Stellar Atmosphere and Magnetism Observing with the ngVLA

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Abstract

The thermal radio emission that might come from the chromosphere of the F, G, and K-type main-sequence stars is detected with the large interferometers recently. However, their sensitivities are not enough for investigating stellar atmosphere and magnetism statistically yet. The next-generation Very Large Array (ngVLA) would bring revolutionary progress to the studies by its unprecedented higher sensitivity. Moreover, its polarization precision would be enough for investigating stellar magnetism using circular polarization signals. In this article, we predict the potential of the ngVLA for investigating stellar atmosphere and magnetism based on solar microwave data and discuss what preparations are needed for maximizing scientific results from ngVLA stellar observations.

Key words: stars: activity — stars: atmosphere — stars: magnetic field — radio continuum: stars

1. Introduction

The activity of a central star is one of the critical keys for considering the habitable zone of its exo-solar system. Especially, stellar wind, flares, and EUV radiation: these phenomena are crucial to comprehend the exoplanet's atmosphere, and the estimation of their influences is essential to understand the exoplanet's habitability. Based on the knowledge about our Sun, the phenomena should strongly depend on stellar magnetic activities. So, stellar magnetism is a fundamental issue of this subject. Additionally, understanding the stable component of the stellar chromosphere is also essential because most UV radiation that affects the higher atmosphere of exoplanets comes from the layer.

Studies of such phenomena and structures were done mainly with emission and absorption lines within optical and UV ranges (Linsky 2017). The radio emission is not used for the studies except for very few cases, even when the radio photosphere with microwave would be located in the stellar chromosphere. The reason for lacking studies using the microwave is that the emission from the main-sequence stars is not bright enough for detecting with most current radio telescopes except for active stars and high mass-loss stars. In the case of active stars, the high-energy electrons created by stellar activities fill the star's magnetosphere. Hence the strong microwave emission comes from the electrons, and we cannot obtain information about its chromosphere from the microwave emission of active stars (Güdel 2002). The radio photosphere of a high mass-loss star is formed by its stellar wind and ejectors. As a result, the radio photosphere's size is significantly larger than the star's size, then the radio flux from the star is bright enough for detection (Wright & Barlow 1975; Blomme 2011). So, the microwave emission from such stars also does not show their chromosphere.

Thanks to the high sensitivity of the large interferometers: Atacama Large Millimeter/submillimeter Array (ALMA) and Karl G. Jansky Very Large Array (JVLA), the thermal radio emission from the F, G, and K-type main-sequence stars that might come from their chromosphere was detected recently (Villadsen et al. 2014; Liseau et al. 2015; Suresh et al. 2020). However, the sensitivity of these instruments is not enough for investigating the chromosphere and magnetism of the stars statistically. The next-generation Very Large Array (ngVLA) would bring revolutionary progress to stellar atmosphere studies by its unprecedented higher sensitivity. Moreover, its polarization precision would be enough for investigating stellar magnetism using circular polarization signals. In this article, we predict the potential of the ngVLA for investigating stellar chromosphere and magnetism based on solar microwave data and discuss what stellar information we can obtain from ngVLA data.

2. Microwave spectra from the Sun and stars

The monitoring observations of the solar flux density in the microwave range started in the late 1940s. Around 20 institutes had carried out the monitoring radio observation of the Sun in the 1970s (Tanaka et al. 1973). However, at present (Feb. 2021), only a few institutes continue to report the daily flux densities of the Sun with the microwave range (1∼10 GHz), and the famous F10.7 (2.8 GHz) index is one of them (Covington 1969). The other famous one is the Toyokawa-Nobeyama Radio Polarimeters (NoRP). The NoRP is constructed for measuring the total flux density and circular polarization degree of the Sun at 1, 2, 3.75, 9.4, 17, 34, and 80 GHz (Tanake & Kakinuma 1957; Nakajima et al. 1985). The daily solar flux densities at 1, 2, 3.75, 9.4, and 17 GHz have been reported monthly via the Internet[1], and the oldest data

[1] https://solar.nro.nao.ac.jp/norp/

of NoRP is the solar flux density at 3.75 GHz in November 1951 (Tanake et al. 1953). Therefore, the NoRP's solar flux database covers 70 years, in other words, six solar cycles.

Figure 1 shows the microwave spectra obtained with NoRP at solar maxima and minima. The right panel shows the microwave spectra at the solar minima of Cycle 20, 21, 22, 23, and 24. Shimojo et al. (2017) revealed no difference in the spectra of solar minima of the recent five solar cycles based on the plot. Since the spectra were observed at the deepest solar minima, which means no sunspot and no active region, it presents the spectrum of thermal emission from the radio photosphere of each frequency. Zirin et al. (1991) observed the center of the Sun that is a quiet region with the 27-m antenna of the Owens Valley frequency-agile interferometer, using the "total power" mode. Figure 2 is their result, the spectra of Quiet Sun, and it is basically the same as the right panel of Figure 1 even when the units are different. Each frequency component in the spectrum comes from the radio photosphere of each observing frequency located in the transition region and chromosphere. Hence, the spectrum reveals the height profile of the temperature and density of the solar atmosphere, and microwave is one of the key observables for investigating the height structure of a stellar atmosphere.

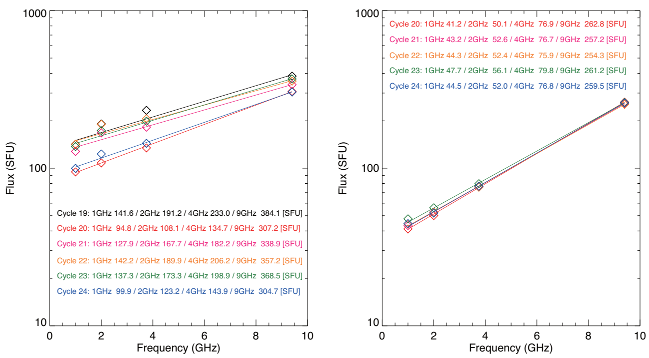

Fig. 1. Monthly mean microwave spectra in the months at the solar maximum (left panel) or minimum (right panel) in each solar cycle. The colors indicate the number of the solar cycle. 1 SFU equals to 10^4 Jy. (Shimojo et al. 2017)

Thanks to the high sensitivity of the JVLA, we can detect the thermal emission from the radio photosphere of solar-type stars now. Figure 3 shows the microwave spectrum of τ Ceti (Villadsen et al. 2014). The solid and dotted lines in Figure 3 are the same as the right panel and left panel of Figure 1, respectively. The spectrum should reveal its atmosphere, but most data points of current data are the upper limits. So, the sensitivity of the JVLA is not enough for investigating the stellar atmosphere even when the star is located only 3.65 pc from us.

The ngVLA would have the potential to induce revolutionary change to the situation. Carilli et al. (2018) investigated the possibility of imaging stellar radio photosphere with ngVLA and presented that the radio photosphere of 538 main-sequence stars included 370 F, G, and K-type stars, can be detected and resolved with 85 GHz. Although we need to evaluate the detectability with lower frequencies, we might obtain mi-

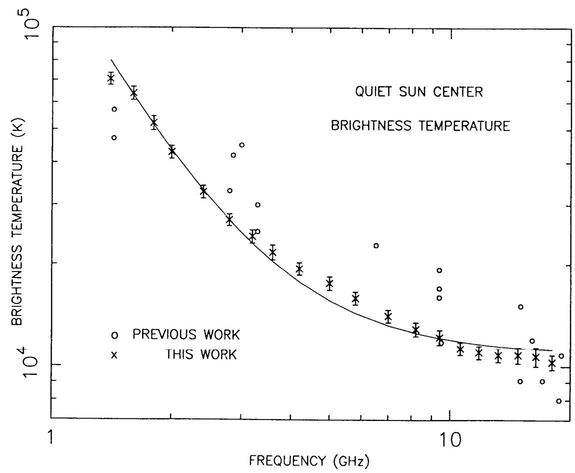

Fig. 2. Observed brightness temperature as a function of frequency ($\times$), compared to the result of Fuerst (1980). The soled line is the best fit. (Zirin et al. 1991)

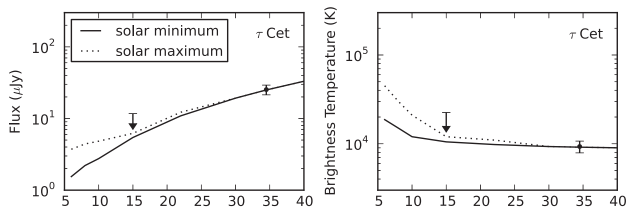

Fig. 3. Left: flux spectra for τ Ceti. Right: stellar disk-averaged brightness temperature spectra. Both columns: non-detections are shown as downwards arrows marking the 99% confidence upper limits and detections as points with 1σ error bars. The plots also show the solar spectra from White (2004) for solar minimum (solid line) and solar maximum (dotted line). (Villadsen et al. 2014)

crowave spectra of the radio photosphere of a hundred main-sequence stars, like Figure 1 and Figure 2, with the ngVLA. Such datasets should reveal the varieties of the stellar atmosphere and progress our understanding significantly.

As mentioned before, Figure 2 and the right panel of Figure 1 show the spectra of the Quiet Sun and reveal the hight structure of temperature and density in the chromosphere and transition region. However, it is the "averaged" spectrum even when it is the solar spectrum because the atmospheric layers have fine structures and dynamics that cannot be resolved with most solar radio telescopes, as shown with the Hinode satellite (Hinode Review Team et al. 2019). Hence, the relation between a stellar microwave spectrum and the hight structures of its atmosphere is not simple, and the relationship is not understood well even in the solar atmosphere (Shibasaki et al. 2011). Recently, solar observations with the ALMA (Shimojo et al. 2017; White et al. 2017) reveal fine structures and dynamics in the mm-wave photosphere located in the chromosphere . On the other hand, thanks to the progress of Radiative-MagnetoHydroDynamics (R-MHD) simulations, we can reproduce the structures and dynamics of the layers in the computers. Therefore, the comparison studies between the solar ALMA data and the solar atmosphere models included the R-MHD simulations become active for solving the relation between the solar microwave spectrum and solar atmosphere now (Martínez-Sykora et al. 2020; Wedemeyer et al. 2020; Alissandrakis et al. 2020; Eklund et al. 2020). The modeling works in solar physics are very important for understanding stellar data obtained with the ngVLA.

The difference between the microwave spectra shown in the left and right panels of Figure 1 shows the microwave component from active regions. To emphasis the component, we show the different spectrum between solar maximum and minimum in the right panel of Figure 4. The spectrum consists of two emissions; one is the thermal emission from the dense coronal plasma, and the other one is the gyroresonance emission above sunspots. The component of gyroresonance emission dominants around 5 GHz (Schmahl & Kundu 1998).

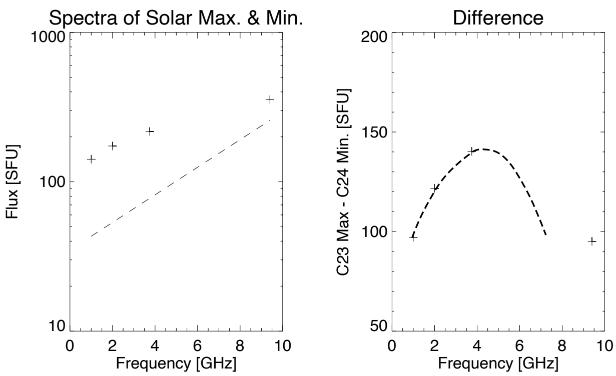

Fig. 4. Left: Microwave spectra at Solar Maximum (Plus marks, 8 July 2014) and Solar minimum (dashed line) observed with the NoRP. Right: Difference between the maximum and minimum. The dash-line is the hand-writing line of the spectrum of gyro-resonance component.

The thermal electrons gyrated by $\boldsymbol{v} \times \boldsymbol{B}$ force resonant with electromagnetic waves when the gyro frequency and its higher harmonics equals the frequency of the electromagnetic wave. The resonance causes increasing the opacity with the frequency, and the resonant plasma emits electromagnetic waves based on the physical temperature of the plasma. The gyro frequency is $2.8 \times B$ MHz, where B is the magnetic field strength measured in Gauss. Considering that the harmonic numbers should be 1, 2, or 3 for solar plasma, the resonance for the GHz range occurs in the corona only above sunspots. So, strong magnetic fields are essential for microwave emission with gyroresonance. The gyroresonance emission is reviewed by Dulk (1985) and White & Kundu (1997). To understand its in detail, we recommend reading these papers.

Considering these solar studies, the gyroresonace emission in the GHz range comes only from strong magnetic fields, like the above starspots, and includes the information of stellar magnetic fields. Due to the rigid relation between magnetic fields and gyroresonance, the peak frequency of the gyroresonace emission indicates the averaged magnetic fields above starspots. It will be a crucial achievement for stellar physics. For the study, we also need the microwave spectrum of the star when its activity is low. Hence, we need to observe the star every day during its rotation period and create a plot like the upper panel in Figure 5, which shows solar rotation.

3. Circular polarization signal from the Sun and stars

The strength of gyroresonance depends on the polarization of electromagnetic waves and magnetic field vectors. The extraordinary mode (x mode) of electromagnetic wave gyrates about the magnetic field with the same sense of rotation as an electron and resonates strongly with the thermal electrons. On the other hand, the other mode, the ordinary mode (o mode), gyrates about the magnetic field with the opposite sense to that of the electron, and its resonance with thermal electrons is weaker than the x mode. Therefore, there is a difference between the optical depths of the modes, and the gyroresonance emission is a circular-polarized wave basically. It means that the circular polarization signal from the gyroresonance emission has the information of the direction of magnetic field vectors. Then, what do the total circular polarization signals from the whole Sun show us? It is a crucial question for understanding stellar circular polarization data obtained with the ngVLA.

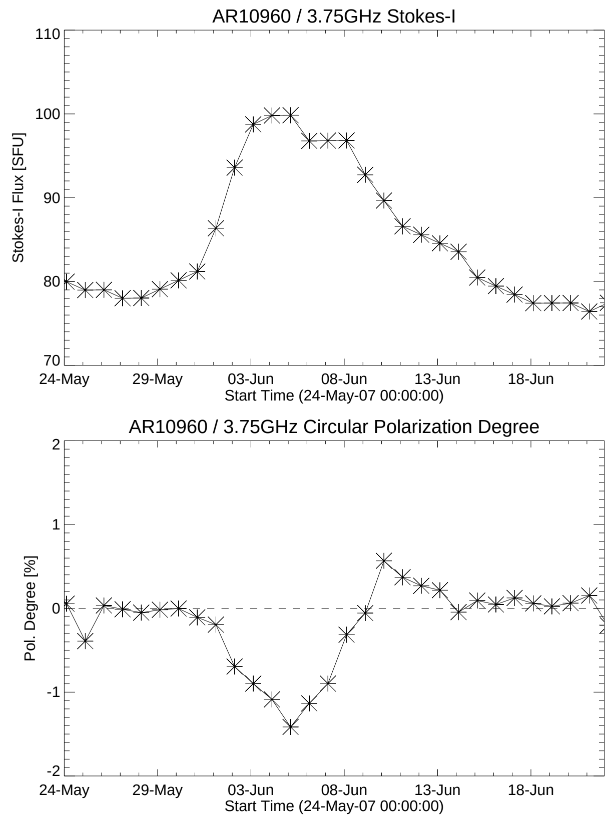

Fig. 5. Upper panel: the time profile of the solar flux density at 3.75 GHz observed with NoRP. The time range is from 24 May to 22 June 2007. Lower panel: the time profile of the circular polarization degree.

At first, to consider the most straightforward case for understanding the circular polarization data, we selected the period that an active region passed the solar disk from west to east. Figure 5 shows the total solar flux density and circular polarization degree at 3.75 GHz from 24 May to 28 June 2007. Although there were two decayed active regions with weak magnetic fields, a major active region on the solar disk was only “NOAA10960”, and most contribution of microwave comes from this active region. The active region appeared from the east limb on 1 June, passed the central meridian on 7 June, and went to behind the limb on 13 June. The period is near the solar minimum of Cycle 23, and then the active region and its sunspots are not so big and not with strong magnetic fields, comparing the active regions in solar maxima. Nevertheless, the variation of the circular polarization degree is around ± 1 % (see the lower panel of Figure 5). It is good news because the 1 % polarization signal should be easily detected with the ngVLA which polarization dynamic range is 35 dB at the center of the field (Murphy et al. 2020).

As shown in Figure 5, the time variation of the polarization is not simple. The peak time of circular polarization is not the same as that of solar flux density. Usually, an active region has two sunspot groups, preceding sunspots and following sunspots, and they have opposite magnetic polarity. The circular polarization signals from both sunspots are canceled out of each other. Hence, the circular polarization degree decreases when both sunspots appear on the disk. When the active region locates near the limb, the resonance layer above a spot is occulted by the limb or the layer above the other spot. Due to the occulting, the circular polarization degree increases (the left panels of Figure 6). Therefore, if we obtain the time profile of stellar microwave emission with circular polarization continuously during its rotation period, we would know the magnetic configuration on the stellar disk even when we cannot resolve the star.

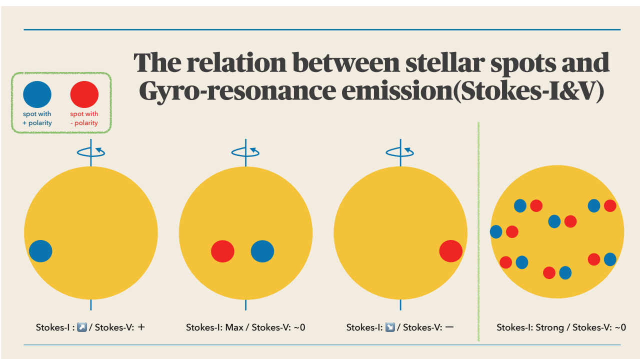

Fig. 6. The relation between stellar spots and gyroresonance emission. Left three panels: the case of one active region with a pair of preceding and following spots on the stellar disk, Right panel: many stellar spot on the disk.

Figure 5 and the left panels of Figure 6 is the simplest case, as mentioned before, and actual stellar activities are not so simple. As shown in the right panel of Figure 6, it is easily imagined that many spots appear on the stellar disk. In this case, intense microwave flux by gyroresonance emission would be observed during the whole rotation period, but the circular polarization degree is always very small. As described above, the successive observations during the rotation period are very critical for investigating the stellar magnetism using microwave and its circular polarization data.

White & Kundu (1997) mentioned that the gyroresonance emission strongly depends on the magnetic configuration of an active region, and the angle between the magnetic field vector and line of the sight. Hence, actually, we need the modeling process to re-construct the stellar magnetic field distribution from microwave data with circular polarization. Unfortunately, such studies in solar physics are not carried out because we can resolve the Sun with microwave using the radio interferometers. We should prepare the modeling for ngVLA stellar observations. Fortunately, we have much data on solar microwave data and solar magnetograms. While there are many works for the preparation, there might not be critical issues for developing the modeling.

4. The possibility of microwave emission from other sources

We discussed the microwave emission and its origin, assuming that the emission comes from the chromosphere or corona of a central star until now. However, the assumption is not always correct. As already mentioned in the Section “Introduction”, the high-energy electrons and dense stellar wind emit microwave. So, we need to distinguish the emissions before discussing the chromosphere and magnetism of the star. We discuss the issue of the data selection as ending remarks.

When the target is a non-active star, in other words, the occurrence rate of stellar flares is low, we can easily avoid the non-thermal emission from a stellar flare using the time variation. If the size of flare loops is smaller than a few times the star’s size, the flare duration is shorter than or similar to the Alfven transit time[2] of the star in corona considering the flare model based on magnetic reconnection (Shibata & Magara 2011). So, we can identify the period of the flare during the observations.

We cannot exclude the microwave emission from stellar wind using the time variation because it is stable. To exclude the stars that its microwave emission from stellar wind dominates, we need to obtain the broad-band spectrum ($1 \sim 20$ GHz) in the microwave range because its spectrum has a significant difference from the chromosphere (Suresh et al. 2020). Obtaining broad-band spectra is crucial not only for investigating the stellar chromosphere and magnetism but also for the data selection.

The possible other source is an exoplanet. If there is a planet with strong magnetic fields, like Jupiter, the planet would be a strong microwave emitter (de Pater et al. 1997). In this case, we need to compare the source position and observing time with the planet orbit and its phase and identify the emission source, like done by Bastian et al. (2018).

As mentioned above, we need to deal carefully with the observing data for identifying the emission source, but there is no doubt that the ngVLA has the potential for the significant progress of stellar atmosphere and magnetism studies. To achieve superior scientific results, the stellar atmosphere model based on solar atmosphere studies is essential, as mentioned before. We should start the preparation in the planning and construction phase of the ngVLA project.

2 The time scale at the Sun is about 20 minutes.

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