Astro2020 Science White Paper

The Importance of Synoptic Solar Radio 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

Principal Author:
Stephen White, *Air Force Research Laboratory*
Email: stephen.white.24@us.af.mil

Co-authors:
Tim Bastian, *National Radio Astronomy Observatory*
Bin Chen, *New Jersey Institute of Technology*
Gregory D. Fleishman, *New Jersey Institute of Technology*
Dale E. Gary, *New Jersey Institute of Technology*

Executive Summary:

The long history of monitoring the Sun's radio flux has led to time series of solar activity that reflect the solar cycle and the physical nature of solar radio emission. Here we discuss some of the results of this monitoring and the importance of maintaining this record. Such monitoring of the Sun also has importance for understanding the impact of stellar activity on exoplanets.

Introduction

When leftover radar equipment led to the new field of radio astronomy after WWII, the Sun was a prime target. One of the brightest radio sources in the sky, it was spatially complex and highly variable, providing intrigue at virtually every wavelength. Radio observations of the Sun participated in the discovery that temperature rises as one moves outwards through the solar atmosphere, that the outer layer reaches millions of degrees, that eruptions are commonplace in stellar atmospheres and drive shocks capable of accelerating particles to GeV energies, and provided the motivation for plasma physicists to develop the theory of the propagation of electron beams.

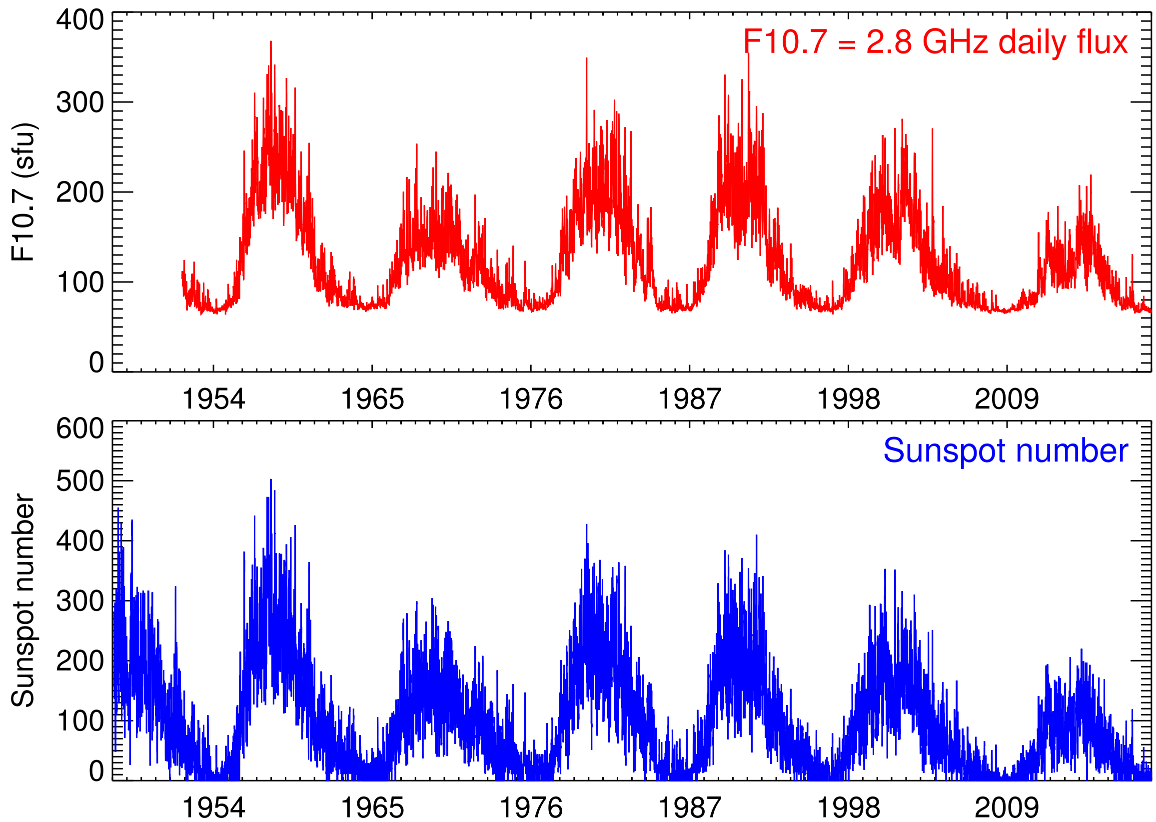

Figure 1: Plots of daily values for sunspot number (lower panel) and the solar radio flux at a wavelength of 10.7 cm (2.8 GHz), known as F10.7 (upper panel) over the past 7 decades.

Amidst the excitement of all these new phenomena, the value of simply tracking the level of the Sun's non-flaring radio flux was also recognized. Starting in 1947, Arthur Covington in Canada began monitoring the solar flux at 2.8 GHz, an effort that continues to this day and has become a critical part of both tracking solar activity as well as understanding the impact of the Sun on the Earth's atmosphere. F10.7, as the measurement of the flux at the wavelength of 10.7 cm is known, is arguably the second-most widely used measure of solar activity after sunspot number, and tends to be favored in atmospheric modelling because it has a more direct physical connection to the sources of the short-wavelength solar emission that is absorbed in the terrestrial atmosphere. When trying to understand such impacts, it is important to have a long time series of data that can be correlated and contrasted with terrestrial measurements. In this way atmospheric models can be tuned to accurately separate the effect of solar variation from other phenomena that drive the atmosphere, such as seasonal effects and neutral winds. Figure 1 shows daily measurements of sunspot number and F10.7 over 70 years, with the strong 11-year solar cycle variation dominating the overall impression: the fact that we have F10.7 values for this length of time has proven to be critical for our ability to model the upper atmosphere.

In this paper we discuss the importance of continuing the decidedly un-romantic monitoring of daily solar radio flux values at a wide range of frequencies. Other white papers will cover the additional value to be gained from daily imaging of the Sun as well.

Current Status

Synoptic observations of all kinds tend to be a hard sell in the current funding climate, usually because they don't fit into the regular funding paths. If a data set is explicitly required for operational space weather purposes (e.g., at the Space Weather Prediction Center operated by NOAA for civilian customers), then the agency that requires it will generally recognize the need to fund its continued acquisition, but if it is not so required it generally has a hard time competing for basic research funding at agencies such as NASA and NSF. The main sources of synoptic solar radio flux measurements at present are:

- Measurement of F10.7 (2.8 GHz) at the Dominion Radio Astronomy Observatory in Penticton, Canada. Currently carried out by Ken Tapping (who, after Covington, is just the second person to lead this effort) with support from Canadian government sources, these measurements continue Covington's work, and supply extremely well-calibrated measurements 3 times per day.[1]
- Measurements at 7 frequencies from 1.0 to 80 GHz with 1-second cadence from the Nobeyama Radio Polarimeters (NoRP), operated by the National Astronomical Observatory of Japan. Like F10.7, these data are regarded as being very well calibrated, supported by regular comparison with a calculable horn feed.
- Measurements at 8 frequencies from 0.245 to 15.4 GHz by the Radio Solar Telescope Network (RSTN) of the US Air Force. Four observatories span the globe to provide 24-hour coverage.

Note that calibration is an important aspect of the measurements that we consider here, and so other data sources that pay less attention to absolute flux calibration may be neglected. In order to be confident that relatively small day-to-day variations in fluxes are real and correlated with changes in the state of the Sun, accurate and repeatable calibration is required. Having multiple sources of overlapping data is important, since comparison with an independent source serves as a check on calibration issues. Of the three data sources listed above, RSTN is expected to continue for the near future as are F10.7 measurements in Canada, while there is some concern for NoRP due to funding competition and the possible closure of Nobeyama Radio Observatory.

The Value of Synoptic Observations

Solar radio measurements are sensitive to the entire depth of the solar atmosphere. At low frequencies (below a few hundred MHz) the solar corona is optically thick due to thermal bremsstrahlung

[1] F10.7 was also measured at Hiraiso by NiCT in Japan until 2016.

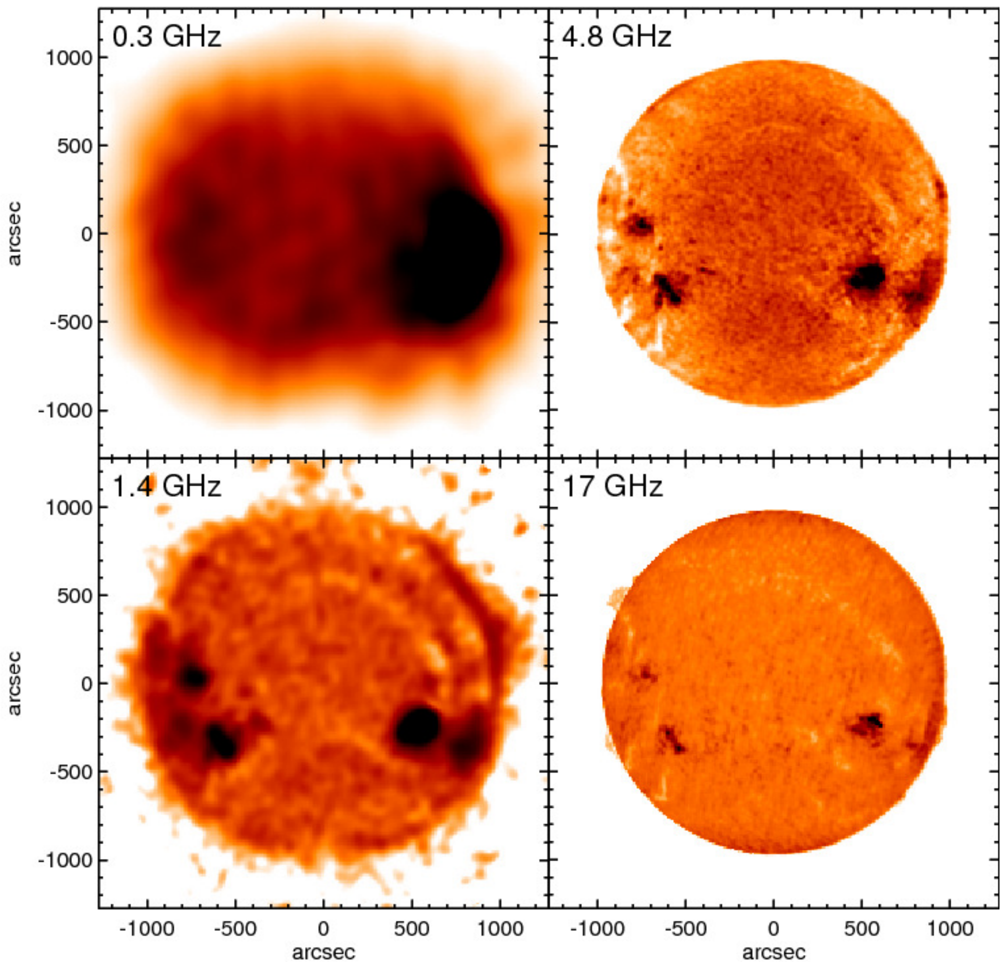

Figure 2: Radio images of the Sun on the same day at four different frequencies, showing how the contrast of different features (e.g., quiet-Sun against the disk, active regions, coronal holes, filament channels) changes with frequency due to varying optical depth effects. The images at 0.3, 1.4 and 4.6 GHz are from the VLA, while 17 GHz is from the Nobeyama Radioheliograph (NoRH).

at a height of order a solar radius, so the Sun appears as a source larger than the visible Sun with a brightness temperature of order 1 MK, and is often distended into a non-round shape by features in the outer atmosphere such as streamers and coronal holes. As frequency increases into the microwave range, the quiet solar corona becomes optically thin and the temperature on the solar disk drops to temperatures characteristic of the upper chromosphere, while active regions, with their higher densities and strong magnetic fields, can still be optically thick. This produces images with a large contrast between bright features over active regions and the solar disk. This contrast means that active regions provide a significant fraction of the solar radio flux, and hence frequencies such as 2.8 GHz show a large relative degree of variation over the solar cycle. At even higher frequencies, the optically-thin coronal contribution of bright features such as active regions drops relative to the optically thick chromospheric flux, and the degree of variation over the cycle diminishes. This trend can be seen in the images at 4 radio frequencies shown in Fig. 2. At millimeter and shorter wavelengths, the optically-thin contribution from the corona is negligible and radio emission is dominated by relatively low-contrast emission from an optically thick layer in the solar chromosphere, providing a probe of energy flux from the solar interior into the atmosphere.

This sensitivity to different layers in the solar atmosphere underpins the value of solar radio observations, as discussed in more detail in other white papers. For synoptic radio observations, we discuss results from F10.7 = 2.8 GHz as an example of the relevance of such monitoring.

- Three different emissions contribute to non-flaring radio emission at microwave frequencies: thermal bremsstrahlung from coronal material, which may be optically thick in dense regions but optically thin outside active regions; optically thick thermal emission from the upper chromosphere; and optically thick gyroresonance emission from the corona where strong magnetic fields ($B>300$ G) render the corona optically thick at MK brightness temperatures.
- F10.7 has very different origins from sunspot number, which is a nonlinear measure of the sunspot content of the solar photosphere. Both represent magnetic activity, but in ways that are different and thus provide different diagnostics of activity.
- In particular, F10.7 comes from the same material that produces the Sun's EUV and UV emission, and so it is a better diagnostic for impact on our atmosphere.
- In recent years small solar cycles have led to a debate about how solar magnetism is changing over time, and whether this will result in differences in the photospheric and coronal response: continued measurements of both radio indices and photospheric magnetic indices are critical for understanding if this is occurring.
- One can see from Fig. 1 that, unlike SSN, F10.7 does not go to zero at solar minimum. It now appears that at least 25% of the radio flux at solar minimum comes from a basal corona. The fact that the radio flux, and hence the basal corona, returns to exactly the same level every minimum implies that the basal corona is disconnected from the normal 11-year activity cycle, which varies greatly from one cycle to the next. Thus the basal corona requires a different mechanism, such as a small-scale local dynamo operating just below the photosphere. The remainder of the minimum flux comes from the chromosphere (White et al, in prep.). This result would not be possible without the evidence that the solar radio flux returns to the same level at every minimum, provided by the long-term well-calibrated measurements.
- The US is currently going through the White House-directed Space Weather Operations, Research, and Mitigation (SWORM) process which includes generating benchmarks for extreme space weather events that need to be anticipated by emergency services. One of the benchmarks is for solar radio emission, which can disable cell phone and GPS reception (critical for future aircraft landing) and knock out radars. Deriving benchmarks for such impacts would not be possible without the long-term synoptic monitoring provided by RSTN, NoRP and other observatories.

These are examples of the value of past monitoring and the need to maintain this capability in the future. An enhancement would be measurements with a more dense coverage of the frequency range than is available from the instruments listed above. Denser spectral coverage will enable us to look for changes in the solar radio spectrum with time that cannot be done with sparse spectral sampling.

There are also a number of instruments monitoring the radio spectrum below 1 GHz, which tends to be dominated by very bursty activity produced by energy releases and electron beams in the outer solar atmosphere. These observations are usually not as well calibrated, and long-term analysis is more difficult, further complicated by the prevalence of bursts during solar maximum.

Conclusions

Continued monitoring of solar radio fluxes across a wide range of frequencies is important for monitoring changes in solar behavior that may impact us on Earth. It is difficult for such monitoring to compete for research funding, but recognition of its value for a wide range of applications, including basic science and understanding of stellar activity that has implications for exoplanets, is important. Similar monitoring of the radio flux from other stars and exoplanetary systems may be possible with sensitive future instruments (e.g., ngVLA, SKA) operating in survey modes.