Toward Investigation of Diffusive Shock Acceleration Mechanism in a Magnetized Collisionless Shock Wave in LArge Plasma Device (LAPD)

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Abstract:

It is believed that high energy particles in cosmic rays can be produced by the particle accelerated in collisionless shock waves in supernova remnants through a process called diffusive shock acceleration (DSA). However, observational astronomy has its natural limitation on further studying the physical mechanism. Recently, it is reported that magnetized magnetosonic shock waves are successfully generated in LArge Plasma Device (LAPD), providing a new platform for such researches. As the laboratory experiments have advantages over the observational astronomy, I will discuss what we can do on LAPD to study the mechanism of DSA.

A. Introduction

Collisionless shock waves can be defined as shock waves having length scale much smaller than the collisional mean free path. Therefore, the structure formation and physical interactions inside must be mediated through electromagnetic forces. In fact, the physics in these waves had been so poorly understood that it wasn't until 1960's that people started to believe in and confirm their existence [1]. Despite the rich physics developed ever since, the investigation of collisionless shock waves have mainly benefited from theoretical modeling, simulations, space missions and astronomical observation. The reproduction of astronomy-relevant collisionless shock waves in laboratory environment had remained a challenge until recent years. In the past decade, the successful generation of strong collisionless shock waves through high-power laser opened a new window to these researches [2-6]. Such method was also applied to the ambient plasma of the LArge Plasma Device (LAPD) in University of California – Los Angeles to generate a collisionless shock wave in magnetized laboratory plasma [7]. Due to its high reproducibility and controllability of plasma parameters, LAPD is a promising device for studying magnetized collisionless shock waves.

Among the important physics in collisionless shock waves, particle acceleration mechanism has attracted special interest. It is suggested that astronomical collisionless shock waves such as a supernova remnant (SNR) can be the source of high-energy cosmic rays via the interaction between particle and the field. Theories of acceleration such as diffusive shock acceleration (DSA) [8-13] have been established to explain how particles can be accelerated to so high energy by the shock waves. However, the quantitative verification of the DSA theories in real systems has mainly relied on astronomical observations. Though observational technology has advanced a lot, its ex-situ nature brings obvious limitations on it. Therefore, in this report I will discuss the potential research work that can be done on LAPD to help us understand the detail physics of DSA.

B. Collisionless shock waves and diffusive shock acceleration

1. Basic structure of collisionless shock waves

The typical structure of a collisionless shock is shown in Figure 1. A shock wave front moves from the downstream region toward the upstream region. In the shock frame, it's the medium flowing from upstream region across the shock to the downstream region. From the strength of magnetic field, we can see that the wave front contains a mildly surging foot, a fast-growing ramp, and one or more overshoots. It is obvious that the field strength is amplified, both in mean value and fluctuation level, and the particles are accelerated in the downstream region. There are also a small population of ions accelerated to high speed in the upstream region, which are the ions reflected by the wave front. Much physics in the downstream and upstream region far from the shock can be described by the magnetohydrodynamic (MHD) fluid model [1]. However, the microphysics in shock itself often needs to be accounted by two-fluid or kinetic theory.

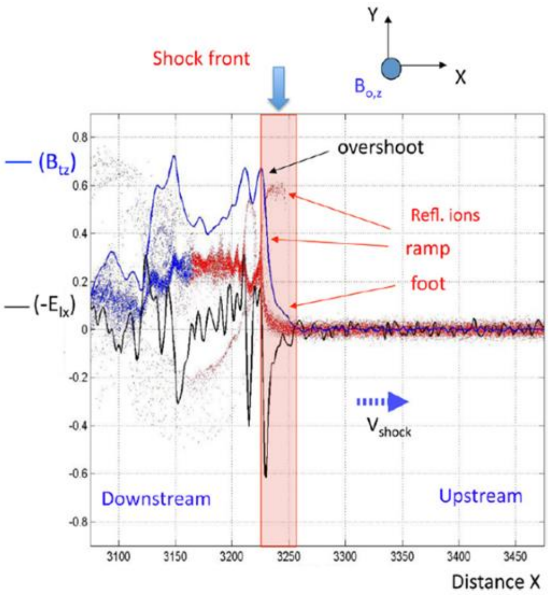

Figure 1. The typical structure of a collisionless shock wave from a 1D PIC simulation [14]. The dots represent ions distribution in phase space.

It should be noted that when studying collisionless shock waves, the orientation of the wave vector is an important parameter. Different orientations can lead to totally different physics involved. It is obvious because particle motion in a magnetized plasma is highly anisotropic. A **perpendicular** shock wave refers to the ones propagating in a direction strictly perpendicular to the background magnetic field, while a **quasi-perpendicular** shock has an angle between 45 and 90 degree. Similarly, a **parallel** shock propagates strictly along the field direction, and a quasi-parallel one has the angle between 0 and 45 degree. For instance, Figure 1 describes a perpendicular shock.

Collisionless shock waves can also be classified by the wave speed. The Alfvenic Mach number of a collisionless shock can be defined by the ratio of shock speed to local Alfven speed, $M_A = u_s/V_A$. A "supercritical" shock has $M_A > 2$, and a "subcritical" shock has $M_A < 2$. Figure 1 shows a shock in supercritical regime. In subcritical shocks, the foot and overshoot structures are absent.

The microphysics involved in the collisionless shock waves, such as shock formation or particle acceleration, have attracted much research attention (see [15] for review). Among them, a particularly interesting topic is the mechanism of cosmic ray generation. It is believed that the collisionless shock waves in supernova remnants (SNRs) can accelerate particles to such a high energy level as the cosmic rays we observe [16]. The most accepted explanation of how cosmic rays are generated by shock waves is the DSA mechanism, which will be briefly introduced in the following section. Nevertheless, it is noteworthy that DSA might happen in a broader variety of shock waves than SNRs [13].

2. Diffusive shock acceleration and magnetic field amplification

DSA is a well-established concept of how particles are accelerated in collisionless shock waves. It is most effective in but not limited to explaining the particle acceleration in parallel shocks. An introductive review can be found in [13].

The concept is simple. When particles cross through the shock wave front, either from downstream to upstream or from upstream to downstream, they will gain kinetic energy because of the difference in flow velocity between the two sides. After crossing, the magnetic fluctuations can lead to small angle scattering with the particles and thus isotropise the particles. A portion of the isotropic particle population can again cross the shock wave front, increasing their kinetic energy again. After many times of shock-crossing, some particles can gain very high energy. Such diffusion-like mechanism is how DSA, a.k.a. Fermi acceleration, gets its name. The resulting particle distribution in momentum space will take the form of a power law:

$$f(p) \sim p^{-q}$$

For the DSA process, the power q can be decided by the compression ratio r [17]:

$$r = \frac{\gamma + 1}{\gamma - 1 + 2/M_A^2} \longrightarrow 4\,;\; q = \frac{r+2}{r-1} \longrightarrow 2$$

, where $\gamma = C_p/C_v \sim 5/3$. We see that $q \longrightarrow 2$ for shocks with high Mach number.

However, there is a main challenge of this concept. When the particles cross a parallel shock wave and enter the downstream or upstream region, they can easily escape along the field lines if the magnetic fluctuation level is low. That is to say, there is only one chance of crossing for each particle. Therefore, we need some mechanisms to amplify the magnetic fluctuations in the downstream or upstream region when the accelerated particles enter. In a strongly fluctuating field, the particles are frequently scattered so that they are not free to escape the region.

The mechanism of magnetic field amplification is a research field under intense investigation. The simplest mechanism is that when the particle moves along the field line, the gyromotion excites Alfven waves of wavelengths comparable to the Larmor radius. The left-hand polarized wave can be thus excited resonantly in linear region until saturation when $\delta B/B_0 \sim 1$. On the other hand, the right-hand polarized wave can also be driven non-resonantly, but still grow rapidly when $\delta B/B_0 > 1$. According to estimation, the PeV energy level cosmic rays needs $\delta B/B_0 \gg 1$ to be generated.

Besides the amplification of field in the Larmor radius scale, generation of cosmic rays also requires field amplification in larger scales, or the "long-wavelength" regime. Proposed mechanisms include current-driven stress tensor instability [18], ponderomotive instability [19], filamentation instability [20], firehose instability [21] and pressure gradient driven instabilities [22].

C. Limitation of observational astronomy for DSA investigation

Supernova remnants (SNRs), especially the young ones, are known as a major source of high-energy cosmic rays. Therefore, observational astronomy is the main approach of investigating DSA mechanism in real systems. Radio-frequency observations can give the morphology information of the SNR, the shocks' orientation, the magnetic field strength and polarization, and the energy spectrum of energetic electrons by their synchrotron emission [23,24]. The optical observation can offer information on the acceleration of ions through their emission spectrum [25]. The X-ray spectrum and gamma-ray spectrum might give information on energetic electrons' synchrotron emission [26] or other emission mechanism [27,28].

However, there are some limitations on observational approach when studying the DSA process. The first limitation is obvious – we don't have control of the astronomical objects. These researches are destined to be case-by-case investigation. Although continuous observation might give a track of how physics changes with the evolution of the system, a control of the parameters is not handy. Second, the large distance between observer and the target not only makes the object small in view but also requires observation to take long time to accumulate. That is to say, when studying the fluctuations of physical quantities, observational data might have poor temporal and spatial resolution. Therefore, it's also hard to study the correlation of fluctuations. Third, no matter it's radio frequency, optical or X-ray, observational data can only detect the photon emitted from the target. It's not easy or sometimes impossible to reconstruct the physical environment of the system just from these emitted photons. Last, local measurement is hard to achieve in observations since data are integrated along the line of sight.

Due to these limitations of the observational science, investigation of DSA mechanism needs a new approach to test the physics models or simulation results. The recent breakthrough in reproducing astronomy-relevant collisionless shock waves in laboratory devices might give an answer [7,28,29]. Among these devices, LAPD offers a magnetized plasma environment, and has high reproducibility and controllability of plasma parameters. In the following part, I will take it as an example to illustrate what these devices can offer, what experiments can be planned and what the limitations on them are.

D. LAPD for investigating DSA

1. Current progress

In the first observation of a magnetosonic collisionless shock wave in LAPD [7], the background hydrogen plasma of $n_i = 1.5 \times 10^{19} m^{-3}$ was generated by electron emitters under magnetic field of 300 G. A solid C_2H_4 target is then shot by a 25 ns laser pulse of 200 J at 1053 nm. The exploding plasma cloud generates a structure clearly shown in the magnetic field fluctuation strength measured by a B-dot probe. It propagates along the perpendicular direction, forming a shock wave when $x = 35 - 40$ cm and dissipated in $x > 40$ cm. The generated shock wave is collisionless ($\lambda_{mfp}/L = 20$), supercritical ($M_A = 2.2$) and magnetized ($L/\rho_a = 176$). A parallel shock wave is planned to be generated in the future [30].

2. Experiments that can be planned

The highly reproducible magnetized plasma in LAPD offers a good environment to compensate the limitations of observational researches in DSA mechanism. The controllability of the background plasma parameters offers the possibility of systematically studying key physical quantities' influence on the mechanism. The fluctuations and their temporal or spatial correlation can be studied by e.g. inserting probes into the plasma. The accessible measurements are not limited to the observation of photons, making it much easier to measure relevant physical quantities such as magnetic fluctuations directly. The probe technology or advanced laser diagnostics also allowed local measurements. In the following, I propose some experiments that can be planned on the device to further understand the mechanism of DSA.

(1) Magnetic field measurement

As illustrated, the magnetic field amplification is an important mechanism in the concept of DSA. The local measurement and the ability to resolve temporal change of magnetic field enable a detail investigation of how the magnetic field gets amplified. For instance, the B-dot probe uses loops of wires to collect the current inductively generated by the magnetic fluctuations. It gives temporal and spatial resolution of the field fluctuations. If an array of these probe is placed, we can monitor the pattern of magnetic field fluctuations around the shock waves.

(2) Velocity space measurement

The question of how particles get accelerated by a shock can be better answered by the investigation of how the distribution function changes across the shock. Although 3D distribution function measurement is still challenging in laboratory plasmas, we still have some tools to study at least the energy distribution. The retarding potential analyzer can be used to find the distribution function of electrons [31,32] and ions [33-37] locally. The ultra-compact plasma spectrometer (UCPS) [38] can offer a non-invasive approach of measuring the particle distribution. The laser-induced fluorescence (LIF) is a non-invasive tool but can measure the local distribution function of certain species of ions [39-49]. Although the most astronomical-relevant gas, hydrogen, cannot be measured by LIF, the influence of ion mass might be investigated by changing the ions to the other species such as argon. These diagnostic tools will be useful to study the issue of a power-law spectrum of particle momentum deviating from the $q \sim -2$ power [13]. Moreover, the advancing technology in diagnostics can be applied to laboratories in the future.

(3) Particle injection

In plasma experiments nowadays, introducing different species of ions into a background plasma is a common approach for investigating physics. The gas puffed into plasma, if not disturbing the original plasma too much, can act as test particles to address the fundamental physics. Besides, ion or neutral beams injected into the plasma can provide a population of particles homogeneous in the velocity space. By introducing different species or energies of ions into an existing background plasma, we might be able to understand the DSA mechanism better.

(4) Parameter scan

Perhaps one of the most powerful feature of laboratory experiments is the ability of controlling the operational parameters. In a carefully designed series of experiment, we might even be able to scan a certain plasma parameter while fixing the others.

For studying the DSA process, background magnetic field strength B_0 is an important parameter. It not only changes the Alfven velocity $V_A = B_0/\sqrt{4\pi\rho}$ and thus the Alfvenic Mach number, but also can possibly change the fluctuation level $\delta B/B_0$, which is a key quantity in DSA concept. On the other hand, by changing the species of the background plasma or introducing different species of gases into a plasma, we might be able to study the ion mass influence on DSA mechanism. The pulsed laser's energy is also an important parameter since it can change the strength of the shock wave. The angle between the shock normal and the background field is also a crucial parameter in determining the dominant physics. Besides these, the parameter scan of plasma density, electron or ion temperature, or even changing the magnetic field configuration to a non-homogeneous one can all quantitatively test the theoretical model of DSA.

(5) Reconstruction of environment by modelling technology

In addition to all the possible experiments proposed above, it is also important to reconstruct the details of experimental environment by modelling technology. It's the same concept as how people reconstruct the environment in astronomical objects via observational data. By these reconstructions, we might be able to study even further details of each experiment.

3. Limitations of laboratory experiments

Despite many advantages of the laboratory experiments, it is also worth mentioning the limitation of experiments. Some of them might be overcome, while the others are the intrinsic limitations of experiments.

(1) Different parameter ranges with astronomical objects

Not all the plasma generated in laboratory is relevant to the target astronomical system. Particularly, the system such as SNRs can emit huge amount of energy, thus forming a very strong shock wave. In contrast, the energy of a shock wave in laboratory is normally constrained by, e.g. the pulsed laser energy that can be achieved. Besides, the magnetic field strength (∼μG) in astronomical objects are often much lower than the field in the laboratories (~100 G). Therefore, the analogy between target systems and laboratory plasmas needs careful comparison by the scaling rules. For example, the key dimensionless parameters such as the magnetic Reynolds number (R_m), the Alfvenic Mach number (M_A), etc, should be matched.

(2) Small length scale

Compared with the length scale of astronomical systems, the total span of the experimental devices is normally limited. This means that the evolution of the shock wave might be terminated by the system itself rather than the relevant physical mechanisms. Another problem of the small length scale is that the spatial structure might be hard to resolved by diagnostics tools with finite length, such as probes.

(3) Limited measurement locations

Another limitation from the instrument is the limited location of the diagnostics. In astronomical system, photons from the whole system can be accumulated. However, due to the mechanical support, vacuum sealing and pumping demand, the available location for diagnostics are comparably few in laboratory devices. This may lead to a poor spatial resolution of the data in some sense.

(4) Invasive diagnostics

Perhaps this is the most important issue of the laboratory experiments. Probes inserted into the plasma, such as Langmuir probes, B-dot probes, Mach probes, etc., can disturb the plasma itself and lead to misinterpretation of the measured data. This problem is especially serious when trying to collect data from a low-density plasma. However, invasive approach is often more convenient and sometimes inevitable to be used in experiments. Therefore, consistency check between invasive and non-invasive diagnostics, the reduction of probe sizes and the estimation of resulting data before each measurement should be taken care of. Of course, the improvement of diagnostic technology is perhaps the most essential way to solve this problem.

E. Conclusion

In this report, I discuss how laboratory plasma experiments in LAPD might benefit the study of DSA mechanism. Advantages and limitations of this approach, and concepts of suggested experiments are mentioned. I believe that in the upcoming future, utilization of laboratory experiments would be a light-shedding and indispensable part of these researches.

F. References

[1] C. Kennel, J. Edmiston, and T. Hada, Collisionless shocks in the heliosphere: A tutorial review **34**, 1 (1985).

[2] L. Romagnani *et al.*, Physical review letters **101**, 025004 (2008).

[3] Y. Kuramitsu *et al.*, Physical review letters **106**, 175002 (2011).

[4] D. Haberberger, S. Tochitsky, F. Fiuza, C. Gong, R. A. Fonseca, L. O. Silva, W. B. Mori, and C. Joshi, Nature Physics **8**, 95 (2012).

[5] H.-S. Park *et al.*, Physics of Plasmas **22**, 056311 (2015).

[6] T. Morita *et al.*, Physics of Plasmas **17**, 122702 (2010).

[7] C. Niemann *et al.*, Geophysical Research Letters **41**, 7413 (2014).

[8] L. O. C. Drury, Reports on Progress in Physics **46**, 973 (1983).

[9] J. Jokipii, The Astrophysical Journal **313**, 842 (1987).

[10] E. Berezhko and D. C. Ellison, The Astrophysical Journal **526**, 385 (1999).

[11] A. Bell, Monthly Notices of the Royal Astronomical Society **353**, 550 (2004).

[12] A. Hillas, Journal of Physics G: Nuclear and Particle Physics **31**, R95 (2005).

[13] K. Schure, A. Bell, L. C. Drury, and A. Bykov, Space science reviews **173**, 491 (2012).

[14] B. Lembège, Y. Ma, and X. Deng, in *AGU Fall Meeting Abstracts*2010).

[15] A. Marcowith *et al.*, Reports on Progress in Physics **79**, 046901 (2016).

[16] W. Baade and F. Zwicky, Proceedings of the National Academy of Sciences **20**, 259 (1934).

[17] D. Caprioli and C. C. Haggerty, arXiv preprint arXiv:1909.06288 (2019).

[18] K. Schure and A. Bell, Monthly Notices of the Royal Astronomical Society **418**, 782 (2011).

[19] A. Bykov, S. Osipov, and D. Ellison, Monthly Notices of the Royal Astronomical Society **410**, 39 (2011).

[20] B. Reville and A. Bell, Monthly Notices of the Royal Astronomical Society **419**, 2433 (2012).

[21] A. M. Bykov, D. C. Ellison, and M. Renaud, Space science reviews **166**, 71 (2012).

[22] L. O. C. Drury and S. Falle, Monthly Notices of the Royal Astronomical Society **223**, 353 (1986).

[23] S. P. Reynolds, Annu. Rev. Astron. Astrophys. **46**, 89 (2008).

[24] G. Dubner, arXiv preprint arXiv:1111.1702 (2011).

[25] K. Heng, Publications of the Astronomical Society of Australia **27**, 23 (2010).

[26] S. Reynolds and R. Chevalier, The Astrophysical Journal **245**, 912 (1981).

[27] S. Gabici and F. A. Aharonian, Monthly Notices of the Royal Astronomical Society: Letters **445**, L70 (2014).

[28] A. Marcowith and F. Casse, Astronomy & Astrophysics **515**, A90 (2010).

[29] D. Yuan *et al.*, High Power Laser Science and Engineering **6** (2018).

[30] M. Weidl, P. Heuer, D. Schaeffer, R. Dorst, D. Winske, C. Constantin, and C. Niemann, in *Journal of*

Physics: Conference Series (IOP Publishing, 2017), p. 012020.
[31] J. E. Henderson and R. Dahlstrom, Physical Review **55**, 473 (1939).
[32] R. D. Young and E. W. Müller, Physical Review **113**, 115 (1959).
[33] G. Conway, A. Perry, and R. Boswell, Plasma Sources Science and Technology **7**, 337 (1998).
[34] D. Rudakov, M. Shats, R. Boswell, C. Charles, and J. Howard, Review of scientific instruments **70**, 476 (1999).
[35] C. Charles, R. Boswell, and R. Porteous, Journal of Vacuum Science & Technology A: Vacuum, Surfaces, and Films **10**, 398 (1992).
[36] C. Charles, Journal of Vacuum Science & Technology A: Vacuum, Surfaces, and Films **11**, 157 (1993).
[37] C. Charles, A. Degeling, T. Sheridan, J. Harris, M. Lieberman, and R. Boswell, Physics of Plasmas **7**, 5232 (2000).
[38] E. Scime, A. Keesee, M. Dugas, S. Ellison, J. Tersteeg, G. Wagner, A. Barrie, A. Rager, and D. Elliott, Review of Scientific Instruments **87**, 11D302 (2016).
[39] F. Skiff, F. Anderegg, and M. Tran, Physical review letters **58**, 1430 (1987).
[40] M. Sarfaty, S. De Souza-Machado, and F. Skiff, Physics of Plasmas **3**, 4316 (1996).
[41] E. E. Scime, P. A. Keiter, M. W. Zintl, M. M. Balkey, J. L. Kline, and M. E. Koepke, Plasma Sources Science and Technology **7**, 186 (1998).
[42] R. Boivin and E. Scime, Review of scientific instruments **74**, 4352 (2003).
[43] A. M. Keesee, E. E. Scime, and R. F. Boivin, Review of scientific instruments **75**, 4091 (2004).
[44] C. Biloiu, X. Sun, E. Choueiri, F. Doss, E. Scime, J. Heard, R. Spektor, and D. Ventura, Plasma Sources Science and Technology **14**, 766 (2005).
[45] E. Scime, C. Biloiu, C. Compton, F. Doss, D. Venture, J. Heard, E. Choueiri, and R. Spektor, Review of scientific instruments **76**, 026107 (2005).
[46] I. A. Biloiu, X. Sun, and E. E. Scime, Review of scientific instruments **77**, 10F301 (2006).
[47] I. Ü. Uzun-Kaymak and F. Skiff, Physics of plasmas **13**, 112108 (2006).
[48] S. Mattingly, J. Berumen, F. Chu, R. Hood, and F. Skiff, Journal of Instrumentation **8**, C11015 (2013).
[49] D. S. Thompson, M. F. Henriquez, E. E. Scime, and T. N. Good, Review of Scientific Instruments **88**, 103506 (2017).