Astrometry and Long Baseline Science

Mark Reid,[1] Laurent Loinard,[2] and Thomas Maccarone[3]

[1]*Harvard-Smithsonian CfA, Cambridge, MA, USA;* `reid@cfa.harvard.edu`

[2]*Centro de Radioastronomía – UNAM, Morelia, Michoacán, Mexico;*
`l.loinard@crya.unam.mx`

[3]*Texas Tech University, Lubbock, TX, USA;* `Thomas.Maccarone@ttu.edu`

Abstract. Recent advances in VLBI have led to astrometric accuracy exceeding that of the *Gaia* mission goals. This chapter describes some important astrophysical problems that can be addressed with sub-milliarcsecond imaging and μas astrometry using the ngVLA with long baselines.

1. Introduction

Astrometry at centimeter to millimeter wavelengths has advanced dramatically over the last decade. VLBI techniques have been perfected and relative positional accuracy of $\approx 10\,\mu$as is routinely achieved for compact sources relative to background quasars (Reid & Honma 2014). Indeed, this demonstrated astrometric accuracy exceeds that of the *Gaia* mission goal and, since radio waves can penetrate even hundreds of magnitudes of visual extinction, provides unique opportunities to fully explore the Galactic plane and deeply embedded sources in star forming regions. Long baseline radio interferometry has produced some remarkable results, including 1) detailed mapping of accretion sub-parsec scale disks around supermassive black holes in galaxies well into the Hubble flow, yielding "gold standard" masses for the black holes and direct estimates of the Hubble constant independent of all other methods (Gao et al. 2016), and 2) measurements of trigonometric parallax to masers in star forming regions across large portions of the Milky Way, revealing its true spiral structure, size, and rotation curve (Reid et al. 2014).

Many potential applications of radio astrometry are currently limited by the sensitivity of long baseline interferometry with, for example, ten antennas of 25-m diameter. The ngVLA Long Baseline Array (LBA), with its baselines comparable to the size of North America, could provide a sensitivity increase of more than an order of magnitude, which translates to the ability to detect > 30-times more sources (for $N \propto S^{-3/2}$), both for astrometric targets and background quasars. The greatly increased background source counts project to a decrease in target-quasar separation by a factor of $\sqrt{30}$, which directly translates to improved astrometric accuracy by the same factor. Thus, the ngVLA could potentially achieve astrometric accuracies of $\approx 1\,\mu$as! In this chapter we explore some of the applications of the astounding capabilities of the ngVLA with long baselines based on our current knowledge of the Universe. Of course, by

2030 and later, new and unknown applications are almost certain to be important for the advancement of astrophysics.

2. Gravitational Wave Sources

The ngVLA has the potential to directly observe the last stages of the inspiral of compact binaries, as well as post merger activity, across the Universe. The merger of two neutron stars, such as recently observed by *LIGO*, or a neutron star and a black hole, can produce emission across the electromagnetic spectrum. Even at distances of hundreds of Mpc, the ngVLA could make movies of expanding ejecta or jets, since at cosmological source distances, scales of ~ 1 pc correspond to ~ 1 mas (Alexander et al. 2017). One can also expect to witness the inspiral of supermassive black holes (SMBHs), complementing a future space-based gravitational wave detector like *LISA*, by providing the only way to achieve *resolved* images of electromagnetic counterparts.

The International Pulsar Timing Array goal is to detect gravitational waves by timing an array of about 30 pulsars. While distances to these pulsars can be solved for from the timing data, having to solve for these terms introduces a noise term and parameter correlations. Obtaining independent pulsar distances via trigonometric parallaxes will be possible with long baselines on the ngVLA, and this could substantially increase the sensitivity of gravitational wave detections. (See also §4 for the importance of accurate distance for the interpretation of the effects of gravitation radiation.)

3. Black Holes

Fermi has detected an amazing variety of energetic phenomena, including beams of particles of unexpectedly high energy. Some of the most energetic sources in the universe are found in AGN. One of the most important and long-standing problems in astrophysics is to answer how do cosmic accelerators work and what are they accelerating? VLBA imaging of AGNs has revealed that gamma-ray emission comes from jet components (Hodgson et al. 2017), and not always from the immediate vicinity of SMBHs. Still, important questions remain: Are jets proton-electron or positron-electron plasma? What powers and collimates AGN jets and how do these jets evolve and interact with their host galaxy? Long baseline radio interferometry provides the highest angular resolution possible to make movies of these amazing phenomena on scales down to the ergospheres of nearby SMBHs. Note that recent advances in theory and computation have opened the possibility of fully relativistic, magneto-hydrodynamic simulations in 3-dimensions. High sensitivity and resolution observations with long baselines on the ngVLA will be critical to guide simulations and finally arrive at a deep understanding of these fundamental astrophysical phenomena.

H_2O masers in AGN accretion disks have been used to measure accurate SMBH masses and the Hubble constant. But they also have the potential to determine physical properties of these sub-parsec scale disks. Of particular interest is mapping the magnetic fields in these disks via spatially resolved polarization measurements (Zeeman effect). Currently, observations have provided upper limits to magnetic field strength (Modjaz et al. 2005), but, with the greatly increased sensitivity of the ngVLA, detection should be possible. Indeed, it will be the only telescope that can make such resolved measurements in the foreseeable future.

Stellar mass black holes pose equally fascinating questions. Do these black holes form from supernova (SN) or by direct collapse without explosions? What is the origin of black hole spin? The ngVLA will be able to provide unique clues that address these questions by measuring parallax and proper motions. For example, the long-standing controversy over the distance to Cyg X-1 (the source of the famous wager between Thorne and Hawking) was recently resolved by long baseline radio astrometry; its accurate parallax distance of 1.86 ± 0.12 kpc (Reid et al. 2011) allowed a precise determination of the mass of the compact object of $15 \pm 1\, M_\odot$ (Orosz et al. 2011), clearly indicating a black hole, and was key to determining that the black hole is spinning maximally with $a_* > 0.92$ (Gao et al. 2011). This binary is too young for accretion to have appreciably spun up the black hole, indicating it was born with great spin. Regarding its birth, its measured distance and proper motion (peculiar motion of only 20 km/s) matches that of the Cyg OB3 star-forming cluster, establishing that it was born in this young cluster. Since a SN explosion would have disrupted the region, the black hole probably formed with a quiet, prompt stellar collapse (Mirabel & Rodrigues 2003). But this is only one source and similar measurements of many more, weaker sources with the ngVLA are needed to understand their complete demographics and determine how they formed. It is important to note that most known black hole X-ray binaries are both too far and too extincted for precise *Gaia* parallaxes.

At the present time, measurements of astrometric wobble of the black hole (induced by the secondary star in the binary) are marginally possible in one X-ray binary, Cygnus X-1 (Reid et al. 2011). With the ngVLA, if it has enough collecting area on long baselines, proper tracing of orbits should become possible for a few X-ray binaries, both due to the increased sensitivity and the ability to work at higher frequencies, which will allow both better angular resolution and more easily manageable systematics due to less extended emission from jets. This is vital, because the biggest uncertainty in black hole mass measurements usually comes from the precision of the estimation of the inclination angle of the orbit, since the inferred mass scales as $\sin^3 i$. Additional uncertainties come into play from having incorrect inclination angles using either the disk continuum method for spin estimation (e.g., Steiner et al. 2017) or the reflection method (e.g., Garcia et al., 2013).

Understanding the distribution of masses of black holes and neutron stars is one of the few means we have to probe the actual process of supernova explosions. At the present time, there appears to be a gap between the lowest mass black holes and the highest mass neutron stars, which would imply that whatever instability causes supernovae to actually blow up must be relatively rapid (Belczynski et al. 2012), but it remains quite possible that the gap is an artifact of the biases in inclination angle measurements from ellipsoidal modulations (Kreidberg et al. 2012). Having even a few systems where direct inclination angle measurements from astrometric wobble can be used to calibrate the ellipsoidal modulation of the secondary's light would be vital for building samples of well-understood black hole masses and spins.

4. Fundamental Physics

Pulsar parallaxes and proper motions precisely locate these stellar remnants in the Galaxy and provide full phase-space information. Coupled with rotation and dispersion measurements, this can be used to model the magnetic field and electron density of the Milky Way (Cordes et al. 1991). Peculiar motions (after removing Galactic ro-

tation) give direct information on "kicks" received at birth by asymmetrical SN explosions. Additionally, knowing distances to pulsars allows accurate mass measurements. Pulsar mass is the key parameter to discriminating among competing models for the equation-of-state of material at the extreme density of neutron stars.

One interesting problem critically dependent on the Galaxy's fundamental parameters (e.g., R_0 & Θ_0; see the Milky Way section below) involves the interpretation of the orbital decay of the Hulse-Taylor binary pulsar system, owing to gravitational radiation as predicted by General Relativity. In 1993, the Nobel Prize in Physics was awarded for this measurement. In order to properly interpret the observed decay rate, one needs to account for the accelerations of the Sun (Θ_0^2/R_0) and the pulsar [$\Theta(R)^2/R$] from their Galactic orbits. In 1993, uncertainties in the values of R_0 and Θ_0 limited the Relativity test to ±0.23%. With improved values based on maser parallaxes, this uncertainty was reduced by a factor of 3. Interestingly, with these values, there is a 3σ discrepancy from General Relativity, using the pulsar distance of 9.9 kpc assumed in 1993. This discrepancy would vanish if the pulsar distance is 7.2 kpc (Reid et al. 2014). An accurate pulsar parallax is critical to test this prediction, but may require the sensitivity of the ngVLA as the pulsar is weak. Of course there are other binaries that can be used to test General Relativity, and distances to these coupled with accurate models of the Galaxy are needed and could be supplied by the ngVLA with long baselines.

Are physical "constants", such as the fine-structure constant and the proton-to-electron mass ratio, different in the early Universe? Does the cosmic microwave background temperature evolve as predicted with redshift? These and other questions (see section on Galaxy Evolution) can be addressed by imaging molecular clouds at high redshift in absorption against bright AGNs. However, high sensitivity and angular resolution (~ 1 mas) are crucial to detecting and isolating (resolving) individual pc-scale clouds, since observations at lower resolutions blend together clouds that have a wide range of physical conditions (Sato et al. 2013).

5. Galaxy Evolution

The Local Group offers a critical opportunity to study the formation and evolution of galaxies with extremely high resolution (i.e., local cosmology). Long baseline observations have been able to measure the proper motions of two of Andromeda's satellite galaxies, M 33 (Brunthaler et al. 2005) and IC10 (Brunthaler et al. 2007). Figure 1 schematically shows the locations of the Milky Way, M 31 (Andromeda) and M 33, along with the motion of M 33. These constrain values of the distance and mass of Andromeda. The key parameter for determining the the distribution of dark matter and the history and fate of the Local Group is the proper motion of Andromeda itself, which would give its 3-D velocity relative to the Milky Way.

Current estimates of Andromeda's proper motion vary considerably, from values near zero to over 100 km/s. This range allows scenarios in which Andromeda directly hits the Milky Way in a few billion years or instead they could orbit each other for a very long time. The most direct and accurate measurement to solve this problem would be astrometric measurements of the AGN in Andromeda, M 31*, with μas accuracy over several years. This may only be possible with the ngVLA LBA, since M 31* is extremely weak, ~ 10 μJy.

How early do SMBHs form and how do they relate to their protogalaxies? When studying protogalaxies, it is crucial to understand what portion of the emission is at-
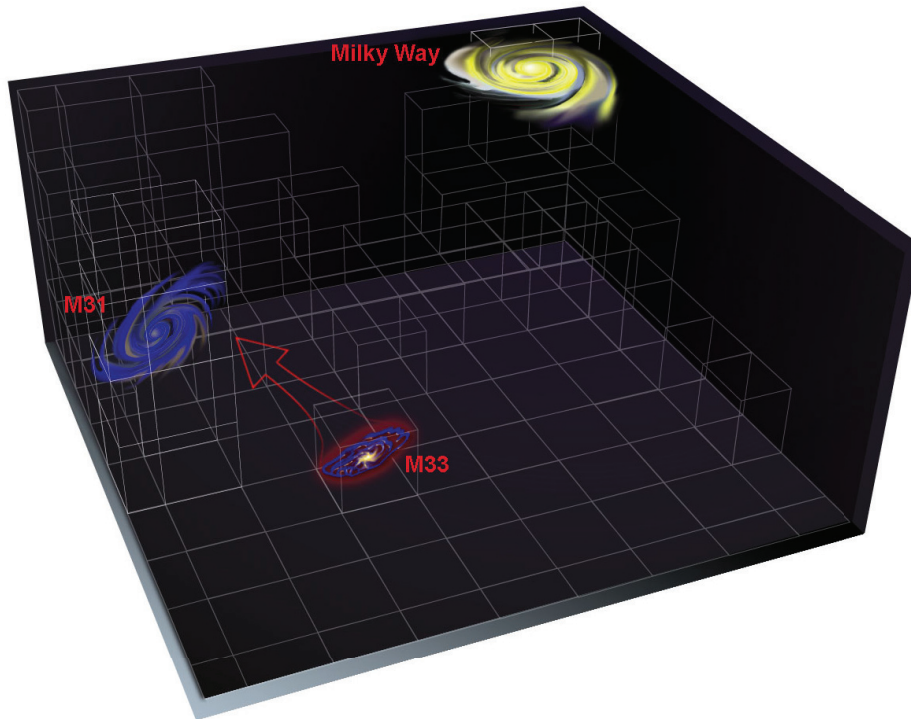
Figure 1.   Local Group proper motions. Schematic view of the Local Group of Galaxies with the Milky Way in the upper right and the Andromeda galaxy (M 31) in the left. The measured 3-D motion of M 33 is indicated with the red arrow. Only the radial component, approaching the Milky Way at $\approx$ 110 km s^{-1}, of the motion of Andromeda is known. If Andromeda's proper motion is small it will collide with the Milky Way in a few billion years. However, if it has a substantial proper motion ($\sim$ 100 km s^{-1}), Andromeda and the Milky Way will orbit each other for a very long time.

tributable to a SMBH and what comes from a more extended star-burst. At $z \approx 6$, a 100 pc sized star-burst nucleus subtends 18 mas (and smaller at intermediate redshifts). For a radio-bright SMBH, the best telescope to resolve and separate AGN from star-bursts would be the ngVLA with long baselines.

Are molecular clouds seen toward high redshift galaxies different than those seen locally? Molecular absorption line observations at the high angular resolution afforded by long baselines on the ngVLA may be the only foreseeable way to probe the density, temperature, and structure (filamentary?) of molecular clouds in the early Universe.

6. Milky Way Structure

VLBI parallax and proper motions of masers have been measured for ≈ 200 high mass star formation regions (HMSFRs), as shown in Figure 2. These clearly trace spiral structure across large portions of the Milky Way (Reid et al. 2014), and provide the most accurate estimates of the distance to the Galactic center, R_0 (currently with about 2% accuracy), the rotation speed of the Galaxy at the Sun, Θ_0, and the Galaxy's rotation curve. However, with current sensitives, very few sources are detected that are beyond the Galactic center. So, roughly half of the Milky Way remains "terra incognito." The ngVLA LBA, with baselines of thousands of km, will have the sensitivity and angular resolution to complete a map of the Milky Way. The greater sensitivity of the ngVLA, compared to the current VLBA, allows the use of weaker QSOs that are then closer in angle to the target sources. This yields improved parallax accuracy which coupled with an increased sample size should allow estimation of R_0 to 1% accuracy.

Pulsar parallaxes can provide an accurate map of their locations in the Galaxy. Coupled with rotation and dispersion measurements, they can be used to model the magnetic field and electron density of the Milky Way. Since radio astrometry improves dramatically at frequencies above a few GHz (to minimize the turbulent and difficult to model ionosphere), the greatly improved sensitivity of the ngVLA, compared to current long baseline interferometers, is needed to do astrometry on these very steep-spectrum sources.

7. Young Stars and Stellar Systems

The evolution of a star is almost entirely determined by its mass (and, to a much smaller extent, its chemical composition). Thus, direct stellar mass measurements are of great importance to constrain theoretical stellar evolution models. Such measurements can be obtained in multiple stellar systems if the orbital motions are monitored with sufficient accuracy and over a period covering a significant fraction of an orbital period. For main and pre-main sequence stars, this is best achieved using optical and near-infrared imaging techniques (adaptive optics, aperture masking interferometry, etc.). However, for protostellar objects one must turn to longer wavelengths on account of the high extinction that affects such deeply embedded objects. Millimeter and centimeter interferometric observations are critical, since they can reach both very high angular resolution and high astrometric accuracy.

At the moment, monitoring of orbital motions has only been possible for a small number of very young (class 0) stellar systems: e.g., IRAS 16293–2422 (Loinard et al. 2002), L1551 IRS5 (Rodriguez et al. 2003), and YLW15 (Curiel et al. 2002), via
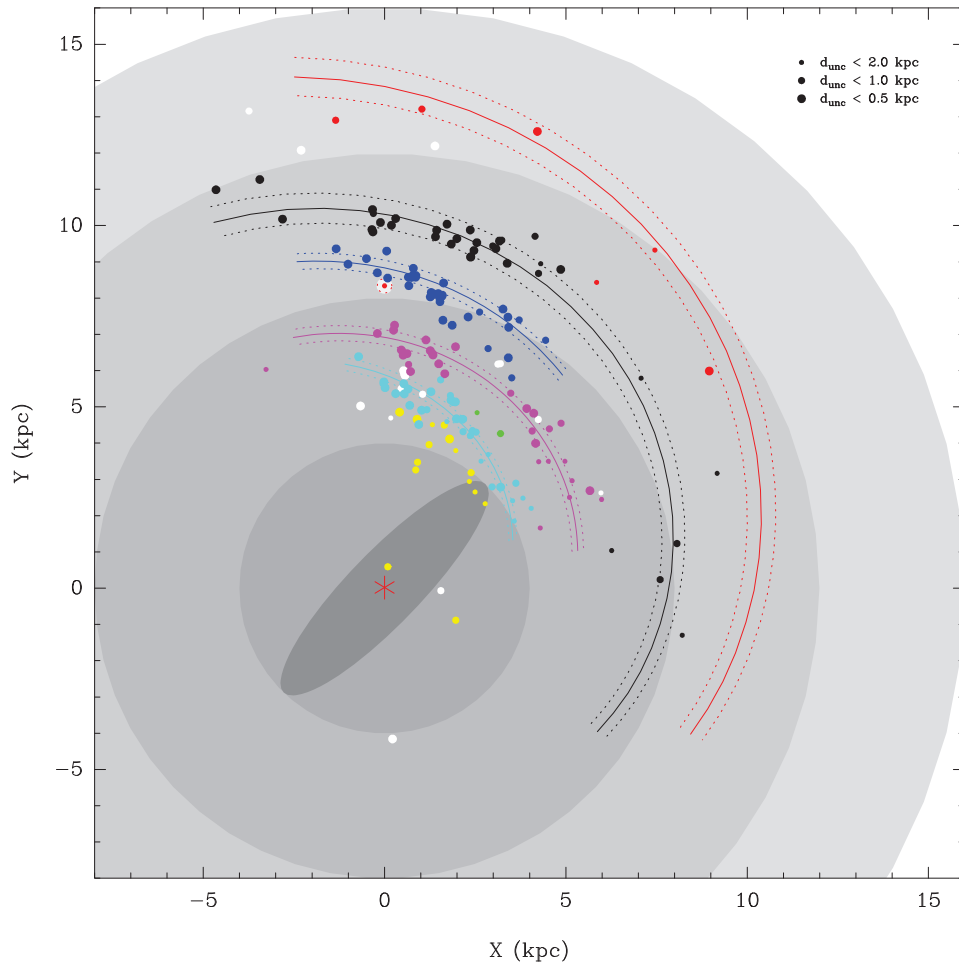
Figure 2. Plan view of the Milky Way showing the locations of high-mass star forming regions (HMSFRs) with trigonometric parallaxes measured with VLBI (Reid et al, in preparation). The Galactic center (*red asterisk*) is at (0,0) and the Sun (*red Sun symbol*) is at (0,8.34). HMSFRs were assigned to spiral arms based primarily on association with structure seen in $\ell - V$ plots of CO and hydrogen emission (and not based on the measured parallaxes): Inner Galaxy sources, *yellow dots*; Scutum arm, *cyan octagons*; Sagittarius arm, *magenta hexagons*; Local arm, *blue pentagons*; Perseus arm, *black squares*; Outer arm, *red triangles*. Distance errors are indicated in the legend. The background grey disks provide scale, with radii corresponding in round numbers to the Galactic bar region (≈ 4 kpc), the solar circle (≈ 8 kpc), co-rotation of the spiral pattern and Galactic orbits (≈ 12 kpc), and the end of major star formation (≈ 16 kpc). The "long" bar is indicated with a shaded ellipse. The *solid* curved lines trace the centers (and *dotted* lines the 1σ widths) of the spiral arms. Note that there are few measurements for sources beyond the Galactic center (negative Y values); long baselines with the ngVLA will provide the sensitivity and angular resolution to help finish this map.

multi-epoch VLA observations. However, none of these observations cover a sufficient fraction of an orbit to enable a reliable mass estimate. The ngVLA, having baselines longer than 300 km and a sensitivity 10-times higher than the VLA, will permit significant progress in two ways. First, relative positions between the members of binary systems could be measured to at least 10-times higher accuracy, and this would result in a much higher precision in orbit (and, therefore, mass) determination. Second, the higher resolution of the ngVLA would enable the identification of much tighter systems (with separations as small as $\sim$ 10 mas, compared with $\sim$ 100 mas for the VLA) with commensurably shorter orbital periods. Reliable mass measurements would be attained for such systems. It is worth emphasizing that the very early evolution of stars is still a very open research topic and that accurate mass measurements at the earliest protostellar stages would have a great impact.

Protostellar jets are ubiquitous in young stellar objects, and two mechanisms have been proposed to explain their launching. In magnetospheric models, they are associated with the accretion mechanisms that occur on scales of $\sim$ 0.1 AU ($\sim$ 1 mas at the distance of nearby star-forming regions). For disk-wind models, in contrast, the launching occurs on scales comparable with those of the inner accretion disk region ($\sim$ 10 AU; or 100 mas). Baselines of at least 300 km would provide an angular resolution in the centimeter regime of about 10 mas, which would be sufficient to discriminate between the two mechanisms, and to resolve the jets in the transversal direction if the disk-wind hypothesis holds. However, baselines of at least a few thousand kilometers (i.e.,the ngVLA LBA) are required to resolve jets launched through magneto-centripetal acceleration.

8.   Commercial Applications

While the benefits of the ngVLA to classical astrophysics have been discussed above, there may be significant other benefits to society. VLBI observations supply accurate telescope locations on a global scale. This is used to calibrate GPS positioning, which is an integral part of our economic activity. Also VLBI has demonstrated that it can track spacecraft with exceptional accuracy. Had VLBI been used to track the Martian lander that crashed into its surface, the metric-vs-English units error that lead to the multi-billion dollar disaster could have been caught and rectified. As the USA aims to send robotic crafts and humans to Mars and beyond, it seems foolish (and dangerous) not to use the best independent method of spacecraft tracking, which the ngVLA LBA could provide.

References

Alexander, K. D. et al. 2017, ApJ, 848, 21
Belczynski, K., Wiktorowicz, G., Fryer, C. L. et al. 2012, ApJ, 757, 91
Brunthaler, A. et al. 2005, Sci, 307, 1440
Brunthaler, A. et al. 2007, A&A, 462, 101
Cordes, J. M. et al. 1991, Nat, 354, 121
Curiel, S., Girart, J. M., Rodriguez, L. F. & Canto, J. 2002, ApJ, 638, 878
Gao, L. et al. 2011, ApJ, 742, 85
Gao, F. et al. 2016, ApJ, 817, 128
Garcia, J., Dauser, T. Reynolds, C. S. et al. 2013, ApJ, 768, 146
Hodgson, J. A. et al. 2017, A&A, 597, 80

Kreidberg, L., Bailyn, C. D., Farr, W. M. & Kalogera, V. 2012, ApJ, 757, 36
Loinard, L. 2002, RMxAA, 38, 61
Mirabel, I. F. & Rodrigues, I. 2003, Sci, 300, 1119
Modjaz, M., Moran, J. M., Kondratko, P. T. & Greenhill, L. J. 2005, ApJ, 626, 104
Orosz, J. A. et al. 2011, ApJ, 742, 84
Reid, M. J. et al. 2011, ApJ, 742, 83
Reid, M. J. & Honma, M. 2014, ARA&A, 52, 339
Reid, M. J. et al. 2014, ApJ, 700, 137
Rodriguez, L. F. et al. 2003, ApJ, 583, 330
Sato, M., Reid, M. J., Menten, K. M. & Carilli, C. L. 2013, ApJ, 764, 132
Steiner, J. F., Garcia, J. A., Eikmann, W. et al. 2017, ApJ, 836, 119