Seeing the Unseen in the *Gaia* Era: Using Multi-Epoch Astrometry to Find Companions to Young Stars

Abstract High-contrast imaging is a powerful method to directly study the atmospheres of self-luminous planets, but the largest barrier to these efforts is the low occurence of massive planets on wide orbits. Instead of blind surveys, target lists need to be informed by additional evidence indicating the presence of a planet to narrow the search and maximize the likelihood of discoveries. **I propose to conduct a high-contrast imaging survey for new faint companions to young stars, using accelerations detected in multi-epoch astrometry to optimize the target list.** I will select targets by combining astrometry from past satellite missions, including *Hipparcos*, with recent high-precision astrometry from the *Gaia* mission, to find young stars undergoing acceleration due to the presence of an unseen companion of planetary mass, but which cannot be readily characterized from the *Gaia* astrometry alone. I will then follow up these detections with a high-contrast imaging campaign to directly detect the companion, using coronagraphy from the ground and eventually space-based imaging. **The results will increase the number directly imaged exoplanets for characterization and result in a more efficient search campaign paradigm.**

Background and Motivation. Direct imaging surveys of young stars to date have resulted in the discovery of about a dozen exoplanets. These valuable systems are being used to inform planetary evolutionary models, distinguish between planet formation pathways, and determine the dependence of atmospheric clouds on mass and age. However, more giant planets are needed to develop meaningful statistical characterization of this population group and their host stars, and understand them as an ensemble outcome of the planet formation process.

Bowler (2016) determined the occurrence rate of planets (5-13 M_{jup}) at separations observable in imagining (30-300 AU) to be $0.6^{+0.7}_{-0.5}\%$, suggesting that giant planets are quite rare at those distances. With such a low occurrence rate, direct imagining survey strategies must be optimized to select targets that maximize the likelihood of finding a giant planet or brown dwarf companion.

An ideal way to narrow the search is to infer the presence of the companion by observing the acceleration of the star in the plane of the sky due to the tug of the companion. The European Space Agency's *Gaia* (Gaia Collaboration 2016) satellite promises to deliver highly accurate astrometric measurements of 1.7 billion nearby stars by the end of the mission in 2022. To date, no extra-solar planet has been discovered astrometrically. With *Gaia*, however, the first detection is likely in the very near future, followed by potentially thousands more by the end of the nominal mission lifetime. *Gaia* astrometry alone will be able to detect planets with complete orbits, and periods on the scale of years, but which are too close to the host to be observed in imaging.

The promise of accurate astrometric measurements is beginning to be exploited to characterize known companions' masses and orbits. Bowler et. al. (2018) used radial velocity and relative astrometric measurements to determine the dynamical mass of the companion to GJ 758. They used this independent mass measurement to test several brown dwarf evolutionary models. Calissendorff & Brown (2018) improved on the mass measurement by exploiting multi-epoch astrometry using the differences between *Hipparcos* and *Gaia* astrometric motions spanning a 24 year baseline. Multi-epoch astrometry from *Hipparcos* and *Gaia* thus provides the baseline and accuracy needed to identify young stars experiencing acceleration due a previously unseen companion that is wide enough to be reached by imaging, and significantly increases the likelihood of detection of giant planets in direct imaging surveys.

Study Design and Intellectual Merit. **I propose a study to identify and characterize new substellar companions to young stars by exploiting the promise of multi-epoch astrometry.** I will use astrometric measurements from *Hipparcos* and *Gaia* of young stars over a several-decade time span to search for stars undergoing accelerations due to the presence of an unseen companion. I will develop a ranking scheme to optimally identify planets by incorporating the magnitude of the acceleration (to be consistent with planet masses), stellar multiplicity (to rule out binary systems), distance (closer objects will have larger angular separations), and age of host star (younger planets will be brighter). I will prioritize the target list to find 50 planet host candidate stars, which is the upper end of the number of targets that could reasonably be surveyed during my PhD tenure.

I will then conduct a high-contrast imaging survey to follow up on the targets I identified from the ground (e.g. the vortex coronagraph on the Keck II telescope) and later from space (e.g. James Webb Space Telescope), primarily in the infrared L-band where the planet's spectral energy distribution peaks and thus it will be brightest in imaging.

In years 1-2 of my graduate study, I will develop and publish a target list for the imaging survey based on multi-epoch astrometry. In years 3-4, I will conduct a high-contrast imaging survey of these targets, publishing newly imaged companions. In my final year, I will consider how my observations impact the field of substellar formation and evolution, culminating in the successful completion of my Ph.D.

This study is a natural extension of my previous experience. My current work with Dr. Adam Kraus (Pearce et. al., submitted) on an orbit study of a planetary companion imaged with Keck II NIRC2 camera has given me great familiarity with planet companions imaged with Keck II. That work uses my measurement of the companion's orbit to constrain its formation mechanism. In the course of that work I have built a collaboration with experts in coronagraphy and high-contrast imaging techniques. In addition, my summer internship at UC Berkeley enabled me to work extensively with *Gaia* data and its catalog. Thus, this proposed study is a next step in my scientific undertakings, one that leverages the promise of current cutting-edge technology.

Caltech is ideally suited for me to carry out this work, because there are many scientists involved in high-contrast imaging and exoplanet characterization studies (e.g. D. Mawet, H. Knutson, L. Hillenbrand), and because the access to Keck and Palomar Observatories is unrivaled.

Broader Impact. As I showed in my personal statement, teachers' engagement in science is vital to our communities. Thus, I intend to pursue funding for a Research Experience for Teachers program at my graduate institution. With this project, I can recruit teachers to collaborate with me and other members of our department during the summer. I will recruit secondary school teachers of math, physics, astronomy, or any subject in which they could incorporate their experience into their classroom, from local or regional area schools. Teacher-researchers will make meaningful contributions to the catalog search and the imaging portion of this project. Teacher-researchers would be able to assist with observations at the Keck Telescope or similar observing facility, learn coding skills through data analysis, learn image manipulation, and to learn scientific professional skills. Under the mentorship of my thesis advisor or another research scientist, I would relish the opportunity for a teacher researcher to learn alongside me and contribute to the analysis.

References Bowler, B. P., Dupuy, T. J., Endl, M. et. al. 2018, ApJ, 155, 159; Bowler, B. P. 2016, PASP, 128, 102001; Calissendorff, P. & Janson, M. 2018, AA 615, 5.; Gaia Collaboration G, Prusti T., de Bruijne J., Brown A., Vallenari A., et. al. 2016. A&A, 595, 36.; Pearce, L., Kraus, A., et. al. 2018. ApJ, Submitted