Astro2020 Science White Paper

Resolving the Radio Photospheres of Main Sequence Stars

Thematic Areas: ☐ Resolved Stellar Populations and their Environments

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Abstract

We discuss the need for spatially resolved observations of the radio photospheres of main sequence stars. Such studies are fundamental to determining the structure of stars in the key transition region from the cooler optical photosphere to the hot chromosphere – the regions powering exo-space weather phenomena. Future large area radio facilities operating in the tens to 100 GHz range will be able to image directly the larger main sequence stars within 10 pc or so, possibly resolving the large surface structures, as might occur on eg. active M-dwarf stars. For more distant main sequence stars, measurements of sizes and brightnesses can be made using disk model fitting to the uv data down to stellar diameters of ~ 0.4 mas. This size would include M0 V stars to a distance of 15 pc, A0 V stars to 60 pc, and Red Giants to 2.4 kpc. Based on the Hipparcos catalog, we estimate that there are at least 10,000 stars that will be resolved by the ngVLA. While the vast majority of these (95%) are giants or supergiants, there are still over 500 main sequence stars that can be resolved, with ~ 50 to 150 in each spectral type (besides O stars).

Main Sequence Stars: Radio Photospheres

The field of stellar atmospheres, and atmospheric activity, has taken on new relevance in the context of the search for habitable planets, due to the realization of the dramatic effect 'space weather' can have on the development of life (Osten et al. 2018, Trigilio et al. 2018). Observations at radio wavelengths provide some of the most powerful probes of exo-space weather, including: (i) high brightness coherent processes, such as masers associated with outflows in forming stars, (ii) non-thermal coherent and incoherent gyro-synchrotron emission due to magnetic activity in stellar coronae, and (iii) thermal emission from extreme mass loss events, such as novae (Gudel 2002, Linford et al. 2018).

In this report, we consider the more quiescent properties of stellar radio photospheres, namely, the thermal emission from the $\tau \sim 1$ surface of the photospheres of stars of different types (see Carilli et al. 2018). The size of stars, as measured by their stellar radio photospheres, is a strong function of wavelength, since the free-free optical depth drops quickly with frequency ($\propto \nu^{-2.1}$). Radio observations over a range in frequencies provide a tomographic image of the density and temperature structure of the transition from the optical photosphere to the chromosphere.

For giant stars, the radio photosphere will be larger, and typically cooler, than the optical photosphere, at long wavelengths, and approach the optical photospheric size and temperature at shorter wavelengths. The topic of the radio photospheres of giant stars is presented in the DS2020 white paper by Mathews & Claussen (2019, 2018).

In this white paper, we consider main sequence stars. For main sequence stars, there should be closer correspondance between radio and optical photospheric sizes, although even in these cases, at cm and mm wavelengths the stellar atmospheres can become optically thick in the chromosphere, which would enhance temperatures by a few thousand Kelvin (eg. the Sun has a brightness temperature at 100GHz of 7300 K; White et al. 2017). For Solar-type and lower mass main sequence stars, recent interest has focused on atmospheric conditions that can drive strong winds, leading to star-planet magnetic interactions, possibly triggering auroral radio emission (Trigilio et al. 2018, Fichtinger et al. 2017, Hallinan et al. 2015).

To date, direct imaging of stellar radio photospheres has been limited to a handful of the largest, closest stars, with a focus on red giants, super-giants, and AGB stars (see Mathews & Claussen 2018, 2019 for review) Detection of thermal emission from nearby Solar-type main sequence stars is just possible with deep observations with the JVLA and ATCA (O'Gorman et al. 2017, Villadsen et al. 2014). Spatially resolved imaging is certainly impossible with current facilities. The situation is similar in the optical and near-IR, with a moderate number of large, hot stars resolved through optical interferometry or direct imaging with HST (see Monnier et al. 2007 for review). For optical interferometers, structure is typically inferred through model fitting of interferometric closure quantities (Monnier 2003, Defrere et al. 2018, Montarge et al. 2018).

With future large area radio telescopes operating in the tens to 100 GHz regime, a new window opens on stellar radio photospheres, through sub-milliarcsecond resolution with sub-μJy sensitivity. In this report we consider the capabilities of an instrument such the Next Generation Very Large Array (ngVLA, Selina et al. 2018). Such an facility will have an order of magnitude better sensitivity, and resolution, than existing facilities, reaching brightness sensitivity in one hour at 85 GHz and 0.4 mas resolution of ~ 1000 K. There are thousands of stars with sizes larger than 0.4 mas, with brightness temperatures above a few thousand Kelvin at 90 GHz. These include nearby main sequence stars, and more distant giants and supergiants. We investigate the ability of the ngVLA to provide spatially resolved observations of the radio photospheres of main sequence stars.

Sirius (α Canis Majoris) at 85 GHz

Sirius is the brightest star in the sky in the optical (α Canis Majoris, J0645-1642), at a distance of 2.6 pc from Earth. It is a binary system, with the brighter star being a hot, 2 $M_{\odot}$, main sequence star of spectral type A0, and the second star being a 1 $M_{\odot}$ white dwarf. We focus on the A0 star.

For the radio model of a Sirius-like star, and subsequent analyses below, we adopt the parameters of the optical photosphere, in terms of diameter and brightness temperature, since the radio and optical photospheres for hot main sequence stars at 85 GHz are likely to be similar at the $\sim 30\%$ level, in size and brightness (White et al. 2018). In this model, the angular diameter is 6 mas and the total flux density at 85GHz is 1.63 mJy. The mean brightness temperature is about 9000 K.

While subtantial substructure is not expected on hot main sequenece stars, in order to exercise the imaging capabilities, our model includes structure on the surface of hotter and colder regions at the $\pm 10\%$ brightness level (see Figure 1a). Large-scale structures remain a possibility on the very active M-dwarf main sequence stars, including non-thermal regions (Hallinan et al. 2015).

The results of the ngVLA simulated image are shown in Figure 1 at 0.7 mas resolution. A necessary part of the process is to fit, and subtract, a smooth disk model from the visibilities before imaging. The resulting image easily resolves the star, and reveals the primary cold and hot spots, to accuracies of 30% of the expected values relative to the mean disk brightness, and even shows marginal evidence for the next lowest cold spot.

We have fit disk models to visibilities, and the results are givein in Table 1. We performed two fits: one using baselines from the ngVLA 'main array' (baselines to a few hundred km), and the second using the long baseline array (out to 9000 km). In this case, the results are much the same, since the star is 6 mas in diameter, and the resolution of even the smaller configuration baselines is a factor few smaller than this.

θ Leonis at 85 GHz

We next consider a model of a hot main sequence star at a distance 20 times that of Sirius, and determine how well the stellar properties can be determined in a one hour synthesis, appropriate for surveys of large numbers of stars. We adopt the parameters comparable to those of θ Leonis, a 2.5 $M_{\odot}$ A2 V star at a distance of 51 pc (J1114+1525). The model in this case has a total flux density at 85 GHz of 25.5 μJy, and a diameter of 0.723 mas. We simulate a 1 hour observation at 85 GHz.

Direct imaging becomes difficult in this regime, hence model fitting to the visibilities becomes the clearest physical diagnostic. Table 1 has the disk modeling fitting results, again using baselines appropiate for the main array only, and then including the long baselines. In this case, the total flux density is well fit by both short and long baselines procedures, but the errors on the diameters are significantly lower when including the longer baselines.

Figure 2 shows a radial binning of the Real part of the visibilities vs uv-distance, plus the model visibilities. The main array does not reach the first null in the visibility function. The longer baselines sample the first three nulls at reasonable signal to noise.

An A2 V Star at 100 pc: limiting case

To test the limits of an array such as the ngVLA, we model a hot main sequence star as above

(A2 V star), but now at a distance of 100 pc. We simulate a 4 hour synthesis at 85 GHz. The total flux density in the model is 6.4 μJy, and the stellar diameter is 0.36 mas. The results for disk fitting to the visibilities are again given in Table 1. We find that the flux density is well determined ($\geq 10\sigma$), and the diameter is fit to $\sim 3\sigma$. We consider this the limiting case for determining stellar properties with the ngVLA.

Number of Stars

Based on the simulations above, we adopt an extreme limiting case for determining stellar parameters of a 1σ limit in 1hr of 1.4 μJy beam^{-1} at 85 GHz and 0.4 mas stellar size. This limit imples an rms brightness temperature limit of 1500 K. M-type stars have optical photospheric temperatures of ~ 3000 to 4000 K, which would be at the limit of detection at this resolution. However, as mentioned above, at cm and mm wavelengths, the stellar atmospheres of main sequence stars can become optically thick in the chromosphere, which would enhance temperatures by a few thousand Kelvin. A size of 0.4 mas corresponds to the diameter of an M0 V star (optical radius of $0.6R_{\odot}$) at a distance of 15 pc. For A0 V stars (radius of $2.5R_{\odot}$), the distance is 60 pc. Red giant stars (radii of order $100R_{\odot}$), could be resolved to 2.4 kpc.

The Hipparcos catalog has a detailed listing of stellar spectral type, luminosity class, and distance (Perryman et al 1997). From these quantities, we derive angular sizes using standard relationships for stellar optical photospheric diameters from Allen's Astrophysical Quantities (Table 15.8). We then select for stars above -40^o Dec, with angular diameters > 0.4 mas. The results as a function of spectral type and luminosity class, are given in Table 2. The total number of stars evaluated was 32886[1]. Of these, 10151 are larger than 0.4 mas. The vast majority of the resolved stars are in the Giant or Supergiant class (9613 or 95% in class IV or lower). Yet there are still more than 500 main sequence stars (class V), that could be resolved by the ngVLA, with $\sim$ 50 to 150 in each spectral type, except for the O stars, including 145 'Solar-analog' stars ($B - V$ color index between 0.62 and 0.71).

For completeness, we have also searched the Gaia catalog. Based on the radii and distances in the catalog, we find that there are about 40,000 stars larger than 0.4 mas and Dec $\geq -40^o$.

Summary

Spatially resolving observations of the radio photospheres of main sequence stars provide critical information on scales relevant to the cooler optical photosphere, and the hot chromosphere. Such studies are fundamental to determining the structure of stars in the key transition region from the optical photosphere to the chromosphere – the regions powering exo-space weather phenomena. Future large area radio facilities, such as the ngVLA will transform the field of stellar radio photospheres, allowing for imaging and parameter estimation of thousands of main sequence and giant stars. For nearby main sequence stars (within ten parsecs or so) direct imaging may be plausible. For more distant stares (out to 100 pc), the primary physical parameters of diameter and brightness will be well constrained through uv-model fitting.

Using the Hipparcos catalog measurements of stellar spectral type, luminosity class, and distance for over 100,000 stars, we estimate that there are at least 10,000 stars that will be resolved by the ngVLA. While the vast majority of these (95%) are giants or supergiants, there are still over 500 main sequence stars that can be resolved, with ~ 50 to 150 of each spectral type (besides O stars).

[1] meaning stars with fully specified spectral type and luminosity class, not Carbon stars, and above -40^o Dec

Table 1: UV Fitting Results

Star	Max Baseline $\times 10^8 \lambda$	S_{mod} mJy	D_{mod} mas	S_{fit} mJy	D_{fit} mas
α Can Maj 85 GHz	3.0	1.63	6.0	1.6295 ± 0.0002	$6.039 \pm 0.005 \times 6.042 \pm 0.003$
α Can Maj 85 GHz	–	1.63	6.0	1.6295 ± 0.0002	$6.040 \pm 0.005 \times 6.043 \pm 0.003$
θ Leonis 85 GHz	3.0	0.0255	0.723	0.0251 ± 0.00077	$0.58 \pm 0.41 \times 0.61 \pm 0.12$
θ Leonis 85 GHz	–	0.0255	0.723	0.0251 ± 0.00075	$0.56 \pm 0.17 \times 0.63 \pm 0.08$
A2 V at 100pc 85 GHz	–	0.0064	0.36	0.0063 ± 0.0004	$0.45 \pm 0.14 \times 0.33 \pm 0.10$

Table 2: Hipparcos Stars > 0.4 mas, Dec $> -40^o$

	I	II	III	IV	V	Total
O	6	1	0	0	2	9
B	114	77	81	55	61	388
A	35	32	105	118	61	351
F	55	47	148	245	159	654
G	67	106	1120	351	107	1751
K	55	117	5351	227	104	5854
M	27	32	1039	2	44	1144
Total	359	412	7884	998	538	10151

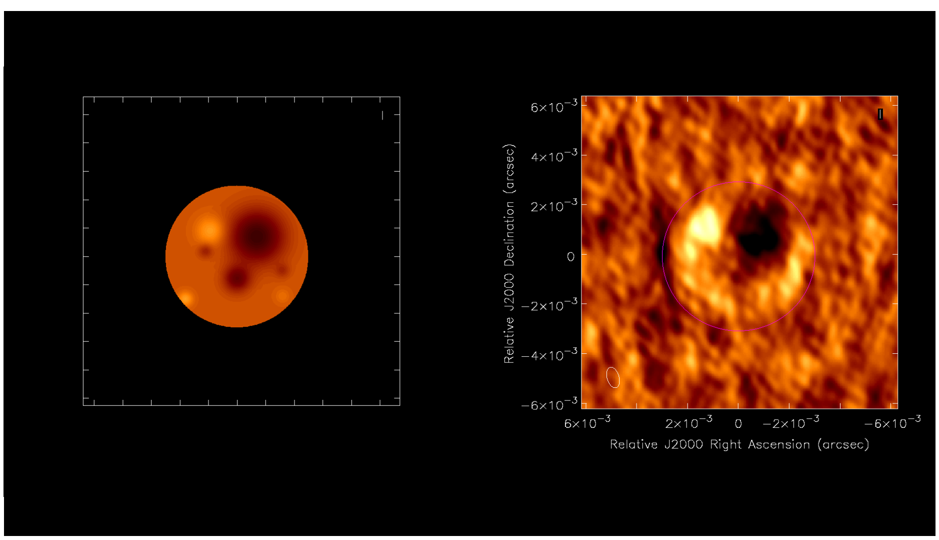

Figure 1: *Left: Input model for the stellar photosphere of Sirius, with artificial structure included at the* $\pm 10\%$ *brightness level to exercise imaging performance. Right: Image of Sirius with the ngVLA for a 16 hour synthesis, after fitting and subtracting a disk model to the visibilities. The resolution is 0.75mas and the rms = 0.5* μ*Jy beam*$^{-1}$.

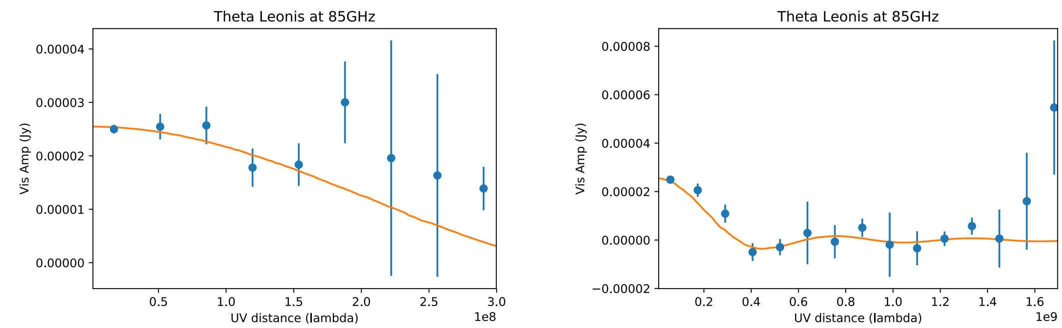

Figure 2: *Left: Azimuthally averaged Real part of the visibility curve for θ Leonis at 85 GHz. Points are the measurements for a 4 hour synthesis with the ngVLA main array to 1000 km. Right: including the long baseline configuration.*

References

Andrae, R., Fouesneau, M., Creevey, O. et al. 2018, A& A, in press ; Bolatto et al. 2013, ARAA, 51, 207 ; Carilli et al. 2018, ASPC, 517, 369 ; Defrere, D., Absil, O., Berger, J.-P., et al. 2018, Experimental Astronomy, in press ; Fichtinger, B., Gudel, M., Mutel, R. et al,. 2017, A & A, 599, 127 ; Gudel, M 2002, ARAA, 40, 217 ; Hallinan, G., Littlefair, S., Cotter, G. et al. 2015, Nature, 523, 568 ; Harper, G. 2018, ASPC, 517, 265 ; Harper, G., O'Riain, N., Ayres, T. 2013, MNRAS, 428, 2064 ; Lim, J., Carilli, C., White, S., Beasley, A., Marson, R. 1998, Nature, 392, 575 ; Linford, J., Chomiuk, L., & Rupen, M. 2018, ASPC, 517, 271 ; Matthews, L. & Claussen 2018a, ASPC, 517, 281 ; Matthews, L. & Claussen 2018b, DS2020 white paper ; Monnier, J. et al. 2007, Science, 317, 342 ; Monnier, J. 2003, Reports on Progress in Physics, 66, 789 ; Montarge, M., Norris, R., Chiavassa, A. et al. 2018, A& A, 614, 12 ; O'Gorman, E. et al. 2017, A& A, 602, L10 ; Osten, R., Crosley, M., Gudel, M. et al. 2018, Report for National Academy of Science Committee on Exoplanet Science Strategy ; Perryman M.A.C., Lindegren L., Kovalevsky J. et al. 1997, A& A, 323, L49 ; Selina et al. 2018, ASPC, 517, 15 ; Trigilio, C., Umana, G., Cavallaro, F. et al. 2018, MNRAS, in press ; Villadsen, J., Hallinan, G., Bourke, S. et al. 2014, ApJ, 788, 112 ; White, S.M., Iwai, K., Phillips, N. et al. 2017, Solar Phys, 292, 88 ; White, S.M., Iwai, K., Phillips, N. et al. 2017, Solar Phys, 292, 88