Astro2020 Science White Paper
Advancing Understanding of Star-Planet Ecosystems in the Next Decade: The Radio Wavelength Perspective

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

Principal Author:
Rachel A. Osten
Institution: Space Telescope Science Institute & Johns Hopkins University
Email: osten@stsci.edu
Phone: 410-338-4762

Co-authors:
Tim Bastian (NRAO), Geoff Bower (ASIAA, Taiwan), Jan Forbrich (University of Hertsfordshire, UK), Manuel Güdel (Univ. Vienna), Melodie M. Kao (Arizona State University), Joseph Lazio (Jet Propulsion Laboratory, California Institute of Technology), Jeffrey Linsky (JILA, University of Colorado), Meredith MacGregor (Carnegie DTM), Sofia P. Moschou (Center for Astrophysics — Harvard & Smithsonian), J. Sebastian Pineda (LASP, University of Colorado), Michael P. Rupen (NRC, Canada), Jackie Villadsen (National Radio Astronomy Observatory), Stephen White (Air Force Research Laboratory), Peter K. G. Williams (Center for Astrophysics — Harvard & Smithsonian, American Astronomical Society), Scott J. Wolk (Center for Astrophysics — Harvard & Smithsonian)

Abstract : A star can influence its near environment through radiation and particles. Stellar flaring, associated coronal mass ejections, a steady stellar wind, and star-planet magnetospheric interactions are all important factors in the space weather environments of exoplanets. These also connect to important stellar astrophysics questions. The next decades will see a broadening of exoplanet science to encompass not just detection and atmospheric characterization, but the study of the stellar-planetary ecosystem and their variety. In this white paper we advocate for stellar radio observations as a way to advance understanding of stars in service of a better understanding of star-planet ecosystems. Specific key advances needed are sensitivity and access to a broader range of frequency space. Implicit in this is a robust funding model for US-based radio astronomy which would enable researchers to compete in the global marketplace of science.

The coming decade will see vigorous activities in exoplanet science. This includes an expansion of exoplanet science to encompass not only exoplanet detection and atmospheric characterization, but also study of star-planet ecosystems and how that affects planetary characteristics and evolution. Indeed, Chapter 6 of NASA's Astrobiology Strategy specifically called out the need for a firmer connection between stellar and planetary studies, asking

> *What are the properties of the host star that are conducive to or prevent the formation of a habitable world: age, size, and elemental composition of the star, its activity, and the properties of nearby stars?*

This importance was reaffirmed in the National Academies' Committee on the Astrobiology Science Strategy for the Search for Life in the Universe. Radio observations are the only method capable of directly constraining the particle environment created by the star. They also uniquely provide direct measurements of the magnetic field strength and electron density in the outer regions of a stellar atmosphere, and radio frequency observations can constrain stellar wind characteristics, in both the steady and non-steady forms. These measurements provide key insights into stellar astrophysics, necessary to inform a broader understanding of how stars influence their environment.

Fundamental Stellar Properties

The magnetic field strength of a star and its spatial distribution is a fundamental property that, for stars on the lower half of the main sequence, is produced as the result of a dynamo process. Kochukhov & Lavail (2017) found that stars with almost the same stellar ages, masses, radii, and rotation periods had different large-scale and local magnetic field topologies, with different amounts of X-ray and radio emission and variability. In contrast to other magnetic activity signatures, radio emission shows no saturation level for exceedingly active stars (Güdel & Gaidos 2001 [G dwarfs]; McLean et al. 2012 [M dwarfs]), making it a useful tool in diagnosing activity trends. The electron density in a stellar outer atmosphere, and its dependence on location and height above the visible stellar surface, are also important for understanding stellar structure. The ubiquity of nonthermal radio emission in the lower half of the main sequence also diversifies the types of magnetic activity available for studies. These studies have historically been *sensitivity limited*, in needing to reach μJy levels (or lower) to assess stellar radio emission from broad classes; this capability has only recently become available.

Coherent emission is produced in the radio spectrum of stars as a result of plasma physics processes. These processes break down naturally into observable emission that can directly constrain either the stellar electron density in the outer stellar atmosphere (by coupling the observing frequency to the plasma frequency, ν_p, $\propto \sqrt{n_e}$), or the magnetic field strength above the stellar surface (through observation of fundamental or harmonic electron gyrofrequencies, ν_B, $\propto B$). Both of these are important parameters that cannot be constrained in any other manner. Zeeman-Doppler Imaging techniques return the large scale photospheric magnetic structure in the photosphere, but not the total magnetic flux (See et al. 2016), and rely on extrapolations to provide constraints in the upper atmosphere, which have concomitant assumptions. X-ray observations probe electron densities much closer to the stellar surface; these densities are

$\sim 3 \times 10^{10}$ cm^{-3} for magnetically active M dwarfs (Ness et al. 2004). In contrast, 300 MHz radio observations probe electron density of $\sim 10^9$ cm^{-3}, and/or magnetic field strengths of $\sim$100 G. Translating these into specific distances above the stellar surface requires models for the expected dependence, but the observations provide much-needed constraints against model predictions. Coherent emission is often time-variable, with variations at the millisecond level (Osten & Bastian 2006, 2008), to minutes to hours (Hallinan et al. 2007). The emission can have dramatic spectral variations as well, being narrow-band or broad-band (Villadsen & Hallinan 2019), spanning the meter-decimeter-centimeter wavelength ranges. Recent results in the substellar regime have clearly indicated the presence of strong magnetic fields (Kao et al. 2016, 2018) which constrain dynamo theory. Stellar radio emission is also a "noise source", which must be disentangled from any putative exoplanetary radio emission.

The Importance of Particle Acceleration

Particle acceleration is an important component of the stellar flare process, which starts with reconfiguration of magnetic fields in the outer stellar atmosphere. This liberated energy channels into plasma heating, particle acceleration, and mass motions.

Flares are the most dramatic example of variability that stars experience while on the main sequence. The radiated flare energies produced from plasma heating are well-studied with the current and future generations of optical telescopes dedicated to detecting planets (Walkowicz et al. 2011; Davenport 2016). Radio observations provide the clearest signature of accelerated particles and shocks in stars arising from transient magnetic reconnection, and provide more realistic constraints on these factors than scaling by solar values (Osten & Wolk 2017). This is important for understanding the radiation and particle environment in which close-in exoplanets are situated.

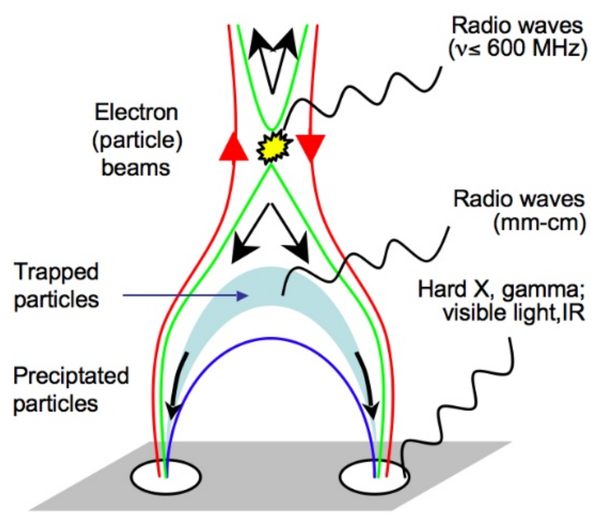

Figure 1: *Schematic figure of flaring loops (from Klein & Dalla 2017). Radio wavelength observations are key to probing mass motions in the outer atmosphere, as well as trapped and precipitating particles.*

Studies over the last several years have cemented the similarity in solar and stellar flares in terms of their radiative properties, even with a disconnect of several orders of magnitude in total radiated energy. For particle acceleration, the continuation of solar trends into the stellar regime is less clear. Güdel et al. (1996) found that M dwarf radio flares were more luminous relative to their X-ray counterpart than in the solar case. More recently, Allred et al. (2005, 2006) and Kowalski et al. (2017) determined that while a solar-like prescription of an electron beam was sufficient to reproduce solar blue-optical flare results, a solar-like electron beam in a flaring M dwarf atmosphere did not reproduce observed properties of blue-optical M dwarf flares. Kowalski et al. (2017) further determined that either a much higher electron beam flux, or changes to the electron beam distribution, were needed to begin to reproduce observational results. Radio observations of optically thin emission from accelerated particles constrains the index of the accelerated particles, and also enables a constraint on the magnetic field strength in the radio-emitting source (Smith et al. 2005, Osten et al. 2016). The integrated radio flare energy provides a constraint on the accelerated particle kinetic energy (Smith et al. 2005), which can be compared against the flare's radiative energy losses to assess the relative levels and whether this indicates agreement with solar studies (e.g. Aschwanden et al. 2017; Emslie et al. 2012).

Recent results reveal that there are still discoveries to be made in understanding particle acceleration in stellar flares. While accelerated particles have traditionally been studied in the microwave region, this frequency range suffers from a mixture of optically thick and thin emission, which hampers interpretation. MacGregor et al. (2018) found unexpected evidence of strong flaring at sub-mm wavelengths in the outer stellar atmosphere of Proxima Cen with ALMA. This was not anticipated based on extrapolations from trends at microwave frequencies. The results indicate optically thin emission, with a surprising detection of linear polarization during the flare. A more recent study (MacGregor et al. 2019, in prep.) reveals additional evidence of flaring at sub-mm wavelengths on another M dwarf star, and suggests that this may be a common feature of stellar flaring. The interpretation is still in its infancy, but suggests a transition to a different emission mechanism at sub-mm wavelengths, possibly synchrotron emission, and indicates the presence of MeV-level electrons in the outer stellar atmosphere.

Stellar Wind Constraints

Stellar angular momentum and mass loss results in a stellar wind, the study of which is important for understanding stellar rotational evolution and the influence on stellar environment, including planetary dynamos (Heyner et al. 2012). Stellar wind observations for stars with known rotation periods are key to determining how much angular momentum is transported away from the star; currently, wind models including magnetic fields and "Alfvén surfaces" are needed to link spin-down to winds (Johnstone et al. 2015). At present only indirect measures of cool stellar mass loss inform these topics. Mass loss for main sequence stars in the cool half of the HR diagram is an exceedingly difficult measurement, due to the generally feeble nature of the mass loss—the Sun loses only about 2×10^{-14} $M_\odot$ yr^{-1}. Optically thick stellar wind emission increases as $\nu^{0.6}$, favoring shorter wavelengths. Osten et al. (2018) described the advantage of a large area radio telescope capable of probing frequencies above 10 GHz; this would increase the constraints on solar analog mass loss rates by about two orders of magnitude compared to what is capable today (Fichtinger et al. 2017; Villadsen et al. 2014). This will increase the look-back time for studying the young Sun, with the ability to provide direct constraints or upper limits on stellar mass loss. Stellar mass loss constraints for M dwarfs in the solar neighborhood will also become possible, at levels within 1-2 orders of magnitude of the present day solar mass loss rate. In the future where all of the solar neighborhood M dwarfs will have been probed for the existence of planets, direct radio measurements or constraints on stellar mass loss will be important ingredients to understanding star-planet ecosystems.

Stars lose mass via a steady stellar wind as well as unsteady mass loss associated with stellar flares. Initial searches for radio signatures of stellar coronal mass ejections have taken place at low frequencies (Crosley et al. 2016, Crosley & Osten 2018ab, Villadsen & Hallinan 2019) and have not produced positive detections to date. Expanding this search to both other stars and more frequencies should continue in the next decade. A search for time-variable stellar wind emission associated with large stellar flares at frequencies above 10 GHz would provide a complementary method to gain insight into stellar mass loss.

Key Advances

Sensitivity The main requirement to make progress on these topics is an increase in sensitivity. Major advances in stellar radio astronomy have previously followed increases in collecting area (e.g., White et al. 2000). Exploring the microwave range with increasingly sensitive radio telescopes will overcome sensitivity-related activity level biases. The upcoming Square Kilometer Array is expected to be transformative in this respect (Umana et al. 2014). The ALMA array is just beginning to make discoveries that stretch our understanding of stellar flares (e.g. MacGregor et al. 2018). A next generation VLA would be more than capable of advancing all of the topics described (Osten et al. 2018).

Frequency range As Fig. 2 demonstrates, stars can be probed at pretty much all frequencies in the radio-mm-sub-mm spectrum. There is a noticeable gap in the 10-100 GHz range; this is based partly on the sensitivity limitations of current radio telescopes and the expected decline in emission at higher frequencies extrapolating from the microwave range. Opening up this frequency range would enable access to fundamental stellar properties, studies of particle acceleration, and mass loss. A next generation VLA could fill in this gap and provide sensitive constraints on particle acceleration in a wide range of stellar environments. Time-variable phenomena often require broad-band frequency access to aid in interpretation. Additionally, long baselines (including connecting to intercontinental arrays) and the ability to react dynamically to schedule observations in the event of large stellar outbursts would provide additional imaging constraints on the near-stellar environment.

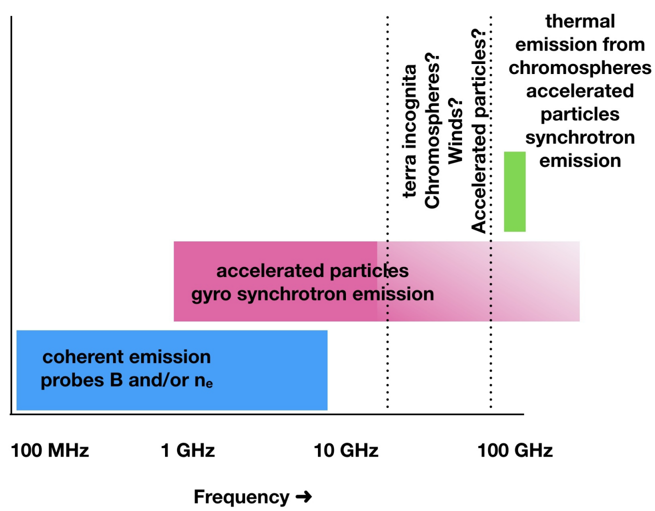

Figure 2: *Schematic diagram of the radio-mm-sub-mm spectral region and the types of fundamental information on stellar atmospheres that can be returned from studies of these different areas.*

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