor coupling in the laminar electric field of Eq. (16) must be considered together to reproduce the measured spectrum of Fig. 7(a), Larmor coupling ultimately accounts for the predominant blue shift.

VI. CONCLUSION

The present research has utilized a unique experimental platform at UCLA to study the interaction of explosive debris plasma with magnetized ambient plasma in a reproducible laboratory setting. Specifically, by jointly employing the LAPD and Raptor facilities, the super-Alfvénic, quasi-perpendicular expansion of laser-produced carbon (C) and hydrogen (H) debris plasma through preformed, magnetized helium (He) ambient plasma has been monitored via a variety of sophisticated diagnostics, including emission spectroscopy, wavelength-filtered imaging, and a magnetic flux probe.

The key result of this work follows from emission spectroscopy. Measurements of the He$^{1+}$ ambient ion 468.6 nm line collected perpendicular to both the blow-off axis and the magnetic field reveal significant, asymmetric Doppler broadening in response to the explosive debris, indicating that the He$^{1+}$ ions accelerate to speeds nearly two orders of magnitude faster than the thermal average in the unperturbed ambient plasma. A qualitative analysis demonstrates that the inferred He$^{1+}$ ion trajectory follows the “hybrid” model laminar electric field (in particular, the transverse component associated with Larmor coupling), consistent with the super-Alfvénic ($M_A > 1$), magnetic pressure dominated ($\beta_e < 1$), collisionless ($\lambda / D \gg 1$), dense debris ($Z_d n_d / Z_a n_a \approx 1$) regime of the experiment.

The quantitative consistency of the observed Doppler broadening to ambient ion acceleration via the laminar electric field is evaluated by developing a custom computational approach. Specifically, radiation-hydrodynamic modeling of...
the laser-target interaction, wavelength-filtered imaging, limited measurements of the magnetic field and ambient density profiles, and a number of simplifying assumptions allow for a simulation of the initial He$^{1+}$ test ion response to the laser-produced debris plasma. Selective sampling of the simulated He$^{1+}$ test ions yields a synthetic Doppler-broadened profile of the He$^{1+}$ 468.6 nm line that excellently reproduces the corresponding measurement, confirming that laminar collisionless coupling accurately explains the observed He$^{1+}$ ion response. In particular, the predominant blue shift and small red shift in the initial measured spectrum ultimately arise due to both the azimuthal electric field component associated with Larmor coupling and the radial-like electric field component associated with magnetic field gradients, both of which contribute non-negligibly.

The present work thus constitutes the first direct laboratory observation of collisionless momentum and energy exchange through the laminar electric field, strongly suggesting that this coupling process plays a key role in the evolution of numerous natural and man-made environments characterized by similar parameter regimes and motivating continued investigation in reproducible laboratory settings. The impressive agreement achieved between data and simulations also provides a strong argument for the validity of the hybrid approach (kinetic ions and inertia-less fluid electrons), which has been utilized in a multitude of previous theoretical and computational investigations of explosive space and astrophysical phenomena.

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