Tilting Gas Giants: A New Window into Planet Formation

Thematic Areas (Check all that apply):

☒ (Theme A) Key science themes that should be prioritized for future JWST and HST observations
☐ (Theme B) Advice on optimal timing for substantive follow-up observations and mechanisms for enabling exoplanet science with HST and/or JWST
☐ (Theme C) The appropriate scale of resources likely required to support exoplanet science with HST and/or JWST
☒ (Theme D) A specific concept for a large-scale (∼500 hours) Director's Discretionary exoplanet program to start implementation by JWST Cycle 3.

Summary: When we look at how planetary spin axes are tilted relative to their orbits in the solar system, we see a range of orientations that tell us stories of major past events and give us unique insight into climate. For example, Uranus is famously spinning on its side due to a past major collision, and our Earth's 23 degree tilt is why we have seasons. For exoplanets, measuring this spin axis tilt, or "planetary obliquity", is observationally intensive, requiring the combination of a planet's projected rotation rate from high-resolution spectra, rotation period from time-series photometry, and orbit from astrometry. To date only three planetary obliquities have been measured outside the solar system. Here we propose a large survey of giant planets and brown dwarfs to measure their obliquities, leveraging critical JWST observations with NIRSpec, NIRCam, and MIRI. While challenging, **these measurements enable new, powerful, and unique insights into planet formation**. This survey will enable novel constraints on planetary evolutionary histories, testing scenarios like giant impacts, stellar fly-bys, secular spin-orbit resonances, accretion histories, formation via gravitational instability, as well as probing climates on these other worlds.

Anticipated Science Objectives: We aim to measure planetary obliquities for a sample of ~30 gas giants and brown dwarf companions (Fig. 1) [1]. We will combine key rotation period measurements from JWST with projected rotation rate ($v \sin i$) measurements from ground-based high-resolution spectrographs such as KPIC/Keck and HIRISE/VLT to measure the companion's spin axis inclination i_p (Fig. 2) [e.g. 1, 2, 3]. Long-baseline low-cadence astrometry will trace out the orbits of the few companions without orbital constraints [4, 5]. With these obliquities, we will look for trends with 1) planet mass; 2) semi-major axis; and 3) planet/star mass ratio. With these we can test the feasibility and frequency of key formation and evolutionary processes, such as giant impacts, stellar fly-bys, secular spin-orbit resonances, accretion histories, and formation via gravitational instability [6, 7, 8, 9, 10]. For example, the likelihood of a giant impact, like the one we think tilted Uranus, depends on planet mass, separation, and stellar mass.

Urgency: Conclusions from this survey will impact our expectations for other key science endeavors exploring the timing of formation, anticipated atmospheric compositions, and more. In addition, the proposed combination of JWST time-series photometry and ground based high-resolution spectroscopy can impact future observational strategies with JWST.

Risk/Feasibility: This program requires coordination with ground based observations, namely measuring $v \sin i$'s with high-resolution spectroscopy. We do not anticipate challenges acquiring these complementary data given past successful proposals and oversubscription rates.

Timeliness: In the past, the only planets amenable to obliquity measurements were a handful of ($\lesssim$100 Myr old), massive (~10-20 $M_{\rm Jup}$), and distant ($\gtrsim$50 AU) super-Jupiters discovered by direct imaging campaigns [11]. It was exceptionally rare to obtain all three observables ($P_{\rm rot}$, $v \sin i$, orbit) for a single object in this limited population [1, 12, 13]. The advent of JWST combined with new ground-based implementations of high-dispersion coronagraphy (KPIC/Keck, HIRISE/VLT), yields the instrumental capability to target planets closer in to their host stars where gas giants are more common, increasing the amenable sample. Critically, the combination of JWST's photometric stability and coronagraphic imaging dramatically improves our ability to measure rotational modulations and thus $P_{\rm rot}$.

Cannot be accomplished in the normal GO cycle: This is an observationally expensive proposal. Rather than accumulating one obliquity at a time we seek to turbocharge our science gains from this new observable by increasing the sample by an order of magnitude.

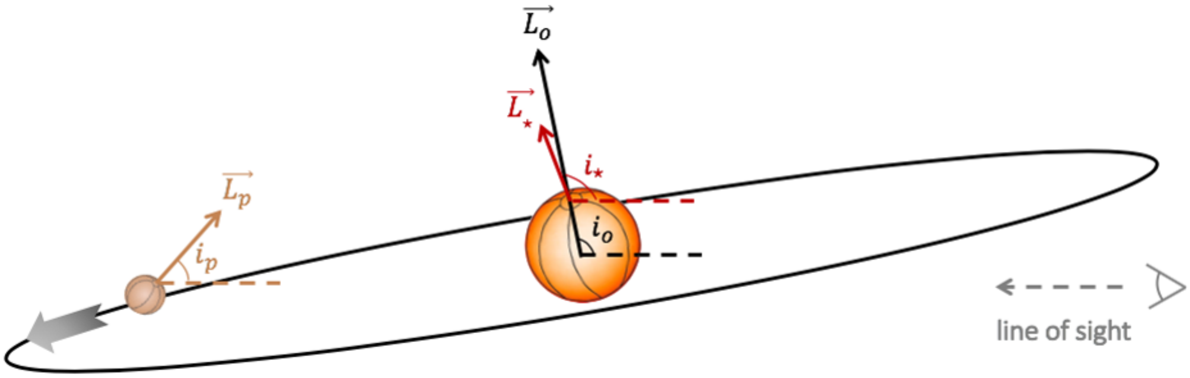

Figure 1: **3D angular momentum architecture of a planetary system.** The 3D geometry of our sample of systems can be described by three angular momentum vectors: L_o for the orbit, L_p for the planet spin, and L_s for the stellar spin. Observations allow us to measure line-of-sight inclinations for all three vectors: i_o, i_s, and i_p. The goal of this proposal is to measure the rotation periods of a sample of ∼30 gas giant and brown dwarf companions with JWST, combining this with a vsini$_p$ from ground-based high-resolution spectroscopy to obtain i_p. Long-baseline low-cadence precision astrometry will trace out the orbits of the few companions without orbital constraints, yielding i_o. The angle between L_p and L_o is the planetary obliquity that we are after. Most systems will also have constraints on i_s, allowing us to place additional constraints on the evolutionary histories of these systems using stellar obliquities as well.

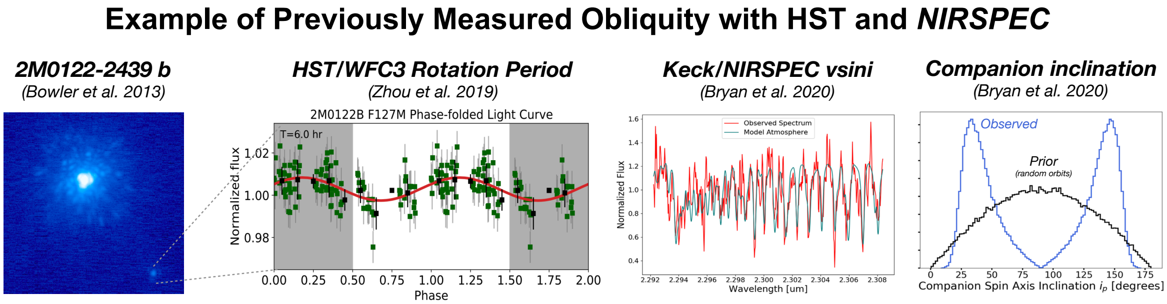

Figure 2: **First measurement of i_p for a planetary-mass companion.** HST observations of the directly imaged planet 2M0122b detected photometric modulations with amplitude ∼0.5% corresponding to a rotation period of 6.0 hours. A high-resolution spectrum from NIRSPEC/Keck yielded a vsini of 13.4 (+1.4 -1.2) km/s for this object. Combined, these observables yielded the posterior distribution shown on the right, corresponding to companion spin axis inclinations of 33 (+17 -9) degrees or 147 (+9 -17) degrees (the distribution is bimodal because we cannot tell from our observations whether this vector is pointing towards us or away from us) [1, 2, 3]. The unprecedented sensitivity and photometric stability of JWST has unlocked an order of magnitude larger sample of potential targets for these measurements.

References

[1] Marta L. Bryan et al. "Obliquity Constraints on an Extrasolar Planetary-mass Companion". In: 159.4, 181 (Apr. 2020), p. 181. DOI: `10.3847/1538-3881/ab76c6`. arXiv: `2002.11131 [astro-ph.EP]`.

[2] Brendan P. Bowler et al. "Planets around Low-mass Stars. III. A Young Dusty L Dwarf Companion at the Deuterium-burning Limit". In: 774.1, 55 (Sept. 2013), p. 55. DOI: `10.1088/0004-637X/774/1/55`. arXiv: `1307.2237 [astro-ph.SR]`.

[3] Yifan Zhou et al. "Cloud Atlas: High-contrast Time-resolved Observations of Planetary-mass Companions". In: 157.3, 128 (Mar. 2019), p. 128. DOI: `10.3847/1538-3881/ab037f`. arXiv: `1902.00085 [astro-ph.EP]`.

[4] Sarah Blunt et al. "orbitize!: A Comprehensive Orbit-fitting Software Package for the High-contrast Imaging Community". In: 159.3, 89 (Mar. 2020), p. 89. DOI: `10.3847/1538-3881/ab6663`. arXiv: `1910.01756 [astro-ph.EP]`.

[5] Brendan P. Bowler, Sarah C. Blunt, and Eric L. Nielsen. "Population-level Eccentricity Distributions of Imaged Exoplanets and Brown Dwarf Companions: Dynamical Evidence for Distinct Formation Channels". In: 159.2, 63 (Feb. 2020), p. 63. DOI: `10.3847/1538-3881/ab5b11`. arXiv: `1911.10569 [astro-ph.EP]`.

[6] Jack J. Lissauer and David M. Kary. "The origin of the systematic component of planetary rotation I. Planet on a circular orbit". In: 94.1 (Nov. 1991), pp. 126–159. DOI: `10.1016/0019-1035(91)90145-J`.

[7] R. Michael Jennings and Eugene Chiang. "Primordial obliquities of brown dwarfs and super-Jupiters from fragmenting gravito-turbulent discs". In: 507.4 (Nov. 2021), pp. 5187–5194. DOI: `10.1093/mnras/stab2429`. arXiv: `2105.12160 [astro-ph.EP]`.

[8] Christian Reinhardt et al. "Bifurcation in the history of Uranus and Neptune: the role of giant impacts". In: 492.4 (Mar. 2020), pp. 5336–5353. DOI: `10.1093/mnras/stz3271`. arXiv: `1907.09809 [astro-ph.EP]`.

[9] Gregory Laughlin and Fred C. Adams. "The Modification of Planetary Orbits in Dense Open Clusters". In: 508.2 (Dec. 1998), pp. L171–L174. DOI: `10.1086/311736`.

[10] William R. Ward and Douglas P. Hamilton. "Tilting Saturn. I. Analytic Model". In: 128.5 (Nov. 2004), pp. 2501–2509. DOI: `10.1086/424533`.

[11] Brendan P. Bowler. "Imaging Extrasolar Giant Planets". In: 128.968 (Oct. 2016), p. 102001. DOI: `10.1088/1538-3873/128/968/102001`. arXiv: `1605.02731 [astro-ph.EP]`.

[12] Marta L. Bryan et al. "Obliquity Constraints on the Planetary-mass Companion HD 106906 b". In: 162.5, 217 (Nov. 2021), p. 217. DOI: `10.3847/1538-3881/ac1bb1`. arXiv: `2108.13437 [astro-ph.EP]`.

[13] P. Palma-Bifani et al. "Peering into the young planetary system AB Pic. Atmosphere, orbit, obliquity, and second planetary candidate". In: 670, A90 (Feb. 2023), A90. DOI: `10.1051/0004-6361/202244294`. arXiv: `2211.01474 [astro-ph.EP]`.