Radio Astrometric Detection and Characterization of Extra-Solar Planets:
A White Paper Submitted to the NSF ExoPlanet Task Force

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ABSTRACT

The extraordinary astrometric accuracy of radio interferometry creates an important and unique opportunity for the discovery and characterization of exoplanets. Currently, the Very Long Baseline Array can routinely achieve better than 100 μas accuracy, and can approach 10 μas with careful calibration. We describe here RIPL, the Radio Interferometric PLanet search, a new program with the VLBA and the Green Bank 100 m telescope that will survey 29 low-mass, active stars over 3 years with sub-Jovian planet mass sensitivity at 1 AU. An upgrade of the VLBA bandwidth will increase astrometric accuracy by an order of magnitude. Ultimately, the colossal collecting area of the Square Kilometer Array could push astrometric accuracy to 1 microarcsecond, making detection and characterizaiton of Earth mass planets possible.

RIPL and other future radio astrometric planet searches occupy a unique volume in planet discovery and characterization parameter space. The parameter space of astrometric searches gives greater sensitivity to planets at large radii than radial velocity searches. For the VLBA and the expanded VLBA, the targets of radio astrometric surveys are by necessity nearby, low-mass, active stars, which cannot be studied efficiently through the radial velocity method, coronagraphy, or optical interferometry. For the SKA, detection sensitivity will extend to solar-type stars. Planets discovered through radio astrometric methods will be suitable for characterization through extreme adaptive optics.

The complementarity of radio astrometric techniques with other methods demonstrates that radio astrometry can play an important role in the roadmap for exoplanet discovery and characterization.

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1.   Radio Astrometry and Extra-Solar Planets

Radio astrometry has long been the gold standard for definition of celestial reference frames (Fey et al. 2004, AJ 127, 3587) and has been used to obtain the most accurate geometric measurements of any astronomical technique. Astrometric results include measurement of the deflection of background sources due to the gravitational fields of the Sun and Jupiter (Fomalont & Kopeikin 2003, ApJ, 598, 704), the parallax and proper motion of pulsars at distances greater than 1 kpc (Chatterjee et al. 2005, ApJ, 630, L61), an upper limit to the proper motion of Sagittarius A* of a few km s^{-1} (Reid & Brunthaler 2004, ApJ, 616, 872), the rotation of the disk of M33 (Brunthaler et al. 2005, Science, 307, 1440), and a < 1% distance to the Taurus star-forming cluster (Loinard 2006, BAAS, 209, 1080).

The Very Long Baseline Array (VLBA) images nonthermal radio emission and can routinely achieve 100 μas astrometric accuracy, but has achieved an accuracy as high as 8 μas under favorable circumstances (Fomalont & Kopeikin 2003). Nonthermal stellar radio emission has been detected from many stellar types (Güdel 2002, ARA&A, 40, 217), including brown dwarfs (Berger et al. 2001, Nat, 410, 338), proto-stars (Bower et al. 2003, ApJ, 598, 1140) , massive stars with winds (Dougherty et al. 2005, ApJ, 623, 447), and late-type stars (Berger et al. 2006, ApJ, 648, 629). Only late-type stars are sufficiently bright, numerous, nearby, and low mass to provide a large sample of stars suitable for large-scale astrometric exoplanet searches. Radio astrometric searches can determine whether or not M dwarfs, the *largest stellar constituent of the Galaxy*, are surrounded by planetary systems as frequently as FGK stars and if the planet mass-period relation varies with stellar type. The population of gas giants at a few AU around low mass stars is an important discriminant between planet formation models.

Radio astrometric searches have a number of unique qualities:

- Opportunity to discover planets around nearby active M dwarfs at large radii;

- Ability to fully characterize orbits of detected planets, without degeneracies in mass, inclination, and longitude of ascending node;

- Sensitivity to long-period planets with sub-Jovian masses currently and Earth masses ultimately;

- Complementary with existing planet searching techniques: most targets cannot be explored through other methods;

- Ability to follow-up detected planets with imaging and spectroscopy; and,

- Absolute astrometric positions within the radio reference frame for stars and planets.

The quality and uniqueness of radio astrometry for planet searches are the result of two factors:
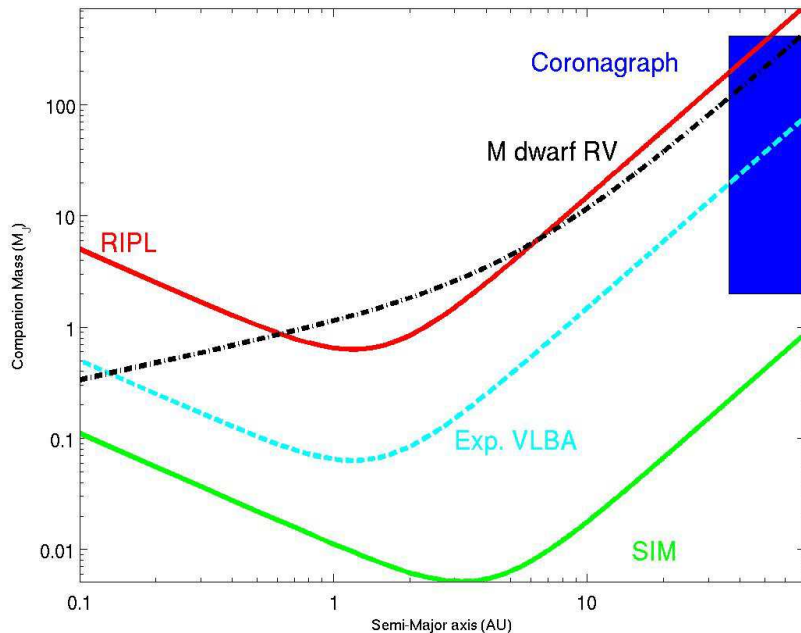
Fig. 1.— Sensitivity of different methods in planet mass and semi-major axis space for radio astrometric surveys and other methods. "Exp. VLBA" refers to the upgraded VLBA described in § 4. The semi-major axis at the minimum in the astrometric search curves is determined by the search duration, which is 3 years for RIPL and the Exp. VLBA campaign.

• **High precision of radio astrometry:** The VLBA can routinely achieve 100 μas accuracy through relative astrometry. This precision is an order of magnitude better than obtained from laser-guide star adaptive optics (e.g., Pravdo et al. 2005). Future instruments will have one to two orders of magnitude more accurate astrometry, comparable to the best accuracy achievable with the proposed SIM spacecraft.

• **Active stars are difficult to study in optical programs:** Our target stars are active M dwarfs, which have radio fluxes on the order of 1 mJy. These radio stars are difficult to study through optical radial velocity techniques because they are faint and because the activity in these stars distorts line profiles, reducing the accuracy of radial velocity measurements.

We give a sketch of the parameter space for RIPL, future radio astrometric searches, the Space Interferometric Mission, radial velocity searches, and coronagraphic searches in Figure 1. A comparison of the radial velocity and astrometric amplitudes indicates that astrometric techniques are favored over radial velocity techniques for long period ($\gtrsim 1$ year) planets for these faint objects, for an astrometric accuracy of ~ 100 μas (Ford 2006, PASP, 118, 364).

In Section 2, we describe the sensitivity and methods of radio astrometry. In Section 3, we describe a new program with the VLBA and the Green Bank 100m telescope to search for planets around nearby M dwarfs. In Section 4, we demonstrate that a bandwidth upgrade for the VLBA will increase astrometric accuracy or stellar sample sizes by an order of magnitude. In Section 5, we discuss the role that the Square Kilometer Array can play with its three order of magnitude increase in sensitivity over the VLBA.

2. Radio Astrometry Sensitivity and Methods

Astrometric exoplanet searches must be able to detect an astrometric signal that has an amplitude of

$$\theta = 2\frac{a}{D} * \frac{M_p}{M_*} = 1400 \ \mu as * \frac{a}{1AU} * \frac{5 \ pc}{D} * M_p/M_J * \frac{0.2M_\odot}{M_*}, \tag{1}$$

for a planet of mass M_p orbiting a star of mass M_* with a semimajor axis a at a distance D from the Sun (a mass of 0.2 $M_\odot$ corresponds to a M5 dwarf). To robustly detect a planet, observations must span at least a significant fraction of a period

$$T = 2.2 \, yr * \left(\frac{a}{1AU}\right)^{3/2} * \left(\frac{0.2M_\odot}{M_*}\right)^{1/2}. \tag{2}$$

The ultimate accuracy that can be obtained through a radio astrometric technique is

$$\sigma_{ast} = \sigma_{beam}/\text{SNR}, \tag{3}$$

where $\sigma_{beam} = b/\lambda$ is the synthetic beam size for an array with maximum baseline b, λ is the observing wavelength, and SNR is the signal to noise ratio of the target source detection. For the VLBA $\sigma_{ast} \approx 500 \ \mu as/\text{SNR}$.

The astrometric position is defined relative to nearby ($\sim 1°$) compact radio sources. Typical observations include switching on minute timescales between the calibrator and the target sources, with less frequent observations of secondary calibrators. The use of multiple calibrators is intended to determine the differential delay in position on the sky due to varying path length from tropospheric water vapor. The extent to which this cannot be calibrated sets the final astrometric accuracy in observations that are not SNR-limited. The nearer the calibrators and the greater sensitivity at which they can be detected typically determines this error. The error decreases linearly with decreasing calibrator-target separation. The increased sensitivity of future arrays will increase the calibrator density and therefore decrease the typical separation from calibrator to target and the uncalibrated astrometric error. For sufficiently small target to calibrator separation, the calibrator will be in the primary beam of the antenna, enabling simultaneous observations of the target and calibrator that also remove temporal dependence of tropospheric variations.
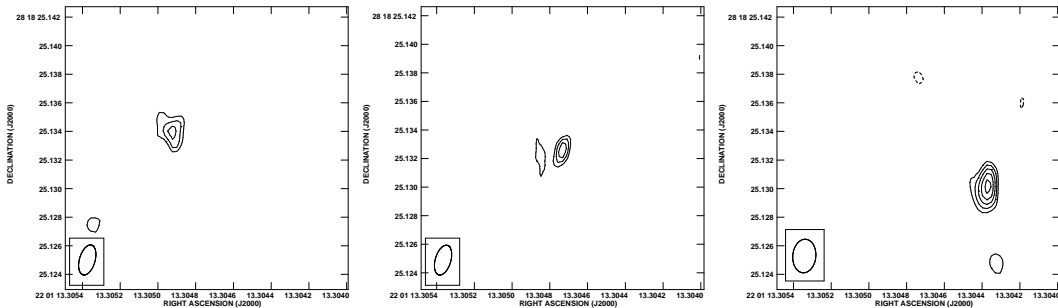
Fig. 2.— Images of GJ4247 in three separate epochs on 23, 25, and 26 March 2006 (right to left) from the VLBA Precursor Astrometric Survey. Contour levels are -3, 3, 4, 5, 6, 7, 8 times the rms noise of 95 μJy. The synthesized beam is shown in the lower left hand corner of each image.

3. RIPL: Radio Interferometric Planet Search

RIPL is a 1400-hour, 3-year VLBA and GBT program to search for planets around 29 nearby, low-mass, active stars. The program will achieve sub-Jovian planet mass sensitivity. The observing program will be completed in 2009.

The most serious limitation to astrometric accuracy may be from stellar activity that jitters the apparent stellar position. Most evidence, however, indicates that this radio astrometric jitter is small. For instance, White, Lim and Kundu (1994, ApJ, 422, 293) model the radio emission from dMe stars as originating within ~ 1 stellar radius of the photosphere. At a distance of 10 pc for a M5 dwarf a stellar radius is ~ 100 μas, roughly an order of magnitude smaller than the astrometric signature of a Jupiter analog. We conducted the VLBA Precursor Astrometric Survey (VPAS) in Spring 2006 to assess the effect of stellar jitter on astrometric accuracy (Bower et al. 2007, in prep.).

For each star, three VLBA epochs were spread over fewer than 10 days. Seven stars were detected in at least one epoch and four were detected in all three epochs (Figure 2). All stars have proper motions and parallaxes determined by Hipparcos or other optical methods with a precision of a few mas per year, yielding predicted relative positions accurate to ~ 100 μas during the length of the study. For all stars detected with multiple epochs, the motions match the results of Hipparcos astrometry well with rms in each coordinate ranging from 0.08 to 0.26 μas. Deviations in the positions appear to be limited by our sensitivity; i.e., the effect of stellar activity on their positions is unimportant.

In fact, the **small** *differences in the fitted proper motion and the Hipparcos proper motion already eliminate brown dwarfs as companions to these objects (Figure 3).* The measured differences are consistent with noise in the VLBA astrometry (200 μas /3day ~ 20 mas/yr). The typical reflex motion due to a long period brown dwarf is ~ 100 mas/yr, which would be apparent. The much longer time baseline and better sensitivity of RIPL will reduce proper motion errors by ~ 2 orders of magnitude.
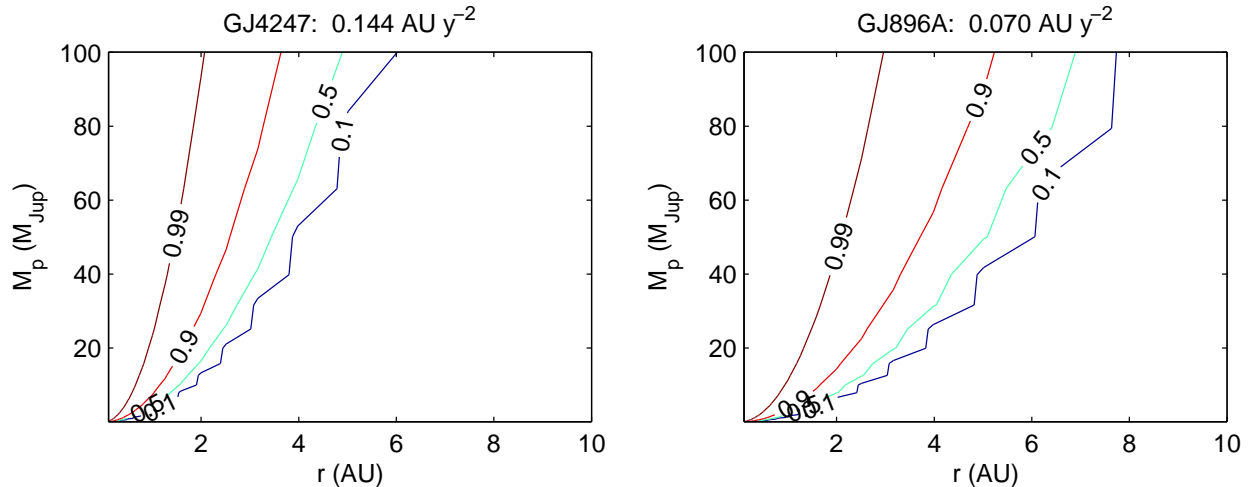
Fig. 3.— Region of planetary mass and semi-major axis phase-space rejected by acceleration upper limits based on combination of 3 epochs of radio astrometric measurements and optical astrometry, primarily from Hipparcos. Different contours indicate confidence intervals for excluded regions.

3.1. Synergy with other Planet Searches

RIPL is synergistic with the existing and future planet-search programs, as well as current ground-based planet searches (including radial velocities, transits, adaptive optics, and interferometry). RIPL provides an opportunity to search for planetary systems in a unique area of parameter space that will not be targeted by other planet searches until the launch of NASA SIM - Planetquest.

Ground based transit searches are most sensitive for very short periods ($P \sim$ days), and the Kepler mission aims to detect planets with orbital periods of slightly more than a year. Thus, RIPL will make a valuable contribution to our understanding of the frequency of long-period planets around M stars. Further, unlike transits and radial velocity observations astrometric measurements directly measure the planet mass, which is important for testing models of planet formation. While the unknown inclination is less of an issue for studying large samples of planets, measuring individual inclinations will be particularly valuable for planets around M dwarfs, since a relatively modest number of M dwarfs are being surveyed by RIPL (~ 30 vs ~ 3000 stars by radial velocities).

Ground-based optical and near-infared interferometers (e.g., PTI, NPOI) require bright stars and are not appropriate for faint low-mass stars. The RIPL astrometric accuracy is an order of magnitude better than the astrometric error from Keck Laser Guide Star Adaptive Optics astrometry (Pravdo et al. 2005, ApJ, 630, 528). *Thus, RIPL is the best means for an astrometric search of M dwarfs until SIM launches* (now estimated for no earlier than 2016).

A long-period planet detected by RIPL would enable exciting scientific investigations such as photometric and spectroscopic observations to determine the planets physical properties. While space based missions such as TPF-C and TPF-I are expected to be extremely powerful and aim to directly detect terrestrial mass planets, these missions are not expected to launch for at least a decade in the future. Knowing which stars have giant planets suitable for direct imaging would enable direct probes of an extrasolar planet.

4. VLBA Upgrade and Planet Detection

The VLBA is presently being upgraded from a typical data rate of 256 Mbit/s to 4 Gbit/s, with project completion estimated by 2010. This will result in a sensitivity increase by a factor of 4, or about a factor of 8 increase in areal density of reference sources on the sky. Thus, the typical distance between a target star and its nearest reference source will decrease by a factor of ~ 3. A few years later we expect a data rate of 16 Gbit/s, yielding a target-calibrator separation more than 10 times smaller than current values. Since in the limit of infinite SNR the astrometric error depends linearly on the separation from the reference source, relative astrometric errors of $\lesssim 10$ μas should be fairly routine; in principle, this would permit detection of a planet with a mass of less than 10% of the mass of Jupiter. The sensitivity increase afforded by these upgrades will also permit a sizable increase of the late-type dwarf sample.

5. Square Kilometer Array

The Square Kilometer Array (SKA; Carilli & Rawlings 2004, New AR, 48, 979) is a proposed future radio telescope that would have a collecting area of a square kilometer, approximately 200 times the collecting area of the VLBA. The SKA would be built toward the end of the next decade; it is planned to cover the frequency range from 0.1 to 25 GHz, with the 5–10 GHz range being most useful for astrometric planet detection. If 25% of the SKA area at ~ 8 GHz is constructed on baselines of 1000-5000 km, it will supply revolutionary astrometric accuracy (Fomalont & Reid 2004, New AR, 48, 1473). With dish antennas of 12m diameter, the combination of sensitivity and wide field of view often will enable many astrometric reference sources to be found in the same antenna field of view as the target star, allowing all temporal variations in Earth's atmosphere to be removed. In such a case, the relative astrometric accuracy may reach ~ 1 μas, competitive with SIM and enabling astrometric detection of Earth-mass planets.

The sensitivity of the SKA will enable astrometric detection of thermal emission from stars. The Sun, for instance, would be detectable to a distance of 10 pc with the SKA. Thus, the SKA will be capable of detecting and characterizing planets around Sun-like stars.