Host Star Metallicity of Directly Imaged Wide-orbit Planets: Implications for Planet Formation

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Abstract

Directly imaged planets (DIPs) are self-luminous companions of pre-main-sequence and young main-sequence stars. They reside in wider orbits (~tens to thousands of astronomical units) and generally are more massive compared to the close-in (<10 au) planets. Determining the host star properties of these outstretched planetary systems is important to understand and discern various planet formation and evolution scenarios. We present the stellar parameters and metallicity ([Fe/H]) for a subsample of 18 stars known to host planets discovered by the direct imaging technique. We retrieved the high-resolution spectra for these stars from public archives and used the synthetic spectral fitting technique and Bayesian analysis to determine the stellar properties in a uniform and consistent way. For eight sources, the metallicities are reported for the first time, while the results are consistent with the previous estimates for the other sources. Our analysis shows that metallicities of stars hosting DIPs are close to solar with a mean [Fe/H] = −0.04 ± 0.27 dex. The large scatter in metallicity suggests that a metal-rich environment may not be necessary to form massive planets at large orbital distances. We also find that the planet mass–host star metallicity relation for the directly imaged massive planets in wide orbits is very similar to that found for the well-studied population of short-period (<1 yr) super-Jupiters and brown dwarfs around main-sequence stars.

Unified Astronomy Thesaurus concepts: Direct imaging (387); Spectroscopy (1558); Bayesian statistics (1900); Markov chain Monte Carlo (1889); Planet formation (1241); Extrasolar gaseous giant planets (509)

1. Introduction

Existing planetary search methods are constrained by severe selection effects and detection biases (e.g., Cumming 2004; Zakamska et al. 2011; Kipping & Sandford 2016). However, multiple detection techniques sample different regions of the star–planet parameter space, thus providing useful insights about the rich diversity and underlying population of the planetary systems. While the transit and radial velocity methods have been successful in unraveling planet populations spanning extremely close-in (~0.1 au) to moderate (~10 au) orbits, the direct imaging is most useful for probing the planetary architecture in the outermost regions (tens to thousands of astronomical units) of stars (Winn & Fabrycky 2015; Bowler 2016; Baron et al. 2019). The planet population discovered by the transit technique and radial velocity largely belongs to main-sequence and post-main-sequence stars. In contrast, the direct imaging method has been most effective in uncovering newly formed warm and massive planets in wider orbits around nearby young stars in the solar neighborhood (e.g., Lagrange 2014; Bowler 2016; Meskhat et al. 2017; Baron et al. 2019).

Following the success of the Kepler space mission, a wealth of new information has emerged about the planet population associated with main-sequence and evolved stars (Borucki et al. 2011; Batalha 2014; Fulton & Petigura 2018; Howard et al. 2012; Johnson et al. 2017; Mulders et al. 2016; Narang et al. 2018; Petigura et al. 2017; Petigura et al. 2018). The growing number of exoplanets from space discoveries and their follow-up studies from the ground are making planetary statistics more robust and significant. Because of their large number, the statistical properties of close-in planets (<1 au) and their host stars are relatively better studied. A great deal of research effort has been devoted to understanding the diversity of planets and the characteristics of their primary hosts. Many useful insights have been gained by studying the interdependence of planetary properties and stellar parameters (Gonzalez 1997; Santos et al. 2000, 2004; Fischer & Valenti 2005; Udry & Santos 2007; Ghezzi et al. 2010; Johnson et al. 2010; Mulders et al. 2016; Mulders 2018; Narang et al. 2018; Adibekyan 2019). Stellar metallicity and planet occurrence rate, for example, make up one such important correlation for testing the veracity of various planet formation mechanisms under different conditions (e.g., Udry & Santos 2007; Santos et al. 2017; Mulders 2018; Narang et al. 2018). However, these results have been demonstrated only for stars with close-in (<1 au) planets that have been detected primarily by radial velocity and transit methods.

Directly imaged planets (DIPs) are located at relatively large orbital distances from their host stars (2.6–3500 au), which provides a unique window to probe an entirely different planetary population. While there is a general consensus that giant planets are common around high-metallicity stars compared to their low-metallicity counterparts, a clear picture is still lacking about the role of metallicity and the exact mechanism of giant planet formation at larger distances.

The majority of the 51 planetary companions discovered so far by direct imaging techniques are massive planets at larger orbital distances from the host stars. Figure 1(a) shows the confirmed exoplanets in a mass–orbital distance plane, where the segregation of planets into different populations is evident. Treating DIPs as a separate population and studying their hosts’ properties can provide vital clues about the dominant mechanism of planet formation at large orbital distances from the star. The parameter
space of massive planets at long orbital periods occupied by DIPs is relatively unexplored for the correlation studies of host star–planet properties. Also, the high-mass limit of wide-orbit planets overlaps with the low-mass tail of brown dwarfs and substellar companions. Therefore, in certain cases, the limitation of low-number DIP statistics can be partly overcome by a complementary study of known brown dwarf companions sharing the same parameter space (Ma & Ge 2014; Vigan et al. 2017; Nielsen et al. 2019). Therefore, it is essential to investigate the role, if any, of the host star metallicity in influencing the process of giant planet and brown dwarf formation over a wide range of astrophysical conditions.

We have examined the confirmed list of DIPs hosted on NASA’s Exoplanet Archive (Akeson et al. 2013). The available stellar and planetary parameters are compiled from the composite planet data table for known exoplanets and published literature. Each of these systems has been studied and discussed in depth by individual discovery and follow-up papers. However, there are limited instances where the DIP distribution and stellar properties are studied as separate ensembles (Neuhäuser & Schmidt 2012; Bowler 2016).

Out of the 45 stars hosting DIPs listed in Table 1 taken from the NASA Exoplanet Archive, we could cross-match 42 of them with the Gaia DR2 catalog, in which \( T_{\text{eff}} \) and luminosity were available for 26 stars (for cross-matching, see Viswanath et al. 2020). The atmospheric properties of the stars hosting these wide-orbit companions are not very well studied, and, most notably, the metallicity is known for only 14 such systems.

In general, previous studies (Buchhave et al. 2014; Santos et al. 2017; Schlaufman 2018; Narang et al. 2018) have shown that the average metallicity of the host star increases as a function of planetary mass. However, the trend reverses for most planetary masses above \( 4\, M_J \) (Santos et al. 2017; Schlaufman 2018; Narang et al. 2018; Maldonado et al. 2019). These results suggest the possibility of two planet formation scenarios, with the Jupiter-like planets \((0.3–5\, M_J)\) likely formed by the core accretion process (e.g., Mizuno 1980; Pollack et al. 1996; Ida & Lin 2004; Mordasini et al. 2012) and the massive super-Jupiters \((>5\, M_J)\) formed via the disk instability mechanism (e.g., Boss 1997, 2002; Mayer et al. 2002; Matsuo et al. 2007; Santos et al. 2017; Narang et al. 2018; Goda & Matsuo 2019). These findings, backed by large statistics, truly reflect the underlying metallicity–mass distribution of compact planetary systems (orbital period \(<1\, \text{yr})\). This raises another important question: whether or not such trends hold for planets formed at vast orbital distances from the central star. Since DIPs are found at large distances from their host stars, this planet population motivates us to explore the mass–metallicity relationship for giant planet populations at large distances in light of various planet formation scenarios. This paper has used high-resolution spectra available from various public archives to determine the stellar parameters and metallicity of 18 stars hosting DIPs in a consistent and homogeneous way to study the various correlations among stellar and planetary properties.

The rest of the paper is organized as follows. In Section 2, we give a brief overview of DIP systems. We describe our sample and give the selection criteria in Section 3. Our methodology and Bayesian approach used for the estimation of various stellar parameters are discussed in Section 4. In Section 5, we discuss our results and compare them with previous findings. Finally, we give our summary and conclusions in Section 6.

2. Directly Imaged Systems

Of the 4200+ confirmed planets, direct imaging techniques account for the discovery of 51 planetary mass objects around 45 stars. Among these, 40 are in a single planetary system, and four are in multiplanetary systems: LkCa 15, TYC 8998-760-1, and PDS 70 with two planets each and HR 8799 with four. The majority of them are discovered from deep imaging surveys of nearby star-forming regions. These planet search programs largely target young pre-main-sequence stars that belong to nearby stellar associations and moving groups, all within 200 pc of the Sun (Bowler 2016). The high luminosity of planets at the early formation stage makes them amenable to direct imaging. Further, the high-resolution and high-contrast imaging of planets is facilitated by adaptive optics technology.

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*Note: The text includes a reference to a figure (Figure 1) which is part of the visual content of the document.*

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\[^{5}\text{https://exoplanetarchive.ipac.caltech.edu/index.html}\]
### Stellar Parameters of DIP Host Stars

| Serial Number | Star      | Age (Myr) | $M_p$ (M$_\odot$) | $T_{eff}$ (K) | log $g$ (cm s$^{-2}$) | [Fe/H] (dex) | $v \cdot \sin i$ (km s$^{-1}$) | References | $T_{eff}$ (K) | log $g$ (cm s$^{-2}$) | [Fe/H] (dex) | $v \cdot \sin i$ (km s$^{-1}$) |
|---------------|-----------|-----------|-------------------|---------------|------------------------|-------------|-------------------------------|------------|---------------|------------------------|-------------|-------------------------------|
| 1             | HD 106906 | 13 ± 2    | 6516 ± 165        | ...           | ...                    | 55 ± 4     | 1, 2, A                        |            | 6798 ± 20     | 4.23 ± 0.02           | 0.04 ± 0.01 | 49.12 ± 0.17                 |
| 2             | AB Pic    | 17.5 ± 0.5| 5378 ± 55         | 4.44 ± 0.21   | −0.05 ± 0.04           | 11.5 ± 0.1 | 3, 4, 5, A, 6, 8               |            | 5285 ± 10     | 4.53 ± 0.01           | 0.04 ± 0.02 | 10.35 ± 0.04                 |
| 3             | GJ 504    | 160 ± 1   | 6234 ± 25         | 4.53 ± 0.10   | 0.28 ± 0.03            | 7.4 ± 0.5  | 7, 8, 12                        |            | 6291 ± 16     | 4.34 ± 0.02           | 0.27 ± 0.03 | 5.41 ± 0.12                 |
| 4             | HR Peg    | 237 ± 2.9  | 6034              | 4.48          | −0.02 ± 0.02           | 10.6 ± 0.2 | 9, 10, 11, A                   |            | 6186 ± 7      | 4.48 ± 0.02           | 0.02 ± 0.02 | 8.73 ± 0.05                 |
| 5             | Sk Eri    | 20 ± 2    | 7146              | 3.99 ± 0.24   | 0.24 ± 0.03            | 71.8 ± 3.6 | 12, 13, A                      |            | 7276 ± 9      | 4.08 ± 0.02           | 0.13 ± 0.02 | 65.19 ± 0.17                 |
| 6             | HR 2562   | 600 ± 30  | 6534              | 4.18 ± 0.05   | 0.08                   | ...        | 14, 15, 16, C                  |            | 6785 ± 27     | 4.40 ± 0.05           | 0.21 ± 0.03 | 43.51 ± 0.15                 |
| 7             | Fomalhaut | 440 ± 0.9  | 8689              | 4.11 ± 0.68   | 0.27 ± 0.19            | 91.06 ± 0.5| 17, 18A                        |            | 8508 ± 12     | 4.02 ± 0.02           | 0.13 ± 0.02 | 75.31 ± 0.14                 |
| 8             | HR 8799   | 30 ± 7    | 7376 ± 217        | 4.22          | −0.5                   | ...        | 19, 20, 21, 22, A              |            | 7339 ± 5      | 4.19 ± 0.02           | −0.62 ± 0.01 | 37.49 ± 0.13                 |

### DIP Host Stars Analyzed in This Paper

| HD 203030 | 220 | 24.09 ± 0.38 | 5472 ± 0.05 | 0.06 ± 0.07 | 6.3 ± 0.3 | 13, 21, 23, 24, D | 5603 ± 0.8 | 4.64 ± 0.03 | 0.30 ± 0.02 | 5.62 ± 0.13 | 0.01 |

### DIP Host Stars with Metallicity from Literature

| HIP 65426   | 14  | 9.0 ± 3.0  | 8840 ± 0.13 | −0.03 ± 0.10 | 299 ± 9   | 42, 43, 44 | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| Kap And     | 220 | 13.66 ± 0.08 | 10.90 ± 0.08 | −0.36 ± 0.09 | 176 | 45, 46, 47 | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| GQ Lup      | 1   | 20         | 4092 ± 0.15   | ...           | 21, 39, A | 4416 ± 3 | 3.65 ± 0.04 | −0.3 ± 0.03 | 6.32 ± 0.07 | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| ROXs 12     | 6   | 16         | 3850 ± 0.40   | ...           | 40, 41, D | 4059 ± 3 | 3.71 ± 0.01 | 0.14 ± 0.01 | 7.20 ± 0.03 | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| GSC 06214−00210 | 11 | 16 ± 1     | 4200 ± 0.150  | ...           | 30, 31, D | 4119 ± 13 | 3.70 ± 0.04 | −0.06 ± 0.04 | 4.24 ± 0.05 | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |

### DIP Host Stars that Are Not Analyzed in This Paper

| ROXs 42B    | 2   | 9 ± 3      | 3850 ± 0.199  | ...           | 21, 54, 55 | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| 2MASS J02192210−3925225 | 20 | 13.9 ± 1.1 | 3064 ± 0.46  | 5.6 ± 0.04 | 56 | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| NAME Oph 11 | 12  | 14.5+4.5  | 2375 ± 0.50  | ...           | 55, 57 | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| VHS J12560.1−125723.9 | 225 | 11.2 ± 0.97 | 2626 ± 0.60  | ...           | 58 | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| WISE P121756.91+162640.2A | 6000 | 22 ± 2.0 | 575 ± 0.5 | ...           | 59 | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| CFBDSIR J145829+101343 | 10.5 ± 0.5 | 581 ± 0.54 | 4.73 ± 0.28 | 60 | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| IRXS J160929.1−210524 | 11 | 8 ± 1 | 4060 ± 0.50 | 4.19 ± 0.06 | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| Serial Number | Star | Age (Myr) | $M_p$ (M$_J$) | $T_{\text{eff}}$ (K) | log $g$ (cm s$^{-2}$) | [Fe/H] (dex) | $v \cdot \sin i$ (km s$^{-1}$) | References | $T_{\text{eff}}$ (K) | log $g$ (cm s$^{-2}$) | [Fe/H] (dex) | $v \cdot \sin i$ (km s$^{-1}$) |
|---------------|------|-----------|---------------|---------------------|---------------------|-------------|------------------------|------------|---------------------|-------------|---------------------|------------------------|
| 30            | 2MASS J21402931+1625183 A | ... | 20.99$^{+35.79}_{-20.95}$ | 2300$^{+80}_{-60}$ | 5.17$^{+0.24}_{-0.61}$ | ... | ... | 21, 61 | ... | ... | ... | ... |
| 31            | 2MASS J22362452+4751425 | 30 | 12.5$^{+1.5}_{-1.3}$ | 4045$^{+45}_{-35}$ | 4.60$^{+0.04}_{-0.05}$ | ... | ... | 3, 21, 62 | ... | ... | ... | ... |
| 32            | DH Tau | 1 | 11.1$^{+0.7}_{-0.5}$ | 3751$^{+501}_{-144}$ | 5.06$^{+0.25}_{-0.30}$ | ... | ... | 21, 33, 63 | ... | ... | ... | ... |
| 33            | TYC 8998-760-1 | 17 | 14.3 | 4753$^{+10}_{-10}$ | 4.44$^{+0.11}_{-0.01}$ | ... | ... | 21, 64 | ... | ... | ... | ... |
| 34            | USco1556 A | 7.5 | 15.2 | 3400$^{+100}_{-100}$ | 4.49$^{+0.10}_{-0.08}$ | ... | ... | 21, 65, 66 | ... | ... | ... | ... |
| 35            | USco1621 A | 7.5 | 16.2 | 3460$^{+100}_{-100}$ | 4.25$^{+0.09}_{-0.11}$ | ... | ... | 21, 65, 66 | ... | ... | ... | ... |
| 36            | HIP 79098 AB | 10 | 20.5 $\pm$ 4.5 | 9192$^{+51}_{-51}$ | ... | ... | 21, 67 | ... | ... | ... | ... | ... |
| 37            | 2MASS J01225093-2439505 | 120 | 24.5 $\pm$ 2.5 | 3530$^{+50}_{-50}$ | ... | ... | 14.3$^{+2.1}_{-1.2}$ | 68 | ... | ... | ... | ... |
| 38            | NAME SR 12 AB | 2.1 | 15.2 | 3828$^{+376}_{-376}$ | ... | ... | ... | 23, 69 | ... | ... | ... | ... |
| 39            | USco CTIO 108 | 11 | 14.3 | 2700$^{+100}_{-100}$ | ... | ... | ... | 31, 70 | ... | ... | ... | ... |
| 40            | WD 0806-661 | 1500 | 7.5$^{+1.5}_{-1.5}$ | 9552$^{+54}_{-1931}$ | ... | ... | ... | 21, 71, 72 | ... | ... | ... | ... |
| 41            | FU Tau | 1 | 16 | 2838 | ... | ... | ... | 33, 73 | ... | ... | ... | ... |
| 42            | 2MASS J04414489+2301513 | 1 | 7.5$^{+2.5}_{-1.5}$ | ... | ... | ... | ... | 74 | ... | ... | ... | ... |
| 43            | 2MASS J12073346-3923539 | 8 | $4^{+1}_{-1}$ | ... | ... | ... | ... | 75, 76 | ... | ... | ... | ... |
| 44            | CHXR 73 | 2 | 12.57$^{+3.38}_{-3.24}$ | ... | ... | ... | ... | 38, 77 | ... | ... | ... | ... |
| 45            | 2MASS J01033563-5515561 | 30 | 13 $\pm$ 1 | ... | ... | ... | ... | 38, 78 | ... | ... | ... | ... |

**References.** 1. Chen et al. (2011); 2. Bailey et al. (2014); 3. Uijjwal et al. (2020); 4. Chauvin et al. (2005); 5. Ghezzi et al. (2010); 6. Torres et al. (2006); 7. Kuzuhara et al. (2013); 8. Maldonado et al. (2015); 9. Lutheran et al. (2007); 10. Ramirez et al. (2009); 11. Boru Saikia et al. (2015); 12. Macintosh et al. (2015); 13. Luck (2017); 14. Konopacky et al. (2016); 15. Maldonado et al. (2012); 16. Lépine et al. (2003); 17. Kalas et al. (2008); 18. Mamajek (2012); 19. Marois et al. (2008); 20. Gravity Collaboration et al. (2019); 21. Gaia Collaboration et al. (2018); 22. Marois et al. (2010); 23. Metchev & Hillenbrand (2006); 24. Faherty et al. (2009); 25. Rameau et al. (2013); 26. Mórd et al. (2013); 27. Meshkat et al. (2013); 28. Snellen & Brown (2018); 29. Heap et al. (1994); 30. Lachapelle et al. (2015); 31. Pecaut et al. (2012); 32. Nguyen et al. (2012); 33. Kenyon & Hartman (1995); 34. Kepper et al. (2018); 35. Haffert et al. (2019); 36. Müller et al. (2018); 37. Schmidt et al. (2008); 38. Manoj et al. (2011); 39. Neuhaus et al. (2008); 40. Kraus et al. (2014); 41. Bowler et al. (2017a); 42. Chauvin et al. (2017); 43. Bochanski et al. (2018); 44. Chauvin et al. (2017); 45. Royer et al. (2007); 46. Bonnefoy et al. (2014); 47. Hinkley et al. (2013); 48. Naud et al. (2014); 49. Malo et al. (2014a, 2014b); 50. Rodríguez et al. (2011); 51. Gaidos & Mann (2014); 52. Burgasser et al. (2010); 53. Houdébine (2010); 54. Currie et al. (2014); 55. Wilking et al. (2005); 56. Artigau et al. (2015); 57. Close et al. (2007); 58. Gauza et al. (2015); 59. Leggett et al. (2014); 60. Liu et al. (2011); 61. Konopacky et al. (2010); 62. Bowler et al. (2017b); 63. Patience et al. (2012); 64. Bohn et al. (2020); 65. Chinchilla et al. (2020); 66. Stassun et al. (2019); 67. Janson et al. (2019); 68. Bowler et al. (2013); 69. Kuzuhara et al. (2011); 70. Béjar et al. (2008); 71. Lutheran et al. (2012); 72. Lutheran et al. (2011); 73. Lutheran et al. (2009); 74. Todorov et al. (2010); 75. Ducourant et al. (2008); 76. Mohanty et al. (2007); 77. Lutheran et al. (2006); 78. Delorme et al. (2013).
and stellar coronography. With advanced differential imaging and point-spread function extraction techniques, a new generation of instruments, e.g., the Gemini Planet Imager, ScExAO on Subaru, and SPHERE on the Very Large Telescope, are capable of probing giant-planet mass companions within a few milliarcseconds of separation from the central star. Masses of self-luminous planets are inferred from hot-star evolutionary tracks and infrared fluxes, but in some cases, they are well constrained by precise astrometric measurements (Baraffe et al. 2003; Snellen & Brown 2018; Wang et al. 2018; Nielsen et al. 2019; Wagner et al. 2019). The onset of the deuterium-burning limit (∼13 MJ) is a commonly used criterion to separate a planet from a brown dwarf (Burrows et al. 1997; Saumon & Marley 2008; Spiegel et al. 2011). However, by taking different composition and formation scenarios into account, the upper cutoff range could be as high as 25–30 MJ (Baraffe et al. 2010; Schneider et al. 2011). We acknowledge this ambiguity of overlapping mass range, but we calm all directly imaged objects up to ∼30 MJ in the DIP category for the present work.

The histogram shown in Figure 1(b) reveals that except for one case, the projected semimajor axis distances of all DIPs are larger than Jupiter’s orbital distance. The distribution peaks at an orbital distance of 150–500 au and extends up to ≈3500 au. The lower limit of the distribution is set by the inner working angle of the coronagraph, while the drop beyond a few thousand astronomical units is influenced by the limited sensitivity to detect the positional change of planets in long-period orbits.

The median mass of the DIP population is about ∼12.5 MJ, with the lowest-mass object at 2 MJ and about half the number more massive than 13 MJ. Most stellar hosts of these planets are also relatively young, i.e., ∼75% below the age of ∼100 Myr and more than two-thirds of the total belonging to the late spectral types with T eff ≤ 4500 K. From the literature, we also find evidence of circumstellar disks around 22 such systems.

The equilibrium temperature of the imaged planets ranges from 300 to 2800 K, though most of them are above 1600 K. The projected angular separation between the host star and planet varies by 4 orders of magnitude ranging from ∼10−2 to 10−4 arcsec. A large angular separation from the central star and the inherent brightness due to their high temperature make this giant planet population ideal for direct detection (Traub & Oppenheimer 2010).

We note that the current DIP sample is not a true representative of the underlying population of planets in outer orbits. It is heavily biased toward young, hot, more massive (>4 MJ) companions of young stars. The complexity of high-contrast instruments and the limitation of observing a single object at a time also makes the discovery rate slow. Studying DIP hosts spectroscopically is a major challenge because of their wide spectral range and the complexities (veiling, extinction, etc.) associated with young and pre-main-sequence stars. Therefore, it is also difficult to apply a strictly uniform and homogeneous methodology for the whole sample’s characterization.

3. Sample Selection

The NASA Exoplanet Archive has 3185 stars with confirmed planets found by various discovery methods. We found 2831 stars cross-matched with the Gaia DR2 catalog, which has the most accurate parallaxes and precise multiband photometry of all-sky stellar sources down to magnitude G ≈ 21. Figure 2 shows the location of these stars in the Hertzsprung–Russell (H–R) diagram with T eff and stellar luminosity L is indicated by orange circles with a plus sign in the middle. Isochrones computed using Choi et al. (2016) are shown for three age groups (red line: 10 Myr; green line: 100 Myr; blue line: 1000 Myr) and metallicity ranges (solid line: [Fe/H] = 0 dex; dotted line: [Fe/H] = 0.5 dex; dashed line: [Fe/H] = −0.6 dex).

We searched various public archives for the availability of high-resolution optical spectra for individual DIP hosts and also surveyed the literature on their metallicity. Based on these findings, we separated the 45 DIP host stars in Table 1 into three distinct groups, demarcated by horizontal lines. The first 18 stars in Table 1 are a subsample of DIP host stars analyzed in this paper for which the spectra are available from public archives, but the literature metallicity is known for only 10 targets. These stars have an effective temperature range between 4059 and 10,690 K and a G-band magnitude smaller than ∼13. For this subsample, we determined the atmospheric parameters and metallicity [Fe/H] homogeneously for the first time. We obtained high-resolution, high signal-to-noise ratio (S/N) spectra for 14 targets from the ESO science archive facility and four targets from the Keck archive. The ESO’s Science Portal provides access to the already

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5. Planet CFBDSIR J145829+101343b is the closest planet at an orbital distance of 2.6 au from the central star that is resolved by the direct imaging.

6. http://archive.exo.org/scienceportal/

7. https://koa.ipac.caltech.edu/cgi-bin/KOA/nph-KOAlogin
reduced and wavelength-calibrated data. Details of the original spectra, e.g., telescope/instrument, resolution, wavelength coverage, and S/N, are listed in Table 2.

3. In the second group of Table 1, there are four DIP host stars for which the metallicity is taken from the literature. The last 23 DIP hosts belonging to the third group in Table 1 are not analyzed in this paper because the majority of them are fainter ($m_v > 13$). For these stars, either the spectra were not available in the public domain or the quality of the data was poor (low S/N). This group also includes some of the hot and very rapidly rotating stars ($\nu \cdot \sin i > 160 \text{ km s}^{-1}$), which do not have clear spectral features and reliable atmospheric models for parameter estimation.

4. Most stellar parameters listed in Table 1 are taken from the NASA Exoplanet Archive. Furthermore, we cross-checked the accuracy of these parameters and replaced the missing values with those from the discovery and relevant follow-up papers. The log $g$ values marked by asterisks are not listed in the standard archives (such as the NASA Exoplanet Archive), and we have calculated them from stellar mass and radius values available from the literature.

4.4. Generation of Model Spectra

We adopted the Bayesian approach to infer the stellar parameters from the model spectra generated using iSpec, an integrated open-source software (Blanco-Cuaresma et al. 2014a). It is a Python wrapper that incorporates various radiative transfer codes and stellar atmospheric models and many ready-to-use tools to derive stellar parameters and abundances (Blanco-Cuaresma et al. 2014a, 2014b). As explained in the next section, we use iSpec only as a back-end module to generate synthetic spectra on the fly to navigate the stellar parameter space for determining the posterior distribution of $T_{\text{eff}}$, log $g$, [Fe/H], and $\nu \cdot \sin i$ for our 18 target stars. For generating the model spectra in iSpec, we selected the radiative transfer code SPECTRUM (R.O. Grey) because of its faster performance compared to other codes (Blanco-Cuaresma et al. 2014b). This code assumes the local thermodynamic equilibrium condition and requires a grid of plane-parallel model atmospheres as input. We chose the ATLAS9 model atmosphere that has grid sampling of 250 K in $T_{\text{eff}}$, 0.5 dex in log $g$, and metallicity sampled over 0.4, 0.2, 0.0, $-0.5$, 1, $-1.5$, $-2$, $-2.5$, $-3$, and $-4$ grid points (Castelli & Kurucz 2003). To generate model spectra for intermediate values, iSpec uses interpolation. The solar abundances are taken from Asplund et al. (2009) and the atomic line list from the VALD database (Piskunov et al. 1995) that also comes bundled with iSpec. We also adjusted the oscillator strengths and broadening parameters for some of the lines in our line list to improve our ability to model the stellar spectrum in the 600–620 nm wavelength regions, following the procedure given by Stempels et al. (2007). The micro- and macroturbulence velocities were internally calculated by iSpec using empirical relations (Blanco-Cuaresma et al. 2014b).

4.5. Data Preparation

Doing Bayesian analysis on the whole spectrum is computationally prohibitive. To reduce the computational load, we considered three distinct wavelength regions of the spectrum. These regions are free from telluric lines and also serve as good proxies for different stellar parameters without any degeneracy (Petigura et al. 2018).

The first region is the Mg I triplet (5150–5200 Å), which is sensitive to log $g$. The second region (6000–6200 Å) includes a significant number of well-isolated and unresolved spectral lines that are sensitive to $\nu \cdot \sin i$ and [Fe/H], and the third region (6540–6590 Å) covers the H$_\alpha$ line, whose outer wings are sensitive to $T_{\text{eff}}$. We have used all three regions for most targets except for HIP 78530, which shows severe line blending due to fast rotation. In that case, we have used only the Mg I triplet and H$_\alpha$ segments.

Additionally, some of the stars in our sample (stars with serial numbers 13–18 in Table 1) have emission features that indicate the presence of an accretion disk around the star. The characteristic veiling-dominated H$_\alpha$ emission for these stars is shown in Figure 3. This accretion-shocked region on the stellar surface generates the veiling continuum and decreases the depth of the stellar absorption lines (Calvet & Gullbring 1998). Since we do not have reliable models for emission lines (such as the H$_\alpha$), we chose the least contaminated and emission-free region 5900–5965 Å for deducing the stellar parameters (Stempels & Piskunov 2002, 2003). In addition, we included

| Instrument | Spectral Range in nm | Resolution | S/N |
|------------|----------------------|------------|-----|
| HARPS      | 378.2–691.3          | 115,000    | 174 |
| UVES       | 472.7–683.5          | 74,450     | 218 |
| FEROS      | 352.8–921.7          | 48,000     | 305 |
| HIRES      | 336.0–810.0          | 85,000     | 60  |

Note. The last column refers to the median S/N of all DIP host star spectra observed with each instrument.
the 6100–6200 Å segment for LkCa 15, Ross 12, PDS 70, and GSC 06214–00210, together with 5900–5965 Å for determining stellar parameters, since this region also lacks emission lines. In the Bayesian analysis discussed in the next section, we considered veiling as a free parameter to account for the excessive line filling due to accretion, following the procedure by Stempels & Piskunov (2002, 2003).

The individual spectra of stars come from single-object spectroscopic observations from the different instruments. The FITS files contain a 1D spectrum with specification of wavelength, flux, and flux errors. If the flux error was not specified, we assumed the errors to be limited by the photon noise. A certain amount of preprocessing was needed to prepare the data for further analysis. We used standard packages in IRAF\(^8\) for continuum normalization and radial velocity correction in the spectra. The model spectrum was generated at the same wavelength grid as the observed spectrum.

### 4.3. Bayesian Inference and Markov Chain Monte Carlo Sampler

We chose the Bayesian approach for probabilistic inference because it eliminates the dependence of the derived stellar parameters on the initial guess values and also places realistic constraints on the errors (Shkedy et al. 2007). We denote our minimal set of model parameters as \( \theta \equiv \{ T_{\text{eff}}, \log g, [\text{Fe/H}], v \cdot \sin i \} \) and observed stellar spectrum as \( D \equiv \{ y_{\text{data}}, y_{\text{err}}, \lambda \} \), where \( y_{\text{data}} \) is the measured flux at wavelength \( \lambda \) and associated uncertainty \( y_{\text{err}} \). The model-predicted normalized flux \( y_{\text{mod}}(\theta, \lambda) \) is calculated from first principles using the radiative transfer code and appropriate model of the stellar atmosphere. The goal is to find the posterior \( p(\theta | D) \), which is the most likely distribution of the model parameters \( \theta \) conditioned on the observed data \( D \). We know from Bayes’ theorem that

\[
p(\theta | D) = \frac{p(D | \theta) \cdot p(\theta)}{p(D)},
\]

where \( p(D | \theta) \) is the likelihood of observing spectra \( D \), given the set of model parameters \( \theta \), and \( p(\theta) \) is the prior function. The term \( p(D) \) in the denominator of Equation (1) is a normalization constant, also called evidence, which is hard to compute but not required when we use a sampler. Note that each term in Equation (1) is a probability density function whose analytical form is rarely known in practice. The Markov Chain Monte Carlo (MCMC) process allows us to numerically estimate the parameters by randomly drawing a sequence of samples from the posterior distribution of model parameters constrained by the data (Hogg & Foreman-Mackey 2018).

We used the \emcee\footnote{\url{https://emcee.readthedocs.io/en/stable/}} implementation of MCMC\(^9\) in Python. The flowchart of the algorithm is shown in Figure 4. First, we initialize the starting parameters \( \theta_0 \) of the model from our prior knowledge of the star, e.g., spectral type, luminosity class, etc. Using \( \theta_0 \) as seed, we generate an ensemble of \( \{ \theta_1, \theta_2, \ldots, \theta_N \} \) called walkers drawn from a physically realistic range of uniform priors, i.e., \( \pm 200 \) K for \( T_{\text{eff}} \), \( \pm 0.5 \) dex for \( \log g \), \( \pm 0.25 \) dex for \([\text{Fe/H}]\) and \( \pm 2 \) to \( \pm 20 \) for \( v \cdot \sin i \), depending on the star.

Each walker is a random realization of \( \theta \) that relies on an algorithm (e.g., Metropolis–Hastings) for sampling the parameter space. A function call to iSpec generates the model spectrum for the proposal parameter from the MCMC sampler. We define a simple log-likelihood function, \( \ln P(D | \theta) \), to compare the observed spectrum \( y_{\text{data}} \) with the model spectrum

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\(^8\) IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract to the National Science Foundation. 

\(^9\) https://emcee.readthedocs.io/en/stable/
Every walker numerically explores the parameter space by taking a “step” to a new value, $\theta_{j+1}$, that is drawn from a normal proposal distribution centered on $\theta_j$. The new proposal, $\theta_{j+1}$, is accepted if it has a higher posterior value than the current sample, $\theta_j$. If the new proposal value has a lower posterior, then the choice to accept or reject a new proposal with a certain probability is made randomly.

The walker, thus guided by Markov’s process, iteratively converges toward the target distribution by producing a chain of accepted parameters, as illustrated in Figure 4. We discard some of the early samples in each chain, as they are likely to lie outside the target distribution. This is termed “burn-in.” Finally, after the burn-in, we obtain a posterior distribution of our stellar parameters.

After some experimentation, we found that by using 300 steps following a burn-in limit of 140 steps for 40 test chains, we get a reasonable posterior distribution to determine the statistics of the stellar parameters. For illustration, the final distribution of $T_{\text{eff}}$, log $g$, [Fe/H], and $v \cdot \sin i$ for HR 2562 is shown in Figure 5. Since our posterior distribution is multivariate, some of the model parameters are likely to correlate. The shape of the contour plots in Figure 5 reflects the degree of correlation between different stellar parameters; e.g., the expected correlation can be seen between log $g$ and $T_{\text{eff}}$ while for others, the scatter is uniform, implying no correlation. As a representative example, we show the synthetic spectra for HR 2562 generated using Bayesian inferred model parameters in Figure 6, which matches reasonably well with the observed spectra.

For the stars with veiling (S.No 13–18 in Table 1), the estimation of stellar parameters was done in parallel with the determination of veiling. This was possible because the line shapes and relative absorption line depths are affected by the stellar parameters and independent of the presence of veiling. We followed a similar procedure as described in Stempels & Piskunov (2002, 2003), where veiling was modeled as a free parameter $V(\lambda)$ in the log-likelihood function in Equation (2). We used the modified log-likelihood function to obtain the stellar parameters with the same procedure as described above.

The final stellar parameters for our selected stars with mean values and $\pm 1\sigma$ uncertainty are listed in Table 1. The errors associated with the stellar parameters are the Bayesian error bars that are related to the sampling of the model spectra. The intrinsic uncertainty associated with the model generating the spectrum is not taken into account. Typical standard errors associated with metallicity ($\pm 0.15$) are discussed in detail by Blanco-Cuaresma et al. (2014a) and Jofré et al. (2019).

5. Results

5.1. Metallicity of DIP Host Stars

We have estimated the stellar parameters for a subset of stars harboring DIPs listed in Table 1. Figure 7 shows the distribution of observed metallicity for 22 stars, 18 of which are analyzed in the present work, and the metallicity value for four stars is taken from previous studies. The metallicities of these targets do not show any trend or clustering but widely vary from +0.30 dex (HD 203030) to $-0.65$ dex (HR 8977) with a median centered at 0.04 dex, which is closer to the solar value. The first and third quartiles are $-0.21$ and 0.14 dex, respectively, with 12 of them having a metallicity higher than the solar value. The large scatter seen in [Fe/H] is not very surprising, as it likely reflects the heterogeneity of the DIP host stars associated with different star-forming regions, parent clusters, or moving groups.

5.2. Metallicity and Planet Mass

To study the relationship between host star metallicity and planet mass, we used the planetary mass data from the NASA Exoplanet Database from the composite planet list. We divided
our DIP sample into three mass bins, $1 M_J < M_p \leq 5 M_J$, $5 M_J < M_p \leq 13 M_J$, and $M_p > 13 M_J$, as shown in Figure 8. The average metallicity is 0.17 ± 0.07 dex for four stars in the first bin, $-0.08 \pm 0.29$ dex for seven stars in the second bin, and $-0.11 \pm 0.30$ dex for 10 stars in the third bin. The mean metallicity in each bin shows a declining trend with increasing planetary mass. We also note that regardless of their orbital distance, DIPs with $M_p \leq 5 M_J$ have mostly metal-rich hosts.

5.3. Metallicity and Other Stellar Parameters

Figure 9 shows the distribution of metallicity as a function of orbital distance, stellar mass, log $g$, and $v \cdot \sin i$. For low-mass stars, $M_* \leq 1 M_\odot$, we find that the average metallicity is near solar with a standard deviation of 0.21 dex. Stars with $M_* > 1 M_\odot$ are found to be slightly metal-poor with an average metallicity of $-0.10$ dex and a standard deviation of 0.30 dex.

We also find that the average metallicity of fast-rotating stars ($v \cdot \sin i > 15 \text{ km s}^{-1}$) is $-0.1$ dex with a standard deviation of 0.29 dex, while for slow rotators ($v \cdot \sin i < 15 \text{ km s}^{-1}$), it is solar, 0.02 dex with a standard deviation of 0.28 dex. The Spearman rank correlation coefficient between the stellar metallicity and projected rotational velocity of the star $v \cdot \sin i$ is $-0.42$ with a $p$-value of 0.05, which suggests a weak negative correlation. Furthermore, there is no noticeable dependence of host star metallicity on orbital distance and log $g$.

5.4. Comparison with Literature

To compare our results in Table 1, we have included the stellar parameters of DIP host stars from the literature. For each stellar parameter, we computed the sample mean difference and the maximum deviation between our values and those reported in the literature. For effective temperature, we find the sample mean difference to be $+103$ K and the maximum deviation to be $380$ K for LkCa 15. We note that the $T_{\text{eff}}$ for most host stars in the literature is determined photometrically, which could account for the observed differences. For surface gravity, the sample mean difference is $-0.06$ dex, and the maximum difference is 0.58 dex for HD 95086. Likewise, for metallicity, the sample mean difference is found to be $-0.035$ dex, and the maximum difference, seen again for HD 95086, is 0.39 dex. For rotation velocity, we find a good match between the literature and our values for slowly rotating DIP hosts ($v \cdot \sin i < 20$), whereas the maximum difference

is found to be about 16 km s$^{-1}$ for the fast-rotating star Fomalhaut. By and large, our values for [Fe/H] and log $g$ determined uniformly using the spectroscopic method are within the error margin of those quoted in the literature. However, for such a heterogeneous sample, the observed differences in stellar parameters obtained by different analysis methods, atmospheric models, radiative transfer codes and line lists, etc., are not entirely unexpected (Jofré et al. 2014; Blanco-Cuaresma 2019; Jofré et al. 2019).

6. Discussion

In the standard paradigm for the formation of a Jupiter-like planet via core nucleated accretion (e.g., D’Angelo & Lissauer 2018), a rocky protoplanetary core forms first, which then accretes gas and dust from the surrounding disk to become a gas giant (Bodenheimer & Pollack 1986; Pollack et al. 1996; Boss 1997; Ikoma et al. 2001). The critical (or minimum) core mass required to form a gas giant depends on various factors (e.g., location on the protoplanetary disk, accretion rate of solids, etc.) and generally decreases with increasing disk radius; the minimum core mass drops from $\sim 8.5 M_\oplus$ at 5 au to $\sim 3.5 M_\oplus$ at 100 au (Piso & Youdin 2014; Piso et al. 2015). If the protoplanetary disk is rich in solids, i.e., higher metallicity, then the rocky core can grow faster and reach the critical mass for gas accretion well before the disk is depleted of gas. Therefore, it is easier to form Jupiter-like gas giants in disks around higher-metallicity stars (e.g., Ida & Lin 2004; Kornet et al. 2005; Wyatt et al. 2007; Boss 2010; Mordasini et al. 2012). Indeed, observations have shown that the frequency of Jupiter-like planets is higher around higher-metallicity stars (e.g., Gonzalez 1997; Santos et al. 2001; Fischer & Valenti 2005; Udry & Santos 2007). While not as strong as that seen for gas giants, smaller planets also show a weaker tendency to occur more frequently around relatively higher-metallicity stars, even though their host stars appear to have a larger spread in metallicity (e.g., Buchhave et al. 2014; Wang & Fischer 2015; Mulders et al. 2016). It has now been adequately established that the host star metallicity ([Fe/H]), on average, increases with increasing planet mass or radius (e.g., Buchhave et al. 2014; Mulders 2018; Narang et al. 2018; Pettigrew et al. 2018). Thus, the observed strong dependence of the planet mass/radius on the host star metallicity supports the core accretion model for planet formation.

However, the observed correlation of increasing host star metallicity with increasing planet mass turns over at about 4–5 $M_J$. For planet masses higher than this (super-Jupiters), the correlation...
reverses, and the average host star metallicity decreases as the mass of the planet increases (Santos et al. 2017; Narang et al. 2018). This suggests that stars hosting super-Jupiters are not necessarily metal-rich, unlike stars hosting Jupiters. This trend appears to continue for more massive companions; the average metallicity of stars with a brown dwarf secondary is also close to solar to subsolar and not supersolar, like stars hosting Jupiters (Ma & Ge 2014; Schlaufman 2018; Narang et al. 2018).

Our sample of DIPs occupies a mass range similar to that of super-Jupiters and brown dwarfs. The fact that the average host star metallicities of brown dwarfs and super-Jupiters are similar and that they differ from that of Jupiter hosts perhaps indicates a similar formation scenario for them that is different from that of Jupiters. It has been suggested that massive planets and low-mass brown dwarfs can form via gravitational fragmentation of the disk rather than core accretion (e.g., Boss 1997; Mayer et al. 2002). This gravitational instability model of planet formation predicts no dependence between planet mass and host star metallicity (e.g., Boss 2002; Cai et al. 2006; Matsuo et al. 2007; Boss 2010), unlike the core accretion model, which predicts such a dependence.

We further compare the DIPs with the large population of giant planets and brown dwarfs around main-sequence stars discovered by techniques other than direct imaging. To this end, we found 637 stars hosting 746 giant planets and massive objects with masses in the range $1$–$55 M_J$ listed in NASA’s Exoplanet Archive. We also searched the above sample in the SWEET-CATALOG (Santos et al. 2013; Sousa et al. 2018), which provides metallicity information for 459 stellar hosts having 494 companions. Additionally, a catalog of 58 brown dwarfs and their stellar companions was chosen from Ma & Ge (2014). A joint sample of 552 objects was formed by combining the giant planets and brown dwarfs. This combined sample has a mass range from $1$ to $80 M_J$ and an orbital distance spanning $0.02$–$20$ au. Since objects in the combined sample come from radial velocity, transit, transit-timing variation, astrometry, and microlensing observations, we have used the minimum mass ($M \cdot \sin i$) wherever the true mass was not available.

We then ran a clustering analysis on the 2D data set of combined samples of giant planets and brown dwarfs with host star metallicity as one parameter and orbital distance and companion mass as another. For the clustering analysis, we considered a Gaussian mixture model and implemented it using a Python library scikit-learn package (Pedregosa et al. 2011). The Gaussian mixture model optimally segregated the combined sample into three clusters in the metallicity–planet mass plane, as shown in the top panel of Figure 10, and two clusters in the metallicity–orbital distance plane, as shown in the bottom panel of Figure 10.

The clustering analysis in Figure 10 (top panel) clearly divides the combined sample into three mass and metallicity bins. The mass boundaries roughly located at $\approx 4$ and $\approx 14 M_J$ are consistent with multiple populations of giant planets (i.e., Jupiters and super-Jupiters) and brown dwarfs, pointing to their different physical origins. Further on, the declining centroid metallicity of each group in Figure 10, i.e., $0.089 \pm 0.02$, $0.023 \pm 0.002$, and $0.013 \pm 0.009$ dex, is also consistent with previous results. The DIP population studied in this work is also shown for comparison in Figure 10. The DIP population falls between the super-Jupiter and brown dwarf populations in both mass and metallicity.
Although the specific factors that influence planet formation are still not fully understood, metallicity seems to be one of the major contributing factors that determine the type of planet likely to be formed around a star. Using synthetic planet population models, Mordasini et al. (2012) showed that a high-metallicity environment determines whether or not a giant planet in the mass range 1–4 $M_J$ can form. But metallicity is not the only parameter in determining the final mass of the planet, except for the very massive planets ($\gtrsim 10 M_J$), as the critical core must form very fast before the dissipation of the gas in the disk by accretion onto the star (Hayashi et al. 1985; Matsuo et al. 2007). The prediction of Mordasini et al. (2012) that the very massive planets ($\gtrsim 10 M_J$) can form only at very high metallicity conditions is contrary to our findings. Our results are indicative of the possibility of two planet formation pathways: one in which the giant planets up to 4–5 $M_J$ are formed by core accretion processes and one in which the massive super-Jupiters and brown dwarfs are formed via gravitational fragmentation of the protoplanetary disk.

Our results for wide-orbit (tens to thousands of astronomical units) planets are also consistent with the mass–metallicity trend observed for super-Jupiters and brown dwarfs in close-in ($\lesssim 1$ au) orbits around main-sequence stars. The formation mechanism of planets in wider orbits is still unclear. However, the mixed metallicity of our DIP host star sample and its close resemblance to the commutative metallicity distribution of brown dwarf hosts make it likely that massive and young planets in wider orbits also formed via gravitational instability. However, a larger sample is required to further validate such conclusions.

7. Summary and Conclusions

We have used high-resolution spectra to measure the atmospheric parameters of young stars that are confirmed host stars of planets detected by direct imaging techniques. Our sample consists of 22 such stars selected from NASA’s Exoplanet Archive. For 18 of these targets, the stellar parameters and metallicity are determined in a uniform and consistent way. The summary of our results is as follows.

1. We used the Bayesian analysis to estimated the atmospheric parameters and metallicity for 18 DIP host stars. The MCMC technique was used to obtain the posterior distribution of stellar parameters using model spectra generated using iSpec. The computed metallicity $[Fe/H]$ of these stars spans a wide range, from $+0.3$ to $-0.65$ dex.
2. We investigated the trend between the average host star metallicity and mass of the planet, which shows that DIPs with $M_p \lesssim 5 M_J$ tend to have metal-rich hosts. This is in line with the predictions of planet formation via core accretion. However, as the planet mass increases, the average metallicity of the host stars shows a declining trend, suggesting that these planets are likely formed by gravitational instability. These findings seem consistent with the results reported by Santos et al. (2017) and Narang et al. (2018). Since the metallicity of a star does not change during evolution, we do not expect these trends to change significantly for the currently undetected population of cool and massive giant planets in the outstretched regions of the main-sequence stars. Moreover, main-sequence host stars in general show a trend of decreasing metallicity with increasing orbital distance of the planet (e.g., Mulders et al. 2016; Buchhave et al. 2018; Mulders 2018; Narang et al. 2018).

3. From clustering analysis, as discussed above in Section 6, we find that the DIP host stars separate as a different class of celestial objects in the stellar metallicity–orbital distance plane. Furthermore, we can see a decreasing trend in the centroids of the host star metallicity as the star–planet separation increases.

4. In the planetary mass–stellar metallicity plane, it is found that Jupiter-like planets are more likely to form around a metal-rich star. It also shows a decreasing trend in average stellar metallicity as the planetary mass increases. The DIP population clusters lie in between the super-Jupiter and brown dwarf populations.

It is also important to recognize that the composition of circumstellar material from which the planets are formed need not necessarily be the same as the composition of the parent star. The degree of similarity or difference would depend on how and where planets are formed, what stage of evolution they are in, and the disk mass and planet multiplicity. A clear picture is expected to emerge from ongoing high-contrast imaging surveys and future experiments aimed at searching for planets in wider orbits.

This work has made use of (a) ESO archival data that were observed under programs 192.C-0224, 098.C-0739, 266.D-5655, 094-A.9012, 084.C-1039, 074.C-0037, and 65.I-0404; (b) the Keck Observatory Archive (KOA), which is operated by the W. M. Keck Observatory and the NASA Exoplanet Science Institute (NExScI), under contract with the National Aeronautics and Space Administration; (c) the NASA Exoplanet Database, which is run by the California Institute of Technology under an Exoplanet Exploration Program contract with the National Aeronautics and Space Administration; and (d) the European Space Agency (ESA) space mission Gaia, the data from which were processed by the Gaia Data Processing and Analysis Consortium (DPAC). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the Gaia Multilateral Agreement.

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Software: astropy (Astropy Collaboration et al. 2013), iSpec (Blanco-Cuaresma et al. 2014a), emcee (Foreman-Mackey et al. 2013), scikit-learn (Pedregosa et al. 2011), IRAF (Tody 1986, 1993).

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