**Planet(esimal)s Around Stars with TESS (PAST) III: A Search for Triplet He I in the Atmospheres of Two 200 Myr-old Planets**

Eric Gaidos⋆1,2,3, Teruyuki Hirano4,5,6, Rena A. Lee1, Hiroki Harakawa7, Klaus Hodapp8, Shane Jacobson8, Takayuki Kotani4,5,6, Tomoyuki Kudo7, Takashi Kurokawa4,9, Masayuki Kuzuhara4,5, Jun Nishikawa5,6,4, Masashi Omiya4,5, Takuma Serizawa5,9, Motohide Tamura4,5,10, Akitoshi Ueda4,5,6, Sebastien Vievard7

1Department of Earth Sciences, University of Hawai‘i at Mānoa, Honolulu, HI 96822, USA
2Institute for Astrophysics, University of Vienna, Türkenschanzstrasse 17, 1180 Vienna, Austria
3Institute for Particle Physics & Astrophysics, ETHZ, Wolfgang-Pauli Strasse, 8093 Zürich, Switzerland
4Astrobiology Center, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan
5National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan
6Department of Astronomy, School of Science, The Graduate University for Advanced Studies (SOKENDAI), 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan
7Subaru Telescope, 650 N. Aohoku Place, Hilo, HI 96720, USA
8Institute for Astronomy, University of Hawai‘i, Hilo HI 96720 USA
9Department of Astronomy, Graduate School of Science, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan
10Department of Astronomy, Graduate School of Science, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan

Accepted 2022 November 4. Received 2022 October 8; in original form 2022 June 28

**ABSTRACT**

We report a search for excess absorption in the 1083.2 nm line of ortho (triplet) helium during transits of TOI-1807b and TOI-2076b, 1.25 and 2.5-R_⊙ planets on 0.55- and 10.4-day orbits around nearby ~200 Myr-old K dwarf stars. We limit the equivalent width of any transit-associated absorption to <4 and <8 mÅ, respectively. We limit the escape of solar-composition atmospheres from TOI-1807b and TOI-2076b to 0.1 and 0.01 M⊙Gyr^{-1}, respectively, depending on wind temperature. The absence of a H/He signature for TOI-1807b is consistent with a measurement of mass indicating a rocky body and the prediction by a hydrodynamic model that any H-dominated atmosphere would be unstable and already have been lost. Differential spectra obtained during the transit of TOI-2076b contain a HeI-like feature, but this closely resembles the stellar line and extends beyond the transit interval. Until additional transits are observed, we suspect this to be the result of variation in the stellar HeI line produced by rotation of active regions and/or flaring on the young, active host star. Non-detection of escape could mean that TOI-2076b is more massive than expected, the star is less EUV-luminous, the models overestimate escape, or the planet has a H/He-poor atmosphere that is primarily molecules such as H_2O. Photochemical models of planetary winds predict a semi-major axis at which triplet He I observations are most sensitive to mass loss: TOI-2076b orbits near this optimum. Future surveys could use a distance criterion to increase the yield of detections.

**Key words:** planetary systems – planets and satellites: atmospheres – planets and satellites: physical evolution – stars: activity – techniques: spectroscopic – Sun: UV radiation

1 INTRODUCTION

The TESS mission is detecting thousands of candidate planets on close orbits around nearby bright stars, some of which are suitable for studies of atmospheres by the method of transmission spectroscopy (during primary transit) or emission spectroscopy (during secondary eclipse of a planet by the star). A key question addressed by such observations is whether H/He-rich atmospheres characteristic of giant planets are also prevalent on numerous Earth-to Neptune-size planets. A small mass fraction in H/He greatly enlarges the radius of a planet but is also susceptible to escape by stellar irradiation or internal energy, and could explain a gap in the radius distribution at 1.7-1.8 R_⊕, i.e. between planets with/without such atmospheres (Fulton et al. 2017; Ginzburg et al. 2018; Owen 2019). This population could include more massive planets with inflated, H_2O-rich “steam” atmospheres (Turbet et al. 2020).

* E-mail: gaidos@hawaii.edu

© 2022 The Authors
Extended/escaping atmospheres of H/He could be confirmed by detection of absorption lines with transit spectroscopy. While transit observations of the 121.4 nm Lyman-α line of H I can only be performed from space, the 1083.2 nm line of metastable neutral orthoheium ("triplet" He I) is accessible from the ground (Oklopčić & Hirata 2018). Transit observations in the triplet He I line are especially interesting for young (≤ 1 Gyr) planets experiencing intense X-ray and UV irradiation by their more active host stars, and more likely to be evolving. X-ray and EUV photons heat the upper atmosphere and drives escape, as well EUV photochemistry produces triplet He I in the ground state of the transition. Several young planets have already been surveyed for triplet He I (e.g., Hirano et al. 2020b; Gaidos et al. 2020a,b; Vissapragada et al. 2021; Gaidos et al. 2022; Zhang et al. 2022a,b).

Two nearby young planetary systems recently discovered by TESS are TOI-1807b (orbiting BD+39 2643) and TOI-2076-b (lead by BD+40 2790) (Hedges et al. 2021, see erratum for revised radii). TOI-1807-b is a 1.26+0.04−0.09 R⊙ planet on an ultrashort period (0.549 day) orbit and highly irradiated. Nardiello et al. (2022) measured a mass of 2.6 ± 0.5 M⊕, consistent with a rocky composition. TOI-2076-b, a sub-Neptune (2.50±0.06 R⊕) on a 10.365 day orbit; it is the innermost of three known transiting planets that are close to mean-motion resonances (Osborn et al. 2022). The two systems are co-moving and presumably co-evol, and their rapid rotation and elevated activity suggest an age of ~200 Myr (Oklopčić et al. 2021). The K3 and K0 spectral types of the host stars are considered favorable for the formation of triplet He I due to the relative fluxes of extreme ultraviolet (EUV) radiation (producing triplet He I in the ground state of the line) vs. near ultraviolet (NUV) radiation (which ionizes it; Oklopčić 2019). Their high activity is presumably accompanied by high coronal temperatures and greater EUV line emission critical to the formation of triplet He I (Poppenhaeger 2022). Due to their proximity and youth, these systems are also promising targets for atmosphere studies by JWST, either by emission (for TOI-1807b, which has an estimated equilibrium temperature of ~2100 K) or transmission (for TOI-2076b; Fig. 1).

3 OBSERVATIONS AND DATA REDUCTION

We obtained time-series spectra of transits of TOI-1807b and TOI-2076b on UT 3 April 2022 and 16 March 2022, respectively, using the Infrared Doppler (IRD) spectrograph on the 8.2-m Subaru telescope (Δλ/Δλ = 70,000, Kotani et al. 2018). The transit durations of the planets are 59 min and 3 hr 15 min, respectively (Hedges et al.; Osborn et al. 2022). Observations of TOI-1807b began 111 min before ingress and ended 60 min after egress. Accounting for its significant transit timing variation (TTV), Osborn et al. (2022) revised the linear ephemeris of TOI-1807b. This predicts a transit 52 min earlier than previously calculated, which meant only a partial transit was observed, with observations beginning 37 min after ingress and ending 127 min after egress. Integration time was 240 sec for TOI-1807b and 13 and 29 spectra were obtained in and out of transit. For TOI-2076b the integration time was 180 sec and 22 and 41 spectra were obtained in and out of transit. SNR per pixel is typically 100. Higher SNR (~200) spectra of the A0 stars HD 109615 and HD 127304 were obtained for telluric correction on the two respective nights. Spectral images were processed and spectra extracted, blaze-corrected, and wavelength-calibrated as described in Hirano et al. (2020a). Spectra were divided by those of the A0 stars and then adjusted to the rest-frame of the stars using the systemic velocities from Gaia DR2: −7.33 ± 0.59 for TOI-1807 and −13.19 ± 0.21 km s−1 for TOI-2076 (Gaia Collaboration et al. 2021).

Figures 2ab compare summed spectra obtained inside and outside of transit (red lines and blue points, respectively). The fractional difference spectra are plotted as the magenta points relative to the grey axis. The difference spectra were constructed by subtracting the out-of-transit mean, Doppler-shifting into the planet rest frame, and then co-added. This procedure removes stellar and the constant component of telluric lines, while preserving any planetary signal. These plots show the nearby stellar Si I line as well as He I, plus variable telluric OH emission (indicated by orange triangles) and H2O absorption (marked by inverted cyan triangles). Figures 2cd are "river" plots of the time-ordered spectra after the mean out-of-transit spectrum (and hence stellar and the constant component of telluric lines) was removed. No triplet He I absorption was detected at the Doppler-shifted location of TOI-1807b (black dotted lines in Fig. 2c). Based on an inspection of the difference spectrum and "river" plots in which artificial signals of varying strength were injected, we limit the equivalent width (EW) of any absorption associated with TOI-1807b to <4 mÅ. (In IRD spectra, an unresolved line at 1038 nm with an EW of 1 mÅ has a depth of 0.60%).

The difference spectrum of TOI-2076 during the planet’s transit (Fig. 2c) contains a feature which closely resembles the He I triplet. Although formally significant, it is only marginally discernible in the river plot (Fig., 2d) and the spectrum contains other features associated with the strong stellar Si line or the variable telluric OH and H2O lines, raising the possibility that it too is a systematic. To evaluate how localized the He I-like signal is to the transit, we halved the out-of-transit interval and constructed the difference spectra between the two sets of spectra. The first half also contains a He I-like feature relative to the second half but with re-
duced strength. This post-egress feature could indicate a persistent systematic but could also be produced by a trailing tail of gas.

To further investigate an instrumental systematic origin (e.g., uncorrected scattered light in the spectral images) we added a uniform offset to the continuum level of in-transit spectrum. We found that the addition of a 2.3% offset completely removed the He I-like feature, demonstrating that it has the same profile as the out-of-transit stellar line. However, such a correction increases the residuals in neighboring photosphere lines (e.g., Si I λ1082.71 nm) and increases the overall χ² in the spectral order. This suggests astrophysical time-variation of the stellar He I line, a reasonable scenario for a young, rapidly rotating (7.3 days) and magnetically active (Ca II HK \( R'_H K = -4.27 \)) star like BD+40 2790 (Hedges et al. 2021, see Sec. 4)¹.

We fit a model of the triplet with four free parameters (equivalent width EW, full-width half-maximum FWHM, ratio of singlet to doublet strength, and centroid Doppler shift) to the spectral feature, with standard errors obtained by Monte Carlo of the input spectra. The best-fit model (black curve in Fig. 2b) has EW = 8.5 <pm 1.4 mÅ and FWHM = 0.64±0.11 Å. The offset of the line centroid with respect to the nominal value is not significant (-0.04±0.05 Å). If the feature is an artefact or result of stellar variability then ~8 mÅ represents an approximate detection limit.

We translated the upper limit for absorption by TOI-1807b in the He I line and the detection or upper limit for TOI-2076b into instantaneous atmosphere mass loss rates using the model of a spherically symmetric, isothermal Parker wind described in Gaidos et al. (2020a). This model tracks the photochemistry of all species of H and He as well as electrons, and calculates the absorption line profiles, including the effects of finite optical depth. For the required XUV spectrum of the host star we adopted that of ε Er, ~400-Myr K2.5 dwarf, from the MUSCLES HST Treasury Survey (France et al. 2016; Youngblood et al. 2016; Loyd et al. 2016). We adjusted this spectrum by 1.21× and 2.34× for TOIs 1807 and 2076 based on the Rosat-measured stellar X-ray luminosities of the host stars (Hedges et al. 2021) relative to that of ε Er (Coffaro et al. 2020). We adopted a mass of 2.5 M\(_{\odot}\) for TOI-1807b (Nardiello et al. 2022) and assumed a mass of 6.8 M\(_{\odot}\) for TOI-2076b based on the mass-radius relations of Chen & Kipping (2017). Figure 3 plots predicted triplet He I EW vs. mass loss rate and wind temperature with the regions excluded by our upper limits shaded grey.

4 DISCUSSION

The He I-like feature in spectra obtained during the transit of TOI-2076b could be the signature of a He-containing atmosphere, or it could represent variability in the host star BD+40 2790. Variation could occur as active regions on the star rotate into and out of the visible disk; these could change the line strength but not profile, since the rotational velocity of the star (4.3 ± 0.5 km sec⁻¹; Hedges et al. 2021) is much smaller than the width of the line (equivalent to about 18 km sec⁻¹). Assuming sinusoidal variation over the stellar rotation period of 7.3 d (Hedges et al. 2021), variation of 2.3% over 2.4 hr (the interval between the mid-points of in- and out-of-transit observations) would require peak-to-peak variation >50%. During solar maximum, rotational variation of 30% in the He I EW has been recorded (Harvey & Livingston 1994). Variability in other stars has been very poorly studied, and detection of rotationally-modulated variation is scarce (Dupree et al. 2018; Fuhrmeister et al. 2020; Gaidos et al. 2022). In the Sun, flares also enhance absorption in the 1083.2 line on hours-long timescales via EUV photoionization and non-thermal electron collisional ionization of singlet He I and subsequent recombination to triplet He I (Kerr et al. 2021), but flares can also be accompanied by emission in the He I triplet (Kanodia et al. 2022), which was not observed here. We analyzed the Paschen-β line of H I, another indicator of flaring (Druett & Zharkova 2018) that falls within the spectral reach of IRD. The strength of the line, measured over the interval λ = 1281.49-1282.03 nm, exhibited no temporal trend and a (non-significant) scatter of only 1%. Thus while we suspect that the stellar feature reflects changes on the star rather than the atmosphere of the planet, we have no corroborating evidence to support this. Observations of another transit, as well as parallel spectroscopy of the Balmer Hα line to identify flares (e.g., Hirano et al. 2020b) would disambiguate these scenarios.

Our upper limits for the EW of any He I associated with the transit of these planets rule out atmospheric escape rates of ≥0.1-1 M\(_{\oplus}\) Gyr⁻¹, depending on wind temperature (Figs. 3ab). We compared these values to a “naive” energy-limited escape calculation \( M_p = \epsilon \pi X_{UV} R_p^3 (\kappa G M_p) \), where \( \epsilon \) is the heating efficiency and \( \kappa \) is a factor that reflects the inclination of the upper atmosphere above the nominal planet radius. Integrated EUV fluxes at each planet’s semi-major axis are based on the MUSCLES spectrum of ε Er. We also retrieved estimates of mass loss from the grid of 1-d hydrodynamic (HD) escape models calculated by Kubyshkina & Fossati (2021). Their calculations assume a pure (molecular) hydrogen atmosphere and include dissociation of H₂, recombination, and ionization. We use the same XUV fluxes as above but the HD calculations assume this to be entirely at 5 and 60 nm, and the heating efficiency is fixed at 15% (Kubyshkina et al. 2018b,a). To stay within the grid, we adjusted the \( T_{eq} \) of TOI-1807b from 2100 K (Hedges et al. 2021) to 2000 K and that of TOI-2076b from 870 K to 1100 K. While energy-limited escape from TOI-1807b is up to 4 M\(_{\oplus}\) Gyr⁻¹ (\( \epsilon = 0.1, x = 1 \)), dotted red line in Fig. 3a) the HD models predict a rate four orders of magnitude higher, indicating that under this high irradiation a H/He atmosphere would swell to a size \( R_p \), weakly bound, and readily escape. The explains why the planet does not possess a H/He envelope, and its current mass and radius are consistent with a rocky planet and the absence of all but a geometrically thin atmosphere.

Assuming a mass of 6.8 M\(_{\oplus}\) for TOI-2076b, the energy-limited escape rate is 0.36 M\(_{\oplus}\) Gyr⁻¹ (dotted red line in Fig. 3b) while HD model interpolation predicts 0.77 M\(_{\oplus}\) Gyr⁻¹ (dashed red line in Fig. 3b), the latter presumably reflecting inflation of the irradiated atmosphere (\( \kappa < 1 \)). These estimates are consistent with a detection with EW=8.5 mÅ only if the wind temperature is >10000K.

The signature of mass loss from mini-Neptunes like TOI-2076b could vary strongly with distance from the host star. Triplet helium in the ground state of the 1083 nm transition is produced primarily by ionization of singlet He I by EUV photons, followed by recombination. The electrons are chiefly from the ionization of H (which is more abundant and more readily ionizes) and this should then give rise to a nonlinear increase in triplet He I production with increasing irradiation. On the other hand, ionization of triplet He I by EUV photons (as well as electron collisions) should increase proportionally with irradiation, thus the abundance of triplet He I and the transit signal should increase inversely with semi-major axis (Oklopčić 2019). Very close to the star, all H is ionized, which not only caps electrons available but also ceases to shield triplet He I.

¹ Planetary occultation of individual stellar active regions in which the He I line is in emission could increase the net equivalent width of the triplet, but since the transit depth is 0.09%, the effect is likely to be negligible.
from ionizing photons. The Strömgren-like radius in the wind at which H is completely ionized is approximately:

$$R_s = d \sqrt{\frac{M_p}{\pi m_p L_{EUV}}} \quad (1)$$

where $L_{EUV}$ is the luminosity of the star in ionizing photons ($\lambda \lesssim 91.2$ nm). The distance at which $R_s$ equals the planet radius $R_p$ (i.e., H is ionized close to the planet surface) is then

$$d_s = R_p \sqrt{\pi m_p L_{EUV}/M_p}.$$
The assumption that the wind terminates at $R_p$ is a gross simplification and instead geometric blow-off occurs (Lecavelier des Etangs et al. 2004). If the orbit is sufficiently close, the escaping material will either be captured onto the star, otherwise it will be blown into a tail by the stellar wind (Shaikhislamov et al. 2016). In either case, the dispersion of the wind in space and velocity will attenuate its contribution to the core of the planetary line of He I in a spectrum obtained during transit. Whether the stellar wind corralls the planetary wind into a tail can be assessed by equating the ram pressure of the stellar wind to the ram or thermal pressure of the planetary wind at $R_p$ (Mitani et al. 2022). Invoking mass conservation to remove the wind densities yields:

$$\frac{M_p}{M_\star} \sim \left( \frac{M_p}{3M_\star} \right)^{2/3} \frac{v_\star}{v_p},$$

where $v_\star$ and $v_p$ are the stellar and planetary wind speeds, a ratio equated to the coronal/wind temperature ratio $\sqrt{T_\omega/T_w}$. Adopting $T_\omega = 5$ MK (Güdel 2009) and $T_w = 5000$ K, using the stellar wind mass loss rate scaling for young stars in the magnetically saturated regime of Johnstone et al. (2015) $\dot{M}_w \propto R_\star^{1.33} M_\star^{1.1}$, and a present solar $\dot{M}_\odot = 6.6 M_\odot$ Gyr$^{-1}$ (Fichtinger et al. 2017) we estimate a mass loss rate of $17.6 M_\odot$ Gyr$^{-1}$ for the central star of TOI-2076b, and a critical planetary mass loss rate of $\approx 0.2 M_\odot$ Gyr$^{-1}$. At mass loss rates below this the planetary wind will be confined to a tail.

If TOI-2076b started off as Neptune-like with a fraction of an Earth mass of H, at the predicted escape rate for the planet and an age of $\sim 200$ Myr, the planet should still possess significant H. Assuming that the feature seen in the transit spectrum is not a planetary signal, our observations could be in tension with model predictions (red dashed lines in Fig. 3b). One explanation could be that the as-yet-measured mass of TOI-2076b is higher than forecast from the mass-radius relation of Chen & Kipping (2017) and that its higher gravity inhibits escape. We repeated the calculations with a doubled mass of $13.6 M_\odot$. The predicted escape rates fall by a factor of a few (light red lines in Fig. 3b) although this effect is partially offset by a slightly larger EW for a given escape rate and wind temperature (not shown). Another explanation is that the star is less EUV-luminous than estimated: such estimates are subject to intrinsic model uncertainties (Oklopičić 2019) as well as uncertain coronal temperature and iron abundance on which the EUV line emission depends (Poppenhaeger 2022). A third explanation is that the model predictions are too high, e.g. by neglecting cooling of the upper atmosphere by molecules such as CO$_2$, thus over-estimating the heating efficiency. Repeated and more sensitive observations
could test this scenario. Finally, TOI-2076b could posses a high molecular weight atmosphere, e.g. of H₂O, in lieu of a H/He-rich atmosphere, and that it is inflated by the intense irradiation (Turbet et al. 2020).

5 CONCLUSIONS

Our transit spectroscopy of the ~200 Myr-old planets TOI-1807b and TOI-2076b in the 1083.2 nm line of triplet HeI further refine our picture of the atmospheres of young planets close to their host stars. We find a He-I-like feature in our transit spectra of TOI-2076b but the line profile and our analysis suggest this could be the result of variability in the stellar line due to rotation of active regions or flares on this young, magnetically active star. Observation of the He I triplet during another transit simultaneous with Hα to monitor stellar activity could resolve this ambiguity. We place upper limits of 4 and 8 mÅ on any absorption associated with TOI-1807b and TOI-2076b, respectively. Using a model of an isothermal, solar H/He planetary wind we limit the mass-loss from the planets to ~0.1 and ~1 $M_{\odot}$ Gyr$^{-1}$, respectively, depending on wind temperature. The non-detection of escaping triplet He from TOI-1807b is consistent with a mass measurement that suggests a primarily rocky composition, plus predictions by a hydrodynamic model that a H-dominated atmosphere would have escaped on a timescale much shorter than the age of the planet. On the other hand, if the TOI-2076b result is a non-detection it could be in tension with predictions for a nominal (but unknown) mass of 6.8$M_{\oplus}$. The tension could be relieved if the planet was more massive, the star was less EUV luminous, model predictions were revised downwards as radiative cooling of the atmosphere by molecules was included, or the atmosphere was H/He-poor, e.g. predominantly steam (H₂O). We find that for mini-Neptunes orbiting stars with a given XUV luminosity there is an optimal semi-major axis at which the He I transit signal is maximized and that TOI-2076b is close to this optimal separation. To maximize detections, future surveys could use semi-major axis as a target selection criterion.

Determination of planet mass is important to interpreting the results of atmosphere measurements, but young host stars like those of TOI-1807b and TOI-2076b are challenging targets for Doppler RV observations. The inferred RV amplitude of TOI-1807b is 2.5 m sec$^{-1}$, much smaller than the stellar uncorrelated “jitter” of 12 m sec$^{-1}$ (Nardiello et al. 2022). The predicted RV amplitudes of the TOI-2076 planets are <2 m sec$^{-1}$ (Osborn et al. 2022) and their longer orbital periods make that approach impractical. Instead, the location of these objects near mean-motion commensurabilities means that their masses might be determined by measurement of TTV. Although current data are insufficient, inclusion of TESS Sector 50 and additional observations with the CHEOPS satellite and from the ground could yield precise masses (Osborn et al. 2022). A mass measurement could discern whether TOI-2076b has a H/He atmosphere and one dominated by heavier molecules such as H₂O as well as CO, CO₂, and/or CH₄. Another, complementary approach is transit observations in the (vacuum ultraviolet) Lyman-$\alpha$ line of H with the Hubble Space Telescope. Detection of Lyman-$\alpha$ absorption is subject to different conditions than that of triplet He I (Zhang et al. 2022b) and such observations remain useful despite the lack of definitive He I detections reported here. Such studies take on greater importance in the JWST era: metal-rich atmospheres have smaller scale heights, meaning that future observations with JWST might prioritize detection of emission during secondary eclipses over transit spectroscopy during primary transits.

ACKNOWLEDGEMENTS

EG and RAL are supported by NASA Award 80NSSC20K0957 (Exoplanets Research Program) and NSF Award 1817215 (Astronomy & Astrophysics Research Grants), and EG was visiting scientist at the International Space Science Institute in Bern. IRD was supported by JSPS KAKENHI Grant Numbers 19J11805, 19K14783, 18H05442, 15H02063, 21H00035, and 22000005.

DATA AVAILABILITY

The relevant portions of the IRD spectra of the science targets and telluric calibrator stars are available by request from the authors.

REFERENCES

Breckinridge J. B., Hall D. N. B., 1973, Sol. Phys., 28, 15
Chen J., Kipping D., 2017, ApJ, 834, 17
Coffaro M., et al., 2020, A&A, 636, A49
Drueet M. K., Zharkova V. V., 2018, A&A, 610, A68
Dupree A., Brickhouse N., Irwin J., Kurucz R., Newton E., 2018, in 20th Cambridge Workshop on Cool Stars, Stellar Systems and the Sun. Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun. p. 87 (arXiv:1811.03572), doi:10.5281/zenodo.1491756
Eggleton P. P., 1983, ApJ, 268, 368
Fichtinger B., Güdel M., Mulet R. L., Hallinan G., Gaidos E., Skinner S. L., Lynch C., Gayley K. G., 2017, A&A, 599, A127
France K., et al., 2016, ApJ, 820, 89
Fuhrmeister B., et al., 2020, A&A, 640, A52
Gaidos et al.
