Planets Around M-dwarfs – Astrometric Detection and Orbit Characterization

N. M. Law (nlaw@astro.caltech.edu), S. R. Kulkarni, R. G. Dekany, C. Baranec

California Institute of Technology, MS 105-24, Pasadena, CA 91125, USA

There are compelling reasons to search for planets around late M-dwarfs: current planet surveys have not been able to target these optically-faint stars, and the reduced primary stellar mass improves planet detection sensitivity for new techniques which can target these stars. In this white paper we argue that one can employ aging 2 m telescopes for dedicated astrometric programs in the spirit of the RESTAR program to revitalize the US 2 m-class telescope population. Using a new low-cost adaptive optics system designed for 2 m-class telescopes we would be able to find planetary systems around late M-dwarfs with detection sensitivities approaching a few Earth masses.

I: Finding Planets Around Late M-dwarfs

The recent great progress in extra-solar planet detection has been almost exclusively targeted at FGK stars. It follows that there are many discoveries to be made by extending the search to hitherto little-covered stellar masses – in particular M-dwarfs, where low stellar mass improves detection sensitivity for many techniques. The Exoplanet Task Force has identified the search for planets around M-dwarfs as one of two priorities for the next 15 years of exoplanet science.

The higher-mass M-dwarfs that have been probed up to now have a low Jupiter-mass planet companion frequency (<~2%; eg. Endl et al. 2007, Johnson et al. 2007), but theorists predict a large population of lower-mass planets (e.g. Ida & Lin 2005, Kennedy & Kenyon 2008). The characteristics of the lower-mass M-dwarf planet population are essentially unknown, mostly because the stars are too faint for current optical RV planet searches. As M-dwarfs are the most common stars in our galaxy, there is a clear gap to be addressed in our knowledge of the galactic planetary population; a detailed understanding of planetary statistics at the low end of the stellar mass scale will provide vital new constraints for planet formation theories.

We here argue that two new technological breakthroughs – sub-milliarcsecond adaptive optics astrometry and low-cost adaptive optics systems suitable for small telescopes – will provide an unmatched M-dwarf exoplanet detection and follow-up capability. In particular, we will be able to address the following fundamental questions for the first time: *(1) what is the planetary system frequency around mid and late M-dwarfs? (2) what are the precise masses and orbital elements of the planets? and (3) how does the planet frequency depend on metallicity and primary mass?*

This white paper is organized as follows: in section II we show that 100 microarcsecond astrometry is within reach, and in section III we detail the relation of astrometric M-dwarf surveys to other planet detection techniques. In section IV we describe a low-cost adaptive optics system that will enable 100 microarcsecond-level astrometry on 2m-class telescopes. In section V we discuss what could be done with a major astrometric AO M-dwarf exoplanet detection

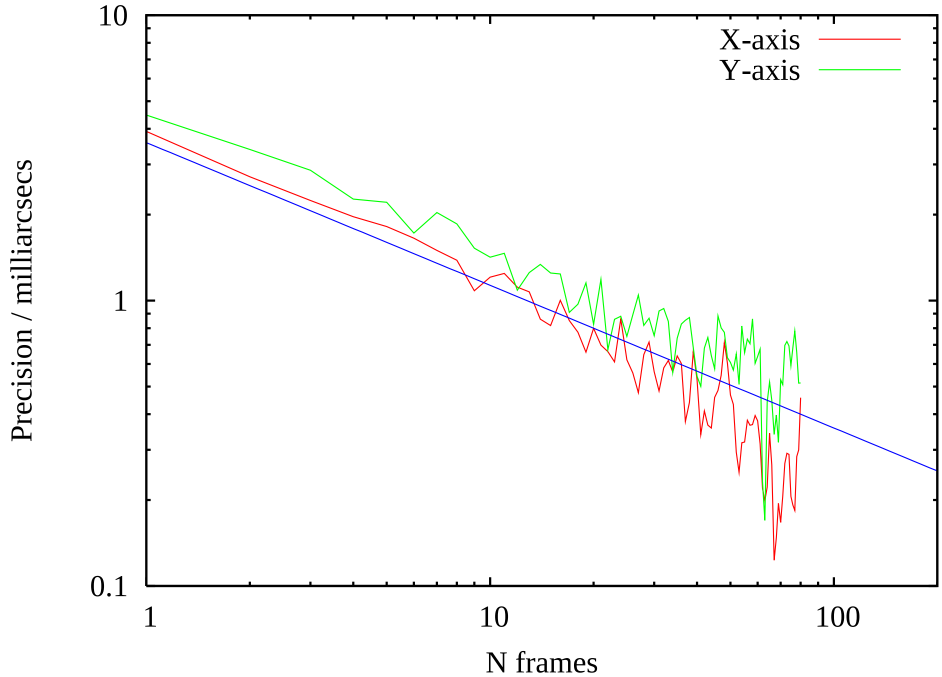

Figure 1: The measured astrometric performance (Allan variance) as a function of total exposure time for a typical target from our 5m-telescope M-dwarf survey. The solid line shows a $\sqrt{Time}$ fit to the precision curves. We reach the expected astrometric precision of ~250 microarcseconds in 200 frames (~10 minutes including overhead), and see no sign of being limited by systematic errors. The astrometric precision scales with $\sqrt{Time}$ and $\sqrt{N_{refstars}}$, and so we are chiefly limited by only having 4 reference stars in this instrument's 25 arcsecond field of view.

and follow-up program.

II: 100 microarcseconds is within reach from the ground

In a recent paper we have articulated the problem of differential AO astrometry in the face of the dominant noise source (which is correlated tilt anisoplanatism), derived its expected contribution to our astrometric uncertainty from theory, developed an optimal estimation algorithm for performing astrometry, and verified our expectations with extensive on-sky tests at Palomar and Keck (Cameron, Britton & Kulkarni 2009). For test targets we achieved ~100 μas precision in 2 minutes with ~100 μas accuracy over 2 months. This is an unprecedented level of precision for routine ground-based astrometry.

Using this technique we have started an M-dwarf planet survey (MAAPS; the M-dwarf Astrometric AO Planet Survey) at Palomar. For typical targets in our planet-search survey, we achieve ~250 μas precision (figure 1), and our best targets reach 100 μas precision.

This level of astrometric precision is possible by (1) controlling systematic effects (distortion, refraction) through careful experimental design (small dithers, consistent zenith angles), (2) proper accounting of atmospheric and

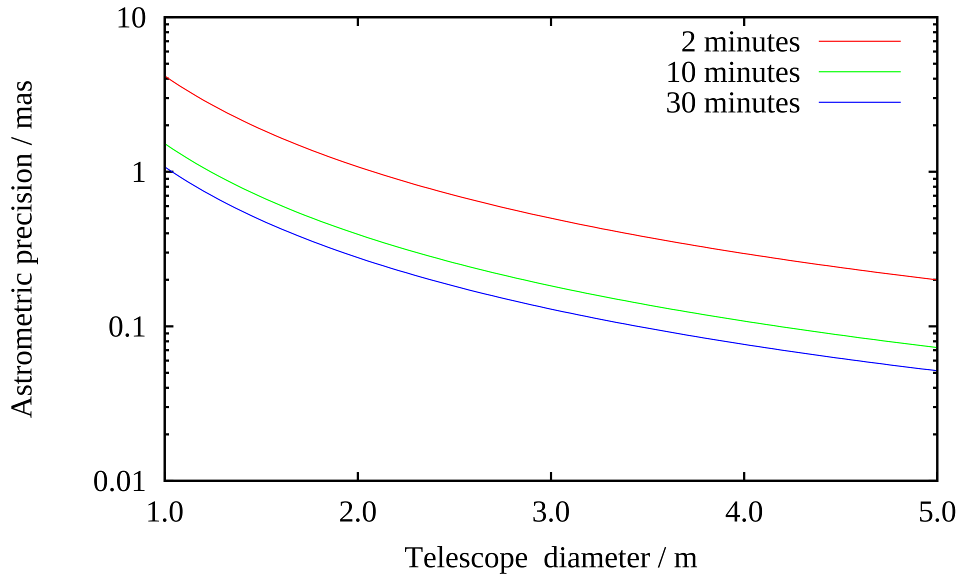

Figure 2: The astrometric precision that can be achieved using adaptive optics, as a function of telescope size and time-per-target. We here assume that five astrometric reference stars are available (typical for the surveys described here), that differential tilt jitter and photon noise are the dominant error terms, and that the system observes with 100% time efficiency.

measurement statistics to construct the covariance matrix, and (3) the use of an optimal estimation algorithm to combine measurements to measure stellar positions. The adaptive optics system both reduces the inherent tilt jitter and sharpens the image point spread function, thus improving the signal-to-noise ratio of faint astrometric reference stars.

In Cameron, Britton & Kulkarni 2009 we derived a scaling relationship for the expected adaptive-optics astrometric performance as a function of integration time, number of reference stars, and telescope size (figure 2). Using this relation, which has been verified against the performance of Palomar and Keck astrometry, we find that an AO-equipped 2m-class telescope could provide astrometric precisions down to the few-hundred microarcsecond level in reasonable (sub-hour) integration times.

III: Survey Phase Space

Radial velocity planet detection methods do not provide unambiguous orbits or masses for detected planets. Transit and microlensing surveys generally find planets around distant stars where follow-up and detections of longer-period planets are difficult. In contrast, targeted astrometric planet searches can find planets around nearby stars and provide orbital inclination constraints. Astrometric surveys are sensitive to planets in all orbital orientations, allowing clear statements to be made about the presence or absence of planetary systems around particular stars. The astrometric signal increases with planetary orbital radius and so very wide, very low-mass companions can be detected if sufficient long-term stability can be achieved (figure 3). As noted by the Exoplanet Task Force re-

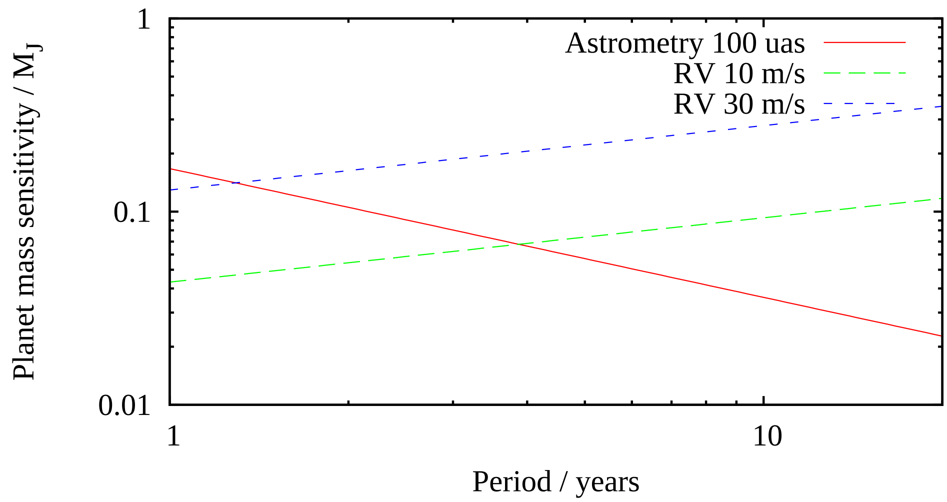

Figure 3: A comparison of the planet-detection sensitivity of radial velocity and astrometric techniques, for a $0.1 M_\odot$ star at 20 pc. We here use a very simple detection model, requiring a 5σ detection of planetary motion in a 10-year project with a dedicated telescope and targets observed with 10-day cadence. We assume that radial velocity and astrometric errors, including stellar jitter, can be averaged down by repeating observations. 5-10 m/s is the radial velocity precision predicted for new generation of infra-red radial velocity techniques (eg. Edelstein et al. 2007); current radial velocity observations of optically-faint M-dwarfs obtain much lower precisions.

port, the development of a high-precision astrometric capability would greatly complement the very large investment in RV planet detection.

A high-precision ground-based astrometric capability would complement the GAIA and SIM-Lite space-based astrometric missions by operating at high-precision on optically faint M-dwarfs which are otherwise very hard to target. For example, for a typical M5 dwarf at 10 pc, m_g = 17.4 (Kraus & Hillenbrand 2007) and the GAIA single-measurement accuracy is ~500 μas, compared to the ~100μas precision possible in the near-IR using astrometric AO. In addition, a targeted survey allows still higher precision by observing stars at any cadence.

For M-dwarfs, stellar astrometric jitter is unlikely to be the dominant noise source. The target stars have radii of ~0.2 R_{sol} (Leggett et al. 2000) and so subtend a diameter of ~100 μas at 15pc. This is a hard upper limit for astrometric variability assuming that *all* emission is concentrated on a single point on the stellar surface; in practice the astrometric variation will always be far lower.

IV: The Instrument

Successful high-precision AO astrometry requires high Strehl ratios to both reduce atmospheric astrometric jitter and to improve reference star detection and measurement. Because the isokinetic patch is the dominant scale for astrometric precision (Cameron, Britton & Kulkarni 2009), a wide field of view of several arcminutes will optimize the number of astrometric reference stars accessible. These capabilities are

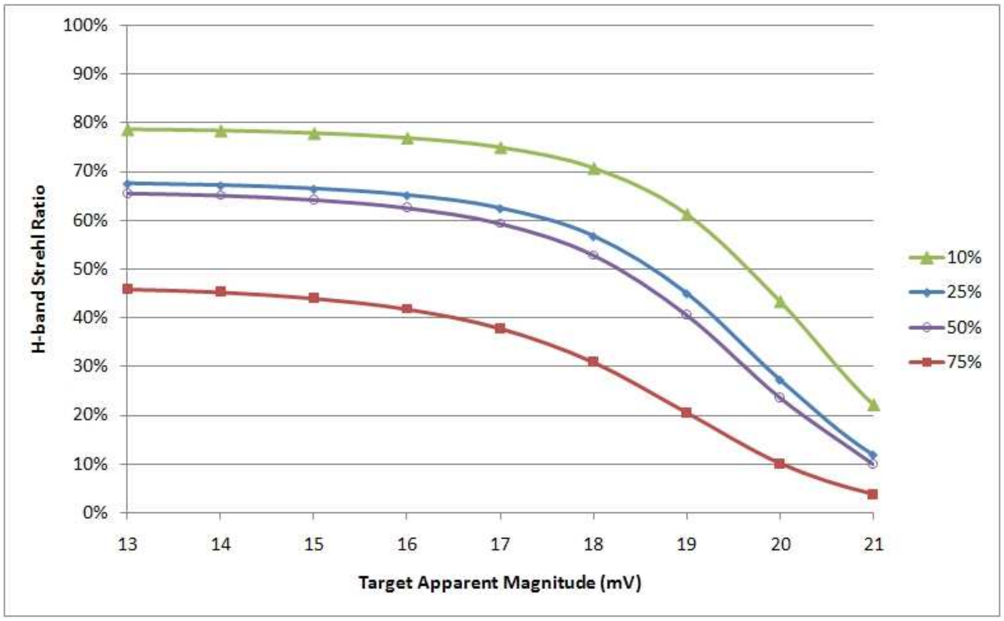

Figure 4: The H-band Strehl obtainable by CAMERA on a 1.5m telescope in a variety of Palomar observatory conditions (seeing percentiles of 10%, 25%, 50% and 75%), as a function of on-axis guide star magnitude.

within reach, using the CAMERA AO system design.

CAMERA (Compact Affordable MEMS-based Rayleigh Adaptive Optics) is a low-cost, autonomous, Rayleigh LGS AO system and science instrument designed for the fully robotic 1.5 m telescope at Palomar Observatory. When deployed on sky, CAMERA will serve as an archetype for a new class of affordable AO system deployable on 1-3 meter telescopes.

CAMERA will provide a unique new capability for large adaptive optics surveys covering several thousand targets. These high-angular-resolution surveys would be extremely time-intensive on currently available LGS AO systems. CAMERA's low overhead time and queued, robotic operation enable very efficient operation, and the system operates on small enough telescopes to consider devoting the entire observing time to single projects.

CAMERA is designed for LGS operation with tip/tilt stars measured in both the visible and infrared. On a 1.5m telescope CAMERA can achieve diffraction-limited visible-light performance for point sources as faint as $m_V = 17$ in median conditions (figure 4). Using an off-axis field star for tip-tilt, approximately 30% sky coverage can be accessed with < 230 milliarcsecond H-band resolution, while 90% sky coverage can be accessed with < 300 milliarcsecond FWHM in median seeing. A CAMERA-like system could enable sub-milliarcscond astrometric precision surveys for very large numbers of targets (figure 2); most nearby M-dwarfs are bright enough to serve as on-axis infrared tip/tilt stars.

The adaptive optics system greatly increases the number of usable astrometric reference stars

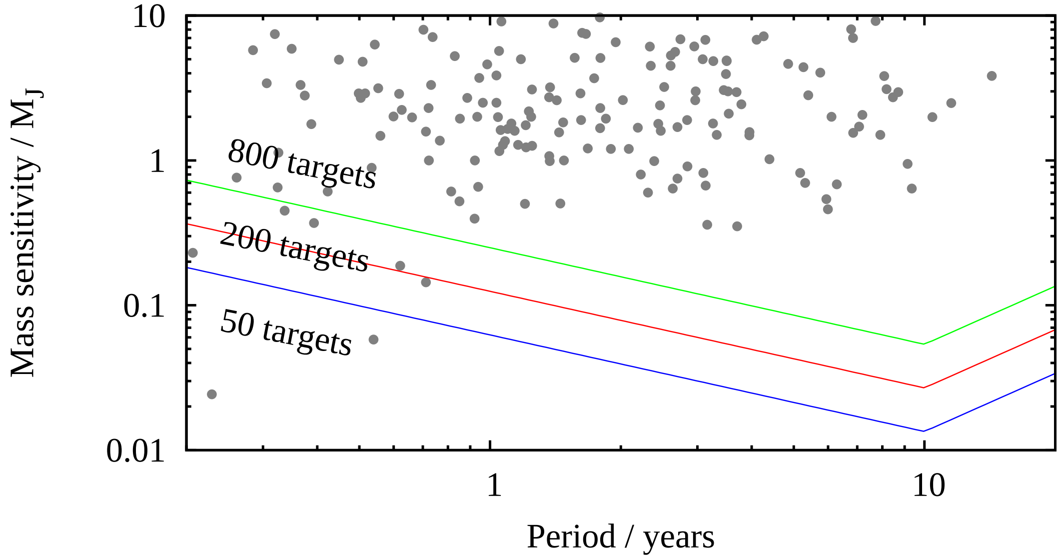

Figure 5: The planet mass sensitivity that can be achieved for a major 10-year astrometric M-dwarf survey using five 2.5m CAMERA-equipped telescopes. We assume a median stellar mass of $0.1M_\odot$ and a median target distance of 20 pc. Detected RV planets around all stellar types are overplotted as a reference. At multi-year periods the astrometric survey is sensitive to several times lower masses than current RV surveys. This is a particularly important capability for these low-mass stars where the Jupiter-mass population of planets is known to be small.

by image sharpening; an AO-equipped 1.5m telescope would be the equivalent of a seeing-limited 4m telescope for reference star detection. CAMERA, in particular, is designed with a particularly important feature for astrometry: a 2-arcminute field of view, wider than most comparable AO systems. Although the Strehl ratios will be low at the edge of this field, the greatly improved probability of having sufficient reference stars more than compensates.

At CAMERA's SNR=5 detection limit of m_K~19 in 10 seconds (typical astrometric observing parameters), we expect between 3000 and 20000 stars per degree (Spagna 2001). With a 4 square arcminute field of view, CAMERA has an excellent chance of having sufficient astrometric reference stars for most targets, although the final astrometric target list will have to be optimized for the best spatial distributions and numbers of guide stars.

V An Astrometric M-Dwarf Exoplanet Detection Program

We conclude by exploring what can be achieved by a major 100-microarcsecond-precision program on dedicated 2m-class AO-equipped telescopes (figure 5). In simulating the survey performance we have assumed that astrometric signals will be recovered by use of joint Lomb-Scargle periodograms; we have designed the survey to yield a 1% false alarm rate and a 50% detection efficiency for planets with orbital eccentricities less than 0.35 (Catanzarite et al.

2006). We assume a fixed-cadence, fixed-target-list survey. More complex survey types (see eg. Ford 2005) will improve performance.

Targeting 800 late M-dwarfs allows detection of Neptune-mass planets in 10-year orbits and Jupiter-mass planets at all accessible periods (limited by the cadence of the survey). A smaller 50-star target list allows detection of ~4-Earth-mass planets.

Using the techniques described in this white paper, 2 m-class telescopes would have very competitive M-dwarf exoplanet detection capabilities. In the spirit of the RESTAR project to renew small telescopes, one could employ these systems for dedicated programs to directly address one of the Exoplanet Task Force's two priorities for the next 15 years of exoplanet science.

References

Cameron, Britton & Kulkarni 2009 AJ 137 83
Catanzarite et al. 2006 PASP 118 1319
Edelstein et al. 2007 SPIE 6693E 26E
Endl et al. 2006 ApJ 649 436E
Ford 2005 AJ 129 1706F
Ida & Lin 2005 ApJ 626 1045
Johnson et al. 2007 ApJ 670 833J
Kennedy & Kenyon ApJ 682 1264
Kraus & Hillenbrand 2007 AJ 134:2340
Leggett et al. 2000 ApJ 548:908
Spagna 2001 STScI-NGST-R-0013B