Astro2020 Science White Paper

Particle Acceleration and Transport

New Perspectives from Radio, X-ray, and γ-Ray Observations

Thematic Areas: ☐ Planetary Systems ☐ Star and Planet Formation
☐ Formation and Evolution of Compact Objects ☐ Cosmology and Fundamental Physics
☑ Stars and Stellar Evolution ☐ Resolved Stellar Populations and their Environments
☐ Galaxy Evolution ☐ Multi-Messenger Astronomy and Astrophysics

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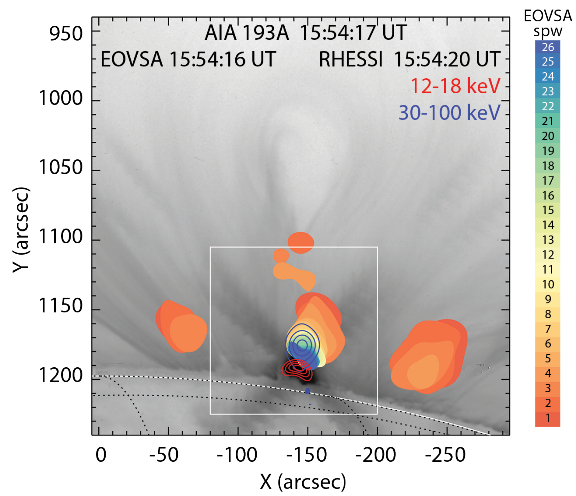

Figure 1: EOVSA radio contours at 28 frequencies (color), and RHESSI HXR contours (red and blue lines) at two energies, on EUV image (grayscale) of 2017 Sep 10 off-limb solar flare[1].

Executive Summary: Particle acceleration and particle transport are ubiquitous in astrophysics. The Sun offers an astrophysical laboratory to study these and other fundamental processes in minute detail. The physical context on the Sun involves solar flares and coronal mass ejections (CMEs). These complex coupled phenomena require comprehensive and complementary observations to disentangle the relevant physical mechanisms at work. Radio observations are emphasized here because they are positioned to make unique and innovative contributions to these important problems, especially in the current era when hard X-ray and gamma-ray spectral imaging capability is lacking. In particular, the transformative technique of ultra-broadband radio imaging spectroscopy is discussed, which serves as the observational basis for new insights into particle acceleration and transport. These include the dynamic measurement of coronal magnetic fields, the measurement of the spatiotemporal evolution of the electron distribution function, and the observation of flares and CMEs as coupled systems.

Introduction

Particle acceleration and particle transport are fundamental astrophysical processes that occur throughout the universe. Energetic electrons and ions are observed indirectly via the electromagnetic radiation they produce and are therefore accessible to study through remote sensing. They are produced in astrophysical contexts as diverse as planetary magnetospheres, stellar atmospheres and winds, accretion disks, supernovae and their remnants, and the lobes of extragalactic radio sources. A detailed understanding of particle acceleration and transport bears on issues ranging from astronaut safety to insights into the most energetic phenomena in our universe.

By virtue of its proximity, the Sun offers an astrophysical laboratory in which fundamental astrophysical processes can be studied in considerably greater detail than is possible for those occurring in remote environments. It therefore serves as an important touchstone against which our understanding of these processes is referenced. The Sun is an efficient particle accelerator: it can release several tenths of the available energy (stored in stressed magnetic fields) in high-energy nonthermal particles and it can promptly accelerate electrons to energies in excess of 100 MeV and ions to energies $\sim$1 GeV/nuc. It does so by a variety of mechanisms occurring in active regions, plasma jets, solar flares down to the nanoflare level, coronal mass ejections, and associated shocks.

Energetic particles on the Sun emit radiation primarily at X-ray, gamma-ray, and radio wavelengths. Soft X-ray (SXR) emission arises from thermal plasma heated to $\sim$20 MK during flares. Hard X-ray (HXR) emission typically arises from nonthermal bremsstrahlung resulting from electrons with energies of $\sim$10 keV to a few $\times$ 100 keV interacting with dense chromospheric material. Continuum gamma-ray emission (E$>$ few $\times$ 100 keV) arises from electron-proton and electron-electron bremsstrahlung and pion decay, and gamma-ray lines are caused by electron-positron annihilation, neutron capture, and nuclear excitation. Radio waves are emitted by hot thermal plasma via thermal bremsstrahlung. Suprathermal electrons (few to $\sim$20 keV) may radiate coherently at radio wavelengths as a result of plasma instabilities. Energetic electrons (10s of keV to many MeV) emit nonthermal gyrosynchrotron radiation. Together, X-ray, gamma-ray, and radio observations provide a powerful and complementary suite of perspectives from which to study particle acceleration.

This white paper emphasizes new opportunities available for studying particle acceleration and transport using a new observational capability now available—radio spectral imaging observations of the Sun. In constrast to radiation mechanisms at X-ray and gamma-ray wavelengths, radio radiation mechanisms are uniquely sensitive to magnetic fields and, moreover, can have a strong dependence on anisotropies in the electron distribution function. Furthermore, solar radio observations can be performed using ground-based instrumentation, which is within the purview of this decadal survey. Radio spectral imaging observations therefore represent both a powerful and cost-effective means of studying fundamental aspects of particle acceleration on the Sun. This is especially needed in the upcoming decade when opportunities for spectral imaging in higher-energy HXRs and gamma rays will be severely limited.

Below we list separately the main acceleration and transport mechanisms but note that the evolving understanding of solar flares [2, 3] suggests that the two are not easily separated. Particle acceleration likely occurs in multiple regions of a given flare, and transport processes may create the turbulent conditions required for further particle acceleration. Quoting A. Benz [2], “The interplay of observations with theory is important to deduce the geometry and disentangle the various processes involved…and every new observation still reveals major unexpected results." This is especially pertinent to the fundamentally new capabilities in radio spectral imaging observations.

Acceleration Mechanisms

The two most prominent types of energetic phenomena on the Sun that accelerate electrons and ions to high energies are solar flares and CMEs although low-level particle acceleration occurs more or less continuously in the Sun's corona [4, 5]. It is widely believed that solar flares are powered by magnetic reconnection (see white paper by **Chen *et al.***) and that the bulk of the released energy is deposited in nonthermal electrons although for some events the ions can also contain comparable amounts of energy [6, 7]. CMEs commonly result from the destabilization of a magnetic flux rope and its ejection from the Sun. Fast CMEs drive a shock far into the interplanetary medium (IPM). Several broad classes of particle acceleration mechanism may be relevant to flares and CMEs [2, 8, 9].

Quasi-static electric fields

Relatively large-scale field aligned quasi-static DC electric fields may arise during the magnetic reconnection process in analogy to those observed in the Earth's auroral zone during magnetic substorms, although radio and X-ray observations suggest that magnetic reconnection is a more fragmentary process [10], and recent particle-in-cell (PIC) simulations suggest a turbulent-like reconnection [11] process where parallel electric fields are not a main cause of electron acceleration [12]. Super-Dreicer electric fields of several V cm^{-1}, which can accelerate both electrons and ions to the required energies in a relatively short distance, are inferred from measurements of overall reconnection rate [13]. The shortest, subsecond episodes of particle acceleration inescapably require a super-Dreicer electric field acceleration. Recent observations, however, do not place particle acceleration in the vicinity of the current sheet. Alternatively, sub-Dreicer fields may also play a role in plasma heating and electron acceleration [4]. Finally, weak electrostatic double layers [14] distributed along the magnetic field may accelerate particles to significant energies.

Stochastic acceleration

Stochastic acceleration is a second-order Fermi process that involves particles scattering from waves, resulting in the diffusion of particles in energy and pitch angle [8, 14]. Typically, a broadband turbulent spectrum of waves (e.g., whistler waves or fast mode MHD waves) with which the particles can resonantly interact is assumed, although interaction with randomly distributed current sheets or magnetic islands can do a similar job. A non-resonant stochastic acceleration is also possible. Stochastic processes can yield plasma heating and/or particle acceleration. An injection or "seed" spectrum of particles is not necessarily required [15]. The spectral and angular distribution of the resulting electrons and ions depends on the details of the magnetic field, background plasma, the turbulent wave spectrum and its intensity.

Shocks

Shocks are produced in the Sun's corona and in the interplanetary medium. They are observed indirectly via coronal and interplanetary (IP) type II radio bursts [16, 17, 18]. However, recent radio spectral imaging observations provide evidence of a fast-mode termination shock associated with magnetic reconnection that can accelerate electrons [19]. IP shocks are observed directly through *in situ* measurements of particles and fields in space, e.g. [20]. Both shock drift acceleration and diffusive shock acceleration are likely relevant.

Particle Transport

Energetic particles are highly mobile. Yet a variety of factors affect their transport and, as a consequence, the transport of energy within and from the environment in which they are accelerated.

Magnetic trapping

The bulk of energetic particles accelerated in a flare remain at the Sun, although recent radio observations [21, 1] show that the sites of emission are far more extended than known from HXR imaging, and include outward-going particles [22, 23]. Those that remain at the Sun are constrained by closed coronal magnetic loops. Particles with sufficiently large pitch angles mirror and remain trapped in the coronal loop for a time; those with small pitch angles "precipitate" from the loop and collide with dense material near the foot points of the loop where they liberate their energy. Trapped particles suffer Coulomb collisions with the ambient plasma and eventually scatter to small pitch angles (weak diffusion) at which point they, too, are lost from the trap. This so-called "trap plus precipitation" model [24] and its variants [25, 26] have been quite successful in accounting for the observed distribution of radio and X-ray emission from flaring loops and their evolution in time.

Wave-particle interactions

Stochastic acceleration may also play an important role in particle transport. The magnetic reconnection process and turbulent outflow may drive a turbulent cascade [27]. Alternatively, or in addition, beamed distributions of particles are unstable to the production of plasma waves. Wave-particle interactions subsequently cause particles to diffuse in momentum and pitch angle (intermediate or strong diffusion). Consequently, scattering on turbulence may strongly affect the transport of fast particles, possibly confining them. Indeed, acceleration and transport are closely intertwined in these circumstances [15, 28].

Energy transport and loss

Most nonthermal electrons eventually lose their energy to Coulomb collisions with the relatively cool chromospheric plasma. Since only a small fraction of the energy is emitted as nonthermal HXR radiation ($\sim 10^{-5}$), most of the energy in nonthermal electrons goes toward plasma heating. The chromospheric plasma responds dynamically, a process given the misnomer "chromospheric evaporation," which fills the magnetic loops with hot plasma (∼10–20 MK) that emits copious thermal SXR and EUV radiation [2]. Therefore, a significant fraction of the energy going into accelerated particles in flares is ultimately radiated away although thermal conduction and mass motions are also important components of the energy budget [6]. A fraction of flare-accelerated electrons and ions escape into the interplanetary medium. Other populations of electrons and ions are accelerated to high energies by a shock driven by CME that is associated with the flare.

The problem of magnetic energy release, particle acceleration, and energy transport in flares and CMEs involves a complex coupled system. Progress in understanding this coupled system requires imaging observations of each of its constituent parts over a broad wavelength range.

Outstanding Questions

There are a number of fundamental questions regarding particle acceleration on the Sun. The two most fundamental questions are:

1. Under what circumstances do various acceleration mechanisms trigger and operate?
2. How do accelerated particles propagate and interact with their environment over their lifetimes?

To answer these requires understanding the following subsidiary questions in detail:

- Where precisely does magnetic energy release occur? In some well-observed events the location of magnetic energy release through 3D magnetic reconnection is becoming clear, but the full range of possibilities is far from understood.
- Where precisely are electrons accelerated? The acceleration region seems not to be co-located with the reconnection site. HXR observational signatures are often relatively remote from the energy release and acceleration site, while radio imaging spectroscopy can fill this gap [1].
- What is the electron distribution function and what is its spatiotemporal evolution? The essential features of the electron distribution have been well established through HXR, gamma-ray, and radio spectroscopy, but only recently have spatially resolved observations begun to show how it varies in space and time [1, 29, 30].
- With what efficiency is magnetic energy converted into nonthermal electrons? Magnetic energy release leads to plasma heating, electron and ion acceleration, and mass motions. The energy budget needs to be refined and reassessed.
- What physical processes affect the transport of energetic electrons? Under what circumstances? It is necessary to disentangle transport effects from the observed spatiotemporal evolution of the electron distribution function in order to constrain acceleration mechanisms and to understand the energy budget and energy transport fully.

Required Observations

To answer these questions, new observations are required from a variety of radio, X-ray, and gamma-ray instruments.

Radio: A breakthrough in radio observations was recently achieved by the *Expanded Owens Valley Solar Array* (EOVSA), which is revolutionizing our view of particle acceleration and transport [1]. This solar-dedicated, 13-antenna array covers the 1-18 GHz frequency range with frequency resolution of order 1%, providing spectroscopic imaging sufficient to exploit the diagnostic potential of spatially-resolved microwave spectra [31]. EOVSA has validated the innovative and unique techniques enabled by broadband radio imaging spectropolarimetry. It sets the stage for a much larger and more capable instrument for the investigation of particle acceleration and transport, the *Frequency Agile Solar Radiotelescope* (FASR), which is urgently needed to fully capitalize on these techniques. We direct readers to white papers submitted by **Bastian *et al.***, **Fleishman *et al.***, and **Chen *et al.*** for additional science addressed by FASR.

Hard X-rays (HXRs): With the retirement of NASA's only solar-dedicated HXR imager, the RHESSI spacecraft, in 2018, there currently exists no dedicated imaging spectroscopy of the Sun. Astrophysical (non-solar) missions have supplemented and augmented RHESSI data and currently remain the only instruments available to measure HXRs from solar flare accelerated electrons. The Fermi spacecraft provides HXR spectra in a similar energy range as RHESSI did, albeit without imaging, and also added the observation of surprisingly high ion energies attained in solar eruptive events. On the other end of the flare scale, NuSTAR has made great strides in investigating the faintest solar flares ever observed in HXRs, by studying microflares in active regions [32, 33] and transient quiet Sun brightenings [34]. NuSTAR has also studied flares on young stellar objects [35], finding similarities with solar flares in the much larger energy releases generated by their strong magnetic fields. While investigation of solar flare particle acceleration has greatly benefited from the use of astrophysical HXR telescopes, these instruments are not optimized for bright solar fluxes and in some cases (e.g. NuSTAR) rarely observe the Sun. By about 2025, the STIX instrument on Solar Orbiter will again provide solar-dedicated HXR imaging capabilities, and will for the first time provide regular observation from non-Earth-view locations, though available observation time will be limited due to spacecraft and telemetry constraints. The next leap forward in studying the physics of flare particle acceleration is hoping to be the *Focusing Optics X-ray Solar Imager* (FOXSI) space-based telescope, which can achieve the sensitivity necessary to observe faint particle acceleration sites and the dynamic range necessary to maintain sensitivity even in the presence of bright flare footpoints. FOXSI has just completed a Phase A concept study for a NASA Heliophysics Small Explorer.

Gamma-rays: Solar flare gamma-ray lines provide one of the few diagnostics of flare-accelerated ions. They also provide information on ambient plasma properties (such as temperatures, densities and composition) deep in the flaring atmosphere. Solar flare gamma-ray continua are believed to be emitted by $\sim$MeV electrons from the same particle population and energies responsible for flare microwave emissions, while HXRs likely come from lower-energy ($\lesssim$100–300 keV) electrons of the same accelerated population. Radio emissions (in particular in the microwave range), hard X-rays, and gamma-rays are hence highly complementary to studying the flare-accelerated particles, particularly in light of the fact that they are magnetic field-weighted (nonthermal gyrosynchrotron) or density-weighted (bremsstrahlung X-rays & gamma-rays). With just a handful of gamma-ray flare observations, RHESSI has raised new, tantalizing questions: how can electron-associated and ion-associated flare footpoints be separated by more than 20000 km [36]? How can relativistic electrons dominate in the corona? Instruments such as the Gamma-Ray Imager/Polarimeter for Solar flares (GRIPS) high-altitude balloon payload seek to shed light on these questions, as well as gathering information on the accelerated particle angular distributions via polarization measurements. Non-solar, but still operating, platforms such as the Fermi Large Area Telescope (LAT) have observed gamma rays from ions accelerated up to at least several GeV. LAT has not only observed pion decay from accelerated ions in many large eruptive events (presumably from the CME shock front), but has located their emission to various regions of the Sun and corona [37], prompting heated debate about how particles gain access to these regions.

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