Particle Acceleration and Transport on the Sun

New Perspectives at Radio Wavelengths

An Astro2010 White Paper

Prepared by

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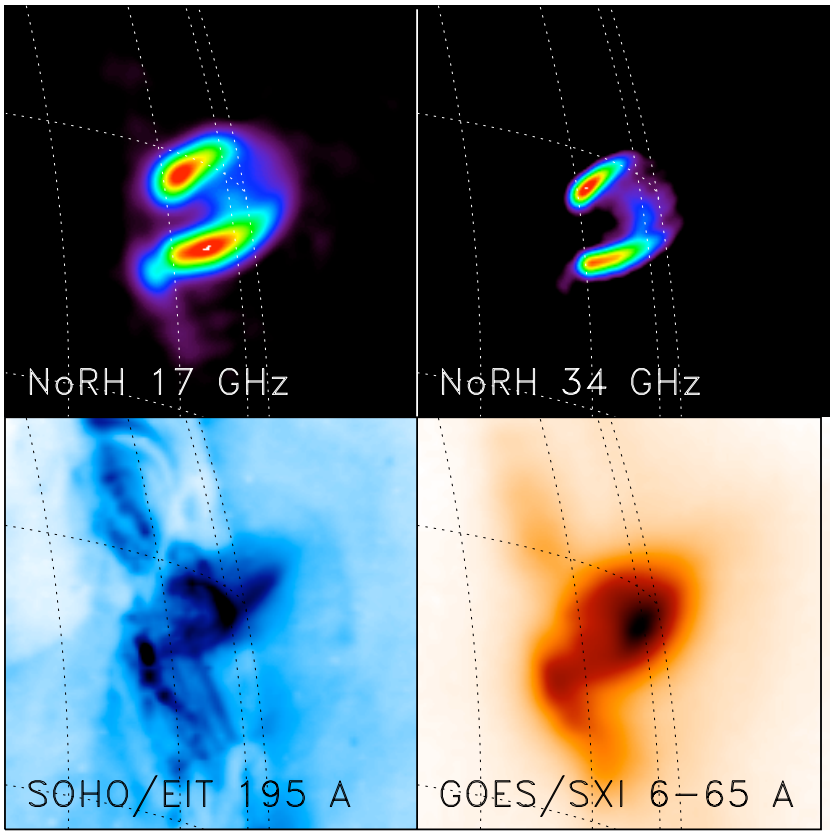

Executive Summary

Particle acceleration and particle transport are ubiquitous in astrophysics. The Sun offers an astrophysical laboratory to study these, and other fundamental processes in considerable 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. In particular, the transformative technique of *ultra-broadband imaging spectroscopy* is discussed, which serves as the observational basis for new insights into particle acceleration and transport. These include the 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 a variety of telescopes. 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 ~1 GeV/nuc. It does so in a variety of energetic phenomena – in active regions, plasma jets, solar flares, and CMEs – and by a variety of mechanisms.

Energetic particles on the Sun emit radiation at X-ray, gamma-ray, and radio wavelengths. Soft X-ray (SXR) emission arises from thermal plasma heated to ~20 MK during flares. Hard X-ray (HXR) emission typically arises from nonthermal bremsstrahlung resulting from electrons with energies of ~10 keV to a few x 100 keV interacting with dense chromospheric material. Continuum gamma-ray emission (E> few x 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 ~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 *radio* observations of the Sun. Unlike 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, and again unlike X-ray and gamma-ray observations, radio observations can be performed using ground-based instrumentation. Radio observations therefore represent both a powerful and cost effective means of studying fundamental aspects of particle acceleration on the Sun.

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[11]. It is widely believed that solar flares are powered by magnetic reconnection and that the bulk of the energy released is deposited in non-thermal electrons although for some events the ions can also contain comparable amounts of energy. CMEs 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[18,20].

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[12], although radio and X-ray observations suggest that magnetic reconnection is a more fragmentary process[14]. Super-Dreicer electric fields, which can accelerate both electrons and ions to the required energies in a relatively short distance, may be produced by mass advection into current sheets[13]. Alternatively, sub-Dreicer fields may also play a role in plasma heating and electron acceleration[10]. Finally, weak electrostatic double layers[18] 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[18,20]. A necessary ingredient is the presence of a broadband turbulent spectrum of waves (e.g., whistler waves or fast mode MHD waves) with which the particles can resonantly interact. Stochastic processes can yield plasma heating and/or particle acceleration. An injection or "seed" spectrum of particles is not necessarily required[20,21]. 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[21].

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[9]. IP shocks are observed directly by *in situ* measurements of particles and fields by space spaced instrumentation. Coronal shocks are driven by flare blast waves and ejecta. Fast mode standing shocks associated with flare magnetic reconnection may also be observed[3]. IP shocks are driven by fast CMEs[7]. 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 on the Sun. They are accelerated and injected into coronal magnetic loops. Those 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[17] and its variants[1,2] 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 play an important role in particle acceleration. The magnetic reconnection process may drive a turbulent cascade[19]. 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. 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[6,21].

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 (~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 (~20 MK), which emits copious thermal SXRs. Therefore, a significant

fraction of the energy going into accelerated particles in flares is ultimately radiated away in the SXR band although thermal conduction and mass motions are also important components of the energy budget. A small 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 observational access to each of its constituent parts.

Outstanding Questions

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

1. What acceleration mechanism or mechanisms are relevant?
2. Under what circumstances do they trigger and/or operate?

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

- Where precisely does magnetic energy release occur? To date, the location of magnetic energy release through 3D magnetic reconnection has in most cases been inferred indirectly or circumstantially, although tantalizing new HXR observation are emerging[x]. More direct signatures are urgently needed.
- Where precisely are electrons accelerated? The acceleration region may not be co-located with the magnetic energy release site. Moreover, observational signatures (e.g., HXR radiation) may be relatively remote from the energy release and acceleration site. Again, complementary and/or more direct signatures are needed.
- 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. Progress has also been made at HXR wavelengths in imaging spectroscopy[22]. However, understanding the detailed evolution of the electron distribution function has been hampered by a lack of adequate spatial and/or temporal resolution.
- 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.

New Insights at Radio Wavelengths

Radio observations are in a strong position[8] to make progress on each of these outstanding questions using a variety of innovative and unique techniques. We emphasize here the need to exploit such observations and techniques, which are highly complementary to studies at optical, UV, EUV/SXR, and HXR/gamma-ray wavelengths. In order fully exploit the diagnostic potential of radio emission from energetic electrons on the Sun the means to perform **ultra-broadband imaging spectroscopy** is urgently needed. The utility and impact of an instrument with this capability will be profound. The key attributes of such an instrument are as follows:

- Exceptionally broad frequency coverage provides access to the entire solar atmosphere from the mid-chromosphere to the upper corona, providing the means of observing the flare/CME phenomenon as a coupled system.

- The instrument will perform coronal magnetography; that is, it will use broadband frequency coverage to make quantitative measurements of the coronal magnetic field before, during, and after flares and CMEs, allowing quantitative measurements to be made of the magnetic fee energy available. See the white paper by White *et al.* on "Coronal Dark Energy".

- The location of nonthermal electrons will be established wherever and whenever they occur. Magnetic energy release is accompanied by multitudes of coherent radio bursts driven by suprathermal electron beams[5], possibly produced by the reconnection process. These will be imaged for the first time. Similarly, the locations of accelerated electrons will be observed via nonthermal gyrosynchrotron, as will their transport to remote locations. See the white paper by Gibson *et al.* on "Thresholds and Triggers".

- The polarized gyrosynchrotron spectrum of the nonthermal electrons will be observed in microwaves in every pixel with high time resolution. Forward fitting techniques will in many cases allow extraction of the electron distribution function, as well as the magnetic field, ambient density, and temperature[6].

- The associated erupting filament and fast CME will be observed at decimeter to meter wavelengths through thermal bremsstrahlung and nonthermal gyrosynchrotron emission. The physical properties of the CME, including its magnetic field and the distribution of entrained energetic electrons will be inferred[5,15]. The associated shock and locations of electron acceleration along the shock will be observed via the type II radio burst.

An instrument with these attributes has already been defined: the *Frequency Agile Solar Radiotelescope* (FASR). The concept is mature and it is ready for implementation. Briefly, FASR is an interferometric array of antennas that would image the Sun over a frequency range of 50 MHz (λ=6 m) to >20 GHz (λ<1.5 cm), thereby imaging the Sun in 3D from the mid-chromosphere well up into the corona. It would do so with an angular resolution as high as 1", a time resolution as high as 20 ms (for coherent bursts) or 1 s (flares), and a frequency resolution up to 0.1%. FASR will transform the study of magnetic energy release, particle acceleration, and transport as well as addressing key questions regarding the structure of the chromosphere and corona.

Broader Implications

A next-generation radioheliograph designed to perform dynamic, ultra-broadband, imaging spectroscopy will provide new traction on outstanding questions regarding magnetic energy release, particle acceleration, and particle transport. It will provide a view of these processes as a coupled system. These processes are ubiquitous in astrophysics, albeit on quite different scales. Active stars produce prodigious flares, but the underlying physics is believed to be similar to that operative on the Sun. Hence, insights gleaned from the Sun find direct application to stars. Similarly, flares in accretions disks share attributes with solar and stellar flares. Finally, the Sun offers unique opportunities to observe shocks and shock acceleration of particles, processes that are also widely relevant to late-type stars, protostars, stellar winds, supernova remnants, and in extragalactic jets.

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