Science with an ngVLA: Stellar Activity on Red Giant and Supergiant Stars: Mass Loss and the Evolution of the Stellar Dynamo.

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Abstract. In this Chapter we examine the role of the ngVLA to further our understanding of the different manifestations of convective or turbulence-driven stellar activity on red giant and supergiant stars. The combination of high spatial resolution and high sensitivity will enable the ngVLA to significantly improve our understanding of the processes that dissipate energy in the extended atmospheres of cool evolved stars, and drive ubiquitous stellar outflows. The high spatial resolution will enable us to image the surfaces of nearby red supergiants, and to measure the atmospheric extent of red giants. Multi-frequency observations will permit thermal continuum tomography on the largest angular diameter stars, providing key empirical data to test theoretical models. The complementary frequencies and similar spatial resolutions of the ngVLA and ALMA will be a powerful synergy.

1. Context

Cool stars have vigorous sub-photospheric convection zones that lead to turbulent motions in their photospheres, and in the layers above. The interaction of surface magnetic fields (e.g., Aurière et al. 2015) and dynamic ionized plasma leads to complex phenomena including starspots, active regions, chromospheres, and stellar outflows. These manifestations of Stellar Activity (Schrijver & Zwaan 2000) are not well understood but have important astrophysical consequences, ranging from the effects of mass loss on galactic structure and chemical evolution, the nature of space-weather for exo-planets orbiting red giants, to the effects of cool supergiant mass-loss history on the interpretation of early-time supernovae spectra (e.g., Dessart et al. 2017). Theoretical models have not been able to reproduce observational signatures of stellar activity, and progress is being led by state-of-the-art observations made at the highest spatial resolution and with the greatest sensitivity.

Thermal radio continuum observations are powerful diagnostics in this context because the atomic cross-sections are very accurately known (Hummer 1988) and the emission source term is the Planck function, which is linear in electron temperature. For example, resolved VLA images provided a ground breaking discovery and new insights into red supergiant (RSG) outflows with the finding by Lim et al. (1998) that Betelgeuse’s extended atmosphere is cooler and much less ionized than predicted by leading theoretical and semi-empirical models of the time (see Hartmann & Avrett 1984; Harper et al. 2001).
However, red giants and supergiants are not strong radio emitters and have relatively small angular sizes so that future progress requires greater sensitivity and higher spatial resolution. The ngVLA will be able to provide both of these.

2. Mass Loss

Red giants and RSGs return mass that is enriched by nuclear processing back into the interstellar medium, supplying giant molecular clouds that may host the next generation of star formation, and leading to new stars and their exo-planets. The rate at which mass is returned by cool stars is, to a first approximation, proportional to a star’s surface area and the inverse cube of the surface escape speed (Holzer et al. 1983). So low surface-gravity cool evolved stars with radii $10^{-10}R_\odot$ currently inject more processed material than their main-sequence progenitors. However, the mechanisms that drive mass-loss for K through mid-M giants and the yellow and RSGs are very poorly understood: They have too little dust or molecules in their outflows for radiation driven winds; they have too little photospheric variability or pulsation to have acoustic and shock driven winds (e.g., Arroyo-Torres et al. 2015), and they are too cool for a Parker-like thermal winds. Some form of magnetic activity, or a combination of processes, is likely to be the cause of these ubiquitous mass outflows (Lamers & Cassinelli 1999). Clearly a quantitative physical model for mass loss is lacking for these stars, and even for the later spectral-type pulsating asymptotic giant branch (AGB) stars the role of magnetic fields in driving and shaping the outflows is not understood.

2.1. What Empirical Data do we Need to Make Progress?

Outflows from cool evolved stars have terminal wind speeds, $v_\infty$, that are typically a small fraction of the surface escape speed, $v_{esc}$. This means that most of the energy that goes into driving the outflows, proportional to $v_{esc}^2 + v_\infty^2$, goes into overcoming the star’s gravitational potential, i.e., $\propto v_{esc}^2$. Therefore, the optimum region to study mass loss mechanisms is within the first few stellar radii where most of the energy goes into the wind and the thermodynamic signatures of the outflow driving mechanisms will be most apparent.

Nearby red giants have photospheric angular diameters, $\theta_*$, of $10-20$ mas, and the two nearest RSGs (Betelgeuse: M2 Iab, and Antares: M1.5 Iab) have $\theta_* \approx 42-44$ mas (Ohnaka et al. 2013; Montargès et al. 2016). The luminous Herschel’s Garnet Star ($\mu$ Cep: M2 Ia) has $\theta_* = 14.1$ mas (Perrin et al. 2005), the next nearest luminosity class Iab-Ib RSG (CE Tau) has $\theta_* \approx 10$ mas (Cružalèbes et al. 2013), and $\alpha^1$ Her (M5 Ib-II) has $\theta_* = 33$ mas (Benson et al. 1993). Importantly, at 50 GHz, the atmospheres of RSGs have angular extents about twice that of their photospheres, and the ngVLA, with baselines of 200 km, would provide a resolution of better than 10 mas. This would match the highest ALMA spatial resolutions, for example, as shown in Figure 1.

This figure shows the 338 GHz (0.89 mm) thermal continuum image of the RSG Betelgeuse obtained with ALMA with the longest (16 km) baselines, providing a spatial resolution of 15 mas (O’Gorman et al. 2017). At this wavelength the atmosphere of the star has an angular diameter of $\sim 55$ mas, and this image shows the non-uniform heating in the atmosphere that might be related to giant convection cells or regions of enhanced magnetic fields. The thermal cm-continuum opacity $\kappa_\lambda \propto \lambda^{-2.1}$, so observations at multiple wavelengths map out the temperature and ion density distribution as a function of radius, providing vital clues to the processes levitating and heating
Stellar Activity on Red Giant and Supergiant Stars

Figure 1. 338 GHz ALMA map of Betelgeuse with a half-power beam width of $\approx 15$ mas (shown lower left), from O’Gorman et al. (2017). The yellow circle is the photospheric angular diameter measured with VLTI-PIONIER in H-band ($\approx 1.6\mu$m) by Montargès et al. (2016). The larger angular extent seen at ALMA frequencies reveals the lower chromosphere and temperature minimum region. In contrast, the frequencies probed by the VLA sample the more extended chromosphere and wind acceleration region. In this image localized excess emission is marked with crosses. The ngVLA would be able to image the extended regions with the same spatial resolution as ALMA, allowing us to build a tomographic map from the upper photosphere out into the region where the outflow is initiated. Credit: O’Gorman et al., A&A, Vol. 602, p. L11, 2017, reproduced with permission © ESO.

the stellar outflow. This requires that the ngVLA 200 km baselines support a range of observing frequencies.

3. Dynamos in Cool Evolved Stars

Most studies of solar-type $\alpha\Omega$ dynamos have focused on main-sequence stars that explore a relatively small parameter space of radius and mass, with a wide range of rotation rates (e.g., Brun & Browning 2017). Red giants, however, provide a different challenge for dynamo theories because they typically have low rotation rates but a much greater range of radii and convection zone depths. It is an open question as to whether an $\alpha\Omega$ dynamo is maintained on the red giant branch or whether a turbulent dynamo (e.g., Durney et al. 1993) is responsible for the generation of magnetic fields that power the ultraviolet (UV) and X-ray emission, and drive stellar outflows. Another important application for the long baselines of the ngVLA is to measure the extent of the magnetically heated chromosphere of red giant stars. Spatial resolution breaks the spatial impasse that limits what can be learned from disk integrated flux diagnostics alone (e.g., Harper et al. 2013). There are some recent clues that red giants show signs of magnetic cycles (Sennhauser & Berdyugina 2011) and non-uniform optical brightness distributions (Richichi et al. 2018), indications that magnetic phenomena might be important
in creating starspots and active regions. High spatial resolution ngVLA observations would reveal the radio size and uniformity of the chromosphere for the nearest red giant stars. This information would help constrain the nature of stellar dynamos, and thus the shape of magnetic fields that drive outflows from red giants. Such radio observations might also help determine whether low-activity red giants, so called basal-flux stars, are heated by acoustic shocks (Pérez Martínez et al. 2014). These would have compact chromospheres, but if they too are heated by magnetic fields (Judge & Carpenter 1998) they may have more extended atmospheres. There are 12 K and M non-Mira red giants with limb-darkened angular diameters >10 mas obtained with the Mark III Stellar Optical Interferometer (Mozurkewich et al. 2003) that would be resolved at 50 GHz with 200 km baselines. These stars are given in Table 1 along with the MK spectral-types from Keenan & McNeil (1989). The atmospheric electron density scale-heights are expected to be small compared to the stellar radii, so that the radio specific intensity distribution is, to first order, a top-hat and thus relatively easy to interpret. A sweep through radio continuum frequencies provides an opportunity to build a tomographic map of the mean atmospheric temperature profile: ngVLA observations would sample the key chromosphere and wind regions, while synergistic ALMA observations would probe the temperature minimum and upper photosphere (see Figures 1 and 2 of O’Gorman et al. 2013).

Table 1. Stellar properties for red giants with θ∗ >10 mas (Mozurkewich et al. 2003).

| HR Name | Spectral-Type | Ang. Diam. (mas) | T_eff (K) |
|---------|---------------|-----------------|----------|
| α Boo   | K1.5 III      | 21.37 ± 0.25    | 4226 ± 53 |
| β Umi   | K4- III       | 10.30 ± 0.10    | 3849 ± 47 |
| α Tau   | K5+ III       | 21.10 ± 0.21    | 3871 ± 48 |
| β And   | M0+ IIIa      | 13.75 ± 0.14    | 3763 ± 46 |
| δ Oph   | M0.5 III      | 10.47 ± 0.12    | 3721 ± 47 |
| α Cet   | M1.5 IIIa     | 13.24 ± 0.26    | 3578 ± 53 |
| η Gem   | M2 IIIa       | 11.79 ± 0.12    | 3462 ± 43 |
| β Peg   | M2.5 II-III   | 17.98 ± 0.18    | 3448 ± 42 |
| μ Gem   | M3 IIIab      | 15.12 ± 0.15    | 3483 ± 43 |
| δ Vir   | M3+ III       | 10.71 ± 0.11    | 3602 ± 44 |
| ρ Per   | M4+ IIIa      | 16.56 ± 0.17    | 3281 ± 40 |
| g Her   | M6- III       | 19.09 ± 0.19    | 3008 ± 37 |

4. Synergies with other Observatories

Free-free radio continuum diagnostics directly relate to the thermodynamic state of the atmospheres, and spatially-resolved multi-wavelength observations provide measures of the temperature and electron (ion) density scale-heights. The radio therefore provides the physical context with which to interpret optical and IR images made at similar high spatial resolutions. The 10 mas spatial resolution obtainable with the ngVLA complements the spectro-interferometry and imaging currently being made with the Very Large Telescope, (e.g., Kervella et al. 2016; Montargès et al. 2017).
Another ngVLA synergy is that with UV spectroscopy. UV emission line fluxes and radio optical depths are proportional to the emission measure, i.e.,

\[ F_{UV} \propto \int n_e n_H \, dR \, dA \quad \tau_{radio} \propto \int n_e^2 \, dR \]

where \( n_e \) and \( n_H \) are the electron and hydrogen densities, respectively. \( dR \) and \( dA \) are the radial and area integral elements, respectively. Since \( n_e \propto n_H \), then

\[ F_{UV} \propto \tau_{radio} \, dA. \]

The combination of radio and UV flux data, especially when spatially resolved, i.e., when \( dA \) is measured, provides very powerful constraints on inhomogeneous atmospheric structures because of the very different temperature sensitivities of radio and collisionally excited UV line emission.

5. Astrophysical Impact

One of the major goals of this research is to be able to build a quantitative predictive model of atmospheric structure and mass loss based on underlying physical principles. Such a model could be used to improve stellar and galactic chemical evolution calculations, and predict the mass-loss histories of RSG which would in turn help to interpret early-time supernova spectra (Moriya et al. 2017). Today we are very far from such a model. The observational constraints that the ngVLA will provide on red giant and RSG extended atmospheres, where the winds accelerate, would be a major step forward. ngVLA would provide the basic measurements of size, electron density scale-height, and degree of uniformity that any theoretical model must satisfy.

6. Uniqueness of the ngVLA Capabilities

The power of the ngVLA lies in its high-spatial resolution and high sensitivity which, when combined, provide the ability to probe the spatial scales of the extended near-star atmospheres of evolved stars. This is the zone where the physics that controls different aspects of stellar activity will reveal itself.

Acknowledgments. GMH thanks CU-CASA for infrastructure resources to support ongoing stellar astrophysics radio research. This research has made use of NASA’s Astrophysics Data System Bibliographic Services and the VizieR catalogue access tool, CDS, Strasbourg, France (Ochsenbein et al. 2000).

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