

A 38 Million Year Old Neptune-Sized Planet in the Kepler Field

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ABSTRACT

Kepler 1627A is a G8V star previously known to host a $3.8R_{\oplus}$ planet on a 7.2 day orbit. The star was observed by the Kepler space telescope because it is nearby ($d = 329$ pc) and it resembles the Sun. Here we show using Gaia kinematics, TESS stellar rotation periods, and spectroscopic lithium abundances that Kepler 1627 is a member of the 38^{+6}_{-5} Myr old δ Lyr cluster. To our knowledge, this makes Kepler 1627Ab the youngest planet with a precise age yet found by the prime Kepler mission. The Kepler photometry shows two peculiarities: the average transit profile is asymmetric, and the individual transit times might be correlated with the local light curve slope. We discuss possible explanations for each anomaly. More importantly, the δ Lyr cluster is one of $\sim 10^3$ coeval groups whose properties have been clarified by Gaia. Many other exoplanet hosts are candidate members of these clusters; their ages can be verified with the trifecta of Gaia, TESS, and ground-based spectroscopy.

Keywords: exoplanet evolution (491), open star clusters (1160), stellar ages (1581)

1. INTRODUCTION

While thousands of exoplanets have been discovered orbiting nearby stars, the vast majority of them are several billion years old. This makes it

difficult to test origin theories for the different families of planets, since many evolutionary processes are expected to operate on timescales of less than 100 million years.

For instance, the “mini-Neptunes”, thought to be made of metal cores, silicate mantles (Kite et al. 2020), and extended hydrogen-dominated atmospheres, are expected to shrink in size by factors of several over their first 10^8 years. Specifically, in the models of Owen & Wu (2016) and

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Owen (2020), the $\approx 5 M_{\oplus}$ planets start with sizes of $4-12 R_{\oplus}$ shortly after the time of disk dispersal ($\lesssim 10^7$ years), and shrink to sizes of $2-4 R_{\oplus}$ by 10^8 years. While the majority of this change is expected to occur within the first few million years after the disk disperses (Ikoma & Hori 2012), stellar irradiation and internal heat can also power gradual outflows which, if strong enough, can deplete or entirely strip the atmosphere (Lopez et al. 2012; Owen & Wu 2013; Ginzburg et al. 2018). The latter photoevaporative and core-powered outflows are thought to persist for $\approx 10^8$ to $\approx 10^9$ years, though the details depend on the planetary masses, the irradiation environments, and the initial atmospheric mass fractions (Owen & Wu 2017; Gupta & Schlichting 2020; Rogers & Owen 2021; King & Wheatley 2021). Discovering young planets, measuring their masses, and detecting their atmospheric outflows are key steps toward testing this paradigm, which is often invoked to explain the observed radius distribution of mature exoplanets (Fulton et al. 2017; Van Eylen et al. 2018).

The K2 and TESS missions have now enabled the detection of about ten close-in planets younger than 100 million years, all smaller than Jupiter (Mann et al. 2016; David et al. 2016, 2019; Newton et al. 2019; Bouma et al. 2020; Plavchan et al. 2020; Rizzuto et al. 2020; Martioli et al. 2021). The Kepler mission however has not yielded any planets with precise ages below one gigayear (Meibom et al. 2013). The reason is that during the prime Kepler mission (2009–2013), only four open clusters were known in the Kepler field, with ages spanning 0.7 Gyr to 9 Gyr (Meibom et al. 2011). Though isochronal, gyrochronal, and lithium-based analyses suggest that younger Kepler planets do exist (Walkowicz & Basri 2013; Berger et al. 2018; David et al. 2021), accurate and precise age measurements typically require an ensemble of stars. Fortunately, recent analyses of the Gaia data have greatly expanded our knowledge of cluster memberships (e.g., Cantat-Gaudin et al. 2018; Zari et al. 2018; Kounkel & Covey 2019; Meingast et al. 2021; Kerr et al. 2021). As part of our Cluster Difference Imaging Photometric Survey (CDIPS, Bouma et al. 2019), we concatenated the available analyses from the literature, which yielded a list of candidate young and aged stars (see Appendix A).

Matching our young star list against stars observed by Kepler revealed that Kepler observed a portion of the δ Lyr cluster (Stephenson-1; Theia 73). More specifically, a clustering analysis of the Gaia data by Kounkel & Covey (2019) reported that Kepler 1627 (KIC 6184894; KOI 5245) is a δ Lyr cluster member. Given the previous statistical validation of the close-in Neptune-sized

planet Kepler 1627b (Tenenbaum et al. 2012; Morton et al. 2016; Thompson et al. 2018), we begin by scrutinizing the properties of the cluster (Section 2). We find that the δ Lyr cluster is 38^{+6}_{-5} Myr old, and in Section 3 show that Kepler 1627 is both a binary and also a member of the cluster. Focusing on the planet (Section 4), we confirm that despite the existence of the previously unreported M3V companion, hereafter Kepler 1627B, the planet orbits the G-dwarf primary, Kepler 1627A. We also analyze an asymmetry in the average transit profile, and a possible correlation between the individual transit times and the local light curve slope. We conclude by discussing broader implications for our ability to age-date a larger sample of planets (Section 5).

2. THE CLUSTER

To measure the age of the δ Lyr cluster, we first selected a set of candidate cluster members (Section 2.1), and then analyzed these stars using a combination of the isochronal and gyrochronal techniques (Section 2.2).

2.1. Selecting Cluster Members

Kounkel & Covey (2019) applied an unsupervised clustering algorithm to Gaia DR2 on-sky positions, proper motions, and parallaxes for stars within the nearest kiloparsec. For the δ Lyr cluster (Theia 73), they reported 3,071 candidate members. We matched these stars against the latest Gaia EDR3 observations using the dr2_neighbourhood table from the ESA archive, taking the stars closest in proper motion and epoch-corrected angular distance as the presumed match (Gaia Collaboration et al. 2021a). For plotting purposes, we focused only on the stars with parallax signal-to-noise exceeding 20. We calculated the tangential velocities for each of these stars relative to Kepler 1627 ($\Delta\mu^*$) by subtracting the observed proper motion from what the proper motion at each star’s position would be if it were co-moving with Kepler 1627.

Figure 1 shows that the reported cluster members (gray and black points) extend over a much larger volume in both physical and kinematic space than the cluster previously identified by Stephenson (1959) and later corroborated by Eggen (1968). While the non-uniform “clumps” of stars might comprise a *bona fide* cluster of identically-aged stars, they could also be heavily contaminated by field stars. One reason to suspect this is that the spread in tangential velocities exceeds typical limits for kinematic coherence (Meingast et al. 2021). We therefore considered stars only in the immediate kinematic and spatial vicinity of Kepler 1627 as candidate cluster members. We performed this selection cut manually, by drawing lassos with the in-

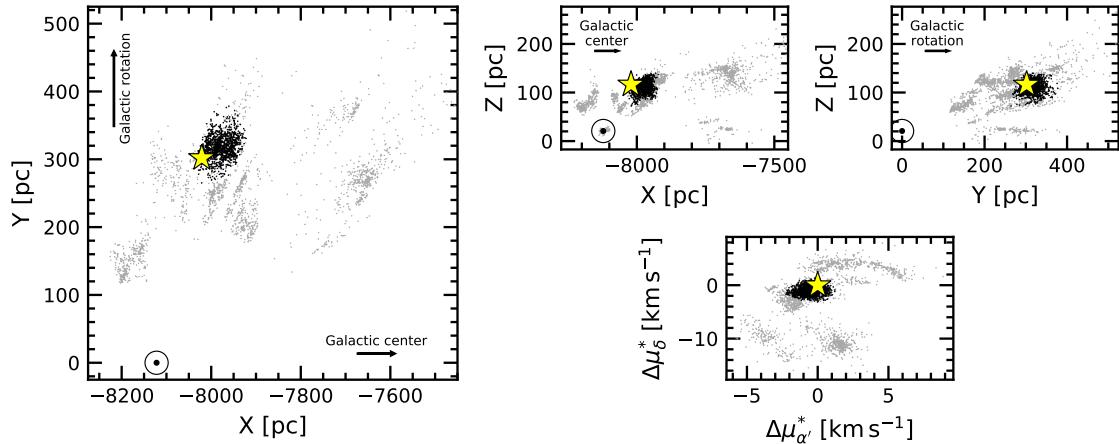


Figure 1. Galactic positions and tangential velocities of stars in the δ Lyr cluster. Points are reported cluster members from Kounkel & Covey (2019). The tangential velocities relative to Kepler 1627 (bottom right) are computed assuming that every star has the same three-dimensional spatial velocity as Kepler 1627. Our analysis considers stars (black points) in the spatial and kinematic vicinity of Kepler 1627 (yellow star). The question of whether the other candidate cluster members (gray points) are part of the cluster is outside our scope. The location of the Sun is (\odot) is shown to clarify the direction along which parallax uncertainties are expected to produce erroneous clusters.

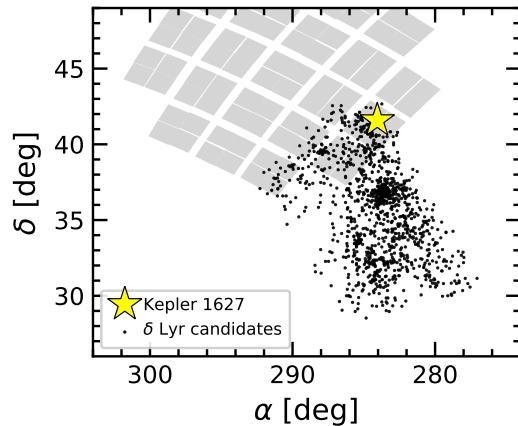


Figure 2. Kepler's view of the δ Lyr cluster, shown in equatorial coordinates. Each black circle is a candidate cluster member selected based on its position and kinematics (Figure 1). Of the 1,201 candidate cluster members, 58 have at least one quarter of Kepler data. TESS has also observed most of the cluster, for one to two lunar months to date.

teractive glue visualization tool (Beaumont et al. 2014) in the four projections shown in Figure 1. The overlap between the Kepler field and the resulting candidate cluster members is shown in Figure 2. While this method will include some field interlopers in the “cluster star” sample, and vice-versa, it should suffice for our aim of verifying the existence of the cluster in the vicinity of Kepler 1627.

2.2. The Cluster’s Age

2.2.1. Color-Absolute Magnitude Diagram

We measured the isochrone age using an empirical approach. The upper left panel of Figure 3 shows the color-absolute magnitude diagram (CMD) of candidate δ Lyr cluster members, IC 2602 (≈ 38 Myr), the Pleiades (≈ 115 Myr), and the field. The stars from the Pleiades and IC 2602 were adopted from Cantat-Gaudin et al. (2018), and the field stars are from the Gaia EDR3 Catalog of Nearby Stars (Gaia Collaboration et al. 2021b). We also compared against μ -Tau (62 ± 7 Myr; Gagné et al. 2020) and the Upper-Centaurus-Lupus (UCL) component of the Sco OB2 association (≈ 16 Myr; Pecaut & Mamajek 2016). We adopted the UCL members from Damiani et al. (2019). For visual clarity, the latter two clusters are not shown in Figure 3. We cleaned the membership lists following the data filtering criteria from Gaia Collaboration et al. (2018a, Appendix B), except that we weakened the parallax precision requirement to $\varpi/\sigma_\varpi > 5$. This also involved cuts on the photometric signal to noise ratio, the number of visibility periods used, the astrometric χ^2 of the single-source solution, and the $G_{\text{BP}} - G_{\text{RP}}$ color excess factor. These filters were designed to include genuine binaries while omitting instrumental artifacts. To correct for extinction, we queried the 3-dimensional maps of Capitanio et al. (2017) and Lallement et al. (2018)¹, and applied the extinction coefficients $k_X \equiv A_X/A_0$ computed by Gaia Collaboration et al. (2018a) assuming that $A_0 = 3.1E(B-V)$. For UCL, IC 2602, the Pleiades, and the δ Lyr cluster, this procedure yielded a respective

¹ <https://stilism.obspm.fr/>, 2021/09/25

mean and standard deviation for the reddening of $E(B-V) = \{0.084 \pm 0.041, 0.020 \pm 0.003, 0.045 \pm 0.008, 0.032 \pm 0.006\}$. These values are within a factor of two of previously reported values in the literature (Pecaut & Mamajek 2016; Gaia Collaboration et al. 2018a; Kounkel & Covey 2019; Bossini et al. 2019), and are all small enough that the choice of whether to use them vs. other extinction estimates does not affect our primary conclusions.

Figure 3 shows that the δ Lyr cluster and IC 2602 overlap, and therefore are approximately the same age. The pre-main-sequence M dwarfs of the δ Lyr cluster were also seen to be “below” UCL and “above” the Pleiades. To turn this heuristic interpolation into a quantitative age measurement, we used the empirical method developed by Gagné et al. (2020). In brief, we fitted the pre-main-sequence loci of a set of reference clusters, and the locus of the target δ Lyr cluster was then modeled as a piecewise linear combination of these reference clusters. For our reference clusters, we used UCL, IC 2602, and the Pleiades. We removed binaries by requiring RUWE < 1.3, radial_velocity_error below the 80th percentile of each cluster’s distribution, and excluded stars that were obvious photometric binaries in the CAMD.² We then passed a moving box average and standard deviation across the CAMD in 0.10 mag bins, fitted a univariate spline to the binned values, and assembled a piecewise grid of isochrones spanning the ages between UCL and the Pleiades using Equation 6 from Gagné et al. (2020). To derive a probability distribution function for the age of δ Lyr cluster, we then assumed a Gaussian likelihood that treated the interpolated isochrones as the “model” and the δ Lyr cluster’s isochrone as the “data” (Equation 7 from Gagné et al. 2020). The cluster’s age and its statistical uncertainty are then quoted as the the mean and standard deviation of this age posterior.

The ages returned by this procedure depend on the ages assumed for each reference cluster. We adopted a 115 Myr age for the Pleiades (Dahm 2015), and a 16 Myr age for UCL (Pecaut & Mamajek 2016). The age of IC 2602 however is the most important ingredient, since it receives the most weight in the interpolation. Plausible ages for IC 2602 span 30 Myr to 46 Myr, with older ages being preferred by the lithium-depletion-boundary (LDB) measurements (Dobbie et al. 2010; Randich et al. 2018) and younger ages by the main-sequence turn-off (Stauffer et al. 1997; David &

² For a description of the renormalized unit weight error (RUWE), see the GAIA DPAC technical note http://www.rssd.esa.int/doc_fetch.php?id=3757412.

Hillenbrand 2015; Bossini et al. 2019). If we were to adopt the 30 Myr age for IC 2602, then the δ Lyr cluster would be 31^{+5}_{-4} Myr old. For the converse extreme of 46 Myr, the δ Lyr cluster would be 44^{+8}_{-7} Myr old. We adopt an intermediate 38 Myr age for IC 2602, which yields an age for the δ Lyr cluster of 38^{+6}_{-5} Myr.³ Follow-up studies of the LDB or main-sequence turn-off in the δ Lyr cluster could help determine a more precise and accurate age for the cluster, and are left for future work.

2.2.2. Stellar Rotation Periods

Of the 3,071 candidate δ Lyr cluster members reported by Kounkel & Covey (2019), 924 stars were amenable to rotation period measurements ($G < 17$ and $(G_{BP} - G_{RP})_0 > 0.5$) using the TESS full frame image data. As a matter of scope, we restricted our attention to the 391 stars discussed in Section 2.1 in the spatial and kinematic proximity of Kepler 1627. We extracted light curves from the TESS images using the nearest pixel to each star, and regressed them against systematics with the causal pixel model implemented in the unpopular package (Hattori et al. 2021). We then measured candidate rotation periods using a Lomb-Scargle periodogram (Lomb 1976; Scargle 1982; Astropy Collaboration et al. 2018). To enable cuts on crowding, we queried the Gaia source catalog for stars within a 21.”0 radius of the target star (a radius of 1 TESS pixel). Within this radius, we recorded the number of stars with greater brightness than the target star, and with brightness within 1.25 TESS magnitudes of the target star.

We then cleaned the candidate TESS rotation period measurements through a combination of automated and manual steps. First, to validate the TESS rotation periods, we compared against 28 stars from McQuillan et al. (2014) that were also observed by Kepler. Of the 23 stars with Kepler periods below 10 days, 21 of the TESS periods agreed with the Kepler rotation periods; the other 2 were measured at the double-period harmonic. Of the remaining 5 stars with Kepler rotation periods above 10 days, none were correctly recovered by TESS, and 3 were near the half-period harmonic. We therefore adopted a general stance of skepticism for TESS rotation periods exceeding 10 days, and used the Kepler rotation periods whenever possible. For the remaining stars with only TESS data, we focused only on the stars for which no companions were known with a brightness exceeding

³ Our exploration of the PARSEC and MIST isochrone models over a grid of ages, metallicities, and reddenings, yielded the best agreement for this ≈ 38 Myr age as well, given $[Fe/H] = +0.1$ and $A_V = 0.2$ (Bressan et al. 2012; Choi et al. 2016); this preferred CAMD reddening is higher than the Lallement et al. (2018) value by a factor of two.

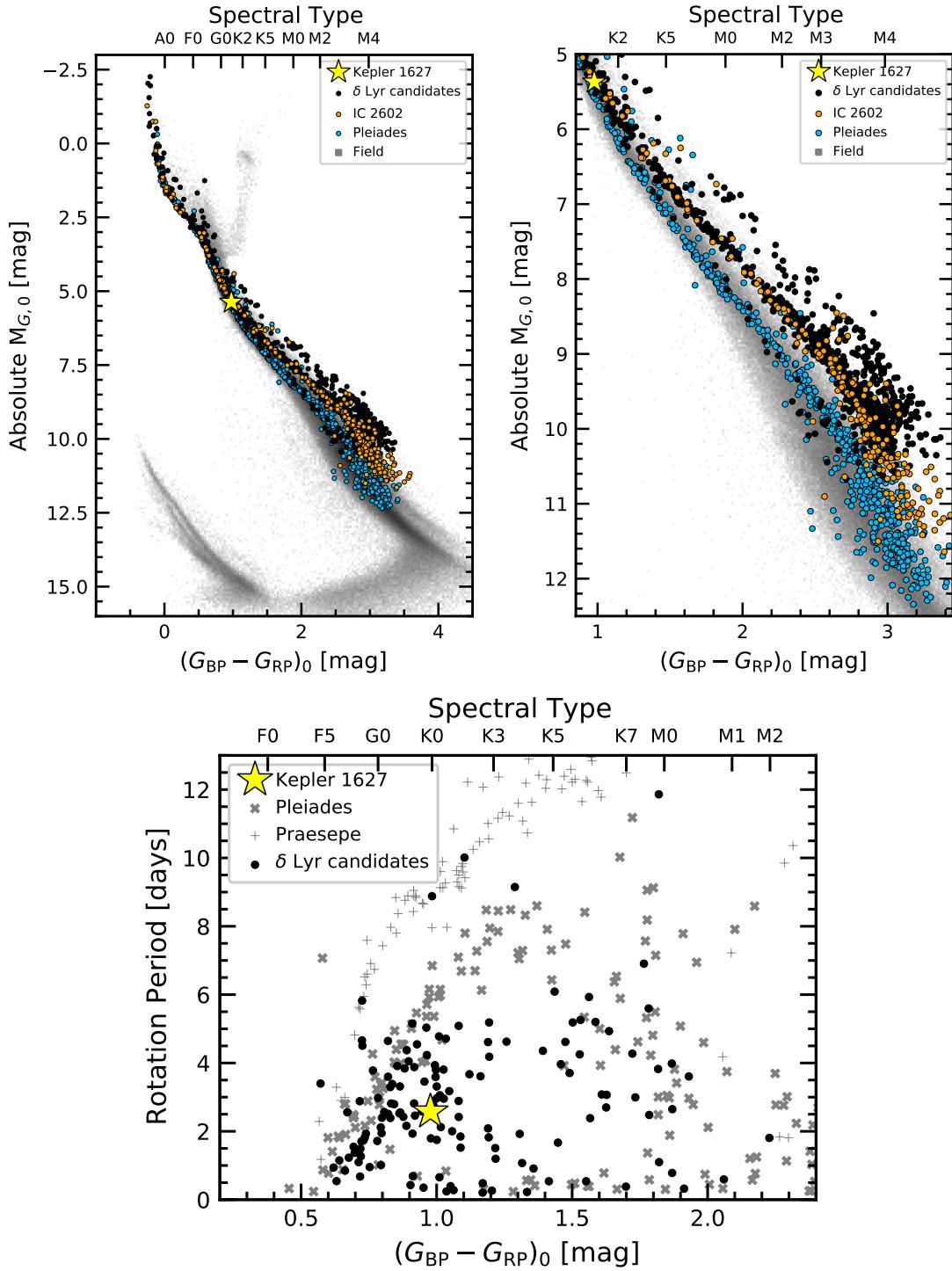


Figure 3. The δ Lyr cluster is 38^{+6}_{-5} Myr old. *Top:* Color-absolute magnitude diagram of candidate δ Lyr cluster members, in addition to stars in IC 2602 (≈ 38 Myr), the Pleiades (≈ 115 Myr), and the Gaia EDR3 Catalog of Nearby Stars (gray background). The zoomed right panel highlights the pre-main-sequence. The δ Lyr cluster and IC 2602 are approximately the same isochronal age. *Bottom:* TESS and Kepler stellar rotation period versus dereddened Gaia color, with the Pleiades and Praesepe (650 Myr) shown for reference (Rebull et al. 2016; Douglas et al. 2017). Most candidate δ Lyr cluster members are gyrochronologically younger than the Pleiades; outliers are probably field interlopers.

307 one-tenth of the target star in a $21.^{\circ}0$ radius. There
 308 were 192 stars that met these crowding require-
 309 ments, and that had TESS data available. For plot-
 310 ing purposes we then imposed a selection based
 311 on the strength of the signal itself: we required the
 312 Lomb Scargle power to exceed 0.2, and the period
 313 to be below 15 days.

314 The lower panel of Figure 3 shows the result-
 315 ing 145 stars. The majority of these stars fall be-
 316 low the “slow sequence” of the Pleiades, consistent
 317 with a gyrochronal age for the δ Lyr cluster below
 318 100 Myr. In fact, the rotation-color distributions
 319 of other 30 Myr to 50 Myr clusters (*e.g.*, IC 2602
 320 and IC 2391) are indistinguishable (Douglas et al.
 321 2021). Approximately 10 of the δ Lyr cluster stars
 322 appear as outliers above the “slow sequence”. As-
 323 suming that they are all false positives (*i.e.*, field
 324 interlopers), our rotation period detection fraction
 325 would be $135/192 \approx 70\%$. Although some of these
 326 outlier stars might be unresolved F+K binaries that
 327 are in the cluster (Stauffer et al. 2016), assuming
 328 that they are field contaminants provides a more
 329 secure lower bound of the rotation period detec-
 330 tion fraction. A final possible confounding factor
 331 – binarity – is known to affect the “fast sequence”
 332 of stars beneath the slow sequence (Meibom et al.
 333 2007; Gillen et al. 2020; Bouma et al. 2021). We
 334 do not expect it to change the central conclusion
 335 regarding the cluster’s age.

3. THE STARS

3.1. Kepler 1627A

3.1.1. Age

399 Based on the spatial and kinematic association of
 400 Kepler 1627 with the δ Lyr cluster, and the assump-
 401 tion that the planet formed shortly after the star, it
 402 seems likely that Kepler 1627 is the same age as
 403 the cluster. There are two consistency checks on
 404 whether this is true: rotation and lithium. Based
 405 on the Kepler light curve, the rotation period is
 406 2.642 ± 0.042 days, where the quoted uncertainty
 407 is based on the scatter in rotation periods measured
 408 from each individual Kepler quarter. This is consis-
 409 tent with comparable cluster members (Figure 3).

410 To infer the amount of Li I from the 6708 \AA dou-
 411 blet (*e.g.*, Soderblom et al. 2014), we acquired
 412 an iodine-free spectrum from Keck/HIRES on the
 413 night of 2021 March 26 using the standard setup
 414 and reduction techniques of the California Planet
 415 Survey (Howard et al. 2010). Following the equiv-
 416 alent width measurement procedure described by
 417 Bouma et al. (2021), we find $\text{EW}_{\text{Li}} = 233^{+5}_{-7} \text{ m\AA}$.
 418 This value does not correct for the Fe I blend
 419 at 6707.44\AA . Nonetheless, given the stellar effec-
 420 tive temperature (Table 1), this measurement is in
 421 agreement with expectations for a ≈ 40 Myr star
 422 (*e.g.*, as measured in IC 2602 by Randich et al.

363 2018). It is also larger than any lithium equivalent
 364 widths measured by Berger et al. (2018) in their
 365 analysis of 1,301 Kepler-star spectra.

3.1.2. Stellar Properties

366 The adopted stellar parameters are listed in Ta-
 367 ble 1. The stellar mass, radius, and effective
 368 temperature are found by interpolating against a
 369 38 Myr MIST isochrone (Choi et al. 2016). The
 370 statistical uncertainties are propagated from the
 371 absolute magnitude (mostly originating from the
 372 parallax uncertainty) and the color; the system-
 373 atic uncertainties are taken to be the difference
 374 between the PARSEC (Bressan et al. 2012) and
 375 MIST isochrones. Reported uncertainties are a
 376 quadrature sum of the statistical and systematic
 377 components. As a consistency check, we ana-
 378 lyzed the aforementioned Keck/HIRES spectrum
 379 from the night of 2021 March 26 using a com-
 380 bination of SpecMatch-Emp for stellar prop-
 381 erties, and SpecMatch-Synth for $v\sin i$ (Yee
 382 et al. 2017). This procedure yielded $T_{\text{eff}} = 5498 \pm$
 383 100 K , $\log g = 4.6 \pm 0.1$, $[\text{Fe}/\text{H}] = 0.15 \pm 0.10$ from
 384 SpecMatch-Emp, and $v\sin i = 18.9 \pm 1.0$ from
 385 SpecMatch-Synth. These values are within the
 386 $1-\sigma$ uncertainties of our adopted values from the
 387 isochrone interpolation.

3.2. Kepler 1627B

390 We first noted the presence of a close neighbor in
 391 the Kepler 1627 system on 2015 July 22 when we
 392 acquired adaptive optics imaging using the NIRC2
 393 imager on Keck-II. We used the narrow camera
 394 (FOV = $10.2''$) to obtain 8 images in the K' fil-
 395 ter ($\lambda = 2.12 \mu\text{m}$) with a total exposure time of
 396 160 s. We analyzed these data following Kraus
 397 et al. (2016), which entailed using PSF-fitting to
 398 measure the separation, position angle, and con-
 399 trast of the candidate companion. The best-fitting
 400 empirical PSF template was identified from among
 401 the near-contemporaneous observations of single
 402 stars in the same filter. The mean values inferred
 403 from the 8 images are reported in Table 1. To es-
 404 timate the detection limits, we analyzed the resid-
 405 uals after subtracting the empirical PSF template.
 406 Within each residual image, the flux was measured
 407 through 40 mas apertures centered on every pixel,
 408 and then the noise as a function of radius was esti-
 409 mated from the RMS within concentric rings. Fi-
 410 nally, the detection limits were estimated from the
 411 strehl-weighted sum of the detection significances
 412 in the image stack, and we adopted the $6-\sigma$ thresh-
 413 old as the detection limit for ruling out additional
 414 companions.

415 We also observed Kepler 1627 on Gemini-North
 416 using the ‘Alopeke speckle imager on 2021 June
 417 24. ‘Alopeke is a dual-channel speckle interfe-
 418 rometer that uses narrow-band filters centered at

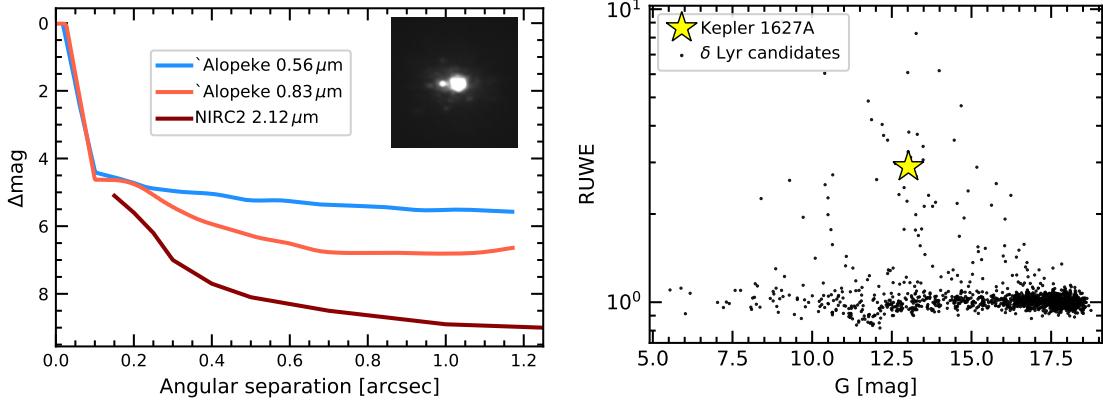


Figure 4. Kepler 1627 is a binary. *Left:* High-resolution imaging from Gemini-North/‘Alopeke and Keck/NIRC2 shows an \approx M3V companion at $\rho \approx 0.^{\prime\prime}16$, which corresponds to a projected separation of 53 ± 4 AU. The inset shows a cutout of the stacked NIRC2 image (North is up, East is left, scale is set by the separation of the binary). The lines show $5-\sigma$ contrast limits for the ‘Alopeke filters, and $6-\sigma$ contrast limits for NIRC2 outside of $0.^{\prime\prime}15$. *Right:* Gaia EDR3 renormalized unit weight error (RUWE) point estimates for candidate δ Lyr cluster members. Since other members of the cluster with similar brightnesses have comparable degrees of photometric variability, the high RUWE independently suggests that Kepler 1627 is a binary.

419 0.83 μm and 0.56 μm . We acquired three sets
 420 of 1000×60 msec exposures during good seeing
 421 ($0.45''$), and used the autocorrelation function of
 422 these images to reconstruct a single image and 5-
 423 σ detection limits (see Howell et al. 2011). This
 424 procedure yielded a detection of the companion in
 425 the 0.83 μm notch filter, but not the 0.56 μm filter.
 426 The measured projected separation and magnitude
 427 difference are given in Table 1.

428 Figure 4 summarizes the results of the high-
 429 resolution imaging. The Gaia EDR3 parallax for
 430 the primary implies a projected separation of $53 \pm$
 431 4 AU, assuming the companion is bound. Although
 432 the companion is unresolved in the Gaia source cat-
 433 alog (there are no comoving, codistant candidate
 434 companions brighter than $G < 20.5$ mag within
 435 $\rho < 120''$), its existence was also suggested by the
 436 primary star’s large RUWE relative to other mem-
 437 bers of the δ Lyr cluster (RUWE ≈ 2.9 ; roughly the
 438 98th percentile of the cluster’s distribution). Based
 439 on the apparent separation, the binary orbital pe-
 440 riod is of order hundreds of years. The large
 441 RUWE is therefore more likely to be caused by a
 442 PSF-mismatch skewing the Gaia centroiding dur-
 443 ing successive scans, rather than true astrometric
 444 motion. Regardless, given the low geometric prob-
 445 ability that a companion imaged at $\rho \approx 0.^{\prime\prime}16$ is a
 446 chance line-of-sight companion, we proceed under
 447 the assumption that the companion is bound, and
 448 that Kepler 1627 is a binary. Given the distance
 449 and age, the models of Baraffe et al. (2015) im-
 450 plify a companion mass of $M_B \approx 0.30 M_{\odot}$ and com-
 451 panion temperature of $T_{\text{eff},B} \approx 3408$ K. The corre-
 452 sponding spectral type is roughly M3V (Pecaut &
 453 Mamajek 2013). These models combined with the

454 NIRC2 contrast limits imply physical limits on ter-
 455 tiary companions of $M_{\text{ter}} < 50 M_{\text{Jup}}$ at $\rho = 50$ AU,
 456 $M_{\text{ter}} < 20 M_{\text{Jup}}$ at $\rho = 100$ AU, and $M_{\text{ter}} < 10 M_{\text{Jup}}$ at
 457 $\rho = 330$ AU.

4. THE PLANET

4.1. Kepler Light Curve

460 The Kepler space telescope observed Kepler 1627
 461 at a 30-minute cadence from 2009 May 2 until
 462 2013 April 8. Data gaps during quarters 4, 9, and
 463 13 led to an average duty cycle over the 3.9 year
 464 interval of 67%. Kepler 1627 was also observed
 465 at 1-minute cadence from 2012 Oct 5 until 2013
 466 Jan 11. The top panel of Figure 5 shows a por-
 467 tion of the 30-minute cadence PDCSAP light curve.
 468 Nonastrophysical variability has been removed us-
 469 ing the methods discussed by Smith et al. (2017);
 470 the default optimal aperture was assumed (Smith
 471 et al. 2016). Cadences with non-zero quality flags
 472 (9% of the data) have been omitted. The result-
 473 ing photometry is dominated by a quasi-periodic
 474 starspot signal with a peak-to-peak amplitude that
 475 varies between 2% and 8%. Given that the sec-
 476 ondary companion’s brightness in the Kepler band
 477 is $\approx 1.5\%$ that of the primary, source confusion for
 478 the rotation signal is not expected to be an issue.
 479 Previous analyses have identified and characterized
 480 the smaller transit signal (Tenenbaum et al. 2012;
 481 Thompson et al. 2018), validated its planetary na-
 482 ture (Morton et al. 2016), and even searched the
 483 system for transit timing variations (Holczer et al.
 484 2016). Nonetheless, since the cluster membership
 485 provides us with more precise stellar parameters
 486 than those previously available, we opted to reana-
 487 lyze the light curve.

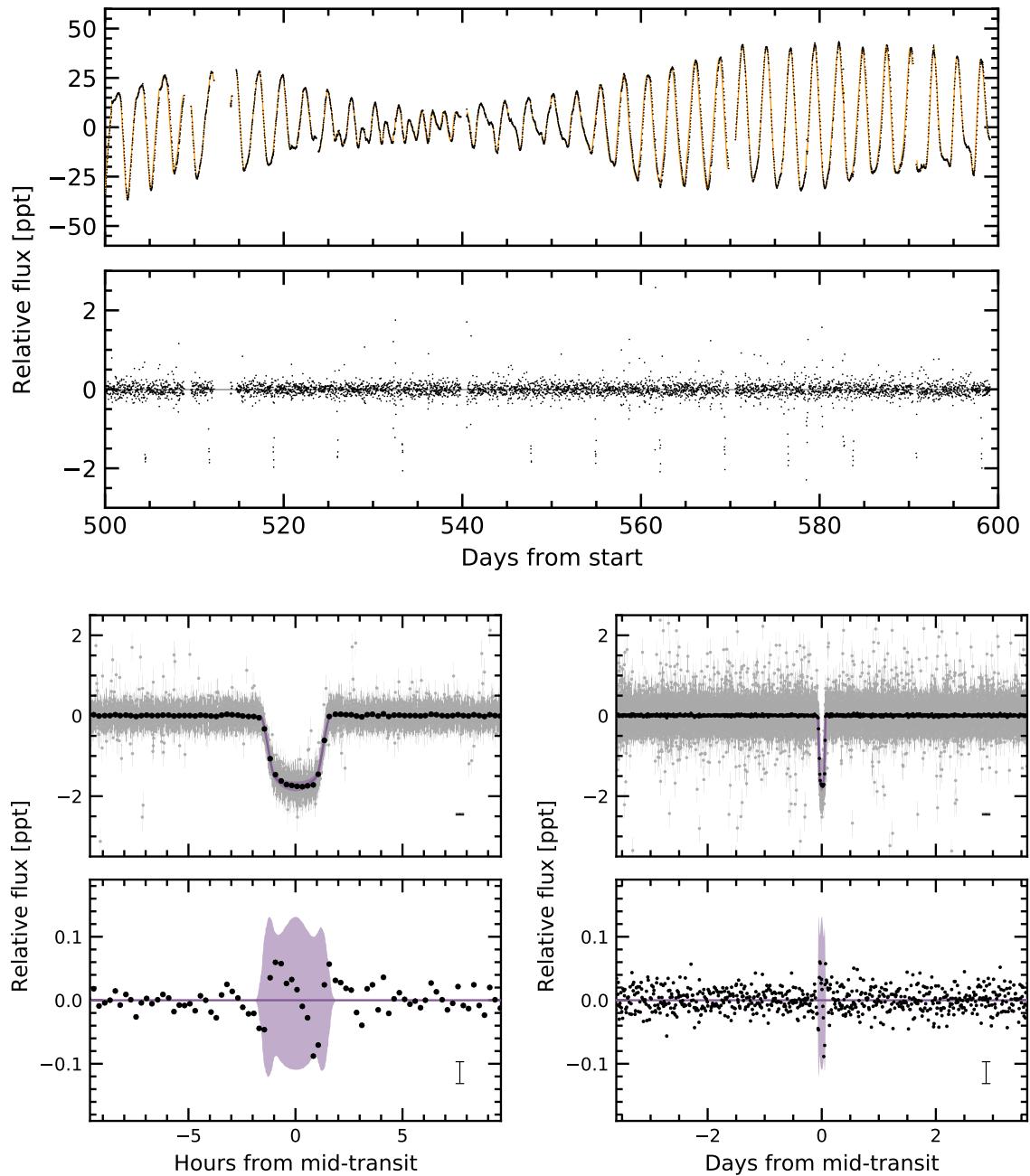


Figure 5. The light curve of Kepler 1627. *Top:* The Kepler data span 1,437 days (3.9 years), sampled at 30 minute cadence; a 100 day segment is shown. The top panel shows the PDCSAP median-subtracted flux in units of parts-per-thousand ($\times 10^{-3}$). The dominant signal is induced by starspots. The stellar variability model (orange line) is subtracted below, revealing the transits of Kepler 1627Ab. The online Figure Set spans the entire 3.9 years of observations. *Bottom:* Phase-folded transit of Kepler 1627Ab with stellar variability removed. Windows over 20 hours (*left*) and the entire orbit (*right*) are shown, and the residual after subtracting the transit is in the bottom-most row. The 2- σ model uncertainties and the best-fit model are the light purple band and the dark purple line. Gray points are individual flux measurements; black points bin these to 15 minute intervals, and have a representative 1- σ error bar in the lower right of each panel. The asymmetric residual during transit is larger than the out-of-transit scatter.

488 **4.1.1. Transit and Stellar Variability Model**

489 We fitted the Kepler long cadence time series with a model that simultaneously included
 490 the planetary transit and the stellar variability. The stellar variability was modeled with
 491 the RotationTerm Gaussian Process kernel in exoplanet (Foreman-Mackey et al. 2020). This
 492 kernel assumes that the variability is generated by
 493 a mixture of two damped simple harmonic oscillators with characteristic frequencies set by $1/P_{\text{rot}}$
 494 and its first harmonic. We additionally included a jitter term to inflate the flux uncertainties in a manner that accounted for otherwise unmodeled excess
 495 white noise, and let the eccentricity float. For the limb-darkening, we assumed a quadratic law, and
 496 sampled using the uninformative prior suggested
 497 by Kipping (2013).

500 Our model therefore included 10 free parameters for the transit ($\{P, t_0, \delta, b, u_1, u_2, R_*, \log g, e, \omega\}$), 2 free parameters for the light curve normalization and a white noise jitter ($\{\langle f \rangle, \sigma_f\}$), and 5 hyperparameters for the GP ($\{\sigma_{\text{rot}}, P_{\text{rot}}, Q_0, dQ, f\}$). We also considered including an additive SHOTerm kernel to account for stochastic noise, but found that this did not affect the results, and so opted for the simpler GP kernel. We fitted the models using PyMC3 (Salvatier et al. 2016; Theano Development Team 2016), and accounted for the finite integration time of each exposure in the numerical integration when evaluating the model light curve (see Kipping 2010). We assumed a Gaussian likelihood, and after initializing each model with the parameters of the maximum *a posteriori* model, we sampled using PyMC3’s gradient-based No-U-Turn Sampler (Hoffman & Gelman 2014) in the bases indicated in Table 2. We used \hat{R} as our convergence diagnostic (Gelman & Rubin 1992).

505 Figure 5 shows the resulting best-fit model in orange (top) and purple (bottom). The model parameters and their uncertainties, given in Table 2, are broadly consistent with a Neptune-sized planet ($3.82 \pm 0.16 R_\oplus$) on a close-in circular⁴ orbit around a G8V host star ($0.88 \pm 0.02 R_\odot$). This best-fit planet size is consistent with those previously reported by Morton et al. (2016) and Berger et al. (2018), and corrects for the small amount of flux dilution from Kepler 1627B.

535 **4.1.2. Transit Asymmetry**

536 The transit fit however is not perfect: the lower panels of Figure 5 show an asymmetric residual in
 537 the data relative to the model: the measured flux
 538 is high during the first half of transit, and low in
 539

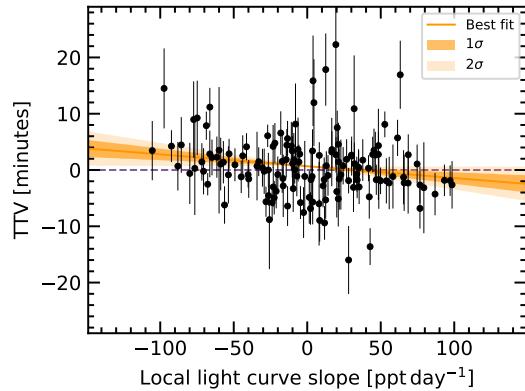


Figure 6. Weak evidence for a prograde orbit of Kepler 1627 Ab. The time of each Kepler transit was measured, along with the local slope of the light curve. The two quantities might be anti-correlated ($\approx 2\sigma$), which could be caused by starspot crossings during the first (second) half of transit inducing a positive (negative) TTV, provided that the orbit is prograde (Mazeh et al. 2015). The units along the abscissa can be understood by considering that the stellar flux changes by ~ 60 ppt per half rotation period (~ 1.3 days).

540 the second half. The semi-amplitude of this deviation is ≈ 50 ppm, which represents a $\approx 3\%$ distortion of the transit depth ($\delta = 1759 \pm 62$ ppm). Note that although this asymmetry is within the 2σ model uncertainties, the model has a jitter term that grows to account for excess white noise in the flux. The significance of the asymmetry is therefore best assessed in comparison against the intrinsic out-of-transit scatter in the data (≈ 16 ppm), not the model uncertainties. The lower right panel of Figure 5 demonstrates that the scatter during transit is higher than during all other phases of the planet’s orbit.

545 To determine whether the asymmetry could be a systematic caused by our stellar variability model, we explored an alternative approach in which we isolated each transit window, locally fitted out polynomial trends, and then binned all the observed transits; the asymmetry was still present at a comparable amplitude. Appendix B describes a more detailed analysis, which finds that the asymmetry also seems to be robust to different methods of data binning in time and by local light curve slope. Possible astrophysical explanations are discussed in Section 5.

565 **4.1.3. Transit Timing and the Local Slope**

566 The previous analysis by Holczer et al. (2016)
 567 did not find any significant long-term transit timing or duration variations (TTVs or TDVs) for
 568 Kepler 1627. Quantitatively, the mean and standard deviation of the TTVs and TDVs they mea-

⁴ Our transit fitting yields $e < 0.48$ at 2σ ; the constraints on the eccentricity are not particularly strong.

sured were -1.1 ± 13.8 min and -3.3 ± 22.1 min. In an earlier analysis however, Holczer et al. (2015) studied correlations between TTVs and local light curve slopes, and for Kepler 1627 found a weak correlation of -29 ± 13 min day $^{-1}$ between the two quantities. Given the possible connection between such correlations and the unresolved starspot crossings that we expect to be present in the Kepler 1627 light curve (Mazeh et al. 2015), we opted to re-examine the individual transit times.

We therefore isolated each of the 144 observed transits to within ± 4.5 hr of each transit, and fitted each window with both *i*) a local second or fourth-order polynomial baseline plus the transit, and *ii*) a local linear trend plus the transit. We let the mid-time of each transit float, and then calculated the residual between the measured mid-time and that of a periodic orbit. This residual, the transit timing variation, is plotted in Figure 6 against the local linear slope for the fourth-order polynomial baseline. The slope of -21 ± 10 min day $^{-1}$ is similar to that found by Holczer et al. (2015). The best-fit line yields $\chi^2 = 306.1$, with $n = 140$ data points. An alternative model of just a flat line yields $\chi^2 = 315.6$. The difference in the Bayesian information criterion between the two models is $BIC_{\text{flat}} - BIC_{\text{line}} = 4.5$, which corresponds to a Bayes factor of ≈ 9.4 . According to the usual Kass & Raftery (1995) criteria, this is “positive” evidence for the model with a finite slope. We view it as suggestive evidence at best, particularly given the excess scatter in the transit timing measurement uncertainties.

A separate concern we had in this analysis was whether our transit fitting procedure might induce spurious correlations between the slope and transit time. In particular, using the second-order polynomial baseline yielded a larger anti-correlation between the TTVs and local slopes, of -79 ± 14 min day $^{-1}$. We therefore performed an injection-recovery procedure in which we injected transits at different phases in the Kepler 1627 light curve and repeated the TTV analysis. This was done at ≈ 50 phases, each separated by $0.02 P_{\text{orb}}$ while omitting the phases in transit. For the second-order polynomial baseline, this procedure yielded a similar anti-correlation in the injected transits as that present in the real transit; using this baseline would therefore bias the result. However for the fourth-order baseline, the correlation present in the data was stronger than in all but one of the injected transits. Possible interpretations are discussed below. Given the lack of statistical significance, this analysis should be interpreted as suggestive at best.

4.2. Planet Confirmation

If the Kepler 1627Ab transit signal is created by a genuine planet, then to our knowledge it would be the youngest planet yet found by the prime Ke-

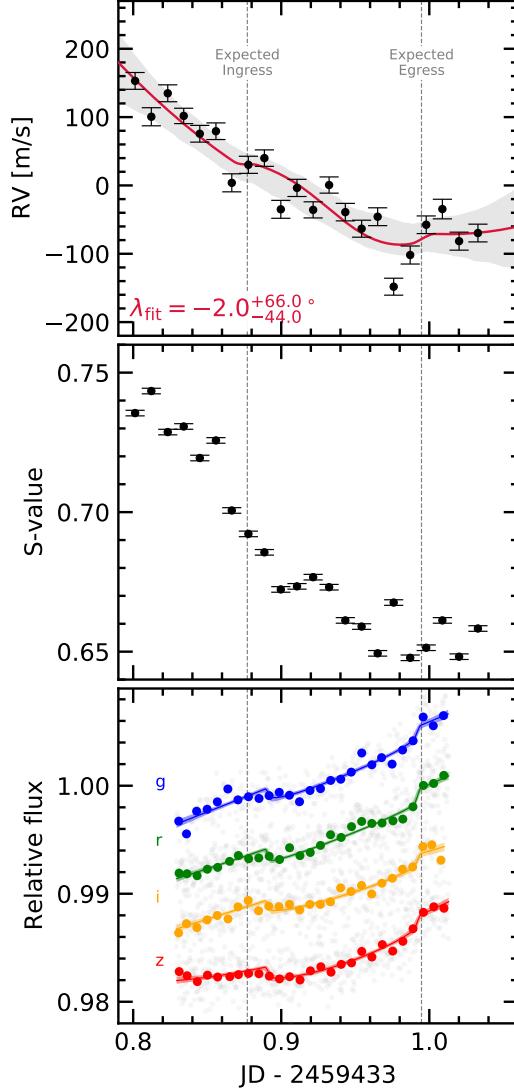


Figure 7. Keck/HIRES radial velocities and MuSCAT3 photometry from the transit of 2021 Aug 7. Top: The radial velocity jitter across the 15 minute exposures ($\sigma_{\text{RV}} \approx 30$ m s $^{-1}$) prevented us from detecting the RM effect; a model including the RM anomaly and a quadratic trend in time to fit the spot-induced ≈ 250 m s $^{-1}$ trend is shown (see Appendix C). Shaded bands show 2- σ model uncertainties. Middle: The RV variations are strongly correlated with varying emission in the Ca H and K lines. Bottom: The photometric transit depths are consistent across the *griz* bandpasses. The photometry is binned at 10 minute intervals.

pler mission.⁵ Could the transit be produced by anything other than a planet orbiting this near-

⁵ The re-purposed K2 mission however has found two younger systems containing five planets: K2-33b (9 ± 1 Myr; Mann et al. 2016; David et al. 2016) and V1298 Tau (23 ± 4 Myr; David et al. 2019).

solar analog? Morton et al. (2016) validated the planet based on the transit shape, arguing that the most probable false positive scenario was that of a background eclipsing binary, which had a model-dependent probability of $\approx 10^{-5}$. However, this calculation was performed without knowledge of the low-mass stellar companion ($M_B \approx 0.33 M_\odot$). Validated planets have also previously been refuted (e.g., Shporer et al. 2017). We therefore reassessed false positive scenarios in some detail.

As an initial plausibility check, Kepler 1627B contributes 1% to 2% of the total flux observed in the Kepler aperture. For the sake of argument, assume the former value. The observed transit has a depth of $\approx 0.18\%$. A 18% deep eclipse of Kepler 1627B would therefore be needed to produce a signal with the appropriate depth. The shape of the transit signal however requires the impact parameter to be below 0.77 (2- σ); the tertiary transiting the secondary would therefore need to be non-grazing with $R_3/R_2 \approx 0.4$. This yields a contradiction: this scenario requires an ingress and egress phase that each span $\approx 40\%$ of the transit duration (≈ 68 min). The actual measured ingress and egress duration is ≈ 17 min, a factor of four times too short. The combination of Kepler 1627B’s brightness, the transit depth, and the ingress duration therefore disfavor the scenario that Kepler 1627B might host the transit signal.

Beyond this simple test, a line of evidence that effectively confirms the planetary interpretation is that the stellar density implied by the transit duration and orbital period is inconsistent with an eclipsing body around the M-dwarf companion. We find $\rho_* = 2.00 \pm 0.24 \text{ g cm}^{-3}$, while the theoretically expected density for Kepler 1627B given its nominal age of 38 Myr and mass of $0.30 M_\odot$ is $\approx 4.6 \text{ g cm}^{-3}$ (Baraffe et al. 2015). The transit duration is therefore too long to be explained by a star eclipsing the M dwarf secondary at 10- σ . Adversarially assuming a younger age (32 Myr) and a larger companion mass ($0.35 M_\odot$), the companion’s density could be as low as $\approx 3.5 \text{ g cm}^{-3}$. This is still in tension with the data. While the planet might hypothetically still orbit a hidden close and bright companion, this possibility is implausible given *i*) the lack of secondary lines in the HIRES spectra, *ii*) the lack of secondary rotation signals in the Kepler photometry, and *iii*) the proximity of Kepler 1627 to the δ Lyr cluster locus on the Gaia CAMD (Figure 3).

The correlation noted in Section 4.1.3 between the TTVs and the local light curve slope might be an additional line of evidence in support of the planetary interpretation. Unless it is a statistical fluke (a $\approx 5\%$ possibility), then the most likely cause of the correlation is unresolved starspot

crossings (Mazeh et al. 2015). These would only be possible if the planet transits the primary star, which excludes a background eclipsing binary scenario. The correlation would also suggest that the planet’s orbit is prograde. The latter point assumes that the dominant photometric variability is induced by dark spots, and not bright faculae. Given the observed transition of Sun-like stellar variability from spot to faculae-dominated regimes between young and old ages, we expect this latter assumption to be reasonably secure (Shapiro et al. 2016; Montet et al. 2017; Reinhold & Hekker 2020).

A third supporting line of evidence for the planetary interpretation also exists. We observed a transit of Kepler 1627Ab on the night of 2021 Aug 7 spectroscopically with HIRES at the Keck-I telescope and photometrically in *griz* bands with MuSCAT3 at Haleakalā Observatory. Details of the observation sequence are discussed in Appendix C; Figure 7 shows the results. Although we did not detect the Rossiter-McLaughlin (RM) anomaly, the multi-band MuSCAT3 light curves show that the transit is achromatic. Quantitatively, when we fitted the MuSCAT3 photometry with a model that lets the transit depths vary across each bandpass, we found *griz* depths consistent with the Kepler depth at 0.6, 0.3, 0.3, and 1.1- σ respectively. The achromatic transits strongly favor Kepler 1627A as the transit host, since Kepler 1627B is a much redder star. Conditioned on the ephemeris and transit depth from the Kepler data, the MuSCAT3 observations also suggested a transit duration 17.3 ± 4.3 min shorter than the Kepler transits. However, given both the lack of TDVs in the Kepler data and the relatively low signal-to-noise of the MuSCAT3 transit, further photometric follow-up would be necessary to determine whether the transit duration is actually changing.

For our RM analysis, the details are discussed in Appendix C. While the velocities are marginally more consistent with a prograde or polar orbit than a retrograde orbit, the spot-corrected exposure-to-exposure scatter ($\sigma_{RV} \approx 30 \text{ m s}^{-1}$) is comparable to the expected RM anomaly assuming an aligned orbit ($\Delta v_{RM} \approx 20 \text{ m s}^{-1}$). We are therefore not in a position to claim a spectroscopic detection of the RM effect, nor to quantify the stellar obliquity.

5. DISCUSSION & CONCLUSIONS

Kepler 1627Ab provides a new extremum in the ages of the Kepler planets, and opens multiple avenues for further study. Observations of spectroscopic transits at greater signal-to-noise should yield a measurement of the stellar obliquity, which would confirm or refute the prograde orbital geometry suggested by the TTV-local slope correlation. Separately, transit spectroscopy aimed at

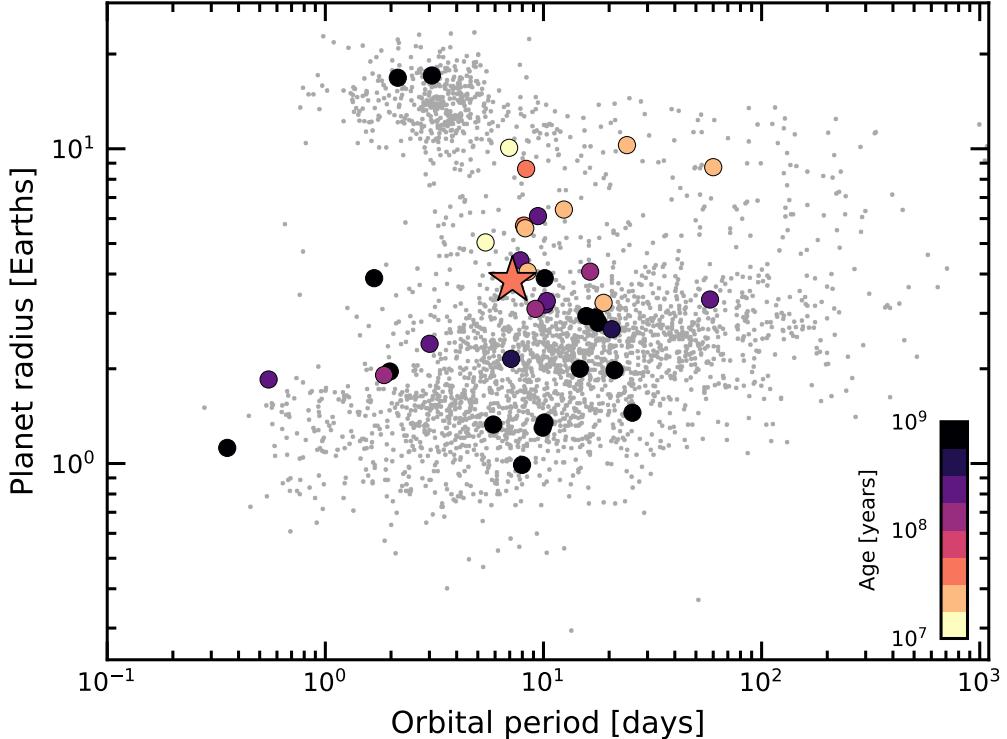


Figure 8. Radii, orbital periods, and ages of transiting exoplanets. Planets younger than a gigayear with $\tau/\sigma_\tau > 3$ are emphasized, where τ is the age and σ_τ is its uncertainty. Kepler 1627Ab is shown with a star. The large sizes of the youngest transiting planets could be explained by their primordial atmospheres not yet having evaporated; direct measurements of the atmospheric outflows or planetary masses would help to confirm this expectation. Selection effects may also be important. Parameters are from the NASA Exoplanet Archive (2021 Sept 15).

detecting atmospheric outflows could yield insight into the evolutionary state of the atmosphere (e.g., Ehrenreich et al. 2015; Spake et al. 2018; Vissapragada et al. 2020). Observations that quantify the amount of high-energy irradiation incident on the planet would complement these efforts, by helping to clarify the expected outflow rate (e.g., Poppenhaeger et al. 2021). Finally, a challenging but informative quantity to measure would be the planet’s mass. Measured at sufficient precision, for instance through a multi-wavelength radial velocity campaign, the combination of the size, mass, and age would yield constraints on both the planet’s composition and its initial entropy (Owen 2020).

More immediately, the Kepler data may yet contain additional information. For instance, one possible explanation for the transit asymmetry shown in Figure 5 is that of a dusty asymmetric outflow. Dusty outflows are theoretically expected for young mini-Neptunes, and the amplitude of the observed asymmetry is consistent with predictions (Wang & Dai 2019). A second possibility is that the planetary orbit is slightly misaligned from the stellar spin axis, and tends to transit starspot groups at favored stellar latitudes. This geometry would be necessary in order to explain how the starspot

crossings could add up coherently, given that the planetary orbital period (7.203 days) and the stellar rotation period (2.642 days) are not a rational combination. Other possibilities including gravity darkening or TTVs causing the asymmetry are disfavored (see Appendix B).

Beyond the asymmetric transits, Appendix D highlights an additional abnormality in the short-cadence Kepler data, in the arrival time distribution of stellar flares. We encourage its exploration by investigators more versed in the topic than ourselves.

In the context of the transiting planet population, Kepler 1627Ab is among the youngest known (Figure 8). Comparable systems with precise ages include K2-33 (Mann et al. 2016; David et al. 2016), DS Tuc (Benatti et al. 2019; Newton et al. 2019), HIP 67522 (Rizzuto et al. 2020), TOI 837 (Bouma et al. 2020), the two-planet AU Mic (Plavchan et al. 2020; Martioli et al. 2021) and the four-planet V1298 Tau (David et al. 2019). Kepler 1627Ab is one of the smaller planets in this sample ($3.82 \pm 0.16 R_\oplus$), which could be linked to the selection effects imposed by spot-induced photometric variability at very young ages (e.g., Zhou et al. 2021). However, it seems that smaller planets could have

been detected: based on the per-target detection contours, the Kepler pipeline’s median completeness extended to $1.6 R_{\oplus}$ at 10 day orbital periods, and $3.3 R_{\oplus}$ at 100 days (Burke & Catanzarite 2021). These limits account for the spot-induced variability in the system through a correction based on the Combined Differential Photometric Precision (CDPP) in the Kepler 1627 light curve over the relevant transit timescales (Burke & Catanzarite 2017). The large size of Kepler 1627Ab relative to most Kepler mini-Neptunes might therefore support a picture in which the typical $5 M_{\oplus}$ mini-Neptune (Wu 2019) loses a significant fraction of its primordial atmosphere over its first gigayear (Owen & Wu 2013; Ginzburg et al. 2018). It could also be consistent with a scenario in which an earlier “boil-off” of the planet’s atmosphere during disk dispersal decreases the entropy of the planetary interior, leading to a $\sim 10^8$ year Kelvin-Helmholtz cooling and contraction timescale (Owen 2020). Confirming either of these scenarios would require a measurement of the planetary mass; otherwise, alternative explanations for its large size also include that it is abnormally massive, or that it has an abnormally large envelope to core mass ratio.

Ultimately, the main advance of this work is a precise measurement of the age of Kepler 1627Ab. This measurement was enabled by identifying the connection of the star to the δ Lyr cluster using Gaia kinematics, and by then using the Gaia color-absolute magnitude diagram and TESS stellar rotation periods to verify the cluster’s existence. Table 3 enables similar cross-matches for both known and forthcoming exoplanet systems (*e.g.*, Guerrero et al. 2021). Confirming these candidate associations using independent age indicators is essential because their false positive rates are not known. A related path is to identify new kinematic associations around known exoplanet host stars using positions and tangential velocities from Gaia, and to verify these associations with stellar rotation periods and spectroscopy (*e.g.*, Tofflemire et al. 2021). Each approach seems likely to expand the census of planets with precisely measured ages over the coming years, which will help in deciphering the early stages of exoplanet evolution.

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Software: `altaipony` (Ilin et al. 2021), `astrobase` (Bhatti et al. 2018), `astropy` (Astropy Collaboration et al. 2018), `astroquery` (Ginsburg et al. 2018), `corner` (Foreman-Mackey 2016), `exoplanet` (Foreman-Mackey et al. 2020), and its dependencies (Agol et al. 2020; Kip-

ping 2013; Luger et al. 2019; Theano Development Team 2016), `PyMC3` (Salvatier et al. 2016), `scipy` (Jones et al. 2001), `TESS-point` (Burke et al. 2020), `wotan` (Hippke et al. 2019).

Facilities: *Astrometry:* Gaia (Gaia Collaboration et al. 2018b, 2021a). *Imaging:* Second Generation Digitized Sky Survey. Keck:II (NIRC2; www2.keck.hawaii.edu/inst/nirc2). Gemini:North ('Alopeke; Scott et al. 2018, 2021). *Spectroscopy:* Keck:I (HIRES; Vogt et al. 1994). *Photometry:* Kepler (Borucki et al. 2010), MuSCAT3 (Narita et al. 2020), TESS (Ricker et al. 2015).

Table 1. Literature and Measured Properties for Kepler 1627

Primary Star			
TIC 120105470 GAIADR2 [†] 2103737241426734336			
Parameter	Description	Value	Source
$\alpha_{J2015.5}$	Right Ascension (hh:mm:ss)	18:56:13.6	1
$\delta_{J2015.5}$	Declination (dd:mm:ss)	+41:34:36.22	1
V	Johnson V mag.	13.11 \pm 0.08	2
G	Gaia G mag.	13.02 \pm 0.02	1
G_{BP}	Gaia BP mag.	13.43 \pm 0.02	1
G_{RP}	Gaia RP mag.	12.44 \pm 0.02	1
T	TESS T mag.	12.53 \pm 0.02	2
J	2MASS J mag.	11.69 \pm 0.02	3
H	2MASS H mag.	11.30 \pm 0.02	3
K _S	2MASS K _S mag.	11.19 \pm 0.02	3
π	Gaia EDR3 parallax (mas)	3.009 \pm 0.032	1
d	Distance (pc)	329.5 \pm 3.5	1, 4
μ_α	Gaia EDR3 proper motion	1.716 \pm 0.034	1
	in RA (mas yr ⁻¹)		
μ_δ	Gaia EDR3 proper motion	-1.315 \pm 0.034	1
	in DEC (mas yr ⁻¹)		
RUWE	Gaia EDR3 renormalized	2.899	1
	unit weight error		
RV	Systemic radial velocity (km s ⁻¹)	-16.7 \pm 1.0	5
Spec. Type	Spectral Type	G8V	5
$v \sin i_*$	Rotational velocity* (km s ⁻¹)	18.9 \pm 1.0	5
Li EW	6708Å Equiv. Width (mÅ)	235 ⁺⁵ ₋₇	5
T_{eff}	Effective Temperature (K)	5505 \pm 60	6
$\log g_*$	Surface Gravity (cgs)	4.53 \pm 0.05	6
R_*	Stellar radius (R_\odot)	0.881 \pm 0.018	6
M_*	Stellar mass (R_\odot)	0.953 \pm 0.019	6
Av	Interstellar reddening (mag)	0.2 \pm 0.1	6
[Fe/H]	Metallicity	0.1 \pm 0.1	6
P_{rot}	Rotation period (d)	2.642 \pm 0.042	7
Age	Adopted stellar age (Myr)	38 ⁺⁶ ₋₅	8
Δm_{832}	Mag difference ('Alopeke 832 nm)	3.14 \pm 0.15	9
θ_B	Position angle (deg)	92 \pm 1	9
ρ_B	Apparent separation of	0.164 \pm 0.002	9
	primary and secondary (as)		
ρ_B	Apparent separation of	53 \pm 4	1, 4, 9
	primary and secondary (AU)		
$\Delta m_{K'}$	Mag difference (NIR2 K')	2.37 \pm 0.02	10
θ_B	Position angle (deg)	95.9 \pm 0.5	10
ρ_B	Apparent separation of	0.1739 \pm 0.0010	10
	primary and secondary (as)		

NOTE—[†] The GAIADR2 and GAIAEDR3 identifiers for Kepler 1627A are identical. The secondary is not resolved in the Gaia point source catalog. * Given only $v \sin i$ and $2\pi R_*/P_{\text{rot}}$, $\cos i = 0.11^{+0.11}_{-0.08}$. Provenances are: ¹Gaia Collaboration et al. (2021a), ²Stassun et al. (2019), ³Skrutskie et al. (2006), ⁴Lindgren et al. (2021), ⁵HIPER spectra and Yee et al. (2017), ⁶Cluster isochrone (MIST adopted; PARSEC compared for quoted uncertainty), ⁷Kepler light curve, ⁸Pre-main-sequence CAMD interpolation (Section 2.2.1), ⁹'Alopeke imaging 2021 June 24 (Scott et al. 2021), ¹⁰NIRC2 imaging 2015 July 22, using the Yelda et al. (2010) optical distortion solution to convert pixel-space relative positions to on-sky relative astrometry. The “discrepancy” between the two imaging epochs likely indicates orbital motion.

Table 2. Priors and Posteriors for Model Fitted to the Long Cadence Kepler 1627Ab Light Curve.

Param.	Unit	Prior	Median	Mean	Std. Dev.	3%	97%	ESS	$\hat{R} - 1$
<i>Sampled</i>									
P	d	$\mathcal{N}(7.20281; 0.01000)$	7.2028038	7.2028038	0.0000073	7.2027895	7.2028168	7464	3.9e-04
$t_0^{(1)}$	d	$\mathcal{N}(120.79053; 0.02000)$	120.7904317	120.7904254	0.0009570	120.7886377	120.7921911	3880	2.0e-03
$\log \delta$	–	$\mathcal{N}(-6.3200; 2.0000)$	-6.3430	-6.3434	0.0354	-6.4094	-6.2767	6457	3.0e-04
$b^{(2)}$	–	$\mathcal{U}(0.000; 1.000)$	0.4669	0.4442	0.2025	0.0662	0.8133	1154	1.6e-03
u_1	–	Kipping (2013)	0.271	0.294	0.190	0.000	0.628	3604	1.5e-03
u_2	–	Kipping (2013)	0.414	0.377	0.326	-0.240	0.902	3209	1.4e-03
R_*	R_{\odot}	$\mathcal{N}(0.881; 0.018)$	0.881	0.881	0.018	0.847	0.915	8977	3.1e-04
$\log g$	cgs	$\mathcal{N}(4.530; 0.050)$	4.532	4.533	0.051	4.435	4.627	6844	1.6e-03
$\langle f \rangle$	–	$\mathcal{N}(0.000; 0.100)$	-0.0003	-0.0003	0.0001	-0.0005	-0.0000	8328	1.1e-03
$e^{(3)}$	–	Van Eylen et al. (2019)	0.154	0.186	0.152	0.000	0.459	1867	2.0e-03
ω	rad	$\mathcal{U}(0.000; 6.283)$	0.055	0.029	1.845	-3.139	2.850	3557	8.6e-05
$\log \sigma_f$	–	$\mathcal{N}(\log \langle \sigma_f \rangle; 2.000)$	-8.035	-8.035	0.008	-8.049	-8.021	9590	3.9e-04
σ_{rot}	d^{-1}	InvGamma(1.000; 5.000)	0.070	0.070	0.001	0.068	0.072	9419	1.4e-03
$\log P_{\text{rot}}$	log(d)	$\mathcal{N}(0.958; 0.020)$	0.978	0.978	0.001	0.975	0.980	8320	2.2e-04
$\log Q_0$	–	$\mathcal{N}(0.000; 2.000)$	-0.327	-0.326	0.043	-0.407	-0.246	9659	2.7e-04
$\log dQ$	–	$\mathcal{N}(0.000; 2.000)$	7.697	7.698	0.103	7.511	7.899	5824	3.7e-04
f	–	$\mathcal{U}(0.010; 1.000)$	0.01006	0.01009	0.00009	0.01000	0.01025	4645	4.0e-04
<i>Derived</i>									
δ	–	–	0.001759	0.001759	0.000062	0.001641	0.001875	6457	3.0e-04
R_p/R_*	–	–	0.039	0.039	0.001	0.037	0.042	1811	1.1e-03
ρ_*	g cm^{-3}	–	1.990	2.004	0.240	1.570	2.461	6905	2.1e-03
$R_p^{(4)}$	R_{Jup}	–	0.337	0.338	0.014	0.314	0.367	2311	1.0e-03
$R_p^{(4)}$	R_{Earth}	–	3.777	3.789	0.157	3.52	4.114	2311	1.0e-03
a/R_*	–	–	17.606	17.619	0.702	16.277	18.906	6905	2.1e-03
$\cos i$	–	–	0.027	0.025	0.010	0.004	0.040	1312	1.2e-03
T_{14}	hr	–	2.841	2.843	0.060	2.734	2.958	3199	3.6e-04
T_{13}	hr	–	2.555	2.539	0.094	2.360	2.692	1960	1.4e-03

NOTE— ESS refers to the number of effective samples. \hat{R} is the Gelman-Rubin convergence diagnostic. Logarithms in this table are base-e. \mathcal{U} denotes a uniform distribution, and \mathcal{N} a normal distribution. (1) The ephemeris is in units of BJDTDB - 2454833. (2) Although $\mathcal{U}(0, 1 + R_p/R_*)$ is formally correct, for this model we assumed a non-grazing transit to enable sampling in $\log \delta$. (3) The eccentricity vectors are sampled in the $(e \cos \omega, e \sin \omega)$ plane. (4) The true planet size is a factor of $((F_1 + F_2)/F_1)^{1/2}$ larger than that from the fit because of dilution from Kepler 1627B, where F_1 is the flux from the primary, and F_2 is that from the secondary; the mean and standard deviation of $R_p = 3.817 \pm 0.158 R_{\oplus}$ quoted in the text includes this correction, assuming $(F_1 + F_2)/F_1 \approx 1.015$.

Table 3. Young, Age-dated, and Age-dateable Stars Within the Nearest Few Kiloparsecs.

Parameter	Example Value	Description
source_id	1709456705329541504	Gaia DR2 source identifier.
ra	247.826	Gaia DR2 right ascension [deg].
dec	79.789	Gaia DR2 declination [deg].
parallax	35.345	Gaia DR2 parallax [mas].
parallax_error	0.028	Gaia DR2 parallax uncertainty [mas].
pmra	94.884	Gaia DR2 proper motion $\mu_{\alpha} \cos \delta$ [mas yr $^{-1}$].
pmdec	-86.971	Gaia DR2 proper motion μ_{δ} [mas yr $^{-1}$].
phot_g_mean_mag	6.85	Gaia DR2 G magnitude.
phot_bp_mean_mag	6.409	Gaia DR2 G_{BP} magnitude.
phot_rp_mean_mag	7.189	Gaia DR2 G_{RP} magnitude.
cluster	NASAExoArchive_ps_20210506.Uma,IR_excess	Comma-separated cluster or group name.
age	9.48,nan,nan	Comma-separated logarithm (base-10) of reported ^a age in years.
mean_age	9.48	Mean (ignoring NaNs) of age column.
reference_id	NASAExoArchive_ps_20210506.Ujjwal2020,CottenSong2016	Comma-separated provenance of group membership.
reference_bibcode	2013PASP..125..989A,2020AJ....159..166U,2016ApJS..225..15C	ADS bibcode corresponding to reference_id.

NOTE— Table 3 is published in its entirety in a machine-readable format. This table is a concatenation of the studies listed in Table 4. One entry is shown for guidance regarding form and content. In this particular example, the star has a cold Jupiter on a 16 year orbit, HD 150706b (Boisse et al. 2012). An infrared excess has been reported (Cotten & Song 2016), and the star was identified by Ujjwal et al. (2020) as a candidate UMa moving group member (≈ 400 Myr; Mann et al. 2020). The star's RV activity and TESS rotation period corroborate its youth.

Table 4. Provenances of Young and Age-dateable Stars.

Reference	N_{Gaia}	N_{Age}	$N_{G_{\text{RP}} < 16}$
Kounkel et al. (2020)	987376	987376	775363
Cantat-Gaudin & Anders (2020)	433669	412671	269566
Cantat-Gaudin et al. (2018)	399654	381837	246067
Kounkel & Covey (2019)	288370	288370	229506
Cantat-Gaudin et al. (2020)	233369	227370	183974
Zari et al. (2018) UMS	86102	0	86102
Wenger et al. (2000) Y*?	61432	0	45076
Zari et al. (2018) PMS	43719	0	38435
Gaia Collaboration et al. (2018a) $d > 250 \text{ pc}$	35506	31182	18830
Castro-Ginard et al. (2020)	33635	24834	31662
Kerr et al. (2021)	30518	25324	27307
Wenger et al. (2000) Y*○	28406	0	16205
Villa Vélez et al. (2018)	14459	14459	13866
Cantat-Gaudin et al. (2019)	11843	11843	9246
Damiani et al. (2019) PMS	10839	10839	9901
Oh et al. (2017)	10379	0	10370
Meingast et al. (2021)	7925	7925	5878
Wenger et al. (2000) pMS*	5901	0	3006
Gaia Collaboration et al. (2018a) $d < 250 \text{ pc}$	5378	817	3968
Kounkel et al. (2018)	5207	3740	5207
Ratzenböck et al. (2020)	4269	4269	2662
Wenger et al. (2000) TT*	4022	0	3344
Damiani et al. (2019) UMS	3598	3598	3598
Rizzuto et al. (2017)	3294	3294	2757
Akeson et al. (2013)	3107	868	3098
Tian (2020)	1989	1989	1394
Goldman et al. (2018)	1844	1844	1783
Cotten & Song (2016)	1695	0	1693
Gagné et al. (2018b)	1429	0	1389
Röser & Schilbach (2020) Psc-Eri	1387	1387	1107
Röser & Schilbach (2020) Pleiades	1245	1245	1019
Wenger et al. (2000) TT?	1198	0	853
Gagné & Faherty (2018)	914	0	913
Pavlidou et al. (2021)	913	913	504
Gagné et al. (2018a)	692	0	692
Ujjwal et al. (2020)	563	0	563
Gagné et al. (2020)	566	566	351
Esplin & Luhman (2019)	377	443	296
Roccatagliata et al. (2020)	283	283	232
Meingast & Alves (2019)	238	238	238
Fürnkranz et al. (2019) Coma-Ber	214	214	213
Fürnkranz et al. (2019) Neighbor Group	177	177	167
Kraus et al. (2014)	145	145	145

NOTE— Table 4 describes the provenances for the young and age-dateable stars in Table 3. N_{Gaia} : number of Gaia stars we parsed from the literature source. N_{Age} : number of stars in the literature source with ages reported. $N_{G_{\text{RP}} < 16}$: number of Gaia stars we parsed from the literature source with either $G_{\text{RP}} < 16$, or a parallax S/N exceeding 5 and a distance closer than 100 pc. The latter criterion included a few hundred white dwarfs that would have otherwise been neglected. Some studies are listed multiple times if they contain multiple tables. Wenger et al. (2000) refers to the SIMBAD database.

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1249

APPENDIX

1250

A. YOUNG, AGE-DATED, AND AGE-DATEABLE STAR COMPILED

1251 The v0.6 CDIPS target catalog (Table 3) includes stars that are young, age-dated, and age-dateable. By
 1252 “age-dateable”, we mean that the stellar age should be measurable at greater precision than that of a typical
 1253 FGK field star, through either isochronal, gyrochronal, or spectroscopic techniques. As in Bouma et al.
 1254 (2019), we collected stars that met these criteria from across the literature. Table 4 gives a list of the studies
 1255 included, and brief summary statistics. The age measurement methodologies adopted by each study differ: in
 1256 many, spatial and kinematic clustering has been performed on the Gaia data, and ensemble isochrone fitting
 1257 of the resulting clusters has been performed (typically focusing on the turn-off). In other studies however,
 1258 the claim of youth is based on the location of a single star in the color-absolute magnitude diagram, or on
 1259 spectroscopic information.

1260 One major change in Table 3 relative to the earlier iteration from Bouma et al. (2019) is that the extent
 1261 of Gaia-based analyses has now matured to the point that we can neglect pre-Gaia cluster memberships,
 1262 except for a few cases with spectroscopically confirmed samples of age-dated stars. The membership lists for
 1263 instance of Kharchenko et al. (2013) and Dias et al. (2014) (MWSC and DAML) are no longer required. This
 1264 is helpful for various post-processing projects, since the field star contamination rates were typically much
 1265 higher in these catalogs than in the newer Gaia-based catalogs.

1266 The most crucial parameters of a given star for our purposes are the Gaia DR2 `source_id`, the cluster or
 1267 group name (`cluster`), and the age. Given the hierarchical nature of many stellar associations, we do not
 1268 attempt to resolve the cluster names to a single unique string. The Orion complex for instance can be divided
 1269 into almost one hundred kinematic subgroups (Kounkel et al. 2018). Based on Figure 1, the δ Lyr cluster may
 1270 also be part of a similar hierarchical association. Similar complexity applies to the problem of determining
 1271 homogeneous ages, which we do not attempt to resolve. Instead, we simply merged the cluster names and
 1272 ages reported by various authors into a comma-separated string.

1273 This means that the `age` column can be null, for cases in which the original authors did not report an age,
 1274 or for which a reference literature age was not readily available. Nonetheless, since we do prefer stars with
 1275 known ages, we made a few additional efforts to populate this column. When available, the age provenance
 1276 is from the original analysis of the cluster. In a few cases however we adopted other ages when string-
 1277 based cross-matching on the cluster name was straightforward. In particular, we used the ages determined
 1278 by Cantat-Gaudin et al. (2020) to assign ages to the clusters from Gaia Collaboration et al. (2018a), Cantat-
 1279 Gaudin et al. (2018), Castro-Ginard et al. (2020), and Cantat-Gaudin & Anders (2020).

1280 The catalogs we included for which ages were not immediately available were those of Cotten & Song
 1281 (2016), Oh et al. (2017), Zari et al. (2018), Gagné et al. (2018a), Gagné et al. (2018b), Gagné & Faherty
 1282 (2018), and Ujjwal et al. (2020). While in principle the moving group members discussed by Gagné et al.
 1283 (2018a,b); Gagné & Faherty (2018) and Ujjwal et al. (2020) have easily associated ages, our SIMBAD cross-
 1284 match did not retain the moving group identifiers given by those studies, which should therefore be recovered
 1285 using tools such as BANYAN Σ (Gagné et al. 2018b). We also included the SIMBAD object identifiers `TT*`,
 1286 `Y*O,Y*?`, `TT?`, and `pMS*`. Finally, we included every star in the NASA Exoplanet Archive planetary system
 1287 (`ps`) table that had a Gaia identifier available (Akeson et al. 2013). If the age had finite uncertainties, we also
 1288 included it, since stellar ages determined through the combination of isochrone-fitting and transit-derived
 1289 stellar densities typically have higher precision than from isochrones alone.

1290 For any of the catalogs for which Gaia DR2 identifiers were not available, we either followed the spa-
 1291 tial (plus proper-motion) cross-matching procedures described in Bouma et al. (2019), or else we pulled the
 1292 Gaia DR2 source identifiers associated with the catalog from SIMBAD. We consequently opted to drop the
 1293 `ext_catalog_name` and `dist` columns maintained in Bouma et al. (2019), as these were only popu-
 1294 lated for a small number of stars. The technical manipulations for the merging, cleaning, and joining were
 1295 performed using pandas (McKinney 2010). The eventual cross-match (using the Gaia DR2 `source_id`)
 1296 against the Gaia DR2 archive was performed asynchronously on the Gaia archive website.

1297

B. THE TRANSIT ASYMMETRY

1298

B.1. How Robust is the Asymmetric Transit?

1299 As a means of exploring the robustness of the transit asymmetry, Figures 9, 10, and 11 show the Kepler data
 1300 binned in three ways: over Kepler quarters, Julian years, and quartiles of local slope. Over Kepler quarters
 1301 (Figure 9), Quarter 6 shows the strongest asymmetry: a deviation of about 3 ppt from expectation. Quarter

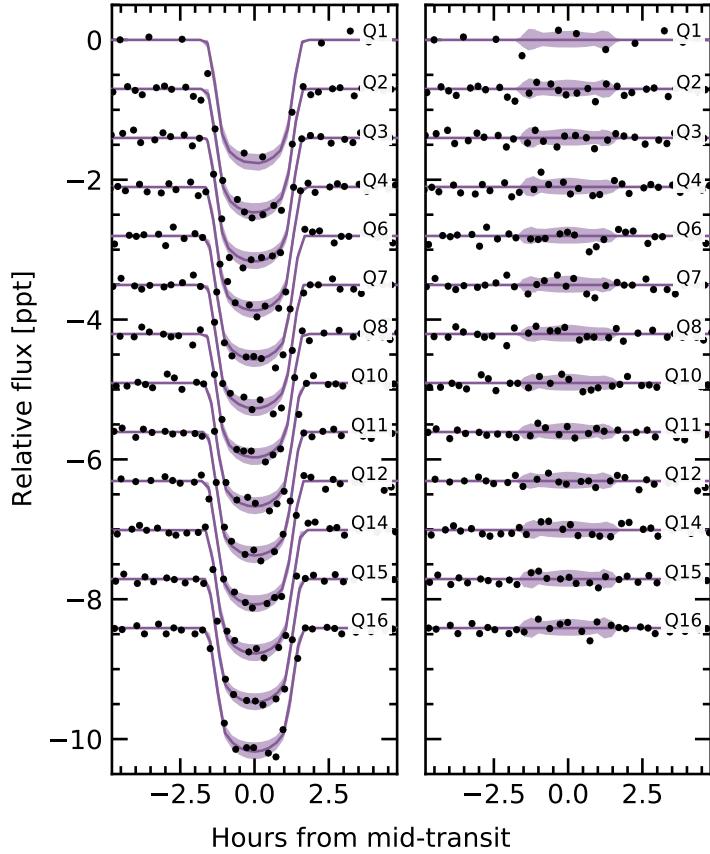


Figure 9. Transit model residuals through time (binned by Kepler quarter). *Left:* Phase-folded transit of Kepler 1627b, with stellar variability removed. Black points are binned to 20 minute intervals. The 2σ model uncertainties and the maximum *a posteriori* model are shown as the faint purple band, and the dark purple line. *Right:* As on the left, with the transit removed.

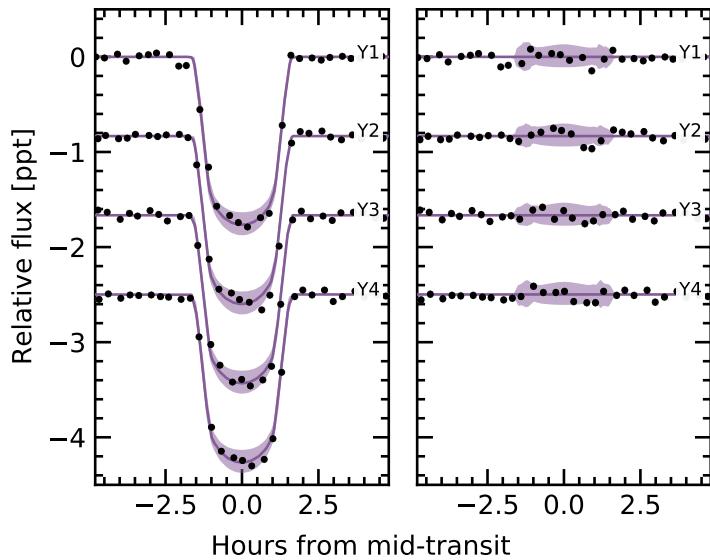


Figure 10. Transit model residuals through time (binned by year of observation). *Left:* Phase-folded transit of Kepler 1627b, with stellar variability removed. Points and models are as in Figure 9. *Right:* As on the left, with the transit removed.

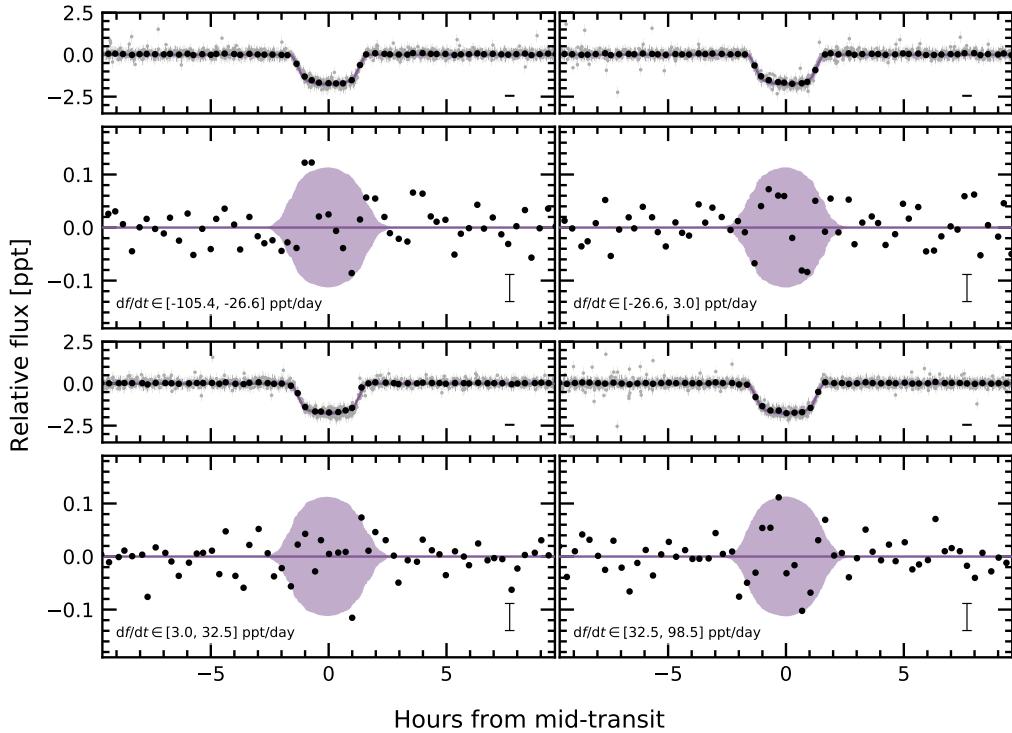


Figure 11. Transit models and residuals, binned by quartiles in the local slope of the light curve. Representative uncertainties for the black points (binned at 20 minute intervals) are shown in the lower right of each panel. A similar transit asymmetry to that shown in Figure 5 seems to be present in three of the four bins.

1302 7 shows an anomaly at roughly the same transit phase. Year 2 correspondingly shows the strongest anomaly
 1303 out of any year in Figure 10; the asymmetry is visually apparent however in each of the four years.

1304 To bin by quartiles in local slope, we used our measurements of the local linear slopes in each of the
 1305 observed transit windows (144 transits total). Four outlier transits were removed, leaving 140 transits. These
 1306 were then divided into quartiles, so that each panel shows 35 transits binned together. The exact light curve
 1307 slope intervals are listed in the lower left panels of Figure 11. Binned by local slope quartiles (Figure 11),
 1308 the asymmetry is visually present in three of the four quartiles: the only bin in which it does not appear is
 1309 $df/dt \in [3.0, 32.5] \text{ ppt day}^{-1}$.

1310 Within the theory presented by Mazeh et al. (2015), unresolved starspot crossings cause the weak correlation
 1311 between TTVs and the local light curve slope (Figure 6). In this model, we would expect the light curves
 1312 with the most negative local slopes to have the largest positive TTVs, due to spot crossing events during the
 1313 latter half of transit. The upper-left panel of Figure 11 agrees with this expectation. However, we would also
 1314 expect the sign of the effect to reverse when considering the most positive local slopes (most negative TTVs).
 1315 The lower-right panel of Figure 11 contradicts this expectation: the residual in both cases maintains the same
 1316 parity! On the one hand, this shows that the residual is not dependent on the local light curve slope, which
 1317 lowers the likelihood that it might be an artifact of our detrending methods. On the other, it raises the question
 1318 of whether unresolved starspot crossings are indeed the root cause of the correlation shown in Figure 6. While
 1319 we do not have a solution to this contradiction, the injection-recovery tests discussed in Section 4.1.3 provide
 1320 some assurance that the TTV-slope correlation is not simply a systematic artifact.

1321

B.2. Interpretation

1322 The transit asymmetry seems robust against most methods of binning the data, though with some caveats
 1323 (e.g., the “middle quartile” in local flux, $df/dt \in [3.0, 32.5] \text{ ppt day}^{-1}$, where the asymmetry does not appear).
 1324 Nonetheless, if the asymmetric were systematic we might expect its parity to reverse as a function of the sign
 1325 of the local slope, and it does not. We therefore entertained four possible astrophysical explanations: gravity
 1326 darkening, transit timing variations, spot-crossing events, and a persistent asymmetric dusty outflow.

1327 Gravity darkening is based on the premise that the rapidly rotating star is oblate, and brighter near the
 1328 poles than the equator (e.g., Masuda 2015). The fractional transit shape change due to gravity darkening
 1329 is on the order of $(P_{\text{break}}/P_{\text{rot}})^2$, for P_{break} the break-up rotation period, and P_{rot} the rotation period. Using

the parameters from Table 2, this yields an expected 0.14% distortion of the ≈ 1.8 ppt transit depth: *i.e.*, an absolute deviation of ≈ 2.5 ppm. The observed residual has a semi-amplitude of ≈ 50 ppm. Since the expected signal is smaller than the observed anomaly by over an order of magnitude, gravity darkening seems to be an unlikely explanation.

The scenario of transit timing variations (TTVs) producing the asymmetry seems unlikely because the transit timing variations we do observe are correlated with the local light curve slope, which increases roughly as much as it decreases. From our analysis, the mean TTV and its standard deviation are 0.66 ± 5.53 min; similarly the mean local slope and its standard deviation are 0.59 ± 45.50 ppt day $^{-1}$. There is therefore little expectation for TTVs to produce the asymmetry. A separate line of argument comes from Figure 11. If the local slope were essential to producing the transit asymmetry, we would expect that in the largest df/dt bin, $df/dt \in [3.0, 32.5]$ ppt day $^{-1}$, the sign of the asymmetry would reverse. We do not see evidence for this being the case.

The third and related possibility is that of starspot crossings. Young stars have higher spot-covering fractions than old stars (*e.g.*, Morris 2020). Young solar-type stars may also host dark starspots at high stellar latitudes (*e.g.*, EK Dra; Strassmeier 2009), though interferometric imaging of spotted giant stars has shown different starspot latitude distributions than those inferred from Doppler imaging (Roettenbacher et al. 2017). Regardless, for any spot-crossing anomalies to add coherently over the 140 Kepler transits, it seems likely that we would need either for spots to be persistent at a particular latitude (and for the planetary orbit to be somewhat misaligned), or for a “stroboscopic” longitudinal phasing (*e.g.*, Dai et al. 2018). For our system, $P_{\text{orb}}/P_{\text{rot}} \approx 2.76$, which means that every 4 transits and 11 stellar rotations, the planet crosses over roughly the same stellar longitude, which might enable the necessary phasing if the spot-groups are large and long-lived. Unfortunately, the S/N per Kepler transit is ≈ 8 , which renders individual spot-crossing events unresolved. This explanation seems marginally plausible, mainly because the expected spot-crossing anomaly amplitudes (≈ 100 ppm) resemble the observed amplitude of the asymmetry (≈ 50 ppm). One issue with this explanation however is that there is no reason to expect starspot crossing events to last exactly half the transit duration.

A persistent feature of the planet itself might therefore be needed to explain the transit asymmetry. An asymmetric outflow from the planet’s atmosphere could at least geometrically meet the requirements (*e.g.*, McCann et al. 2019). To explain the asymmetric transit, a small, dense component would lead the planet, and a long, more rarefied (and variable) component would trail it. This might also explain the slight flux decrement visible for ~ 1 hour pre-ingress (Figure 5). The amplitude of the asymmetry is roughly in line with theoretical expectations for dusty outflows (Wang & Dai 2019), and based on the planet’s size, its mass is likely in a regime where such outflows are possible. Out of the four explanations discussed, this one at least theoretically seems the most plausible. By composition, the expectation would be that the envelope is mostly hydrogen and helium gas, with a dust or haze component providing the broadband opacity in the Kepler bandpass. A natural path for testing this idea would be to observe additional transits of the planet in hydrogen absorption, metastable helium absorption, or across a broad wavelength range in the near-infrared.

C. SPECTROSCOPY AND PHOTOMETRY DURING THE TRANSIT OF 2021 AUG 7

We used the ephemeris of Holczer et al. (2016) to observe a transit of Kepler 1627Ab on the night of 2021 Aug 7 both spectroscopically and photometrically. We used the HIRES echelle spectrograph at the Keck-I telescope and the MuSCAT3 photometer at Haleakalā Observatory on Maui, HI (Narita et al. 2020). For the HIRES wavelength calibration, we used the iodine cell, and extracted the 1-D spectra using the standard California Planet Survey pipeline (Howard et al. 2010). Given the faintness of the target ($V = 13.1$), we observed using the C2 decker, which yielded an instrument resolution of $\approx 50,000$. The airmass ranged between 1.1 and 2.2 from the start through the end of observations; the seeing ranged from $1.^{\prime\prime}1$ at the beginning to $1.^{\prime\prime}5$ at the end. The HIRES exposure time was set at ≈ 15 minutes in order to resolve the 2.8 hour transit event, which yielded a S/N per resolution element of ≈ 75 (low for precision radial velocity standards). For the MuSCAT3 observations, we observed simultaneously across the *griz* bands. The exposure times in each bandpass ranged between 23 and 46 seconds, and were chosen in order to yield a S/N in the peak pixel that exceeded 130 while also preventing saturation. Performing aperture photometry on the latter image stack yielded the data given in Table 5.

We considered two approaches to measuring the velocities: in the first, hereafter “Method 1”, we cross-correlated against a template found via spectral classification with SpecMatch-Emp (Yee et al. 2017). In “Method 2”, we used a high S/N template of V1298 Tau. Although V1298 Tau is cooler than Kepler 1627A by ≈ 500 K, it has a comparable amount of line-broadening ($v \sin i = 23$ km s $^{-1}$), and a comparable level of stellar activity. The mean and standard deviation of the internal RV uncertainties averaged over all epochs were 16.2 ± 1.1 m s $^{-1}$ from Method 1, and 12.6 ± 0.6 m s $^{-1}$ from Method 2. The corresponding time-averaged

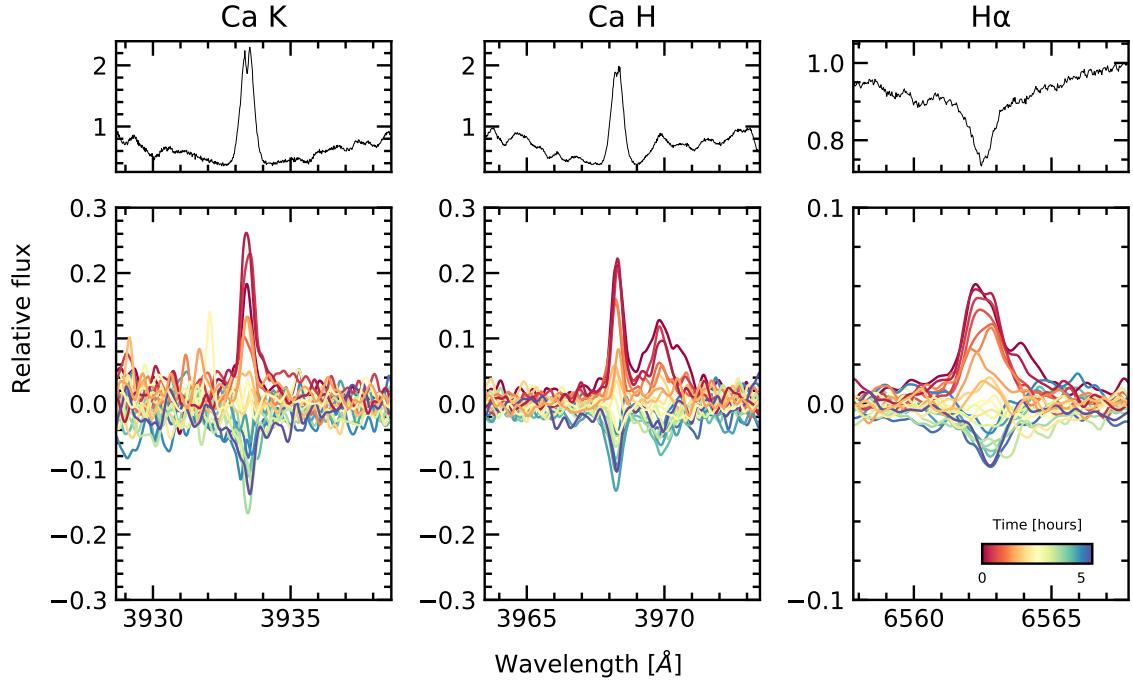


Figure 12. Spectroscopic activity indicators during the transit of 2021 Aug 7. The *top panels* show the median line profiles Ca K, Ca H, and H α line profiles from the HIRES spectra. The *lower panels* show the differences of each individual spectrum relative to the median spectrum. The bump in the red wing of Ca H is He ϵ . The spectra in the lower panels are smoothed for visualization purposes.

reduced χ^2 from the template match was 1.57 ± 0.04 (Method 1) and 1.30 ± 0.02 (Method 2). Given these diagnostics, we adopted the velocities from the second approach, which are reported in Table 6.

Figure 7 shows the results. The MuSCAT3 photometry shows the expected starspot trend, along with the transit and what is likely a chromatic starspot crossing event at JD – 2459433 = 0.955. The radial velocities decrease by $\approx 250 \text{ m s}^{-1}$ over the six hour window. This decrease in RV is correlated with a decrease in the S-indices derived from the Ca HK lines. One outlying RV point is apparent shortly before egress; it is temporally coincident with an outlying value in the S-index time series.

Overall, we expect the dominant trends in both the photometry and radial velocities to be caused by starspots on the stellar photosphere rotating into and out of view. The plasma in the leading and receding limbs of the stellar disk has an apparent line-of-sight velocity of $\pm 20 \text{ km s}^{-1}$. Over 10% of a rotation cycle ($P_{\text{rot}} = 2.6 \text{ days}$), spots near these limbs come into and out of view, modulate the stellar velocity profile, and can thereby produce the overall $\approx 250 \text{ m s}^{-1}$ trend. The Ca HK and H α emission profiles support this interpretation; Figure 12 shows that each line gradually decreases in intensity over the course of the six hour sequence.

The expectation however is for the starspot-induced signals to be smooth, at worst with contributions at $0.5P_{\text{rot}}$ or $0.25P_{\text{rot}}$ (Klein & Donati 2020). We therefore fitted the RVs using the Hirano et al. (2010, 2011) models for the Rossiter-McLaughlin (RM) effect, and allowed for an optional linear and quadratic trend in time to fit the $\approx 250 \text{ m s}^{-1}$ spot-induced trend. We followed the methodology developed by Stefansson et al. (2020). We allowed the sky-projected obliquity, the projected stellar equatorial velocity, and the Gaussian dispersion of the spectral lines to vary, and fixed the limb-darkening using the V-band tabulation from Claret & Bloemen (2011). We assumed a Gaussian prior on $v\sin i$ and a/R_* from Table 1, and also allowed for a white-noise jitter term to be added in quadrature to the measurement uncertainties. We used a 15 minute exposure time to numerically evaluate the model.

The quadratic model with the RM effect is shown in Figure 7; the jitter term is incorporated in the model uncertainties, but not the plotted measurement uncertainties. The plotted measurement uncertainties are the internal uncertainties on the RVs ($\approx 13 \text{ m s}^{-1}$), and are dominated by the $v\sin i$ broadening. However, between exposures, the RVs show significant additional scatter that is not captured by the slow quadratic trend. The

¹⁴¹² white-noise jitter for this particular model is $\sigma_{\text{RV}} = 27^{+6}_{-5} \text{ m s}^{-1}$, which is comparable to the expected RM
¹⁴¹³ anomaly of $\Delta v_{\text{RM}} \approx f_{\text{LD}} \cdot \delta \cdot v \sin i \cdot \sqrt{1 - b^2} \approx 20 \text{ m s}^{-1}$, assuming a perfectly aligned orbit.

The presence of this additional scatter prevents a convincing detection of the RM effect. The reason can be understood via model comparison. If we compare the model with a quadratic trend and the RM effect against a model with a linear trend and the RM effect, or even a model with no RM effect at all, then the respective Bayesian Information Criterion (BIC) values are as follows.

$$\begin{aligned} \text{BIC} &= 227.1 \quad (\text{Quadratic + RM}) \\ \text{BIC} &= 231.1 \quad (\text{Linear + RM}) \\ \text{BIC} &= 221.4 \quad (\text{Only Quadratic}). \end{aligned} \quad (\text{C1})$$

¹⁴¹⁴ There is therefore no evidence to prefer the model with the RM effect against a model that only accounts
¹⁴¹⁵ for the stellar variability. The “only quadratic” model does particularly well because it can inflate the jitter
¹⁴¹⁶ term to account for scatter during the transit (even if the scatter contains astrophysics!), and it has fewer free
¹⁴¹⁷ parameters. However, we cannot justify a physical prior on the jitter term, because we do not understand
¹⁴¹⁸ the origin of the exposure-to-exposure scatter. As noted above, the velocity deviations from starspots are
¹⁴¹⁹ expected to have contributions at the stellar rotation frequency, or harmonics thereof. This jitter is present on
¹⁴²⁰ the exposure timescale (15 minutes), which is only 0.4% of the stellar rotation period; it is not obvious that
¹⁴²¹ starspots would be the culprit.

¹⁴²² The amplitude of both the spot-induced trend and the jitter are somewhat larger than recent comparable
¹⁴²³ measurements in systems such as AU Mic (Palle et al. 2020), DS Tuc (Montet et al. 2020; Zhou et al. 2020)
¹⁴²⁴ and TOI 942 (Wirth et al. 2021). One possible explanation for the jitter is that it is astrophysical in origin,
¹⁴²⁵ and that it is caused by some novel process operating on the surface of Kepler 1627A. Another possibility
¹⁴²⁶ is that our RV analysis underestimates our measurement uncertainties; in order to achieve the requisite time-
¹⁴²⁷ sampling the S/N per resolution element in our spectra was 70 to 80, which is lower than desired for deriving
¹⁴²⁸ high-precision velocities. In addition, the rapid rotation of the star could affect accuracy of the uncertainties
¹⁴²⁹ from the velocity extraction. Observations at higher S/N are necessary to distinguish these two possibilities,
¹⁴³⁰ and remain worthwhile in order to clarify the orbital geometry of Kepler 1627Ab. Useful next steps would
¹⁴³¹ include transit observations with a stabilized spectrograph in the optical (e.g., Gibson et al. 2016; Seifahrt
¹⁴³² et al. 2018), or in the near-infrared (e.g., Feinstein et al. 2021).

Table 5. MuSCAT3 photometry of Kepler 1627.

Time [BJD _{TDB}]	Rel. Flux	Rel. Flux Err.	Bandpass
2459433.829202	0.99719	0.00091	g
2459433.829324	0.99849	0.00112	r
2459433.829117	0.99611	0.00116	i
2459433.829406	0.99941	0.00136	z

NOTE— Table 5 is published in its entirety in a machine-readable format. Example entries are shown for guidance regarding form and content.

Table 6. Kepler 1627 radial velocities.

Time [BJD _{TDB}]	RV [m s^{-1}]	σ_{RV} [m s^{-1}]	S-value
2459433.801306	152.97	12.29	0.7355
2459433.812255	100.5	13.23	0.7434

NOTE— Table 6 is published in its entirety in a machine-readable format. Example entries are shown for guidance regarding form and content.

D. FLARE ANALYSIS

¹⁴³⁴ In addition to the 3.9 years of long cadence data,
¹⁴³⁵ short cadence (1-minute) Kepler observations were
¹⁴³⁶ acquired over 97.7 days during Quarter 15. The

¹⁴³⁷ short cadence light curve shows a higher rate of
¹⁴³⁸ flaring than visible in the long cadence data (Figure 13). We analyzed the short cadence light curve
¹⁴³⁹ and its flares according to the following procedure.
¹⁴⁴⁰

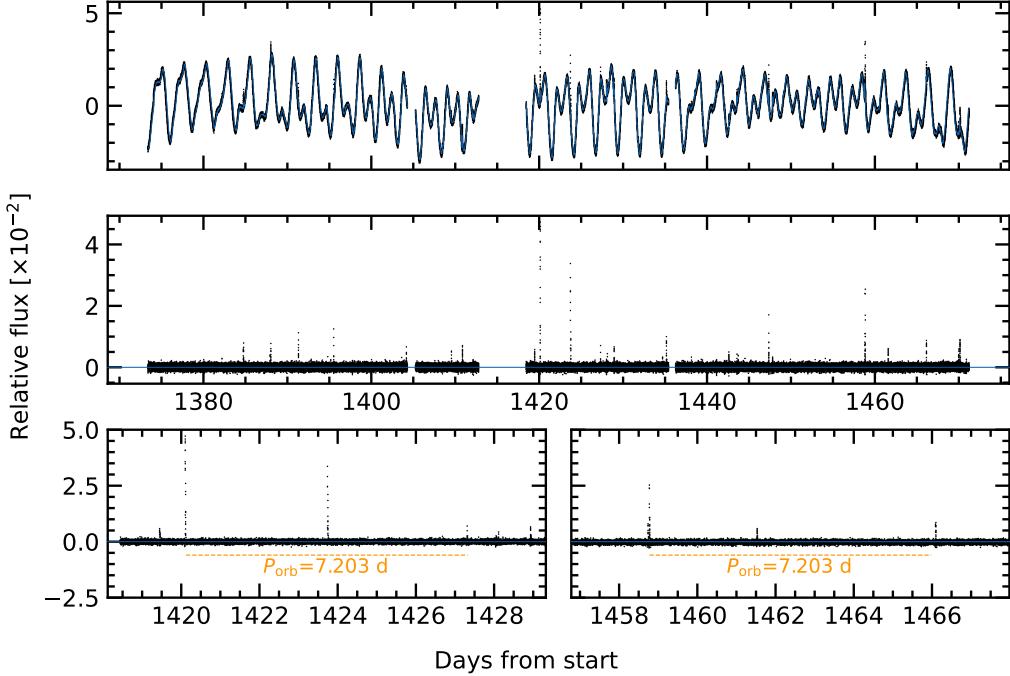


Figure 13. Flares in Kepler 1627. *Top:* The 1-minute cadence Kepler data (black points) is shown with a stellar variability model superposed (blue line). *Middle:* Residual after subtracting the stellar variability model. Flares appear as spikes. *Bottom:* Zooms of the brightest, and third-brightest flares. A timing coincidence – that both flares have “successors” approximately one planetary orbital period after the initial event – is emphasized.

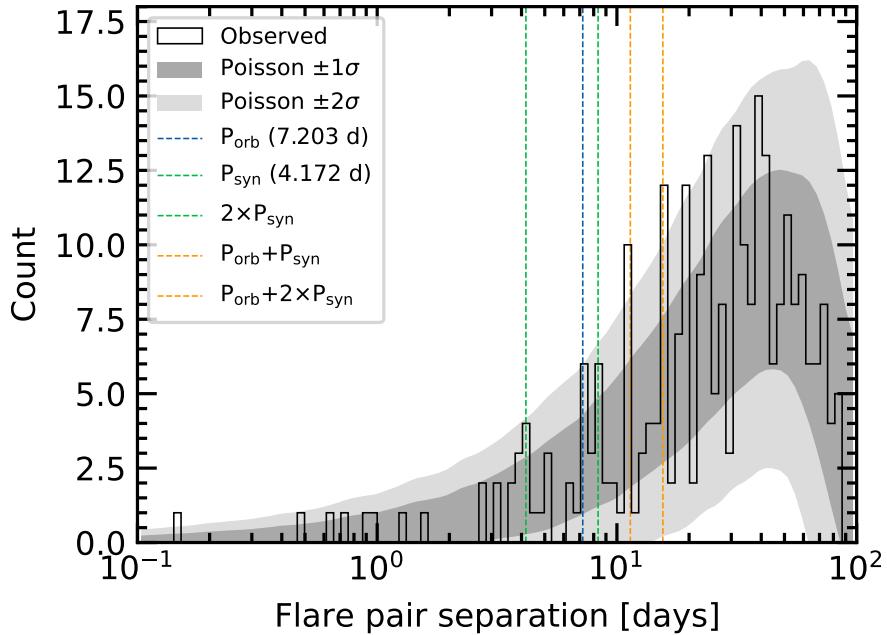


Figure 14. Statistics of inter-flare arrival times. 24 flares were recorded with amplitudes exceeding 0.5% over the 97.7 days of short cadence observations. The histogram of the time intervals between every possible pair of flares is shown in black. Some plausibly important timescales for star-planet interactions, namely the planetary orbital period and synodic period (the orbital period as seen from the rotating stellar frame) are shown along with their linear combinations. Monte Carlo draws from a Poisson distribution are shown with the gray bands. While peaks in the observed distribution do coincide with some of the “special periods”, the statistical evidence for a non-Poissonian process driving the flares does not clear the 5σ threshold.

- 1441 1. Fit the starspot-induced variability using a
 1442 Gaussian Process with a SHOTerm kernel,
 1443 a white-noise jitter term, and the mean flux.
 1444 2. Select points more than twice the median ab-
 1445 solute deviation from the residual, and ex-
 1446 clude them from the light curve (these points
 1447 include the flares). Repeat Step 1.
 1448 3. Using the residual from Step 2, identify all
 1449 flares, requiring them to be at least 20 ca-
 1450 dences apart, at least 7 median absolute de-
 1451 viations above the median baseline, and last-
 1452 ing at least 2 cadences in duration. Build the
 1453 mask spanning these times, from 5 minutes
 1454 before each flare begins to 2.5 minutes after
 1455 the final flare cadence. Repeat Step 1 a final
 1456 time.

1457 The final step of flare identification and fitting was
 1458 performed using `altaipony` (Davenport 2016;
 1459 Ilin et al. 2021). The analytic flare model is from
 1460 Davenport et al. (2014) and it parametrizes the flare
 1461 with a start time, an exponential lag time, and an
 1462 amplitude.

1463 There were $N_f = 24$ flares that exceeded 0.5% in
 1464 relative flux during the short cadence observations.
 1465 These 24 flares spanned a total of 6.5 hours (~ 15
 1466 minutes per flare). Inspecting the data, we noticed
 1467 a coincidence in the flare arrival times. The co-
 1468 incidence is that despite the low flare duty cycle,
 1469 one orbital period after the brightest flare, a second
 1470 flare followed. This and a similar event are shown
 1471 in Figure 13. The timing error is good to a $\approx 0.2\%$
 1472 difference from the orbital period, which given the
 1473 duty cycle seems *a priori* unlikely. If we consider
 1474 flares falling within 2% of the planet’s orbital pe-
 1475 riod after a previous flare, then 4 of the 24 flare
 1476 events have candidate “successors”.

1477 As with any coincidence, if one does not have a
 1478 firm prediction, it is difficult to assess whether a
 1479 surprise is statistically significant. Since our sur-
 1480prise was specifically at the inter-arrival time of
 1481 certain flares coinciding with special time inter-
 1482 vals, we performed the following analysis. First,
 1483 we considered all unordered pairs of flares. For
 1484 N flares there are $\binom{n}{2}$ such pairs (for our case,
 1485 276 pairs). We then compared the distribution of
 1486 the pair separations against that of a Poisson dis-
 1487 tribution. Specifically, we drew $N_f = 24$ samples
 1488 from a Poisson distribution with $\lambda = \Delta t / N_f$, for
 1489 $\Delta t = 97.7$ days the total duration of the observa-
 1490 tions, and repeated the draw 10^3 times with unique
 1491 random seeds.

1492 Figure 14 shows the results. The vertical lines
 1493 in the figure show the planetary orbital period,
 1494 the synodic period $P_{\text{syn}} = (P_{\text{rot}}^{-1} - P_{\text{orb}}^{-1})^{-1}$, and lin-
 1495 ear combinations thereof. The tidal period (half
 1496 the synodic period) is not shown. The bins are

1497 logarithmically spaced to give 100 bins between
 1498 the minimum and maximum ordinate values. The
 1499 gray bands express the range of values observed
 1500 from the Poissonian draws. While it does seem
 1501 like an odd coincidence for peaks in the observed
 1502 flare arrival time distribution to coincide with the
 1503 locations of these “special intervals”, the statisti-
 1504 cal evidence for a non-Poissonian process driving
 1505 the flares does not seem especially overwhelming.
 1506 More quantitatively, the peaks observed at the or-
 1507 bital and synodic periods are within the $\pm 2\sigma$ range
 1508 of a Poissonian process, and those at $P_{\text{orb}} + P_{\text{syn}}$ and
 1509 $P_{\text{orb}} + 2P_{\text{syn}}$ are only slightly above this range. With
 1510 that said, future analyses of these data by investiga-
 1511 tors with more knowledge of this topic could very
 1512 well yield more quantitative insights. Such analy-
 1513 ses should keep in mind an important caveat: the
 1514 amplitude distribution of M-dwarf flares extends
 1515 up to many times the quiescent flux (see Figure 7 of
 1516 Günther et al. 2020). A flare on Kepler 1627B pro-
 1517 ducing double its quiescent white-light flux would
 1518 yield a $\approx 1\%$ apparent amplitude. Such flares could
 1519 represent a significant fraction of those in the Ke-
 1520 pler observations.