K2-232c: The Cold Jupiter That Redefined the Origins of Hot and Warm Jupiters

Jessica Ranshaw[1], Songhu Wang[1], Xian-Yu Wang[1] & California-Carnegie APF team

[1]Indiana University **Email:** jranshaw@iu.edu

INDIANA UNIVERSITY

1 Introduction

- Hot Jupiters (HJs) are a well characterized population in the field of exoplanet research, yet **their origins remain elusive.**
- Two paths can describe a HJ's formation: dynamically hot (e.g., high-eccentricity migration [1][2]) or dynamically cold (e.g., disk migration and in-situ formation [3][4][5][6]).
- Orbital eccentricities can help us determine which of these paths are more likely [7].
- Current evidence shows that HJs are dynamically hotter than WJs, suggesting that **some form of high-eccentricity migration mechanism is responsible for creating HJs**.
- Cold Jupiters (CJs) are supposedly prevalent in both HJ (51% [8]) and WJ (~70% [9]) systems, indicating that **planet-planet interactions could be the primary driver for HJ production**.
- Yet, there is a significant lack of investigation into the search for CJs in known WJ systems to also find evidence of outer companion perturbers.
- In this work, we undergo that search and further investigate the difference in dynamical temperature between HJ and WJ systems.

2 Discovery

- In 2018, two separate papers [10] [11] simultaneously discovered K2-232b, a transiting WJ (P = 11 days) orbiting a late F-type star (Vmag = 9.9).
- Given the stellar brightness and the presence of a transit, the system was ideal for Rossiter-McLaughlin (RM) effect observations. In 2021, RM measurements were taken and found the planet was well-aligned with the spin axis of its host star [12].
- However, the data taken in 2021 [12] and 2018 [11] were offset from each other even though both used the same instrument.
- This was indicative of the **possible existence of another planet in the system with a larger semi-major axis** (See Figure 1).

3 Results

- We **present the discovery of a CJ (K2-232c) in a known WJ system (K2-232b)** that may help us understand how high-eccentricity migration initiated by an outer planetary perturber creates HJs.
- With an e = 0.2 for the inner WJ, its formation is best described by either disk migration or in-situ formation.
- However, with the companion we are introducing, the high-eccentricity migration pathway can also explain the inner planet's presence.
- The current population of CJs makes up a substantial fraction of all exoplanets. Knowing how and where to search for such planets is imperative to learning more about the evolution of gas giants along with their characteristics and demographics.

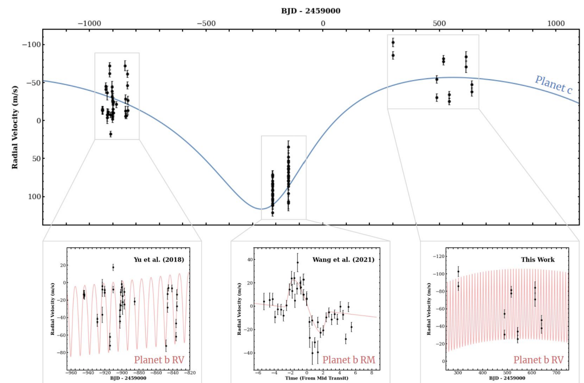

Figure 1: Top panel: RV measurements versus time for K2-232b; the blue trend line indicates an outer long-period gas giant companion affecting the RV measurements of the inner planet. Bottom left panel: RV measurements versus time for K2-232b from original discovery paper [11]. Bottom middle panel: RM effect RV measurements versus time from mid-transit for K2-232b [12]. Bottom right panel: RV measurements versus time for K2-232b obtained in this work. All data shown here is taken with APF-Levy.

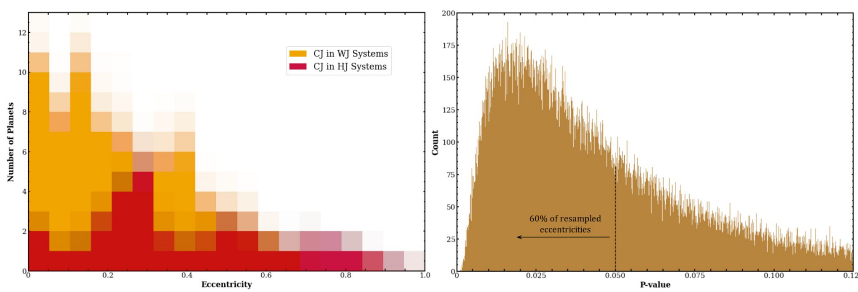

Figure 2: Left panel: Histogram of CJ orbital eccentricities in WJ (orange) and HJ (red) systems. Right panel: Histogram of p-value distribution calculated from two-sample Anderson-Darling test. To the left of the black dashed line indicates where 60% of our test iterations reject our null hypothesis of a shared parent CJ eccentricity distribution at the p = 0.05 level.

4 Discussion

- If planet-planet interactions are the dominate channel of high-eccentricity migration producing HJs, then **the long term giant companions of those HJs should be more eccentric than those in WJ systems** [13].
- We utilized confirmed HJ/CJ and WJ/CJ systems to investigate this prediction and provide evidence for the dynamical temperature difference of HJs and WJs at the population level.
- Our results show that **CJs in HJ systems tend to have more eccentric orbits, whereas those in WJ systems concentrate around more circular values** (see Figure 2).
- This contributes another line of evidence supporting that HJs are dynamically hotter than WJs.

5 Next Steps

- High-eccentricity migration can describe WJs with intermediate eccentricities if an outer planetary companion is also present, suggesting **some WJs are on a high-eccentricity migration path to become HJs.**
- Given this notable possibility, there is a significant lack of investigation into the search for CJs in known WJ systems to find outer companion perturbers.
- We are remedying this with the **MACAWS Survey (a Mass Analysis of Cold and Warm Jupiter Systems)**; a survey dedicated to observing long RV baselines in WJ systems to search for possible CJ companions.
  - Specifically, we further investigate K2- and TESS-discovered WJ systems with the exact instruments used to confirm them.

The MACAWS Survey

6 References

[1] Rasio & Ford 1996, Dynamical Instabilities and the Formation of Extrasolar Planetary Systems
[2] Wu & Murray 2003, Planet Migration and Binary Companions: The Case of HD 80606b
[3] Goldreich & Tremaine 1980, Disk-satellite Interactions.
[4] Lin et al. 1996, Orbital Migration of the Planetary Companion of 51 Pegasi to its Present Location
[5] Ward 1997, Protoplanet Migration by Nebula Tides
[6] Batygin et al. 2016, In Situ Formation and Dynamical Evolution of Hot Jupiter Systems
[7] Dawson & Johnson 2018, Origins of Hot Jupiters
[8] Knutson et al. 2014, Friends of Hot Jupiters. I. A Radial Velocity Search for Massive, Long-Period Companions to Close-in Gas Giant Planets
[9] Bryan et al. 2016, Statistics of Long Period Gas Giant Planets in Known Planetary Systems
[10] Brahm et al. 2018, K2-232 b: A Transiting Warm Saturn on an Eccentric *P* = 11.2 d Orbit Around a *V* = 9.9 Star
[11] Yu et al. 2018, Two Warm, Low-density Sub-Jovian Planets Orbiting Bright Stars in *K2* Campaigns 13 and 14
[12] Wang et al. 2021, The Aligned Orbit of the Eccentric Warm Jupiter K2-232b
[13] Wu et al. 2023, Evidence for Hidden Nearby Companions to Hot Jupiters