Massive and Evolved Stars with the ngVLA

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Abstract.
The Next Generation Very Large Array will have excellent sensitivity for detecting the thermal emission from massive stars and from red giants. This will allow direct imaging of the winds for a large number of hot massive stars. It will also allow using the radio emission for the massive stars as a way to detect stars to allow high resolution measurements can be made, even with large extinction. A few examples of the utility of the high resolution measurements are given: dynamics of globular clusters with red giants, detection of intermediate mass stripped stars in binaries, and measurement of masses of stars in massive binaries.

1. Description of the problem

Winds of hot massive stars are strong, spatially extended sources of free-free emission in the radio band. The acceleration of stellar winds is often probed via optical and ultraviolet emission lines, but is rarely directly resolved. Stellar winds from many classes of stars allow us to have bright radio sources that can be used as dynamical tracers, both for measuring the masses of massive stars in binaries and for measuring the gravitational potential fields in globular clusters, and should also provide a check on orbits around the Galactic Center. Estimates of the masses of the most massive stars have been extremely difficult in the past, with luminosities and single star evolutionary tracks and/or the Eddington limit used for mass estimates, rather than dynamical measurements typically used as a technique. By providing a tool for obtaining precise astrometry and high dynamic range, even in highly obscured parts of the sky, radio measurements of stellar masses will provide crucial information for understanding massive stars.

With globular clusters, it is quite controversial about whether the clusters contain intermediate mass black holes. Radial velocity measurements and proper motions of stars in the optical band are a valuable tool for probing the inner dynamics of star clusters, but are complicated by hard-to-constrain crowding effects. Using radio tracers of stellar dynamics will allow a complementary test of whether there are intermediate mass black holes in clusters, and will also allow measurements of the proper motions of the most extincted clusters.
Finally, observations with the Next Generation Very Large Array (ngVLA) should also be able to resolve stellar winds directly, and provide direct imaging constraints on the clumpiness and acceleration of stellar winds. They should also be able, through direct imaging, to determine whether stellar winds are anisotropic, as may be expected for rapidly rotating stars.

2. Scientific importance and Astronomical Impact

2.1. Understanding massive star winds

The winds from massive stars affect the whole evolution of the stars as well as the properties of the supernovae and massive remnants produced later in their lifetimes (see e.g Smith (2014) for a review). Understanding the stellar wind mass loss rates, and how the winds are accelerated, is thus an important process for interpreting supernovae, understanding the formation of compact objects, and understanding the deposition of metals into the Universe. Furthermore, the kinetic power of the winds themselves can sometimes be important for powering superbubbles.

Direct imaging of stellar winds has been done for some low mass stars, but never for massive stars. First, one can study, in detail, the spatial scale on which clumping in stellar winds takes place. It can be well established from the difference between line strengths in P Cygni profiles, which scale linearly with density, and free-free and recombination line tracers, which scale as density squared, that significant clumping must be present (Abbott et al. 1981; Smith 2014). For massive stars, the clumping factors are typically $\sim 5$ (Repolust et al. 2004; Markova 2004). Analysis which ignores clumping overestimates the mass loss rates by factors of $\sim 3$ in most cases, but in some extreme cases, overestimates of a factor of 10 have been suggested (Fullerton et al. 2006). Similar clumping factors have been suggested for cool evolved stars (Harper 2010).

Theoretical considerations suggest that the clumping is taking place primarily in the inner regions of the stellar wind, but at the present time, there is no direct imaging evidence of this. The spatial scale for the clumping should be smaller than the size scale of the star, but with the Long Baseline Major Option, this may be resolvable with ngVLA. Regardless, it should be straightforward to determine whether the clumping is taking place preferentially in the inner region of the wind.

Additionally, studies can be made of the departures from isotropy of stellar winds. Be star winds show a variety of lines of evidence for being disk-like. Understanding these stars’ winds is essential for developing a universal theory of mass loss, since it is generally believed that stellar winds from rapidly rotating stars are launched through a fundamentally different mechanism than those from other stars (Araya et al. 2018).

The core figure of merit for stellar wind observations would be the ability to make good measurements of the flux density per beam in each beam in reasonable exposure times. As a conservative flux estimate, we start with the equations from (Wright & Barlow 1975) for a constant velocity, smooth stellar wind, using the form from Güdel (2002):

$$R_{\text{thick}} = 8 \times 10^{28} \left( \frac{\dot{M}}{v} \right)^{2/3} T^{-0.45} v^{-0.7}$$

(1)
where \( R_{\text{thick}} \) is the radius of the optically thick part of the stellar wind, \( \dot{M} \) is the mass loss rate in \( M_\odot \text{ yr}^{-1} \), \( T \) is the wind temperature in K, \( v \) is the wind velocity in km/sec, and \( \nu \) is the frequency in Hz at which the observations are made.

Then, the flux density, \( S_\nu \) in mJy from the stellar wind is given by:

\[
S_\nu = 9 \times 10^{10} \left( \frac{\dot{M}}{v} \right)^{4/3} T^{0.1} d_{\text{pc}}^{-2} \nu^{0.6}
\]  \( \text{(2)} \)

if \( R_{\text{thick}} \) is greater than the stellar radius and

\[
S_\nu = 5 \times 10^{39} \left( \frac{\dot{M}}{v} \right)^2 T^{-0.35} R_*^{-1} d_{\text{pc}}^{-2} \nu^{-0.1}
\]  \( \text{(3)} \)

if \( R_{\text{thick}} \) is smaller than the stellar radius, \( R_* \), with \( d \) the distance to the star in pc.

For a massive star with a reasonably high mass loss rate, we can take \( \dot{M} = 10^{-5} M_\odot \text{ yr}^{-1} \), \( v=1000 \text{ km/sec} \), \( T = 10^4 \text{ K} \) and \( \nu=15 \text{ GHz} \). We find that the wind will be optically thick out to about 30 AU, considerably bigger than the stellar radius of massive stars. Next we can take \( d = 1 \text{ kpc} \), and we find that \( S_\nu = 6 \text{ mJy} \) for such a star, with an angular size scale of 30 milliarcseconds. With 1000 km baselines, the angular resolution at 15 GHz would be 4 milliarcseconds, allowing for about 50 beams across the source. If one assumes homogeneous surface brightness, this would yield 100 \( \mu \text{Jy/beam} \) flux densities, meaning that \( \sim 100 \sigma \) detections would be possible in each beam. Having so many well-detected beams would allow for careful studies of source structure, source variability, and source spectra, by making similar measurements at other frequencies. This would thus allow, in turn, for many stars, the decomposition of the radio emission into components from the thermal part of the wind, synchrotron emission from shocks (which should mostly contribute at lower frequencies), and from the stellar photosphere (which should contribute most at higher frequencies — see the contribution by Chris Carilli in this volume).

2.2. **Understanding massive star masses and orbits**

It is expected that the most massive stars should be found predominantly in binary (or other multiple) star systems with other massive stars, unless they have undergone mergers (\(?\)). Still, with the most massive stars, binary companions can be emitting a small fraction of the total starlight in the system, and hence can be extremely difficult to detect. Additionally, the radial velocity wobbles in such systems can also be very small. Precise astrometric measurements of the stars can provide an alternative means of establishing binarity in many cases, and, in the best cases, of estimating the masses of the stars.

The highest mass stars are expected to be about \( \sim 300 M_\odot \) or more (Crowther et al. 2010, 2016), and they show mass loss rates of \( 2 - 5 \times 10^{-5} M_\odot/\text{yr} \), despite being in the Large Magellanic Cloud, where low metallicity might be expected to suppress mass loss(Crowther et al. 2010). A small number of similar stars have been seen in the Milky Way, but extinction has generally made it difficult to identify such stars in our own Galaxy; the Magellanic Cloud stars themselves obviously cannot be measured with the ngVLA, but these similar stars can be identified in Galactic radio plane surveys, and studied carefully with additional follow-up. Conservatively assuming a typical 10 kpc distance, along with \( M = 2 \times 10^{-5} M_\odot/\text{yr} \), \( v_W \) of 2500 km/sec, we can expect radio
flux densities of about 50 $\mu$Jy for these stars at 15 GHz, and angular sizes of about 3 milliarcseconds (and perhaps a bit smaller if the winds are significantly hotter).

These objects are thus well-suited for astrometric work with the ngVLA. Positional measurements with precision of about 50 $\mu$arcsec should be reached in about one hour of observations, and with a set of longer observations, it should be possible to make geometric parallax measurements for these stars. Furthermore, if there are binary companions with even 10% of the flux of the primary stars, they should be detectable as well. In such a case, following the proper motions of both stars gives a “visual binary” type mass estimate for the two stars.

To establish that a system is a binary without detecting its companion star, one needs to make a measurement of the acceleration of the motion of the object. As a rule-of-thumb, let us consider a binary with separation of 100 AU (a fairly typical value in star-forming regions – Griffiths et al. (2018)). Such a binary, if the total system mass is 100 $M_\odot$ will have an orbital period of about 100 years. If the two stars are 10 $M_\odot$ and 90$M_\odot$, then the more massive star will have a reflex motion of about 10 AU, which will correspond to a total variation in position of 1 milliarcsecond. Over the course of 10 years of observations, it will move through 12° of its orbit, meaning that the deviation from a pure straight line will be about 20 $\mu$arcsec. The $\approx 0.1$AU/year velocity of the star’s motion, corresponding to 0.5 km/sec, is beyond present capabilities for radial velocity precision for massive stars, and is likely to remain that way – thus even if such a star can be detected in the infrared or optical bands with high signal-to-noise, its binarity can be studied only astrometrically. For a star like the one discussed in the preceding paragraph, spending about 20 hours per year on obtaining positions accurate to 10 $\mu$arcsec each would yield a data set sufficient for ruling out a straight-line fit. For more nearby star-forming regions, of course, such measurements could be made more quickly. For supergiant stars where the stellar photosphere may exceed the brightness of the stellar wind, such measurements could be made even more easily using the photospheric emission.

2.3. Detecting intermediate mass stripped stars

Stripped stars produced by binary stellar evolution are likely to be quite common in the Galaxy due to binary interactions, and to be an important source of ionizing radiation, due to their exceptionally hot temperatures (Götberg et al. 2018). Despite their importance, they can be difficult to detect when they have a massive binary companion, because of the higher luminosities (especially in the less extincted red bands) of their companion stars. The stellar winds from these stars can make them detectable in the radio. Taking numbers typical for these stars (Vink 2017), $M=10^{-7}M_\odot$/yr, $v = 2000$ km/sec, $T=50000$ K, $d = 2$ kpc, and an observing frequency of 30 GHz, the expected radius of the optically thick part of the stellar wind is 0.2 AU (meaning that these objects would appear to be point sources with inverted radio spectra unless they are very nearby), and the expected flux density is 0.2$\mu$Jy. In such systems, then, either two objects will be seen as a resolved binary, or the stellar winds are likely to be interacting such that synchrotron emission will be seen, and the systems will be identifiable as colliding wind binaries.

2.4. Proper motions of globular cluster and Galactic Center stars

The search for intermediate mass black holes in globular clusters has been a long-running source of controversy. A few approaches are typically used – searches for
accretion (e.g. Bahcall & Ostriker (1975); Maccarone (2004); chapter by Wrobel in this volume), searches for radial velocity excesses toward the center of the cluster (Watkins et al. 2015). All of these approaches have caveats. E.g. searches for evidence of accretion have been upper limits in current work, and only in a few cases is the gas content of the cluster well-established. With optical measurements, there are always potential problems associated with crowding in the inner regions of the clusters. Crowding problem will, in fact, be worse with JWST than with Hubble in the modes with large fields of view, but can be ameliorated with aperture masking. For radial velocities there can be additional complications due to the effects of rotation and binarity of the stars measured. Radio-based proper motions are ideal for solving this problem, so long as a sufficiently abundant set of dynamical tracers can be detected in the radio band.

Detection of photospheric emission from globular cluster stars in the radio will require prohibitive exposure times. Attempts to make radio measurements of globular cluster star motions thus rely on the use of radio-bright tracers. At the present time, pulsars and X-ray binaries may provide such tracers for a subset of clusters. These can be useful for bulk proper motion measurements and, in M4, for geometric parallax measurements. No cluster has a large enough number of detected pulsars and X-ray binaries to make useful radial velocity dispersion measurements.

It may become possible with ngVLA to make sure measurements with pulsars in Terzan 5, but ideally, we would be able to obtain larger samples of objects which are bright enough in radio to allow proper motion measurements. In fact, the stellar winds from red giants should provide such tracers. For a wind mass loss rate of $10^{-8} M_\odot/yr$ (Meszaros et al., 2008), a wind speed of 10 km/sec, and a distance of 4 kpc, the expected radio flux density is 11 $\mu$Jy, while the flux density would be 4 $\mu$Jy for $2 \times 10^{-9} M_\odot/yr$ (Cohen 1976), and clumping in the winds may make the radio fluxes brighter than these values.

To this sample of objects we can add the millisecond pulsars and X-ray binaries, which will generally be significantly brighter than 11 $\mu$Jy. With such a flux, using the Long Baseline Major Option, using only the antennas on the long baselines, with angular resolution of about 1.5 milliarcsecond (approximately the same as the expected angular size of the optically thick part of the stellar wind), each one-hour measurement will have a positional accuracy of about 150 $\mu$arcseconds. Over a 2-year time baseline, then, the proper motion accuracy of each star would be obtained to a precision of about 0.8 km/sec. As a result, then, the precision of the velocity dispersion within a bin would be set by the sampling of the velocity distribution, rather than by the precision of the measurements, unless very large numbers of stars were detected.

The uncertainty on the one-dimensional velocity dispersion from a set of Gaussian-distributed measurements will be $\sigma_v \sqrt{1/(2N)}$, where $\sigma_v$ is the velocity dispersion of the sample and $N$ is the number of stars measured. With two dimensions measured, there will be an extra $\sqrt{2}$ term, meaning that $\sigma_{v,m}$ for a bin, the measured velocity dispersion within that bin, will have a precision of $\frac{1}{2} \sqrt{1/N}$. Thus, with 20 stars per bin, 30% changes in the velocity dispersion will be measurable at the $3\sigma$ level. The massive globular clusters in the Galaxy tend to contain a few hundred to a few thousand bright red giant stars, meaning that the velocity dispersions should be measurable to ~ 5% for these clusters, providing significantly better tests of the IMBH hypothesis than can currently be achieved. For some of the less massive clusters it will, at least, be possible
to use the few brightest red giants to measure the clusters proper motions, and often geometric parallaxes, even for the case of heavily extincted clusters where Gaia is not effective.

3. Connection to unique ngVLA capabilities

The interest in resolved emission at high frequencies on angular scales of $\sim 10 - 100$ milliarcseconds is fundamentally ngVLA science. At the present time, only eMERLIN covers a similar angular resolution scale, but eMERLIN has much worse sensitivity than the ngVLA will, is located far North so that a much smaller fraction of the Galactic Plane is observable, and is in a location where the prevailing weather conditions make an expansion beyond 22 GHz unlikely to occur (or to provide much useful data). For the astrometric work on massive stars, ngVLA allows seeing through large extinction and looking at the Galactic massive star population in a way that cannot be done easily in optical and infrared. For the astrometric work on giants in globular clusters, the ngVLA measurement allow avoidance of the crowding and the highest possible angular resolution through the use of the Long Baseline Major Option. Without the Long Baseline Major Option, the proper motion precision could still be obtained by achieving higher signal-to-noise measurements, but it would be more difficult to ensure that there was no crowding affecting the measurements.

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References

Abbott D.C., Bieging J.H., Churchwell E., 1981, ApJ, 250, 645
Araya I., Curé M., ud-Doula A., Santillán A., Cidale L., 2018, MNRAS, 477, 755
Bahcall J.N., Ostriker J.P., 1975, Nature, 256, 23
Cohen J.G., 1976, ApJ, 203, 587
Crowther P.A., Schnurr O., Hirschi R., Yusof N., Parker R.J., Goodwin S.P., Kassim H.A., 2010, MNRAS, 408, 731
Crowther P. et al., 2016, MNRAS, 458, 624
Fullerton A.W., Massa D.L., Prinja R.K., 2006, ApJ, 637, 1025
Götberg Y., de Mink S.E., Groh J.H., Kupfer T., Crowther P.A., Zapartas E., Renzo M., 2018, A&A, 615, A78
Griffiths D.W., Goodwin S.P., Caballero-Nieves S.M., 2018, MNRAS, 476, 2493
Güdel 2002, ARA&A, 40, 217
Harper G.M., 2010, ApJ, 720, 1767
Maccarone T.J., 2004, MNRAS, 351, 1049
Markova N., Puls J., Markov H., 2004, A&A, 413, 693
Meszaros S., Dupree A.K., Szentgyorgyi A., 2008, AJ, 135, 1117
Noyola E. Gebhardt K., Bergmann M., 2004, A&A, 413, 693
Repolust T., Puls J., Herrero A., 2004, A&A, 415, 349
Sana H., et al., 2012, Science, 337, 444
Smith N., 2014, ARA&A, 52, 487
Vink J., 2017, A&A, 607L, 8
Watkins L.L., van der Marel R.P., Bellini A., Anderson J., 2015, ApJ, 803, 29
Wright A.E., Barlow M.J., 1975, MNRAS, 170, 41