Highlights of Spanish Astrophysics XII, Proceedings of the XVI Scientific Meeting of the Spanish Astronomical Society held on July 15 - 19, 2024, in Granada, Spain. M. Manteiga, F. González Galindo, A. Labiano Ortega, M. Martínez González, N. Rea, M. Romero Gómez, A. Ulla Miguel, G. Yepes, C. Rodríguez López, A. Gómez García and C. Dafonte (eds.), 2025

On the limits of the innermost planetary orbits

Mendigutía, I.[1]

[1] Centro de Astrobiología (CAB), CSIC-INTA, Camino Bajo del Castillo s/n, 28692 Villanueva de la Cañada, Madrid, Spain

Abstract

The orbits of hot Jupiters could be explained from the innermost properties of the protoplanetary disks where they born. In particular, the hot region where dust sublimates, and the magnetosphere where gas is truncated, have both been proposed as effective disk barriers limiting the smallest orbits that planets can have. However, observational tests aiming to disentangle between the two previous barriers are difficult because the location of the inner dust and gas disks roughly coincide for low-mass stars (0.5 – 1.5 $M_\odot$).

This proceedings paper summarizes our work in Mendigutía et al. (2024, A&A, 686, L1), where we compared the orbits of hot Jupiters with the positions of the inner dust and gas disks. Intermediate-mass stellar hosts (1.5 – 3 $M_\odot$) were included in the analysis because the dust and gas barriers are spatially separated for these stars. Our results support that the inner gas -and not the dust- disk limits the innermost planetary orbits. A major implication is that hot Jupiters should be more probably swallowed by their host stars when magnetospheres are absent.

1 Introduction

Hot Jupiters are gas giant planets orbiting very close to their host stars. This combination between large sizes -and masses- and small orbits makes hot Jupiters the easiest exoplanets to detect, but it also challenges the standard picture of planet formation [1]. Given that in-situ formation requires too large amounts of material very close to the star, the most common scenario assumes that hot Jupiters formed further away and then migrated inwards due to interactions with the planet-forming disk (e.g. [2] and references therein). But then, what interrupts inward migration?

The material in protoplanetary disks does not reach the central stars due to the presence of two physical barriers. First, the dusty disk dissapears close to the stellar surfaces because dust grains sublimate at temperatures above $\sim$ 1500 K. Similarly, the innermost gaseous disk is absent because this is truncated by the stellar magnetic field. Both previous dust and gas inner disks have been proposed as effective barriers limiting the smallest exoplanetary orbits (e.g. [3, 4, 5, 6]). Unfortunately, most hosts identified are low-mass FGK stars, for which the stellar luminosities and magnetic fields lead to very similar sizes for the dust and gas inner disks (typically larger than five stellar radii, R_*). Thus, it is hard to unambiguously disentangle between the two scenarios based only on observations of low-mass stars.

This proceedings paper summarizes our work in [7]. In order to observationally test whether it is the dust or the gas barrier that drives the orbits of hot Jupiters, we followed an alternative approach by including in the analysis intermediate-mass host stars (1.5 – 3 $M_\odot$). Although exoplanets found around these sources are scarce mainly due to observational biases, they have an important advantage. Because intermediate-mass stars are hotter and more luminous, the size of the dust barrier tends to be at least one order of magnitude larger than in low-mass stars ([8]). In addition, because magnetic fields are weaker in intermediate-mass stars, the magnetospheric gas barrier is typically smaller than for low-mass stars ($< 5R_*$; [9]). Thus, the spatial separation between the dust and gas inner disks in intermediate-mass stars should be large enough to probe which one limits the orbits of hot Jupiters. Section 2 briefly describes the methodology, Sect. 3 shows the main results, and Sect. 4 outlines some final remarks and implications.

2 Sample and Method

We adopted the common definition according to which hot Jupiters have sizes larger than Neptune's and orbital periods smaller than 10 days. Hot Jupiters were identified based on the most recent TESS ([10]) and Gaia DR3 ([11]) data. In particular, we selected the hot Jupiters included in the "TESS Objects of Interest" list (TOIs, [12]) that orbit around intermediate-mass (1.5 – 3 $M_\odot$), main sequence (MS) stars. Gaia DR3 stellar parameters and evolutionary classification ([13, 14]) were used to asses the latter conditions. A strict filtering process that prevents contamination of the light curves by additional stars within the TESS apertures (see [15, 16]) led to a final sample of 47 intermediate-mass, MS stars hosting hot Jupiters. A similar procedure based on TESS and Gaia data led to 298 low-mass (0.5 -1.5 $M_\odot$), MS stars that host hot Jupiters, which were used as a control sample for comparison purposes.

In order to test whether it is the dust or the gas barrier that limits the orbits of hot Jupiters, we compared the sizes of such orbits with the ones of the protoplanetary disk barriers. The orbits were inferred from the information in the TOIs list and the Gaia DR3 data, and the disk barriers were defined from the stellar luminosities and radii that the stars had during the pre-MS. The actual Gaia DR3 stellar luminosities and radii were converted into the ones that the sample stars had at 3 Myr based on evolutionary tracks and isochrones ([17]).

3 Results

Figure. 1 (top) summarizes our main results. The orbital radii of the hot Jupiters are plotted versus the pre-MS stellar luminosities (left) and radii (right). Overplotted with dashed lines are the location of the dust destruction front for a sublimation temperature of 1500 K (fol-

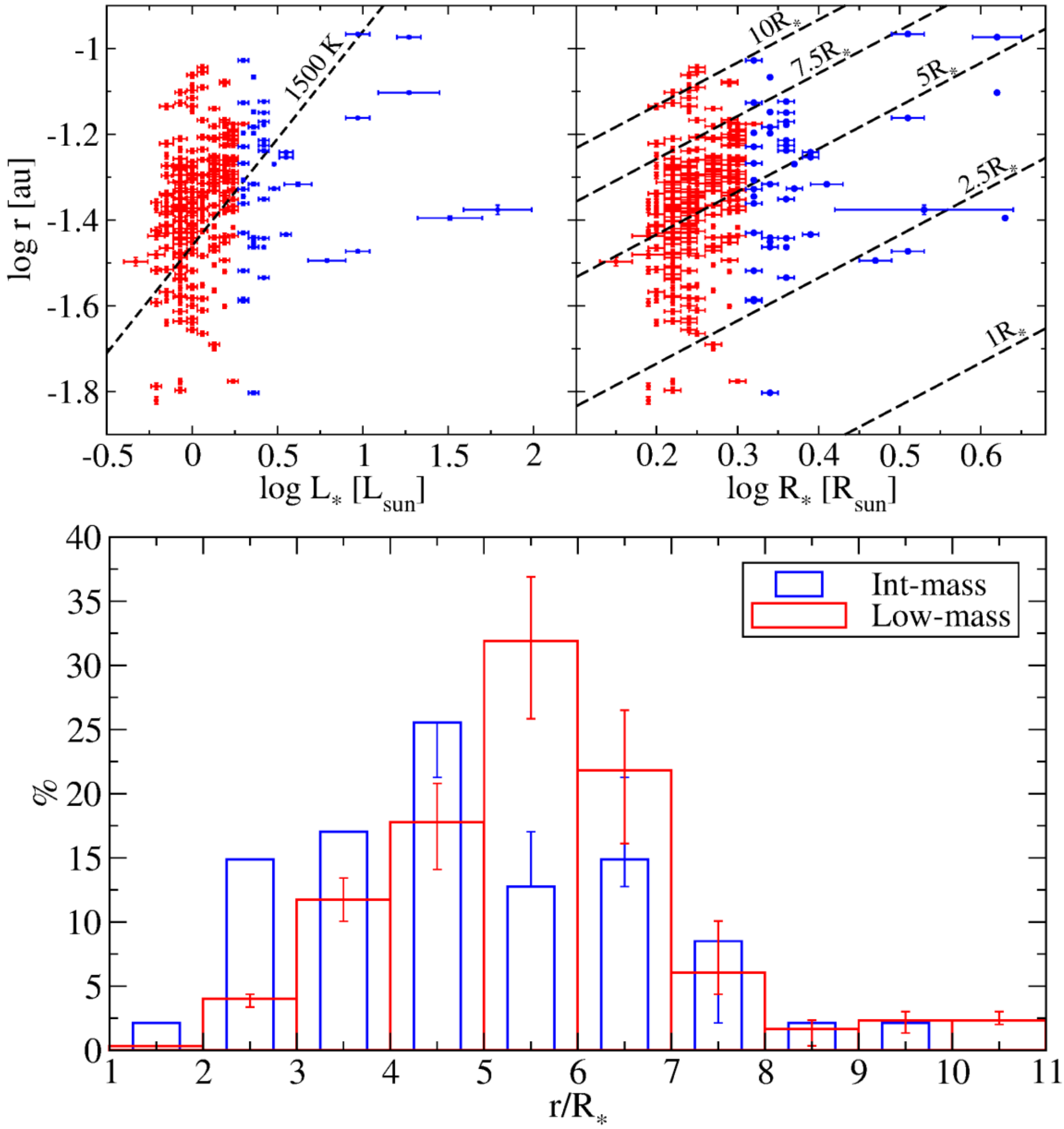

Figure 1: (Adapted from [7]). **Top**: Planetary orbital radii versus pre-MS stellar luminosities (left) and radii (right). Intermediate- and low-mass stars are in blue and red (47 and 298 sources, respectively). The dashed line in the left panel shows the location of the inner dust disk below which dust is sublimated. The dashed lines in the right panel show the magnetospheric inner gas disk at 10, 7.5, 5, 2.5, and 1R$_*$. **Bottom**: Distributions of planetary orbital radii in terms of of pre-MS stellar radii.

lowing the prescription in [18]), and different gas barriers with sizes 10, 7.5, 5, 2.5, and 1R$_*$. Roughly 70% of the intermediate-mass stars have hot Jupiters with orbits closer to the central source than the dust-destruction radius, and $\sim$ 60% coincide with the small magnetospheres typical of intermediate-mass young stars ($<$ 5R$_*$). Thus, the orbits of the majority of the hot Jupiters around intermediate-mass stars are consistent with being determined by the gas -and not the dust- barrier. Concerning the sample of low-mass stars, almost 80% host hot Jupiters in orbits equal or larger than the dust sublimation radius, but $\sim$ 65% have orbits also consistent with the large magnetospheres typical of low-mass young stars ($>$ 5R$_*$). The previous numbers illustrate the fact that was introduced in Sect. 1. Namely, the locations of the gas and dust barriers in low-mass stars are similar, for which based on this sample alone it cannot be disentangled which one drives the orbits of hot Jupiters.

Nevertheless, considering the whole sample we do not find that hot Jupiters around intermediate-mass stars tend to be further from the central hosts than those around low-mass stars, as expected if the dust barrier drives their orbits (dashed line in the top left panel of Fig. 1). On the contrary, the bottom panel of Fig. 1 shows that the orbits of hot Jupiters around low- and intermediate-mass stars dominate above and below 5R$_*$, respectively, which is the rough limit dividing between the large and small magnetosphere sizes typical of each stellar regime. Thus, we conclude that the gas barrier is probably driving hot Jupiter's orbits for the whole stellar mass range.

4 Final remarks

Our results suggest that magnetospheres in protoplanetary disks act as effective barriers limiting the innermost orbits of hot Jupiters in all types of stars. It is important to note that the previous conclusion could be reached by including in the analysis stars with intermediate-mass, a regime that is barely considered in exoplanetary studies. However, direct imaging of long-period exoplanets and radial velocity analyses of post-MS stars indicate that the occurrence rate of giant planets peaks in the intermediate-mass stellar regime ([19, 20, 21]). Thus, a complete understanding of planet formation requires the assessment of stars more massive than the sun (e.g. [22]). Moreover, protoplanetary disks around young, intermediate-mass stars are comparatively larger and brighter than around their less-massive counterparts, making the former ideal for high-angular resolution observations aiming to probe the process of planet formation (e.g. [23, 24, 25]).

Intermediate-mass stars are also key to further test our main conclusion. For instance, if magnetospheres limit the innermost planetary orbits, then these should be smaller for fast-rotating stars ([26, 3]). This can be best tested from observations by using intermediate-mass stars, given that their rotational velocities span from a few to a few hundred km s^{-1}. In addition, if magnetospheres are the last barrier preventing inward migration, then intermediate-mass stars more massive than $\sim$ 3-4 M$_\odot$ should show a deficit of hot Jupiters because most would be engulfed by their stellar hosts. The reason is that young stars more massive than the previous limit probably lack from magnetospheres ([27, 28]).

Acknowledgments

IM is funded by grants PID2022-138366NA-I00, by the Spanish Ministry of Science and Innovation/State Agency of Research MCIN/AEI/10.13039/501100011033 and by the European Union, and by a Ramón y Cajal fellowship RyC2019-026992-I. IM acknowledges Jorge Lillo-Box, Miguel Vioque, Jesús Maldonado, Benjamín Montesinos, Nuria Huélamo and Jiaqi Wang for their collaboration to the original work that led to this proceedings paper (Mendigutía et al. 2024, A&A, 686, L1). IM acknowledges the use of public TOI Release data from pipelines at the TESS Science Office and at the TESS Science Processing Operations Center. Funding for the TESS mission is provided by NASA's Science Mission directorate. This work has made use of data from the European Space Agency (ESA) mission Gaia (https://www.cosmos.esa.int/gaia), processed by the Gaia Data Processing and Analysis Consortium (DPAC, https://www.cosmos.esa.int/web/gaia/dpac/consortium). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the Gaia Multilateral Agreement.

References

[1] Mayor, M., & Queloz, D. 1995, Nature, 378, 355

[2] Fortney, J. J., Dawson, R. I., Komacek, T. D. 2021, JGRE, 126, 3

[3] Lee, E. J., & Chiang, E. 2017, ApJ, 842, 40

[4] Flock, M., Turner, N. J., Mulders, G. D., et al. 2019, A&A, 630, A147

[5] Romanova, M. M., Lii, P. S., Koldoba, A. V., et al. 2019, MNRAS, 485, 2666

[6] Batygin, K., Adams, F. C., & Becker, J. 2023, ApJ, 951, L1

[7] Mendigutía, I., Lillo-Box, J., Vioque, M. et al. 2024, A&A, 686, L1

[8] Marcos-Arenal, P., Mendigutía, I., Koumpia, E., et al. 2021, A&A, 652, A68

[9] Mendigutía, I. 2020, Galaxies, 8, 39

[10] Ricker, G. R., Winn, J. N., Vanderspek, R., et al. 2015, J. Astron. Telesc. Instrum. Syst., 1, 014003

[11] Gaia Collaboration (Vallenari, A., et al.) 2023a, A&A, 674, A1

[12] Guerrero, N. M., Seager, S., Huang, C. X., et al. 2021, ApJS, 254, 39

[13] Creevey, O. L., Sordo, R., Pailler, F., et al. 2023, A&A, 674, A26

[14] Fouesneau, M., Frémat, Y., Andrae, R., et al. 2023, A&A, 674, A28

[15] Gaia Collaboration (Arenou, F., et al.) 2023b, A&A, 674, A34

[16] Lillo-Box, J., Morales-Calderón, M., Barrado, D. et al. 2024, A&A 686, A232

[17] Siess, L., Dufour, E., & Forestini, M. 2000, A&A, 358, 593

[18] Monnier, J. D., & Millan-Gabet, R. 2002, ApJ, 579, 694

[19] Reffert, S., Bergmann, C., Quirrenbach, A., Trifonov, T., & Künstler, A. 2015, A&A, 574, A116

[20] Wagner, K., Apai, D., Kasper, M., McClure, M., & Robberto, M. 2022, AJ, 163, 80

[21] Wolthoff, V., Reffert, S., Quirrenbach, A., et al. 2022, A&A, 661, A63

[22] Delorme, P. , Chomez, A. , Squicciarini, V. et al. 2024. Accepted in A&A. arXiv:2409.18793

[23] Mendigutía, I., Oudmaijer, R. D., Garufi, A. et al. 2017, A&A, 608, A104

[24] Huélamo, N., Chauvin, G., Schmid, H.M. et al. 2018, A&A 613, L5

[25] Currie, T., Lawson, K., Schneider, G. et al. 2022, NatAs, 6, 751

[26] Shu, F., Najita, J., Ostriker, E., et al. 1994, ApJ, 429, 781

[27] Wichittanakom, C., Oudmaijer, R. D., Fairlamb, J. R., et al. 2020, MNRAS, 493, 234

[28] Vioque, M., Oudmaijer, R. D., Wichittanakom, C., et al. 2022, ApJ, 930, 39