PERSPECTIVES

PLASMA PHYSICS

Understanding particle acceleration in astrophysical plasmas

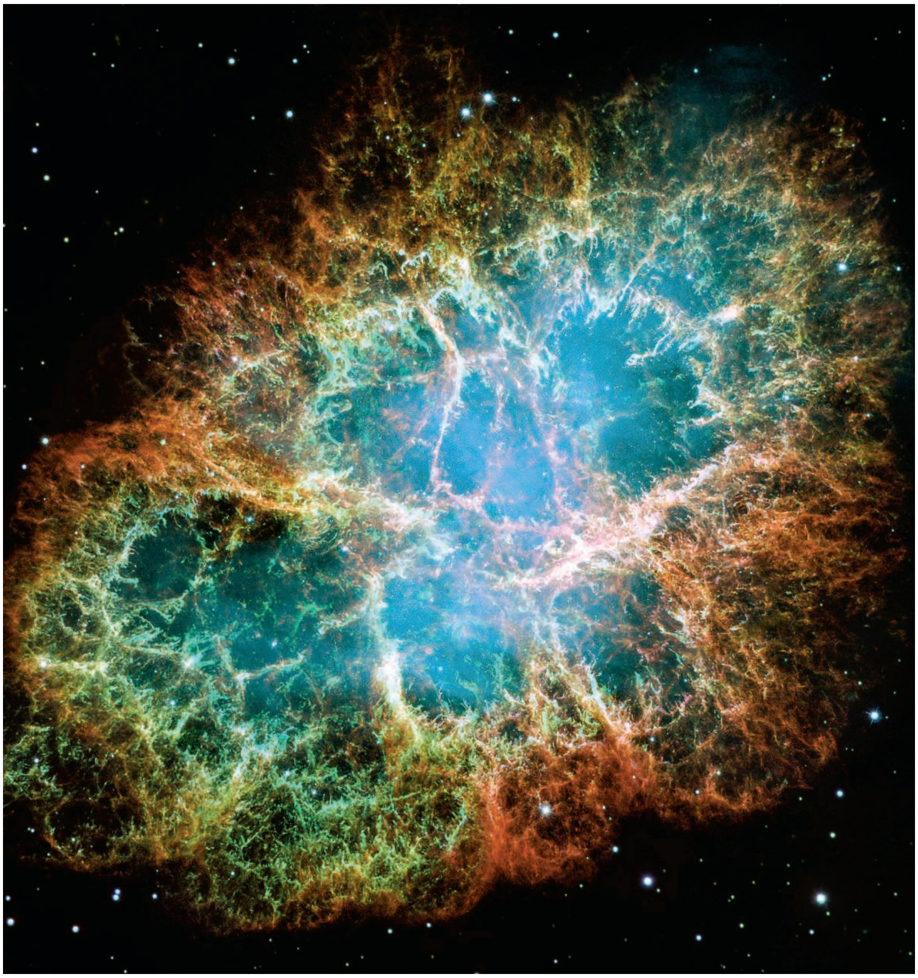
Simulations reveal new scenarios to accelerate electrons to extremely high energies

By **Hantao Ji**[1,2] *and* **Ellen Zweibel**[3]

Energetic electrons are ubiquitous in astrophysical plasmas, as they are considered to be behind the surges of emission across the electromagnetic spectrum at wavelengths from radio to gamma rays. These dynamic phenomena include stellar flares, supernova explosions (see the figure) (*1*), gamma ray bursts, and extragalactic jets. Energetic electrons are also directly observed in situ during terrestrial substorms. Despite these rich observations and substantial progress in theory, numerical simulations, and laboratory experiments over the past few decades, however, the mechanisms by which the electrons obtain their energy still remain elusive. On page 974 of this issue, Matsumoto *et al.* (*2*) make progress toward resolving these issues.

Shocks are an attractive venue for particle acceleration at the expense of energy from supersonic flows. Although the primary energy release sites are often relatively small (a thin electric current sheet for a stellar flare, a collapsing stellar core for a supernova), the shocks they drive have a large geometrical cross section, allowing many more particles to tap that energy. And whereas shocks in dense, homogeneous fluids are thin, laminar structures mediated by viscosity, high-velocity shocks in plasmas are known to spawn a complex array of plasma waves and insta-

[1]Department of Astrophysical Sciences and Princeton Plasma Physics Laboratory, Princeton University, Princeton, NJ 08544, USA. [2]Laboratory for Space Environment and Physical Sciences, Harbin Institute of Technology, Harbin, Heilongjiang 150001, P.R. China. [3]Departments of Astronomy and Physics, University of Wisconsin, Madison, WI 53706, USA. E-mail: hji@princeton.edu



A cosmic accelerator. The Crab Nebula as a remnant of a supernova explosion exhibiting a dramatic example of synchrotron emission from energetic electrons, shown in bluish glow. Powerful gamma ray flares have been observed during which electrons are accelerated to the PeV energy range. Blue in the filaments in the outer part of the nebula represents neutral oxygen, green is singly ionized sulfur, and red indicates doubly ionized oxygen. Orange filaments are remains of the star and consist mostly of hydrogen. Size of image is about 6 light-years.

PHOTO: NASA, ESA, AND J. HESTER/ARIZONA STATE UNIVERSITY bilities that thermalize flow energy within a broad and turbulent transition layer (*3*). Inhomogeneities in the upstream fluid only exacerbate the turbulence generation process. In the best-known shock acceleration scenario, diffusive shock acceleration (DSA), ions become trapped within this layer and are energized by the overall converging shock flow through a so-called first-order Fermi process. DSA operating in young supernova remnants may be the source of galactic cosmic rays (*4*).

But DSA is thought not to work as well for electrons. To reach both sides of the converging shock flow separated by ion scales would require a large initial threshold energy. Various mechanisms based on resonant electromagnetic waves to accelerate electrons to the threshold energy have been proposed, but whether these waves are sufficiently coherent for efficient acceleration in a turbulent shock remains unresolved.

> *"efficient electron acceleration is accomplished by combining two different mechanisms ..."*

Alternatively, charged particles can be accelerated by magnetic reconnection, during which magnetic energy is rapidly released through the rearrangement of field lines (*5*, *6*). Highly dynamic structures such as outflow jets and contracting islands during the development of turbulent multiscale reconnecting current sheets can energize electrons efficiently [e.g., (*7*, *8*)]. Some models (*9*) have been proposed to accelerate electrons through reconnection in attempts to explain the recently observed gamma ray flares from the Crab Nebula (*10*, *11*). Unlike shocks, however, specific astrophysical scenarios for the realization of such turbulent reconnection with multiple temporospatial scales still remain to be developed.

In the scenario proposed by Matsumoto *et al.*, multiscale turbulent reconnection is realized in a shock propagating into a uniform medium with a weak magnetic field parallel to the plane of the shock. The background ions, reflecting from the shock, form a beam that propagates upstream and excites the electromagnetic Weibel instability (*12*). As the Weibel modes grow to nonlinear amplitude, they draw out the upstream magnetic field into thin, hairpin-like structures with oppositely directed field lines in close proximity. This magnetic field reconnects, producing structures with multiple scales. Electrons that encounter these structures are rapidly energized, producing a high-energy tail in the initial electron distribution. It is estimated that 1% of the flow energy can be transferred to a relativistic electron population this way. Thus, efficient electron acceleration is accomplished by combining two different mechanisms (turbulent shock and turbulent reconnection) into one united, self-consistent mechanism (a shock undergoing turbulent reconnection) through a chain that transforms flow energy to electromagnetic energy and then to particle energy. Because energization occurs in multiple small structures, the fraction of particles that are boosted to high energies is larger than in the case where the primary energy release mechanisms are localized in a single site, but energization is far from ubiquitous. Thus, this is a true acceleration process rather than a bulk heating process, in the sense that only a small fraction of particles are energized.

Many questions remain and are sure to be topics for future work. The simulations achieve a high numerical resolution and a fairly high ion-to-electron mass ratio at the cost of two-dimensionality; the turbulence could appear quite different in three dimensions. Whether ions are accelerated as well remains unclear, and an accurate assessment would require a large simulation domain. The reconnection sites and the electromagnetic fields within them are not well resolved. Scaling studies are not reported. All of these problems could be addressed by more and larger simulations, which should be a high priority given the promise of these initial results. Finally, laboratory plasma experiments could be used to test some of these key ideas, either in flow-dominated regimes in focusing on turbulent collisionless shocks (*13*, *14*) or in magnetically dominated regimes focusing on turbulent reconnection, as will be feasible in the soon-to-be-deployed FLARE (Facility for Laboratory Reconnection Experiments) (*15*) at Princeton and the planned Space Physics Research Facility as part of the Space Environment Simulation and Research Infrastructure at Harbin, China. ■

REFERENCES

1. J. Hester, *Annu. Rev. Astron. Astrophys.* **46**, 127 (2008).
2. Y. Matsumoto *et al.*, *Science* **347**, 974 (2015).
3. R. A. Treumann, *Astron. Astrophys. Rev.* **17**, 409 (2009).
4. R. Blandford, D. Eichler, *Phys. Rep.* **154**, 1 (1987).
5. E. Zweibel, M. Yamada, *Annu. Rev. Astron. Astrophys.* **47**, 291 (2009).
6. M. Yamada *et al.*, *Rev. Mod. Phys.* **82**, 603 (2010).
7. J. F. Drake *et al.*, *Nature* **443**, 553 (2006).
8. M. Hoshino, *Phys. Rev. Lett.* **108**, 135003 (2012).
9. D. Uzdensky *et al.*, *Astrophys. J.* **737**, L40 (2011).
10. M. Tavani *et al.*, *Science* **331**, 736 (2011).
11. A. A. Abdo *et al.*, *Science* **331**, 739 (2011).
12. E. S. Weibel, *Phys. Rev. Lett.* **2**, 83 (1959).
13. W. Fox *et al.*, *Phys. Rev. Lett.* **111**, 225002 (2013).
14. C. Huntington *et al.*, *Nat. Phys.* **11**, 173 (2015).
15. H. Ji, W. Daughton, *Phys. Plasmas* **18**, 111207 (2011).

10.1126/science.aaa6113

ANTHROPOLOGY

How wheat came to Britain

Wheat reached Britain from the Near East at least 2000 years before the arrival of wheat farming

By **Greger Larson**

Settled communities dependent on agriculture and animal husbandry emerged independently on several continents over the past ~10,000 years. In many cases, farmers began to disperse out of regions where plants and animals were domesticated and into areas occupied by hunter-gatherer populations. This process of Neolithization certainly took place in Europe. Dating of artifacts and bones indisputably associated with human farming has led to a chronological framework for the spread of the Neolithic along two primary routes into Europe that ended with the arrival of farming in Britain ~6000 years ago (*1*). Yet, on page 998 of this issue, Smith *et al.* (*2*) report genomic sequences of wheat in an ~8000-year-old soil sample collected off the coast of southern England, suggesting that domestic crops first appeared on the British Isles long before they were cultivated there.

By ~10,500 years ago, farmers in ancient Anatolia possessed a full complement of domestic plants and animals, yet farmers only arrived in the Balkans between ~8000 and ~9000 years ago. From there, they spread west across the Mediterranean and north along the Danube, reaching western France and the central Rhineland by ~7500 years ago. The first evidence for cereal cultivation on what is now mainland Britain dates back only to ~6000 years ago, suggesting a substantial temporal gap between the two sides of the English Channel (*1*). Because rising sea levels created the English Channel in the early Holocene, it is possible that agricultural products arrived before their accepted appearance on mainland Britain, but that the evidence was flooded by the incoming sea.

A preserved ancient layer of soil had previously been identified at a site called Bouldnor Cliff that rests under marine sediments off the coast of the Isle of Wight (*3*).