ATREIDES

A TREK ACROSS THE EXO-NEPTUNES LANDSCAPE

CONTEXT

Close-in exoplanets are shaped by processes to which exo-Neptunes appear to be particularly sensitive (Owen+2018). While atmospheric erosion played a major role in forming the Neptunian Desert (e.g. Mazeh+2016), it is not clear how far into the Savanna (a milder deficit of warm Neptunes at longer periods, Bourrier+2023) this process is active and when in a planet life it occurs (Fig 1). Determining the fraction of Neptunes brought close-in by early disk-driven migration (DDM) or late high-eccentricity migration (HEM) is thus essential to understand their overall evolution.

OBSERVATIONAL STRATEGY

Ephemeris : Transit timing precision quickly degrades for close-in planets. We are carrying out an extensive campaign with our photometric facilities, combined with a re-analysis of archival data, to get below 5 min precision.

Transits : Each planet is observed with ESPRESSO with baseline on each side of the transit to measure the unocculted stellar spectrum and perform various corrections. We attempt to catch spot crossings and characterize stellar activity using simultaneous photometry.

Long-term monitoring : We exploit archival / new photometric and RV observations to measure host star rotations and search for outer companions.

REDUCTION METHODOLOGY

ESPRESSO datasets are run through the ANTARESS workflow (Bourrier+2024), a set of methods to process high-resolution transit spectroscopy in a robust way, extract accurate exoplanetary and stellar spectra, and analyze them for stellar, orbital, atmospheric characterization. This will ensure homogeneous and reproducible results for the sample.

INTERPRETATION PLAN

Orbital architecture: Planet-occulted stellar spectra extracted with ANTARESS are analyzed with the RM *Revolutions* technique (Bourrier+2021) to derive the stellar rotational velocity and sky-projected angle. Combined with the stellar rotation period, this yields the 3D orbital architecture, which informs evolutionary models (Attia+2021).

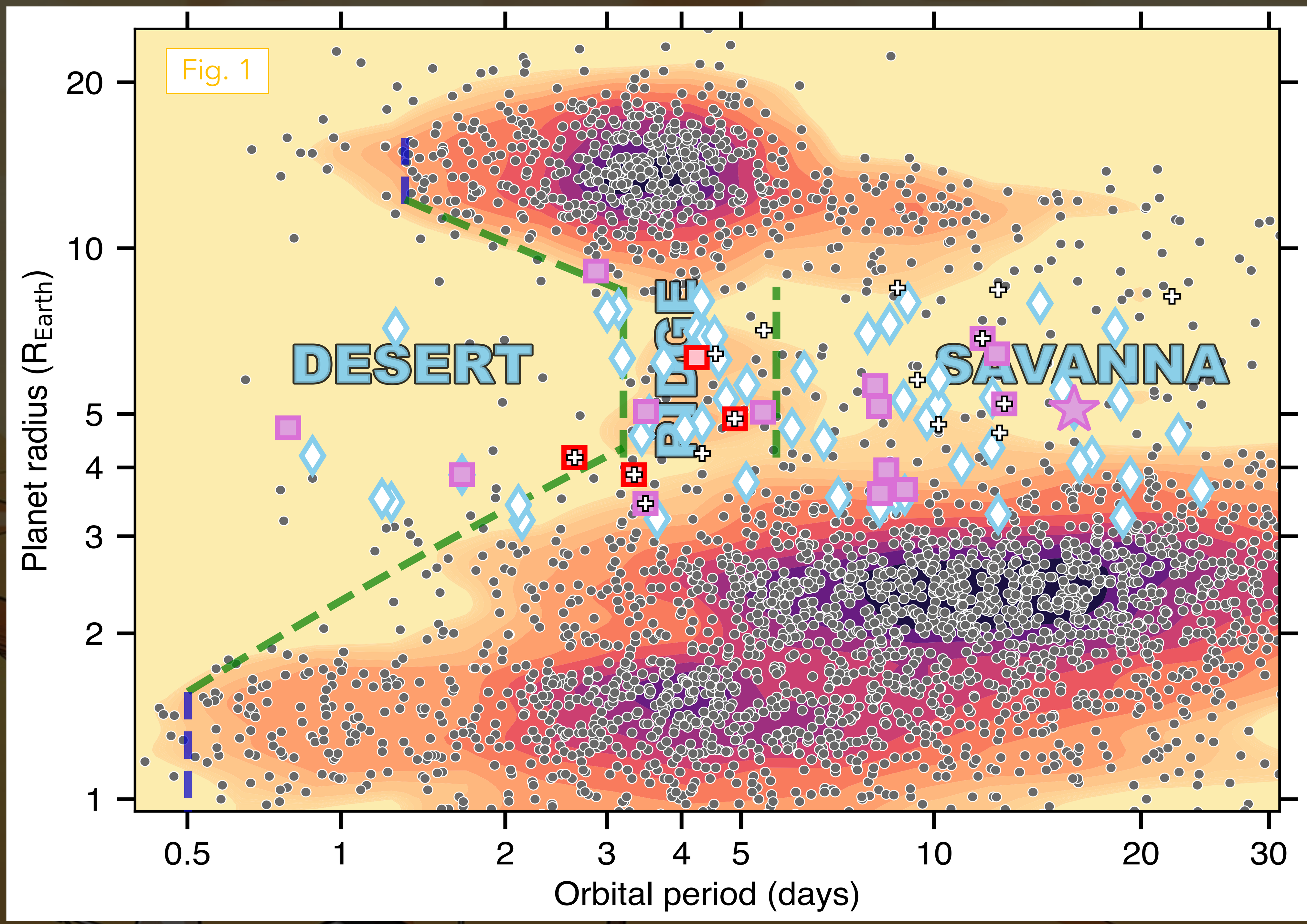
Upper atmospheres: Transmission spectra calculated with ANTARESS are fitted with the EVE code (Bourrier & Lecavelier 2013, Dethier & Bourrier 2023), which generates realistic spectra accounting for the system's architecture, 3D atmospheric structure, and spectral variations over the stellar disc. This allows characterizing atmospheric signals, disentangled from occulted stellar lines (Carteret+2024).

Global view: The primary goal of ATREIDES is to build the distribution of 3D orbital architectures for close-in Neptunes, and thus disentangle the roles of migration processes. A secondary goal is to probe the irradiation threshold for atmospheric expansion and evaporation.

THE ATREIDES COLLABORATION

The Ancestry, Traits, and Relations of Exoplanets Inhabiting the Desert Edges and Savanna collaboration (Bourrier+2025) is built upon a large VLT/ESPRESSO program to probe the orbital architecture of close-in Neptunes. To mitigate selection biases we defined a volume-limited sample (Fig. 1, green diamonds) encompassing all transiting Neptunes with a detectable Rossiter-McLaughlin (RM) signal. ATREIDES includes collaborators with access to complementary photometry from NGTS, TRAPPIST, SPECULOOS, MUSCAT2, and EULER.

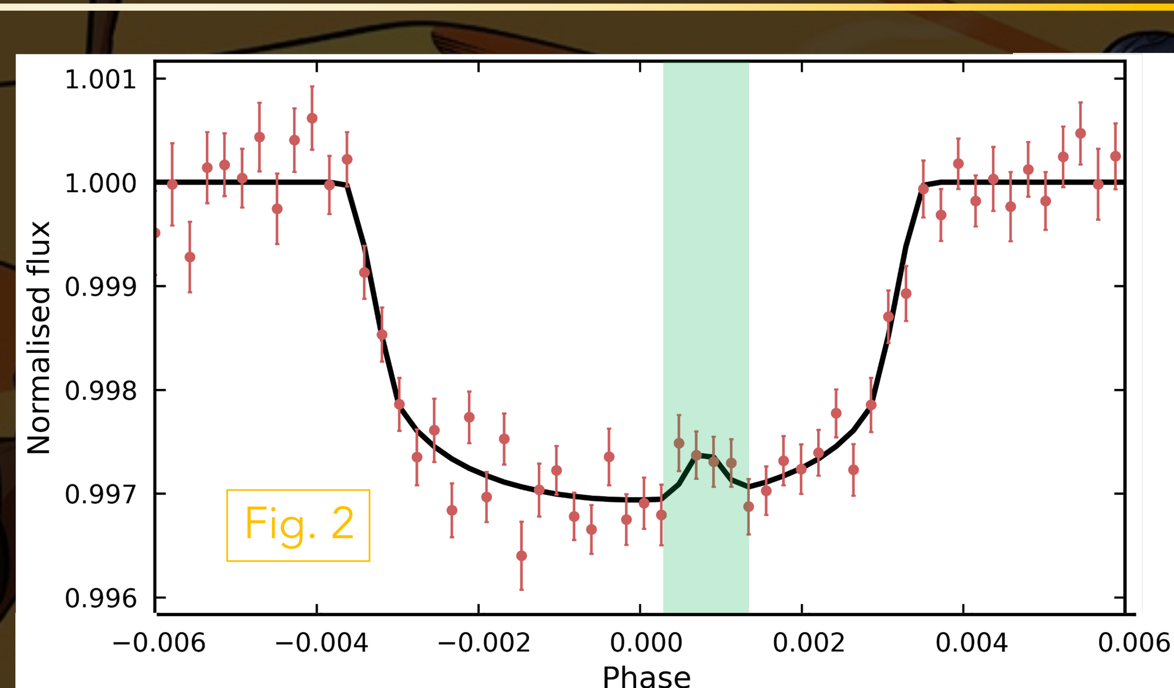
MEMBERS: V. Adibekyan, S. Aigrain, Y. Alibert, K. Al Moulla, J. M. Almenara, R. Allart, D. R. Anderson, E.-M. Ahrer, D. J. Armstrong, M. Attia, M. P. Battley, K. Barkaoui, S. C. C. Barros, D. Bayliss, V. Bourrier, E. M. Bryant, A. Y. Burdanov, Y. Carteret, A. Castro-González, H. M. Cegla, H. Chakraborty, A. C. M. Correia, Y. T. Davis, E. Delgado Mena, W. Dethier, R. F. Díaz, L. Doyle, E. Ducrot, D. Ehrenreich, F. Eeles-Nolle, J. A. Egger, P. Eggenberger, J. Fernandez, M. A. Fetzner Keniger, G. Frame, E. Friden, S. Gill, E. Gillen, M. Ghachoui, M. Gillon, Y. Gómez Maqueo Chew, F. Hawthorn, A. Heitzmann, E. Jehin, M. Lafarga, B. Lavie, A. Leleu, M. Lendl, J. Lillo-Box, I. S. Lockley, C. Lovis, X. Luo, A. Meech, S. J. Mercier, C. Mordasini, F. Murgas, A. Osborn, E. Palle, F. Pepe, P. P. Pedersen, A. C. Petit, A. G. M. Pietrow, K. Poppenhaeger, F. J. Pozuelos, A. Ringham, N. C. Santos, M. G. Scott, J. V. Seidel, J. Serrano Bell, S. G. Sousa, M. Steiner, M. Timmermans, A. H. M. J. Triaud, J. Venturini, P. J. Wheatley, M. R. Zapatero Osorio, S. Zúniga-Fernández.



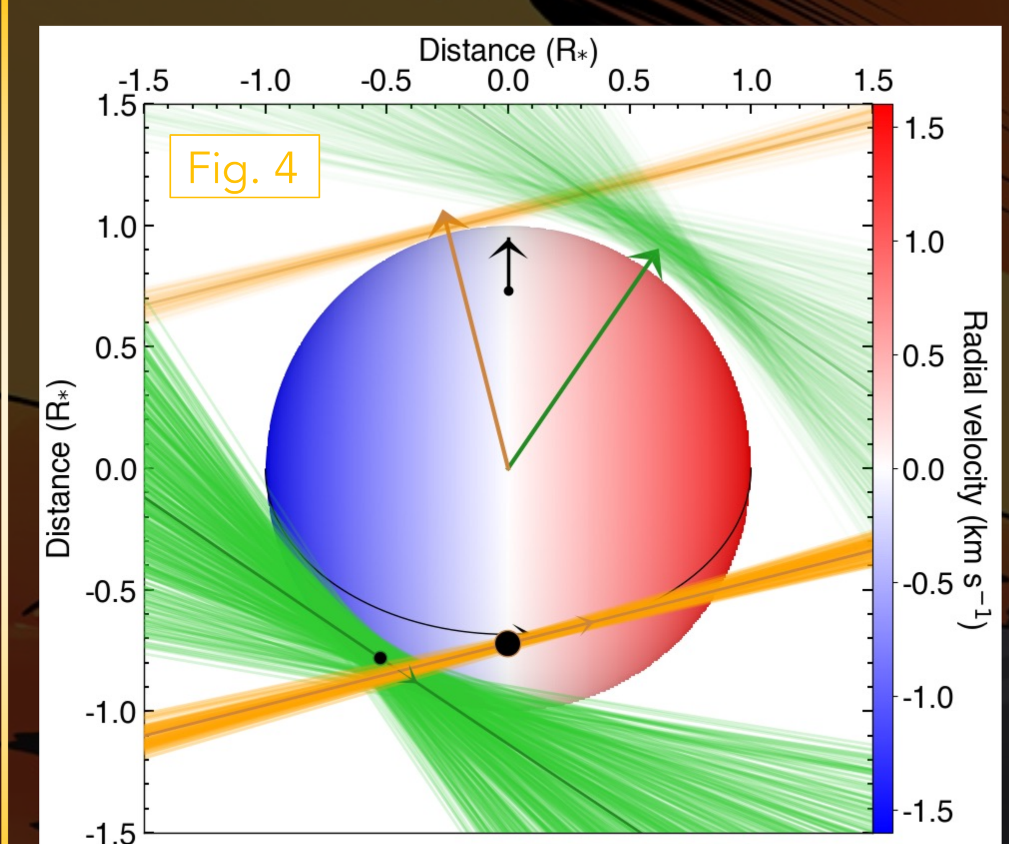
FIRST RESULT
THE TOI-421 SYSTEM

Bourrier+2025

The warm Neptune TOI-421 c, located within the Savanna (Fig. 1, purple star), was the first planet observed in ATREIDES. Its transit was monitored simultaneously with NGTS, revealing a spot crossing.

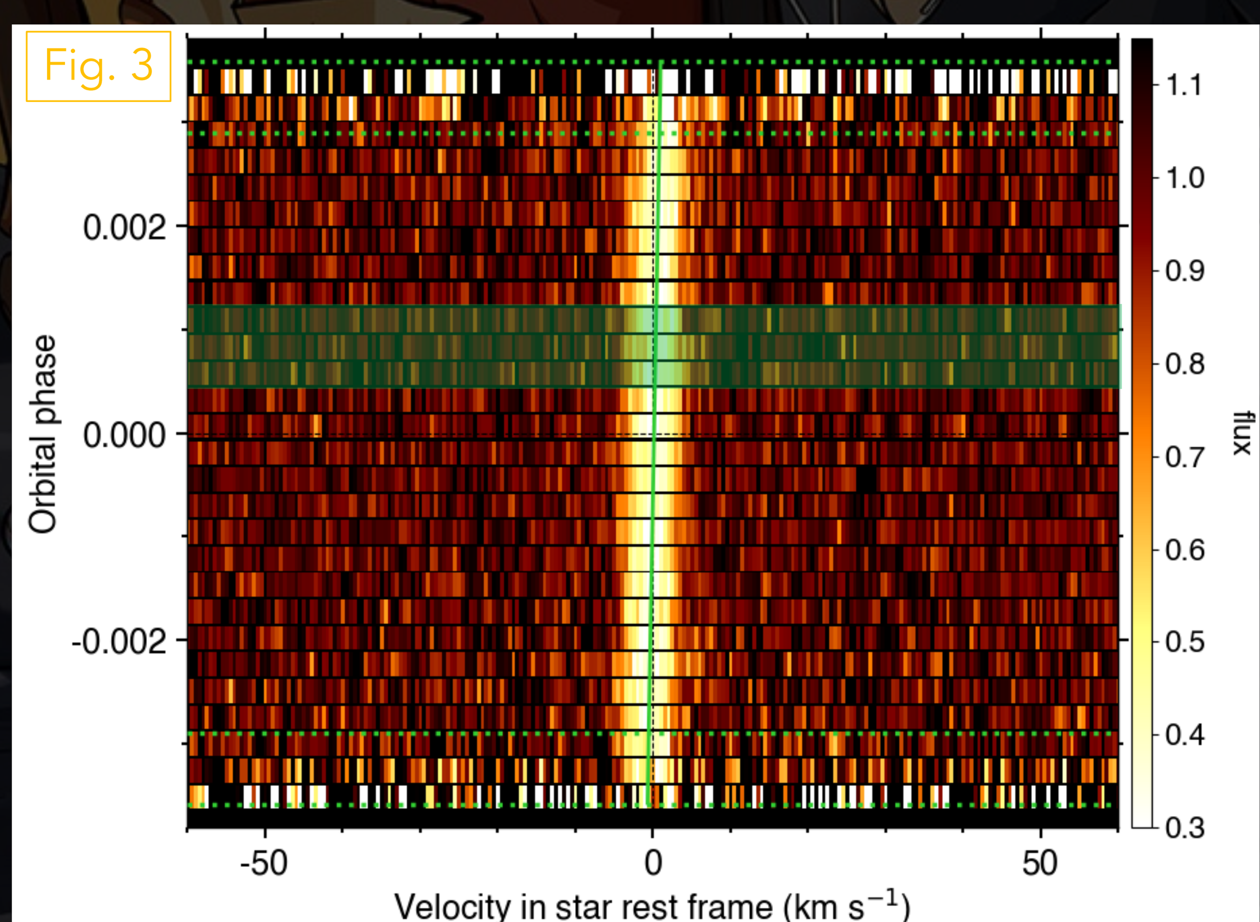


ESPRESSO echelle spectra were corrected for tellurics, Earth diffusion, cosmics, and interferences. They were then detrended for activity / ambient variations, aligned in the star rest frame, and scaled to their correct relative flux level using a SAGE model (Chakraborty+2024) to the NGTS light curve (Fig. 2). Planet-occulted spectra were extracted along the transit chord (excluding spotted exposures) and cross-correlated with a stellar mask.



The local stellar lines occulted by TOI-421c are detected with high precision (Fig. 3). The same analysis was applied to archival ESPRESSO data of the inner sub-Neptune TOI-421b. Combined with the stellar rotation period we find that the planets' orbits are moderately misaligned ($\Psi_b=57^{+11}_{-15}{}^{\circ}$; $\Psi_c=44.9^{+4.4}_{-4.1}{}^{\circ}$) and possibly mutually inclined (Fig. 4), hinting at a chaotic dynamical origin that could result from DDM followed by HEM.

Beyond TOI-421 we propose a comprehensive scenario to explain the distribution of close-in Neptune properties, in which they formed as two populations distinct in density. Most low-density Neptunes would be spread by DDM across a broad range of orbital periods, maintaining their primordial orbits, while most dense Neptunes would be brought through HEM to the Ridge and the Desert, acquiring eccentric and misaligned orbits.



CONTRIBUTIONS WELCOME

If you are interested in close-in Neptunes and have transit datasets that you want to study as part of ATREIDES sample, you are welcome to join the collaboration. We are also interested in any complementary data that you may have on close-in Neptune systems. Send an email to vincent.bourrier@unige.ch

UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES
Département d'astronomie
erc
FNSNF
SWISS NATIONAL SCIENCE FOUNDATION
SPICE DUNE

Attia+2021, A&A, 647, A40; Bourrier & Lecavelier 2013, 557A, 124B; Bourrier+2021, A&A, 654, A152; Bourrier+2023, A&A, 669, A63; Bourrier+2024, A&A, 691, A26; Bourrier+2025, A&A, 190, A30; Dethier & Bourrier, A&A, 674A, 86D; Carteret+2024, A&A, 683, A63; Mazeh+2016, A&A, 685A, 173C; Owen+2018, MNRAS, 479, 5012

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