HR 8799: The Benchmark Directly-Imaged Planetary System

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ABSTRACT

HR 8799 harbors arguably the first and best-studied directly-imaged planets. In this brief article, I describe how the HR 8799 planetary system is a benchmark system for studying the atmospheres, orbital properties, dynamical stability, and formation of young superjovian planets. Multi-wavelength photometry and spectroscopy show that HR 8799 bcde appear to have thicker clouds than do field brown dwarfs of similar effective temperatures and exhibit evidence for non-equilibrium carbon chemistry, features that are likely connected to the planets’ low surface gravities. Over 17 years of astrometric data constrain the planets’ orbits to not be face on but possibly in multiple orbital resonances. At orbital separations of 15–70 au and with masses of \( \approx 5–7 \, M_J \), HR 8799 bcde probe the extremes of jovian planet formation by core accretion: medium-resolution spectroscopy may provide clues about these planets’ formation conditions. Data from the next generation of 30 m-class telescopes should better constrain the planets’ orbits, chemistry, gravity, and formation history.

1. Introduction

In March 2008, Christian Marois noticed one (Figure 1, left panel), and then two, faint point sources located at a projected separation of 68 and 38 au from the nearby, dusty A5 star HR 8799. Follow-up observations in July–September 2008 confirmed that these objects were bound companions and added a third at \( \rho \sim 24 \) au (Marois et al. 2008, hereafter Ma08). Two years later, Marois et al. (2010) announced the discovery of a fourth companion at \( \rho \sim 15 \) au: HR 8799 e (Figure 1, right panel). Given the estimated age of the system (\( t \sim 30 \, M\text{yr} \), Ma08, Baines et al. 2012), HR 8799 bcde’s low luminosities imply masses of \( \approx 5–7 \, M_J \), below the deuterium-burning limit (\( \approx 13 \, M_J \)) nominally separating planets from brown dwarfs. Analyses focused on atmospheric modeling (Currie et al. 2011a, hereafter Cu11), dynamical stability (Marois et al. 2010, Cu11), and formation (Kratter et al. 2010, Cu11) likewise corroborate the conclusion that HR 8799 bcde are bona fide planets, not brown dwarfs.

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The HR 8799 planetary system resembles a scaled-up version of our outer solar system. The planets orbit in between a warm dust belt ($r_{\text{inner}} \approx 6-12 \text{ au}$) and a cold Kuiper belt-like structure at $r_{\text{outer}} \approx 90-145 \text{ au}$ (Su et al. 2009; Booth et al. 2016). Due to HR 8799’s higher luminosity, the planets and dust belt populations receive about as much energy as the solar system’s gas/ice giant planets and asteroid belt/Kuiper belt receive from the Sun.

Fig. 1.— (left) The first direct image of an extrasolar planet: detection of HR 8799 b from October 2007 Gemini/NIRI data reduced in March 2008, the first of three planets (HR 8799 bcd) announced by Marois et al. (2008). (right) Image of HR 8799 b cde from November 2009 Keck/NIRC2 data (Marois et al. 2010) depicting the planets’ counterclockwise orbital motion. The planets’ discoveries were enabled by advances in observing and image processing techniques (e.g. Marois et al. 2006; Lafrenière et al. 2007).

HR 8799 harbors arguably not just the first directly-imaged planets but among the best

\footnote{While Fomalhaut b was announced on the same day as HR 8799 bcd and claimed to produce variable, accretion-driven emission at 0.6 $\mu$m and thermal emission at longer wavelengths (Kalas et al. 2008), later work cast doubt on its existence (Janson et al. 2012) and then showed that instead Fomalhaut b is made visible entirely by circumplanetary dust emission (Currie et al. 2012b; Galicher et al. 2013). Thus, it is on slightly shakier ground and instead, as noted in Currie et al. (2012b), is likely a “planet [of unknown mass] identified by direct imaging but not a directly-imaged planet.” While other planet-mass objects were announced prior to HR 8799 bcd (e.g. 2M 1207 B; Chauvin et al. 2004), their lower mass ratios (compared to the primary) and/or wider separations suggest that they represent the low-mass tail of the substellar mass}
studied ones. Photometry and/or low-resolution spectroscopy for HR 8799 bcde span 1–5 µm (e.g. Cu11; Barman et al. 2011a; Galicher et al. 2011; Zurlo et al. 2016). HR 8799 bc have 1.4–2.5 µm medium-resolution spectroscopy (Konopacky et al. 2013; Barman et al. 2015). After the reported discovery of HR 8799 bcd, multiple studies revealed at least one of the HR 8799 planets from data between 1998 and 2007 (e.g. Lafrenière et al. 2009; Metchev et al. 2009; Soummer et al. 2011; Currie et al. 2012a). The planets have been imaged by nearly all other 5–8 m telescopes with adaptive optics systems (e.g. Cu11; Currie et al. 2014a; Ingraham et al. 2014; Oppenheimer et al. 2013; Zurlo et al. 2016).

This wealth of data makes HR 8799 a benchmark system for studying the atmospheres, orbital properties, dynamical stability, and formation of young superjovian planets.

2. HR 8799 bcde as a Probe of Young Jovian Planet Atmospheres

HR 8799 bcde provide the first glimpse at how the atmospheric properties of young, self-luminous planets compare to both old field brown dwarfs and younger, lower-mass brown dwarfs. Typical luminosity evolution models (e.g. “hot start” models) predict that directly-imaged, superjovian (5–10 M_J) planets between 10 and 100 Myr old cover a temperature range of ≈ 600 to 1800 K characteristic of field early L to late T dwarfs (e.g. Baraffe et al. 2003; Burrows et al. 2006; Stephens et al. 2009). Coarsely speaking, the L to T transition at ≈ 1200–1400 K (for the field) covers a transition from an object with a near-infrared spectrum lacking methane absorption and a cloudy atmosphere to an object with near-infrared methane absorption and weaker/negligible clouds (Saumon and Marley 2008). For ages of ∼ 30 Myr and masses of 5–7 M_J, standard luminosity evolution models predict that the HR 8799 planets should, if like field objects, have temperatures of T_{eff} ≈ 850–1100 K characteristic of mid/late field T dwarfs (Stephens et al. 2009).

Ma08 found hints of differences between the HR 8799 planets’ infrared (IR) colors and the field L/T dwarf sequence. Subsequent studies that focused on a wider range of HR 8799 planet colors reveal clear departures from the field sequence (Bowler et al. 2010; Cu11). Compared to mid/late T dwarfs, HR 8799 b(cd) are up to 2.5 (1.5) magnitudes redder (Cu11). Generally speaking, HR 8799 bcde appear to lie on a reddened extension of the L dwarf sequence past the field L/T transition to fainter magnitudes, a sparsely populated region whose other members are almost unanimously young, low (planetary) mass, and low gravity (e.g. Bonnefoy et al. 2016).
The HR 8799 planets’ IR spectral shapes likewise reveal differences with field objects but (imperfect) similarities with young, dusty, and low-gravity/mass brown dwarfs. Although formally no object appears well matched to HR 8799 bc’s combined near-IR spectra and thermal IR photometry, reddened versions of the youngest T0 dwarf spectra reproduce their spectra well (Bonnefoy et al. 2016). HR 8799 de appear best matched by particularly red and dusty/low gravity L6-L8 dwarfs which likewise deviate from the field sequence. However, fitting near IR and thermal-IR data simultaneously remains challenging.

As shown in Cu11, the HR 8799 planets appear different than field brown dwarfs of the same effective temperatures in large part because they have thicker clouds (Figure 2). Thicker clouds change the optical depth profile as a function of wavelength, making it more uniform in and out of major molecular opacity sources (e.g. water) since the $\tau = 1$ surface is achieved at a more uniform altitude. The planet spectrum appears redder and more blackbody like. Furthermore, the clouds may be non-uniformly distributed or “patchy” (Cu11) with 10-50% of the visible surface covered by thinner clouds/cloudless regions. Additionally, at least some HR 8799 planets show clear evidence for non-equilibrium carbon chemistry (Barman et al, 2011a; Galicher et al. 2011; Skemer et al. 2012). In addition to the absence of strong $CH_4$ absorption in HR 8799 b’s low-resolution near-IR spectrum, at longer wavelengths at least some of the planets exhibit weak to negligible methane absorption at $3.3 \mu m$ and enhanced $CO$ absorption at $5 \mu m$ (Galicher et al. 2011; Skemer et al. 2012). Medium-resolution near-IR spectra for HR 8799 bc reveal molecular species in the planets’ atmospheres and additional evidence for non-equilibrium carbon chemistry (Konopacky et al. 2013; Barman et al. 2015).

The planets’ low surface gravities (and, thus, their youth and low mass) explain both thick clouds and non-equilibrium carbon chemistry. Lower gravities ($\log(g) \sim 4$ instead of $\sim 5$ for field objects; Cu11, Konopacky et al. 2013) yield temperature-pressure profiles more characteristic of hotter, cloudier L dwarfs (Madhusudhan et al. 2011). Lower gravities also move the depth at which carbon-based chemical reactions (i.e. $CO+3H_2 \longleftrightarrow CH_4+H_2O$) are quenched deeper in the atmosphere, resulting in an overabundance of CO (Barman et al. 2011a; Marley et al. 2012). Other young, directly-imaged 5-13 $M_J$ planetary-mass objects with a range of temperatures also show evidence for thicker clouds and/or non-equilibrium carbon chemistry (e.g. ROXs 42Bb and 2M 1207 B; Currie et al. 2014b; Barman et al. 2011b), although the lowest mass, coldest and oldest imaged planets have very different spectra (Kuzuhara et al. 2013; Macintosh et al. 2015).
3. The Orbits of HR 8799 bcde

HR 8799 bcde’s orbits provide crucial input for studying the configuration of multi-planet systems and a limit on the planets’ masses. Soon after HR 8799 bcd were announced, (Fabrycky and Murray-Clay 2010) noted that for nominal face-on orbits and nominal masses, the system would be dynamically unstable in 0.1 Myr, far less than the system age. Placing these planets in a 4:2:1 orbital resonance makes the system dynamically stable for tens of Myr up to masses of 10–20 $M_J$. However, a 4th planet at 15 au makes dynamical stability more challenging, favoring masses of 5 (7) $M_J$ or less for HR 8799 b (cde) and precluding masses above 13 $M_J$ (Marois et al. 2010; Cu11). Assuming different orbital properties (e.g. inclined orbits) further lowers the maximum allowable planet masses (e.g. less than 10 $M_J$ Sudol and Haghighipour 2012).
HR 8799 bcde are not in face-on orbits but instead are inclined between 20 and 45° from face-on (Soummer et al. 2011; Currie et al. 2012a; Pueyo et al. 2015; Konopacky et al. 2016), similar to HR 8799 A’s rotation axis and the inclination of the star’s cold debris disk (Reidemeister et al. 2009; Booth et al. 2016). Circular orbits are formally consistent with the data for all planets (Currie et al. 2012a; Konopacky et al. 2016). HR 8799 bcd’s allowable orbits include a stabilizing 4:2:1 resonance, a possible outcome of the planets’ formation/migration histories (Figure 3, Konopacky et al. 2016; Gozdiewski & Migazewski 2014). However, it is unclear whether a 2:1 or 3:2 resonance is favored between HR 8799 d and e (Zurlo et al. 2016).

The planets’ relative inclinations are uncertain. Currie et al. (2012a) argue that coplanar orbits comprise a small fraction of acceptable orbits drawn from 1998-2010 measurements but are still possible; Pueyo et al. (2015) suggest that the planets’ orbits are not coplanar. While Konopacky et al. (2016) find no evidence for non-coplanarity from a set of self-consistently reduced data sets originating from the same telescope/instrument configuration, they do not consider astrometry for HR 8799 d (bc) prior to 2007 (2004), measurements largely responsible for favoring non-coplanarity.

Fig. 3.— Range of orbital periods for different orbital solutions from (Konopacky et al. 2016), showing that HR 8799 bcde may be in an 8:4:2:1 resonance.
4. Formation

HR 8799 bcde are important tests of jovian planet formation. Forming 5–7 $M_J$ planets at 25–70 au in situ by core accretion is extremely difficult, consistent with the fact that HR 8799-like planetary systems are extremely rare (e.g. Galicher et al. 2016). The mass ratios and separations of the HR 8799 planets are contiguous with the population of radial-velocity/transit detected planets, at least some of which formed by core accretion (Cu11; Kratter et al. 2010). Nevertheless, uncommon conditions – a particularly massive disk, very rapid and efficient build up of protoplanetary cores, and/or scattering of massive cores to wider separations prior to runaway gas accretion (e.g. Kenyon and Bromley 2009; Cu11; Lambrechts and Johansen 2012) – are likely required to explain HR 8799 bcde.

Atmospheric chemistry may also provide clues to HR 8799 bcde’s formation. If the planets formed by disk instability, their atmospheres should have solar C/O ratios; if they formed by core accretion near their current locations with a modest intake of solids, they should have enhanced C/O (Oberg et al. 2011). While HR 8799 c may have an enhanced C/O ratio, HR 8799 b’s C/O ratio is less constrained (Konopacky et al. 2013; Barman et al. 2015).

5. Future Prospects

Many challenges remain in better understanding the atmospheres, orbits, and formation of the HR 8799 planets. For example, HR 8799 b remains a sort of “Kobayashi Maru” test for planet atmosphere models, as not a single one has reproduced all of the planet’s spectrophotometry while yielding parameters (e.g. mass, radius) that are physically plausible and consistent with other constraints (planet cooling models; dynamical stability limits). Likely (partial) solutions to this problem include updated near-IR opacities and a better understanding of clouds at low gravities. By 2019, we will have astrometric points for roughly 20% of HR 8799 d and e’s orbit. New data combined with a self-consistent reanalysis of older astrometry will be needed to better constrain key orbital properties (e.g. resonances, eccentricities, and coplanarity).

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2 Portrayed in Star Trek II: The Wrath of Khan (and in the 2009 franchise reboot), the Kobayashi Maru test is simulation in which Starfleet cadets captain a starship to rescue a freighter and are subsequently ambushed by three Klingon battlecruisers. It is designed such that saving the ship is impossible, thus testing how cadets deal with a “no-win scenario”. James T. Kirk nevertheless beat it by “changing the rules of the game” (cheating) to allow the ship to be saved. We cannot similarly change the atmospheres of extrasolar planets so that our models fit them.
The next generation of extremely large telescopes will provide powerful probes of the HR 8799 planets’ chemical abundances, gravity, and formation history. For example, the IRIS integral field spectrograph on the Thirty Meter Telescope covers 0.8–2.5 μm and should be capable of providing high signal-to-noise spectra of all four planets at $R = 4000–8000$, building upon previous Keck/OSIRIS studies of HR 8799 bc at $H$ and $K_s$ bands (Konopacky et al. 2013; Barman et al. 2015). Such data should resolve multiple gravity sensitive lines and better determine abundances of multiple species. As a result, we may better constrain the C/O ratio and formation environment for planets of comparable mass from 15 au to 70 au.

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