The Orbit of the Wide-Orbit Giant Planet HD 106906 b

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Abstract

Direct imaging surveys for extrasolar planets have discovered a small number of planetary-mass companions (perhaps "planets", but hereafter PMCs) that orbit >100 AU from their host stars. These wide companions pose a significant challenge to models of giant planet assembly and evolution, and there are still many puzzling questions regarding their formation. In particular, orbital information can test whether companions form in situ or are ejected from inner solar systems.

We propose an archival program to analyze the 2004 and 2016 epochs of ACS/HRC and WFC3/IR HST imaging data on HD 106906 b, an 11 MJup companion located 650 AU away from its host star (which also hosts a perturbed debris disk) in the Sco-Cen OB association. We will measure the proper motion of the companion in order to determine its orbital motion over the 12 year time baseline, achieving a proper motion uncertainty of <0.5 mas/yr. A dynamical model of the disk+planet system predicts a total motion of ~34 mas between 2004 and the present (Nesvold et al. 2017). The magnitude of this motion is well constrained by the model, so the level of agreement or discrepancy provides a direct test of whether the model is valid or instead the disk is being sculpted by another body. If the disk does appear to be sculpted by HD 106906b, then the direction of our measured velocity vector (which is totally unconstrained in the model) will provide additional data to constrain the orbit.

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Dataset Summary:

Instrument	No. of Datasets	Retrieval Method	Retrieval Plan
ACS	4	FTP	FTP
WFC3	12	FTP	FTP

■ Scientific Justification

Giant Planets in Ultrawide Orbits

Over the past decade, direct imaging surveys for extrasolar planets have discovered a small number of planetary-mass companions ($\lesssim$15 M_{Jup}; perhaps "planets", but hereafter PMCs; Figure 1) at $\gtrsim$50 AU orbital radii from their primaries. The prototypical wide PMC, 2M1207-3933 b, consists of a 4–8 M_{Jup} companion located $\rho \sim 40$ AU away from a 10 Myr old brown dwarf (Chauvin et al. 2004). Since its discovery, $\sim$10 other PMCs have been found, most of which orbit higher-mass primaries ($\sim$0.3–2.0 $M_{\odot}$; Neuhauser et al. 2005; Lafreniere et al. 2008; Ireland et al. 2011; Bowler et al. 2013; Kraus et al. 2014; Figure 1) and at much wider radii (100–500 AU). These ultrawide companions are intriguing analogs to more traditional planets like HR 8799 bcde (Marois et al. 2008), Beta Pic b (Lagrange et al. 2009), 51 Eri b (Macintosh et al. 2015), HD 95086 b (Rameau et al. 2013), and LkCa15 b (Kraus & Ireland 2012). PMCs' orbits are very different from Solar System and RV/transiting planets, so it is unclear if they form via similar processes. However, if they form in disks via the same process as bona fide "planets", then PMCs are a boon for exoplanet studies; their wide orbits make them easier to observe, so they are the high-S/N templates for interpreting difficult observations of traditional planets.

Planetary-mass companions in ultrawide orbits pose a significant challenge to existing models of planet formation. Their orbital radii are so large that it is unlikely that they could form like traditional planetary systems, as the classical core accretion timescale is far too long ($\gg$100 Myr at $a > 100$ AU; Pollack et al. 1996) and Class II disks (Andrews & Williams 2005) should not become Toomre unstable to direct fragmentation of $\sim$5 M_{Jup} objects at these extreme radii (Dodson-Robinson et al. 2009; Kratter et al. 2010, and references therein). However, it is equally unlikely that PMCs could form like binary companions during the Class 0/I stages, since they fall near or below the opacity-limited minimum mass (Bate et al. 2005), and should accrete to become massive binary companions unless they form exactly as the circumstellar envelope is exhausted (Kratter et al. 2010). Nonetheless, if PMCs form in situ then one of these outcomes must occur.

However, it also remains plausible that PMCs form at much smaller orbital radii, but are ejected onto wide orbits via dynamical interactions. This model would be a low-energy analog of the embryo ejection model for brown dwarf formation (Reipurth & Clarke 2001). There is circumstantial evidence against it. Many of the youngest PMCs have circumsubstellar disks, despite the dynamical stripping that would occur in the close encounters needed to eject them from inner solar systems (e.g., Bowler et al. 2011). However, the presence of disks is not conclusive since they might be replenished by accretion from the circumprimary disk or envelope. While the orbital periods of PMCs are far too long for full orbit fits, measured orbit arcs for the first 2–3 objects show substantial tangential motion (e.g., Ginski et al. 2014; Schwartz et al. 2015; Bryan et al. 2016; Pearce et al., in prep) that is not consistent with the highly eccentric orbits and almost purely radial motion that would result from ejections. Orbit measurements are slow and costly, though, so the sample is growing slowly and every available opportunity must be seized.

HD 106906: A Wide-Orbit Giant Planet Perturbing a Debris Disk

HD 106906 is composed of a close binary pair of intermediate-mass stars in the Sco-Cen OB association (τ ∼15–20 Myr; Pecaut et al. 2012), which until recently was relatively anonymous. Chen et al. (2005) demonstrated that the system also harbors a debris disk with an outer radius of roughly $50 - 100$ au; due to the presence of this disk, it was observed with HST/ACS/HRC in 2004. The disk is viewed nearly edge-on, with a viewing inclination of 85 degrees, and exhibits a brightness asymmetry towards the east side of the disk and a long, faint extended tail towards the west. Bailey et al. (2014) later observed the system with ground-based adaptive optics and found, in combination with the 2004 HST imaging, that the HD 106906 system also harbors an 11 M_{Jup} companion, HD 106906b, at a projected distance of 650 au from its central star (Figure 1).

The projected separation of HD 106906 is even wider than many other PMCs, and is nearly an order of magnitude larger than for more traditional planetary systems like HR 8799, so it is one of the most extreme outliers for planet-like formation. At the same time, its host stars (a close binary pair) are substantially more massive than the Sun, making the mass ratio of the companion ($< 1\%$) even more of an extreme outlier for binary-like formation (e.g., Reggiani & Meyer 2013). As we discuss above, the companion may have formed interior to the disk and then been scattered outwards, but stabilization of its orbit by a stellar flyby has a low probability (Rodet et al. 2017). Alternatively, the companion may have formed *in situ* in its current wide orbit, via either the planetary or binary channel.

One major obstacle to determining the formation history of this system is HD 106906b's extremely underconstrained orbit, as its position has only been measured in a single epoch. Nesvold et al. (2017) demonstrated that HD 106906b could produce the asymmetric disk features via gravitational perturbations and placed some constraints on the companion's orbit (Figure 2). This orbit is not a unique solution for creating the observed disk morphology, but variations in the orbit's longitude of nodes, argument of pericenter, inclination, semi-major axis, and eccentricity within the constraints placed by the Nesvold et al. (2017) model (pericenter is on the east side of the star, inclination of the companion's orbit relative to the disk is $\lesssim 20°$, secular timescale of the companion's perturbations on the disk is less than the age of the system) yield similar predicted amplitudes, but varying directions of motion.

The Nesvold et al. (2017) model orbit predicts that the companion should have moved by 34 milliarcseconds since its first measurement in 2004 (Fig. 1). As we discusss above and demonstrate in Figure 3, this level of motion is now routinely measurable with select observatories and high-resolution imaging instruments, including HST with both ACS and WFC3. Fortuitously, another HST program obtained imaging of HD 106906b with WFC3/IR (to measure cloud variability and the rotation period) in 2016, providing a second epoch to measure the companion's true motion (Figure 4). A measurement of the companion's new position would help us better understand the orientation of the companion's orbit relative to the disk in 3D space, constraining the companion's formation history.

Proposed Program: The Orbital Motion of HD 106906 b

We propose an archival program to analyze the 2004 and 2016 epochs of HST imaging data on HD 106906 b, measuring the proper motion of the companion in order to determine its orbital motion over the 12 year time baseline. A dynamical model of the disk+planet system predicts a total motion of $\sim$34 mas between 2004 and the present (Nesvold et al. 2016). The magnitude of this motion is well constrained by the model, so the level of agreement or discrepancy provides a direct test of whether the model is valid or instead the disk is being sculpted by another body. If the disk does appear to be sculpted by HD 106906b, then the direction of our measured velocity vector (which is totally unconstrained in the model) will provide two more degrees of freedom in solving for the orbit of the companion.

The proposed observations are not difficult for a given observatory and its high-resolution imaging camera, as long as the system is kept stabilized, the geometric distortion and pixel scale are well calibrated, and the PSF is understood. However, the only observatories currently calibrated to this level are Keck/NIRC2 (e.g., Yelda et al. 2010) and HST with most of its cameras, including ACS/HRC (Anderson & King 2004) and WFC3/IR (Kozhurina-Platais et al. 2009). Our group has demonstrated its ability to measure that astrometry from ground and space (Kraus et al. 2014; Dupuy et al. 2016; Pearce et al., in prep; Figure 3.) However, there is one twist that will require developmental work. HD 106906 is extremely bright and is saturated in the HST images. In fact, the high contrast ($\Delta R \sim 17$ mag) will always make direct relative astrometry between companion and host star difficult, especially since the host star is itself a binary. We therefore need to develop methods to measure the astrometry of the companion with respect to the (mostly nonmoving) faint field stars seen in Figure 4, calibrate any remaining motion with those stars' Gaia DR2 proper motions, and then compare our results to the Gaia DR2 proper motion of the primary star.

Even an observation of the companion's motion outside of the predicted range (or the absence of motion), would be an informative result. If the companion is orbiting too far from the disk to perturb it on a timescale shorter than the age of the system, this would indicate that a second perturber may be orbiting interior to the disk, producing the observed asymmetries. Alternatively, HD 106906b may be on its way out of the system after a scattering event, although the timescale of such an event would make this highly unlikely. Any of these outcomes would provide new context for the system geometry, indicating if HD 106906b is sculpting the debris disk (or perhaps the system hosts another planetary companion). If we can use that sculpting to obtain the first full orbital solution for a wide-orbit giant planet, it will provide new context for their formation channel and dynamical evolutionary history.

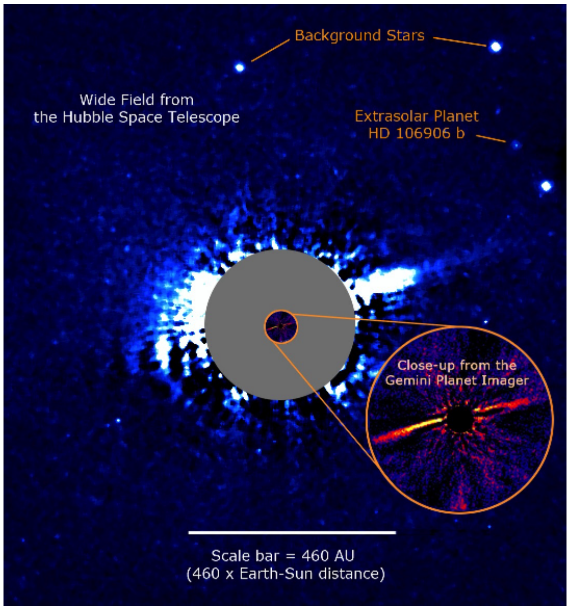

Fig. 1. From Kalas et al. (2015), the HD 106906 system with its debris disk and wide-orbit panetary companion. The disk is seen nearly edge-on, with a truncated non-symmetric morphology in the outer portion of the disk. HD 106906 b was first observed with ACS/HRC in 2004, but not recognized as a comoving planetary companion until second-epoch observations with ground-based telescopes by Bailey et al. (2014). The system was observed again with WFC3/IR as part of a photometric monitoring campaign in early 2016; given the known stability of ACS and WFC3, the expected orbital motion ($\sim$34 mas) should be easily measurable with proper analysis.

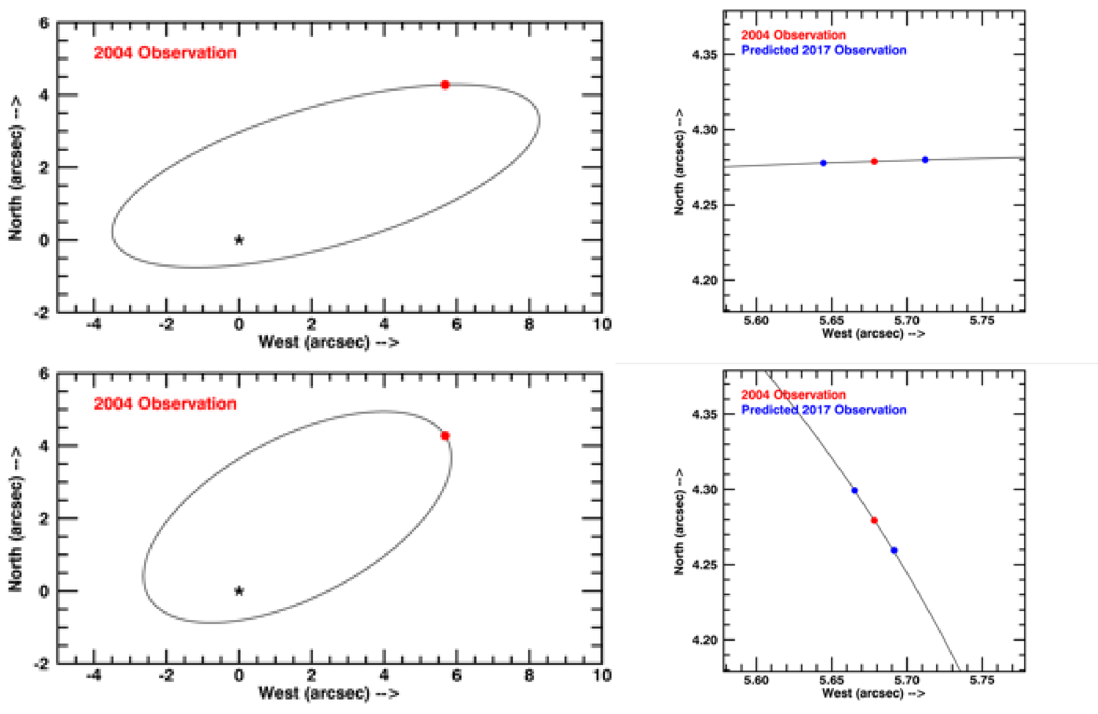

Fig. 2. Two possible models that could explain the truncated and asymmetric debris disk around HD 106906 A. The orbital elements are not unique, so the proposed measurement of $\vec{v}_{tan}$ will have substantial constraining power. However, many possible combinations of direction and speed are disallowed; if we observe one of these values, it would demonstrate that the truncation of the debris disk is caused by other effects (such as another planet) and does not constrain the planet's orbit.

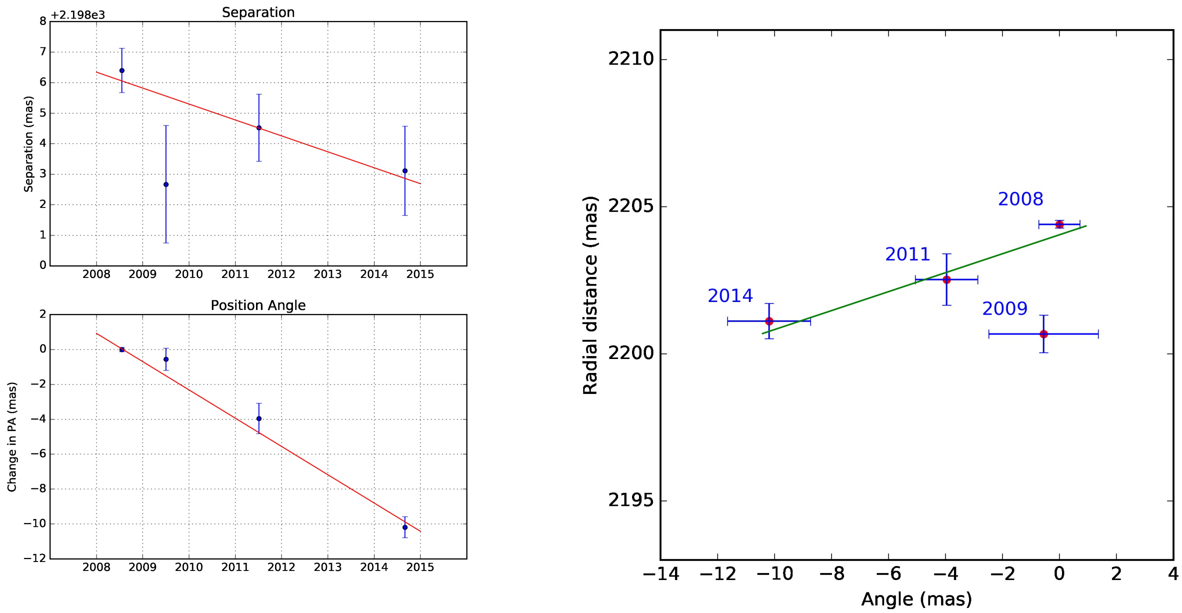

Fig. 3. Orbital motion of another wide-orbit giant planet, GSC 6214-210 b (Pearce et al., in prep). As we demonstrate with our ground-based observations with Keck/NIRC2, milliarcsecond-level precision is now becoming routine for well-calibrated high-resolution imaging data, yielding proper motion uncertainties of <<1 mas/yr over decade timescales. However, the only telescopes/instruments currently calibrated at this level are Keck/NIRC2 (for which HD 106906 is too far south) and HST (for which multi-epoch data already exists; see Figure 4).

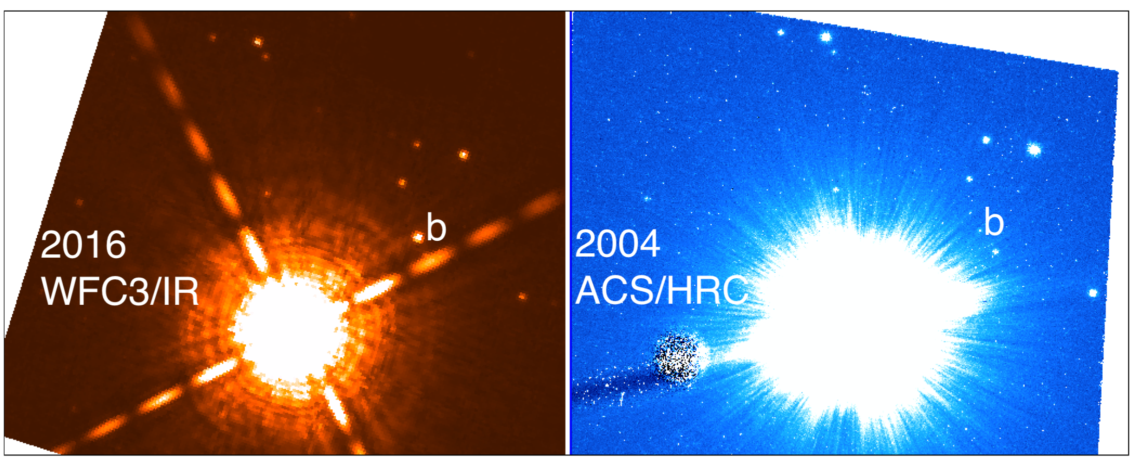

Fig. 4. HST images of the HD 106906 system in 2016 (left) as compared to 2004 (right). HD 106906 b is clearly detected at both epochs, offering accurate astrometry across a 12 year time baseline. Numerous background stars are available for establishing an absolute astrometric reference frame. The ACS/HRC observation detected the companion at $S/N = 30$, so the corresponding astrometric uncertainty is $\sigma_{ast} = \frac{FWHM}{SNR}$ ~2–3 mas. The ten WFC3/IR observations detected the companion at $S/N > 100$ in each image, so the uncertainty will be set by distortion ($\lesssim$5 mas; Kozhurina-Platais et al. 2009). **The predicted velocity ($\mu \sim 34$ mas/yr) will be measured at $\gtrsim$6–7σ.**

Analysis Plan

We propose an archival program to measure multi-epoch astrometry for the HD 106906 system using archival HST data, measuring the orbital motion of HD 106906b in order to test models that include its interaction with the system's debris disk, as well as provide new inputs to those models. This program will exploit the well-established data analysis techniques pioneered by Anderson & King (2004) to measure astrometry from the 2004 ACS/HRC data set, combining it with analyses of the 2016 WFC3/IR data using the geometric distortion solution of Kozhurina-Platais et al. (2009). The data volume is very modest, so we can acquire all datasets through the MAST website.

The ACS/HRC and WFC3/IR data reductions and astrometric measurements will be conducted using the ePSFs and distortion solution generated by Anderson & King (2004) for ACS, and by Anderson (2010) and Kozhurina-Platais et al. (2009) for WFC3/IR. Anderson & King found that the geometric distortion of ACS could be accurately corrected to as little as $\sigma{\sim}0.01$ pixels ($\sim$0.25 mas) using a distortion solution that they derived from observations of dense globular cluster fields. In our case, the uncertainties will be set by the photon noise limit (σ ~2–3 mas/yr, given the detection significance of $S/N = 30$). The WFC3/IR distortion solution has been validated to $\sigma < 5$ mas (see also Beichman et al. 2014). The second-epoch data do not have much rotation or dithering, so we might be able to average this value down a little, but it will likely set our proper motion uncertainty of $\sigma_\mu \sim 0.4$ mas/yr. The stars are all well isolated, so each can be fit independently with its own ePSF model in each image.

We note that these solutions include linear corrections unique to each observation that correct for telescope breathing and differential velocity aberration. The field contains $\sim$15 bright field stars in common, so we can fit for these corrections in all cases. The astrometric algorithm also uses a grid of spatially-dependent empirical PSFs (derived from on-sky data) to refine the centroiding process. Also, we will explore the need for any PSF subtraction of the primary star, but its flux contribution at the location of HD 106906b is negligible (Figure 4) and it is safer to not use any field stars that might be contaminated, given the presence of many others to use.

It would normally be extremely difficult to measure the astrometry of the planet compared to its host star, due to the high contrast. In fact, the primary star is completely saturated in the 2004 epoch. However, there are numerous background stars available for measuring (nearly) absolute astrometry. We therefore expect that after we have measured image-space positions for HD 106906b and each field star, we will use the field stars common to both observations in order to measure the relative motion of HD 106906b with respect to the background star grid. Many of these sources are in Gaia DR1, so we expect that Gaia DR2 proper motions will allow us to establish an absolute frame. We then can compare this motion to the Gaia DR2 motion of HD 106906 A to determine the relative motion of the companion. The expected uncertainties of Gaia ($\sigma_\mu \lesssim 0.1$ mas/yr) are negligible compared to our astrometric uncertainties for HD 106906b that are driven by the 2004 epoch.

Management Plan

We expect that this program will support the senior undergraduate thesis project for an undergraduate student who will begin the project in their junior year (possibly Co-I L. Pearce, who has already developed some of the necessary tools while pursuing her current project; Figure 4). The student will be supported to invest 10–20 hours per week during the school year and 40 hours/week during summers. PI Kraus will advise the student on this project, while CoIs Bowler and Dupuy will provide input and assistance on the aspects of astrometric analysis (such as high-precision astrometry and orbit fitting) for which they have suitable expertise. CoI Nesvold will provide input to guide the comparison to her dynamical models and will update her models using the resulting astrometric measurements.

We expect to pursue the data reduction, ePSF fitting, and distortion correction during the 2017–2018 academic year. Many of our students are trained in basic image analysis and programming as part of our Research Methods class, so some of these tasks will be straightforward, but others might require development of new software or learning of new techniques. During the following summer, the student will develop code to plate-solve each image's astrometry against Gaia DR2 (which will be released in April 2018), computing the absolute proper motion vector of the companion. Finally, during the 2018–2019 academic year, the student will interpret the companion proper motion in the context of the Gaia DR2 proper motion of the primary star, and write a paper reporting the implications for the dynamical model of planet-disk interactions and more generalized posterior distributions for the orbital elements of the companion.

We also expect this program to support travel for CoI Nesvold and team members in UT-Austin to collaborate on the theoretical aspects of this project, travel for team members to present on the results at one or more astronomical conferences, and page charges to publish the results.

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