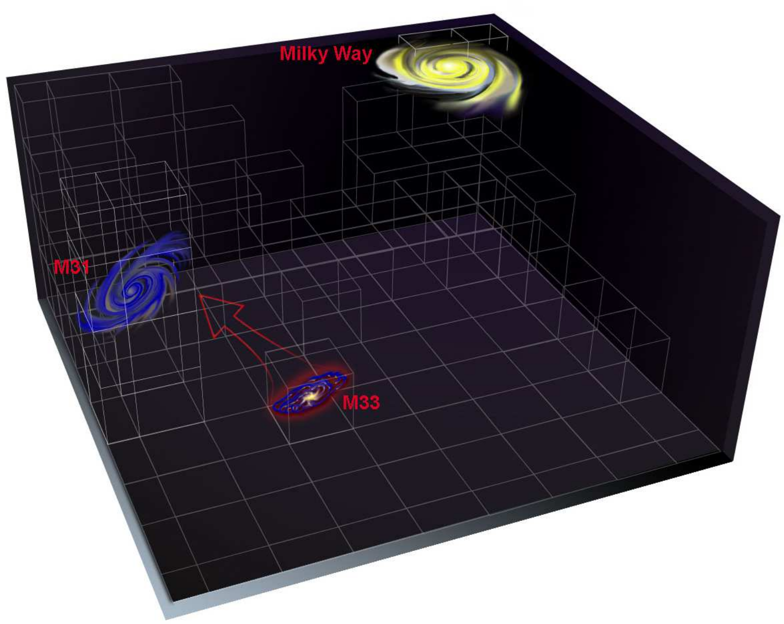
Astro2020 Science White Paper

Science Opportunities with Long Baseline Radio Interferometry and Micro-arcsecond Astrometry

Thematic Areas: ☑ Planetary Systems ☑ Star and Planet Formation
☑ Formation and Evolution of Compact Objects ☑ Cosmology and Fundamental Physics
☑ Stars and Stellar Evolution ☑ Resolved Stellar Populations and their Environments
☑ Galaxy Evolution ☑ Multi-Messenger Astronomy and Astrophysics

Principal Author:
Name: Mark J. Reid
Institution: Center for Astrophysics | Harvard & Smithsonian
Email: reid@cfa.harvard.edu
Phone: 617 495 7470

Co-authors:
Laurent Loinard, Centro du Radioastronomía – UNAM, Mexico
Thomas Maccarone, Texas Tech. University
Carl Melis, UCSD



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). 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 highly extincted regions such as galactic nuclei and the plane of the Milky Way. VLBI has produced some remarkable results, including 1) detailed mapping of sub-parsec scale accretion 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). With increased sensitivity, such as could be provided by the ngVLA, 1 μas astrometry can be achieved, opening a unique window for a wide variety of astrophysical sources and problems associated with all Decadal thematic areas.

2 Gravitational Wave Sources

Long baseline interferometry at centimeter and millimeter wavelengths 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, one could make movies of expanding ejecta or jets, since at cosmological distances, scales of ~ 1 pc correspond to ~ 1 mas. With current sensitivity limits of $\sim 10\ \mu$Jy, detections have been made (Alexander et al. 2017), but with an order of magnitude improvement in sensitivity such observations could be routine. With 1 μJy sensitivity, one can also reasonably 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.

3 Supermassive 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 can come 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 interferomet provides the highest angular resolution possible to make movies of these amazing phenomena on scales down to the ergospheres of nearby SMBHs (Blecha et al. 2018). 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 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.

4 Stellar Black Holes

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? Long baseline interferometry can 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 VLBI 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 ± 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 (giving a 3-Dpeculiar 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 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 increased collecting area on long baselines, proper tracing of orbits should become possible for a reasonable sample of 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 largest uncertainty in black hole mass measurements usually comes from the accuracy of the estimation of the inclination angle of the orbit, since the inferred mass scales as $\sin^3 i$ (e.g. Steiner et al. 2017 and 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 a reasonable sample of systems with direct inclination angle measurements from astrometric wobble, we can then calibrate the ellipsoidal modulation of the secondary's light in order to building large samples of well-understood black hole masses and spins.

5 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 rotation) 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 (eg, 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 $\pm 0.23\%$. 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 increased sensitivity compared to current arrays, since 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.

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).

6 Galaxy Evolution

The Local Group offers a critical and unique opportunity to study the formation and evolution of galaxies with extremely high resolution (ie, 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). The cover figure 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. However, 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 (Loeb et al. 2005, van der Marel et al. 2012). This large 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 an order of magnitude increase in sensitivity compare to current VLBI arrays, since M 31* is extremely weak ($\sim 10\ \mu$Jy).

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 attributable to a SMBH and what comes from a more extended star-burst. At $z \approx 6$, a 100 pc scale 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 a sensitvie long baselines radio interferometer.

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

7 Milky Way Structure

VLBI parallax and proper motions of masers have been measured for ≈ 200 high mass star formation regions (eg, Reid et al 2014). These clearly trace spiral structure across large portions of the Milky Way, and provide very 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." With improved sensitivity compared to current VLBI observations, we could complete a map of the Milky Way. Note that improved sensitivity allows the use of weaker QSOs that are generally closer in angle to the target sources. This yields improved astrometric accuracy which, coupled with an increased sample size, should allow estimation of R_0 to better than 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 effects of the turbulent and difficult to model ionosphere), greatly improved sensitivity compared to current long baseline interferometers, is needed to do astrometry on these very steep-spectrum sources.

8 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 protostellar objects one must use radio wavelengths owing to the high extinction for such deeply embedded objects. Millimeter and centimeter interferometric observations are critical, since they can reach both very high angular resolution and high astrometric accuracy.

Currently, monitoring orbital motions has only been possible for a small number of very young (class 0) stellar systems: eg, IRAS 16293–2422 (Loinard 2002), L1551 IRS5 (Rodriguez et al. 2003), and YLW15 (Curiel et al. 2002), via multi-epoch VLA observations. However, none of these observations cover a sufficient fraction of an orbit to enable a reliable mass estimate. With baselines longer than 300 km and a sensitivity 10-times higher than the VLA significant progress can be made in two ways. Firstly, relative positions between the members of binary systems could be measured to 10-times higher accuracy, resulting in a much higher precision in orbit (and, therefore, mass) determination. Secondly, higher resolution would enable the identification of much tighter systems (with separations as small as ~ 10 mas, compared with ~ 100 mas for the VLA) with commensurably shorter orbital periods. It is worth emphasizing that the very early evolution of stars is still a open research topic and that accurate mass measurements at the earliest protostellar stages would have a great impact.

9 Exoplanets

A wealth of exoplanets and planetary system architectures have been identified – many dramatically different from our solar system – and yet, the contents and breadth of outer planetary systems has barely been touched upon. This is due to sensitivity issues in radial velocity surveys and lack of temporal coverage and completeness in both radial velocity and transit studies. Gaia will supposedly detect thousands of exoplanets astrometrically, many of them Jovian-mass planets in outer planetary systems. However, Gaia will not obtain its best performance on nearby, bright, active (spotted) stars and long baseline radio astrometry at the ~ 1 μas level would be far better. It could be capable of operating long after Gaia is taking data, thus making it essential for characterizing exoplanets with longer orbital periods like Saturn. Observations of active stars can also serve as a complement to Doppler surveys which suffer higher noise levels on such targets, rendering it incapable of achieving the necessary sensitivity to detect Jovian- and Saturn-like planets.

References

Alexander et al. 2017, ApJ, 848, L21
Blecha et al. 2018, arXiv181006609
Brunthaler et al. 2005, Sci, 307, 1440
Brunthaler et al. 2007, A&A, 462, 101
Cordes et al. 1991, Nature, 354, 121
Curiel et al. 2002, ApJ, 564, L35
Gao et al. 2017, ApJ, 834, 52
Garcia et al. 201, ApJ, 768, 146
Gou et al. 2011, ApJ, 742, 85
Kreidberg et al. 2012, ApJ, 757, 36
Loeb et al. 2005, ApJ, 633, 894
Loinard 2002, RMxAA, 38, 61
Mirabel & Rodrigues 2003, Science, 300, 1119
Modjaz, et al. 2005, ASPC, 340, 192
Orosz et al. 2011, ApJ, 742, 84
Reid & Honma 2014, ARAA, 52, 339
Reid et al. 2014, ApJ, 783, 130
Reid et al. 2011, ApJ, 742, 83
Rodriguez et al. 2003, ApJ, 583, 330
Sato et al. 2013, ApJ, 764, 132
Steiner et al. 2017, ApJ, 836, 119
van der Marel et al. 2012, ApJ, 753, 9