High Frequency Solar Observing at the Green Bank Observatory

Adam Kobelski

West Virginia University, Department of Physics and Astronomy

adam.kobelski@mail.wvu.edu

ABSTRACT

The millimeter spectrum offers a truly unique insight into the Sun by providing a linear thermometer into the chromosphere. Due to line-of-sight effects in optically thin observations these layers of the chromosphere are largely unresolved. Recently, significant progress has been made with observations via the Atacama Large Millimeter Array (ALMA) in Chile. These observations have hinted at the power of millimeter wave radiation to diagnose and understand the dynamics of the solar chromosphere and transition region. Here we discuss the utility of performing similar observations with the 100 m Green Bank Telescope at 100 GHz.

1. Introduction

The Green Bank Telescope (GBT) is a 100 m radio telescope located in Pocahontas County, WV. The telescopes location within the National Radio Quiet Zone provides observations relatively free from radio frequency interference. While most of the telescopes observations are of non-solar sources, the facility can provide important insight into the atmosphere of our star, the Sun. Recently, Wexler et al. (2017) were able to utilize the GBT to study density fluctuations in the outer corona ($> 2R_{\odot}$) by observing distant satellite carrier signals at 8 GHz. Direct measurement of the Sun is possible with the GBT at centimeter wavelengths. These observations can provide measurements of the coronal magnetic field and coronal topology, but the spatial resolution of the GBT generally still low enough that the Sun is still smaller than the observing element and thus a smaller and cheaper instrument can provide similar effective results. Otherwise, an interferometer is needed to resolve individual solar features. Discussion of these possibilities in Green Bank are left to other papers and proposals. At the high frequency end of the GBT spectrum, in particular at W-band and above (>86 GHz), a spatial resolution element is of order 10-20", and the instrument can begin to distinguish different features of the Sun, such as active regions and coronal holes (see e.g. Brajša et al. 2018, though note it covers a higher frequency than discussed here). At these frequencies, we are working within the Rayleigh-Jeans limit and can directly relate the observed intensity to the emission temperature, providing one of the most direct temperature probes of the solar chromosphere. In this white paper, we will discuss some of the capabilities and unique advantages to observing the Sun with the GBT in the coming decade.

2. Solar Science at High Frequencies

To quickly discuss many possible uses for the GBT for hight frequency solar observations, only a brief overview can be provided here. For a more thorough discussion of the solar astronomy capable with millimeter wavelength observations, we direct the reader to Wedemeyer et al. (2016). While that paper is ALMA focused, the discussion of ALMA solar science possible at Band 3 is relevant for GBT observations as long as spatial resolutions of order 10" are acceptable. The 100 GHz frequencies probe the chromosphere at an average height of 960$\pm$440 km above the photosphere according to the quiet sun models of Wedemeyer-Böhm et al. (2007). Here we summarize some of capabilities of observing the Sun at 3mm wavelengths with the GBT.

Limb Brightening/Center to Limb Variation: In visible wavelengths, the limb of the Sun is darker than the central disk. This is effect is caused by a combination of geometry and decreasing temperature with atmospheric height (Foukal 2004). However, between the temperature minimum and transition region in the chromosphere, the temperature *increases* with height, causing the limb to be **brighter** than the central disk. The broad features of this can be shown with models and low resolution images, but high spatial resolution data from the GBT could provide vital insight and comparison to models of chromospheric structure. An additional form of limb brightening in the Sun has been observed in the polar regions. Nindos et al. (1999) used an interferometer to observe the poles from 17-86 GHz to show a diffuse background radiation 1500 K warmer than the disk, with small bright patches containing up to 3500 K of excess brightness. The dynamic bright patches could not be easily explained, nor could counterparts in other wavelengths be found. Follow-up observations with the GBT could better understand the nature of these bright patches, while also improving our knowledge of the diffuse background. Connecting these polar features to the solar cycle could be incredibly important for understanding the movement of magnetic flux towards the poles. The GBT is advantaged compared to interferometers such as ALMA for limb brightening studies due to its ability to accurately measure the background solar flux.

Spectral Signatures of Solar Radio Recombination Lines: It has been hypothesized that Radio Recombination Lines from excited atoms in the chromosphere should be observable in the chromosphere. Observing these lines would be great for understanding the atomic processes in plasmas. While these lines have not yet been observed in the Sun, if present they should be most readily observed in millimeter wavelengths. The spectral resolution of single dish instruments such as the GBT may prove useful in detecting these features.

Wave Propagation: A combination of waves and magnetic reconnection are necessary to heat the MK corona from the 7 kK photosphere. While some magnetic waves (such as pure Alfv́en waves) are not compressive and thus not directly observed, magnetic waves commonly couple with acoustic waves as magnetosonic waves (Tarr et al. 2017) which can cause temperature and density fluctuations. Observing these waves in the chromosphere is critical for diagnosing the energy balance between different wave modes and reconnection. The thermal measurement capabilities of the millimeter emission can provide direct insight into the heating done in relation to these type of waves, and GBT observations in conjunction with coronal observations should provide sufficient angular, spectral, and temporal resolution to observe this heating. It will be enlightening to see how these wave signatures vary across different solar features, as one should expect different driving and heating phenomenon in the quiet sun compared to the active sun. There is particular interest in understanding this wave activity above sunspot umbra and penumbra, which will allow improved models of their atmospheric stratification and dynamics.

Transient Phenomena: In addition to observed wave features, millimeter radiation can also provide vital insight into transient phenomena, such as microflares or Ellerman bombs. Many of these features are believed to be the results of magnetic reconnection, whose chromospheric counterparts are yet to be fully understood. Proper observational coverage of transient events in the millimeter range with telescopes such as the GBT will provide the most direct insight into the chromospheric heating involved in reconnection including the import of particle beam heating in flares and potential chromospheric triggering.

Chromospheric magnetic fields: One of the ultimate goals for radio solar physics is to be able to use the polarization signature to measure the magnetic field of the Sun. Current techniques for measuring the magnetic field rely on difficult spectral line inversions, and are currently only available for the photosphere or low chromosphere. The magnetically sensitive chromospheric lines (such as Ca II at 854.2 nm and He I at 1083 nm) are also characterized by a poor polarization signature, non-LTE effects, and wide formation heights (de la Cruz Rodríguez et al. 2010). By instead exploiting the opacity dependence on polarization of thermal bremsstrahlung, the chromospheric magnetic field can be obtained (Grebinskij et al. 2000). This requires fairly accurate (1% or better) measurements, which can be difficult but possible with a well understood instrument such as the GBT. Regular measurements of the chromospheric magnetic field would allow ground breaking insight into the dynamics of the solar atmosphere.

Continuous Power Spectra: The resolution of the GBT should be similar to observations from BIMA White et al. (2006). These observations will be able to localize power spectra in network and internetwork regions since there shouldn't be any issues of power spectral features in low flux regions leaking to high flux regions due to the well understood beam patter of the GBT. The ability to stare for extended periods of time should allow GBT to better measure long period events (¿ 909s such as hinted at in White et al. (2006)).

3. Uniqueness of GBT observations

There are a few other telescopes worldwide which are capable of observing the sun at 3 mm, though most of them are smaller single dish instruments not capable of observing a 7000 K source. ALMA and the GBT are notable exceptions. While ALMA has a notable resolution benefit (since it can currently use up to 500 m baselines), there are a few distinct aspects of the GBT which make advantageous compared to the ALMA interferometer for measuring. By nature of being a single dish instrument, the GBT can much more easily record the background flux of an extended source like the Sun. ALMA attempts to recover this lost information by adding in the antennae of its total power array, but this is not a trivial problem to solve, nor does it completely fill the gaps between the largest recoverable size from the array and the total power array field of view. Due to being a single dish, many aspects of the calibration are also more simplified. This could enable a better opportunity to getting adequate accuracy with the polarization measurements to obtain magnetic field information. Additionally, ALMA has significant observing pressure, which has made it difficult to obtain solar observations, even when proposals are selected at an A or B rank. The lowered observing pressure and scheduling flexibility with the GBT can help obtain solar observations more regularly.

A notable distinction between observing the sun compared to many other astronomical sources is the dynamic nature of the Sun and the observations of it. This means that supporting observations must be taken at the same time to ensure that the same plasma features are observed. This can make coordinating observations difficult for ground based observatories, where the longitudinal separation between telescopes can make observing the Sun at the same time impossible. Fortunately, the GBT (located at 38.4330° N, 79.8399° W) is longitudinally separated from ALMA (located at 23.0234° S, 67.7538° W) by only 0.8 hours, ensuring that (assuming good weather) almost all GBT solar observations can be co-observed with ALMA and vice versa. This can provides for some of the most capable multi-wavelength millimeter observations of the Sun possible, with the GBT observing at 100 GHz and ALMA observing at higher frequencies. This would improve the capabilities of both instruments greatly.

4. Future Potential

In recent years, the GBT has made significant progress with its high-frequency capabilities. In particular, in the past few years, the Argus instrument has come on-line, which provides 16-pixel single polarization spectral observations at 100 GHz. Test observations of using the GBT with Argus are being scheduled. This instrument is scheduled to be updated to include more pixels, which will greatly improve the ability to study the Sun. Additionally, improvements to the surface accuracy of the GBT are planned, which should allow enhanced observations at high frequencies, improved daytime observing, and improved spatial resolution. All of these improvements greatly increase the utility of the GBT to provide invaluable scientific insight into the physics of our star, the Sun, in the coming decade.

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