Astro2020 Science White Paper

Realizing the Promise of High-Contrast Imaging: More Than One Hundred Gas-Giant Planets with Masses, Orbits, and Spectra Enabled by *Gaia*+*WFIRST* 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

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Abstract

We identify full-sky absolute astrometry as a powerful complement to direct imaging surveys of exoplanets. A single astrometric epoch measured with the Wide Field Imager (WFI) on *WFIRST* will extend *Gaia*'s high-precision coverage by years. This will enable the astrometric detection of ∼1–10 Jupiter mass planets ∼3–30 AU from nearby stars, which can then be directly imaged. Assuming a single epoch of 50 μas precision in 2030, we show that *WFIRST* can help discover and weigh ∼160 planets accessible to direct imaging by 30-m-class telescopes, and more than 10 planets on 10-m telescopes. This precision is within the theoretical reach of *WFIRST*-WFI for an $R = 13$ star with ∼100 seconds of integration, corresponding to ∼6 months of integration time to survey the entire sky, or ∼9 months including overheads. The combination of radial velocity time series, absolute astrometry, and direct imaging would produce a sample of ∼100 nearby exoplanets with known masses, ages, and spectra, and a well-defined selection function. This sample will enable rigorous tests of the theoretical models currently used to infer masses from ages and luminosities. It will also enable us to measure atmospheric chemistry, and connect planet masses and present-day orbits to the locations in the protoplanetary disks where they formed.

1 Introduction

High-contrast imaging and spectroscopy can discover massive, wide-period exoplanets and measure their atmospheric properties and chemistry. The field is being driven by new facilities, including extreme adaptive optics, integral-field spectroscopy, extremely large (20–30 m) telescopes, and the coronagraphic imager on *WFIRST* (Spergel et al., 2015). While the current sample of imaged planets is small, we can study these companions in exceptional detail, and have discovered water, methane, and carbon monoxide in their atmospheres (Konopacky et al., 2013; Macintosh et al., 2015). With a large sample of well-characterized gas giant planets, we will be able to measure the outcomes of planet formation and migration and use chemical abundance ratios to determine where in the disk these planets formed (Öberg et al., 2011).

Most imaged planets currently have measured spectra and luminosities, but their ages, orbits, and masses may not be well-constrained. Ages are estimated from the host star; these have widely varying precision depending on the star's membership in a kinematic moving group and the availability of secondary age indicators (Soderblom, 2010). Masses are typically inferred by inverting the measured luminosity and estimated age using theoretical cooling models. As the known systems have orbital periods ranging from decades to millenia, their orbits are usually not well-determined.

A goal of direct imaging is to produce a large sample of imaged planets with known masses, orbits, spectra, and age. Such a sample could statistically address the location and efficiency of massive planet formation in protoplanetary disks. With independent masses and spectra, we could test models of planet formation and cooling, atmospheric chemistry, and circulation. So far the field has fallen well short of this goal. High-contrast surveys have invested at least 1000 nights of 8–10-m telescope time to search thousands of stars for companions, but have found only ∼1–2 dozen planets (depending on the adopted definition of planet; Bowler, 2016).

Upcoming 30-m-class telescopes will dramatically improve our sensitivity to faint planets. However, telescope time will be too valuable to repeat the strategy of imaging every nearby young star. Imaging new planets will not directly measure their masses: without supporting radial velocity and/or astrometry, we would have to continue to assume an age and cooling model to infer mass from the observed luminosity. The strategies of the past will not yield the planet sample we need to test models of gas giant formation and evolution.

2 Absolute Astrometry

Absolute stellar astrometry measures a star's position and proper motion in an inertial reference frame, that of the distant quasars. It can probe the acceleration of a star due to unseen companions. The *Gaia* satellite is now measuring astrometry to exceptional precision across the sky, and has enough fuel for a total mission lifetime of 9 or 10 years (Gaia Collaboration et al., 2016). *Gaia* expects to discover thousands of new exoplanets (Perryman et al., 2014). Some of these will be excellent candidates for high-contrast imaging. However, *Gaia* will have two main shortcomings from the perspective of high-contrast imaging:

- Limited independent verification of precision; and
- A lack of sensitivity to orbital periods significantly longer than 10 years.

A single epoch of high-precision astrometry with *WFIRST*-WFI can address both problems.

Processed *Gaia* data include both the internal errors estimated by setting the reduced χ^2 to unity and external errors, which are often unknown (Lindegren et al., 2018). The published uncertainties will generically underestimate the true uncertainties, but the form of error inflation that is needed may depend on magnitude, color, and position. In order to calibrate the errors, a comparison sample is needed. For the bright ($V \lesssim 10$) *Gaia* stars, *Hipparcos* provides this sample (Brandt, 2018). *Hipparcos* and *Gaia* together measure a mean proper motion by the difference in position divided by the ∼25 years between the missions; the precision of this mean proper motion is generally much higher than that of *Gaia*. As *Gaia* continues to observe, this will not remain true. Calibrating future *Gaia* data releases, which will contain acceleration measurements, will ultimately demand a new reference catalog.

While *Gaia* will not be able to measure orbits longer than ∼10 years, it will be able to measure accelerations. Already, we can combine astrometry from *Hipparcos* and *Gaia* to measure accelerations induced by companions on century-long periods (Brandt et al., 2018). This is because for short orbital arcs, the positional departure from linear motion scales as t^2. The long time baseline between *Hipparcos* and *Gaia* compensates for the former's inferior precision. After the end of *Gaia*, its positions and proper motions may be combined with new measurements to probe ever lower accelerations, and ever-longer orbital periods. These subsequent measurements will gain by the time since the end of *Gaia*'s mission.

Assuming a proper motion precision of 5 μas yr^{-1} at the end of an extended *Gaia* mission in 2023, a positional measurement to 50 μas ten years after the midpoint of *Gaia* observations will effectively extend its time baseline to 15 years. This will enable an independent calibration of *Gaia*'s astrometry, particularly of its uncertainties, and provide sensitivity to longer orbital periods. Our fiducial precision of 50 μas is likely within reach of *WFIRST* with 100 seconds of integration on an $R \lesssim 13$ star (Melchior et al., 2018), with an additional ∼60 seconds of overhead to slew by the field-of-view[1]. *WFIRST*'s complex pupil, with its many diffraction spikes, enables precise centroiding of even saturated stars. There is no need for *WFIRST* to measure parallaxes internally: *Gaia*'s end-of-mission parallaxes will be a factor of 2–10 better than our assumed 50 μas precision (Gaia Collaboration et al., 2016).

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[1] `https://wfirst.gsfc.nasa.gov/science/WFIRST_Reference_Information.html`

For this white paper, we have taken the *Gaia* DR2 positional uncertainties (Gaia Collaboration et al., 2018; Lindegren et al., 2018) and divided by the square root of the number of epochs to estimate the uncertainty of each positional measurement, scaling the number of observations to a nine-year extended mission. This approach assumes the uncertainties to be fully uncorrelated. Any correlations or systematics will reduce *Gaia*'s end-of-mission precision, and increase the gain from a single post-*Gaia* astrometric measurement. Over the next decade, *WFIRST* is the only mission capable of making this single measurement to the required precision over the entire sky.

3 Dynamical Masses

Absolute astrometry, like radial velocity data, measures accelerations in an inertial reference frame. A combination of astrometry and radial velocity can measure the full three-dimensional acceleration of a star in response to an unseen companion. This acceleration is sensitive only to the companion's mass and separation, not to the reduced mass or system mass. An independent measurement of the separation from imaging then determines the dynamical mass, even if the measurements cover only a small fraction of an orbit (Brandt et al., 2018). In the limit of instantaneous and simultaneous measurements, measuring a companion's dynamical mass M_2 is as simple as solving the system of equations

$$a_{\rm Gaia+WFIRST} = \frac{GM_2}{r^2}\cos i, \qquad a_{\rm RV} = \frac{GM_2}{r^2}\sin i, \quad \text{and} \qquad \rho = r\cos i$$

where $a_{\rm Gaia+WFIRST}$ and $a_{\rm RV}$ are measured accelerations, r is the physical separation, i is the angle of r with respect to the plane of the sky, and ρ is the projected separation.

The growing array of radial velocity instruments will enable first-principles mass measurements for all imaged planets discovered astrometrically. This stands in sharp contrast to the current situation, where most masses of imaged planets are determined by assuming stellar ages and planet cooling curves and fitting to observed luminosities (Bowler, 2016). As soon as stars show hints of acceleration in *Gaia*, we can begin radial velocity follow-up to achieve the long time baselines that are necessary. A large sample of planets with precise dynamical masses will test, rather than assume, models of planet formation and evolution.

4 Imaging Astrometric Discoveries

The companions discovered by combining *WFIRST*-WFI and *Gaia* will typically be old and relatively cold, with atmospheric processes and chemistry more similar to that of the outer gas giants in the Solar system than to most currently imaged exoplanets. Finding them in thermal emission requires a large telescope operating in the near to mid infrared. We assume a high-contrast instrument operating from at L'-band on either a 10-m or a 30-m telescope. We take a planet to be astrometrically detected if fitting a full orbital model improves the astrometric residuals by $\Delta\chi^2 \geq 30$ over a fit assuming constant proper motion (Perryman et al., 2014).

We model the exoplanet population around *Gaia*-detected stars within 100 pc using the fit to Kepler occurrence rates provided by NASA's Exoplanet Program Analysis Group (ExoPAG) Science Analysis Group 13 (SAG13). We scale the distribution by an exponential falloff function of the form $\exp\left(-(a/10\ {\rm AU})^2\right)$, motivated by the lack of observed outer wide-separation giant planets (McBride et al., 2011). We adopt $a_0 = 10$ AU, as suggested by attempts to reconcile the Cumming et al. (2008) occurrence rate model with ground-based direct imaging campaigns (Macintosh et al., 2008; Vigan et al., 2012). We do not assume the occurrence rates rising with separation that overpredicted the yield of some imaging surveys.

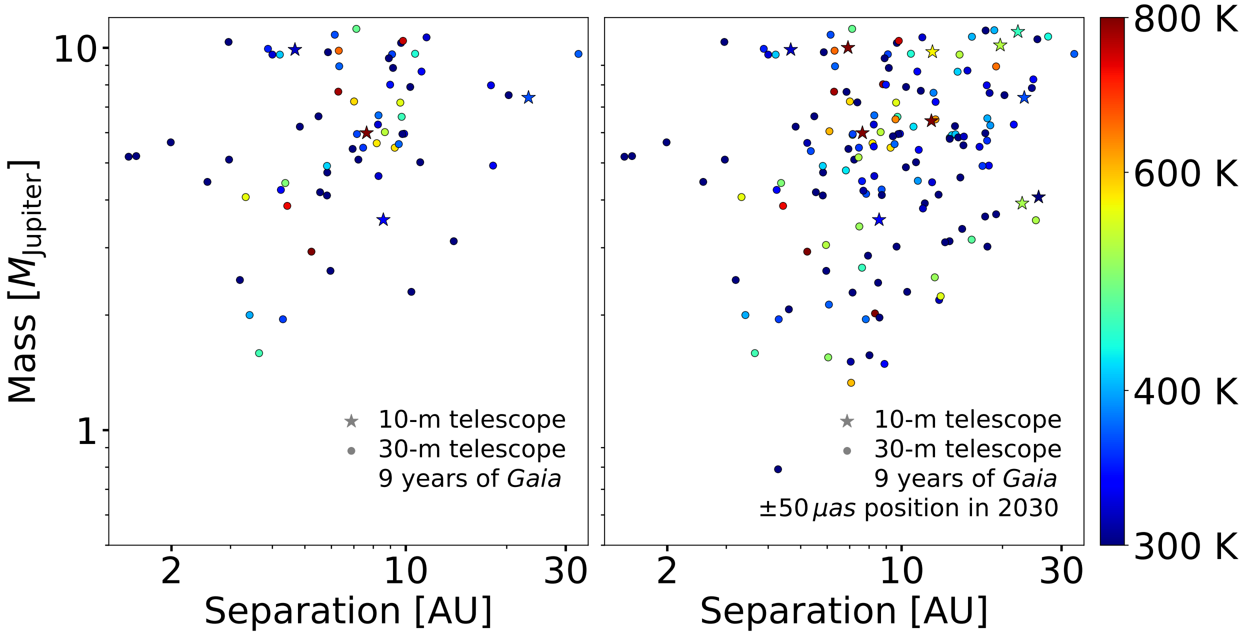

Figure 1: Planets accessible to direct imaging via thermal emission assuming a 9-year extended *Gaia* mission without (left panel) and with (right panel) a single position measured by *WFIRST*-WFI in 2030. Star symbols show planets that can be imaged by a 10-m telescope operating at L' band; circles show those accessible to a 30-m telescope. A single *WFIRST*-WFI position measurement enables the discovery of 161 planets by a 30-m telescope and 13 by a 10-m telescope in this simulation, versus the 69 and 4 seen by *Gaia* alone. It will also significantly improve the precision of dynamical masses. Correlated uncertainties and systematics in *Gaia* would degrade the precision of *Gaia* alone and make the increases more dramatic. Our assumed planet occurrence falls off exponentially past 10 AU; it is not the optimistic model that overpredicted the yields of some earlier imaging surveys.

For direct imaging follow-up, we assume a high-contrast integral-field spectrograph operating from 2–5 μm. For a 10-m telescope, we take the Keck M-band contrast curve from Mawet et al. (2019), scale it in separation by a factor of 3.8/4.8 to convert from M to L' in units of λ/D and adopt a sensitivity floor of $L' = 19$ mag assuming 10 hours of integration. For a 30-m telescope, we scale the separation by a further factor of 3 to account for the improved diffraction limit, and adopt a sensitivity floor of $L' = 21.9$ mag assuming 3 hours' integration (Skemer et al., 2018). We adopt 1 magnitude of improvement from the ability of an integral-field spectrograph to chromatically distinguish diffraction speckles from real companions (Marois et al., 2014). We assume a uniform distribution of ages between 1 Myr and 10 Gyr and adopt the COND cooling models (Baraffe et al., 2003); we then refine the photometry by using spectra from Morley et al. (2014) to select the bandpass that maximizes the planet's signal-to-noise ratio.

Figure 1 shows the planet yield with an extended *Gaia* mission without (left) and with (right) a single epoch from *WFIRST*-WFI. The combination of *Gaia*, *WFIRST*, and 30-m telescopes can image over 160 planets. Even for those planets that could be discovered without *WFIRST*, the additional astrometric epoch will verify the uncertainties (and the planet's existence), and will improve the precision of the dynamical masses.

5 Science with More than 100 Imaged Exoplanets

A sample of exoplanets discovered astrometrically will have masses, approximate ages (from their host stars), and spectra. Today, we can correlate planet masses and radii with stellar and orbital properties to compare to predictions of planet formation theory (Winn & Fabrycky, 2015). With the sample promised by *WFIRST*-WFI and the 30-m-class telescopes, we will be able to correlate planets' chemistry and elemental abundances with their masses and orbits, and study the dependence of planet properties on stellar properties. Given the large range of observables, a sample of hundreds of planets might be needed to confidently detect these trends and compare them to the predictions of planet formation theory.

High-contrast imaging is most sensitive around young stars, while transit and radial velocity surveys are most sensitive around old stars. Stellar astrometry is almost free of these biases: its sensitivity depends only on stellar brightness and distance from Earth. *WFIRST* will open up the coldest planets for spectroscopy, down to effective temperatures as low as ∼300 K, where models have not yet been tested. With a nearly unbiased initial selection and a 30-m telescope providing sensitivity to old and cold planets, we can resolve the theoretical uncertainties over initial entropy (Marley et al., 2007), and study the evolution of planetary systems over billions of years.

In the late 2020s, the European Space Agency will launch ESA's its ARIEL mission (Tinetti et al., 2016) to measure the transmission spectra of hundreds of massive transiting planets. *Gaia*, *WFIRST*-WFI, and 30-m-class telescopes can obtain a large sample of emission spectra from planets at much wider separations. With these two large samples, we will be able to correlate chemistry, cloud cover, and metallicity with exoplanet orbital properties over orders of magnitude in separation and widely varying stellar properties.

6 Conclusions and Recommendations

This white paper has argued that a single epoch of high-precision astrometry provides exceptional value to exoplanet science in general and to high-contrast imaging in particular. A shallow, full-sky *WFIRST* survey will help discover ∼160 exoplanets accessible to direct imaging from the ground. These companions will have masses measured from first principles, age and abundance constraints from their hosts, and thermal emission spectra to enable detailed characterization. Such a full-sky survey will have enormous ancillary benefits not explored here. To name just a few, these include a cross-calibration and verification of *Gaia*'s precision, full-sky reference images for transient astronomy, and detailed comparison maps for LSST enabling further cross-calibrations. While we have focused on planets, *WFIRST*-WFI could also discover hundreds of brown dwarfs, white dwarfs, and perhaps even nearby neutron stars and black holes.

A full-sky astrometric survey with *WFIRST*-WFI will enable large-scale imaging surveys using 30-m telescopes that would otherwise have prohibitively low discovery rates. The sample would also have well-defined selection criteria, making it ideally suited to detailed comparisons to planet formation models. ESA's ARIEL mission will provide hundreds of exoplanet transmission spectra at close-in orbits. *WFIRST*-WFI and 30-m telescopes promise a large and rich sample in emission at wider separations. With hundreds of exoplanet spectra covering a wide range of planet and stellar properties, we will finally be able to address where massive exoplanets form, and how they migrate and evolve.

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