

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 M2.5V 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-

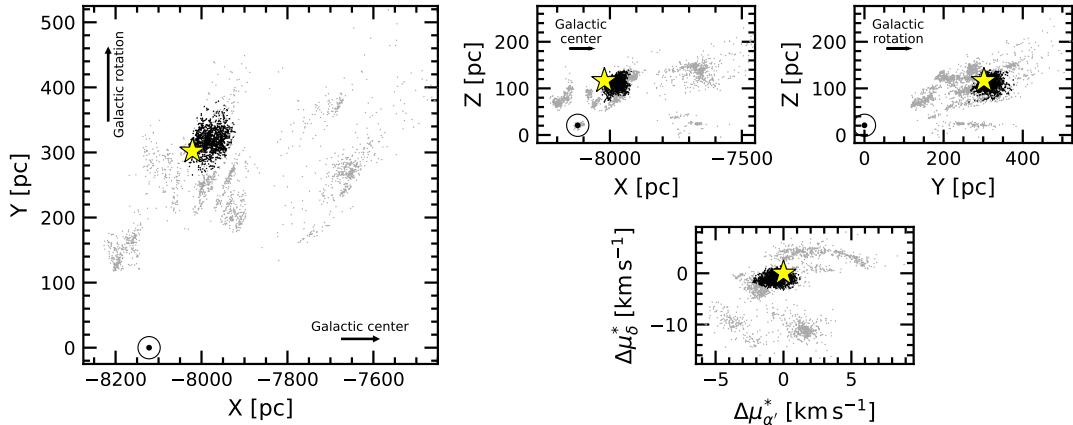


Figure 1. Galactic positions and tangential velocities of stars in the δ Lyr cluster. Points are reported cluster members from Kounkel & Covey (2019). The tangential velocities relative to Kepler 1627 (bottom right) are computed assuming that every star has the same three-dimensional spatial velocity 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.

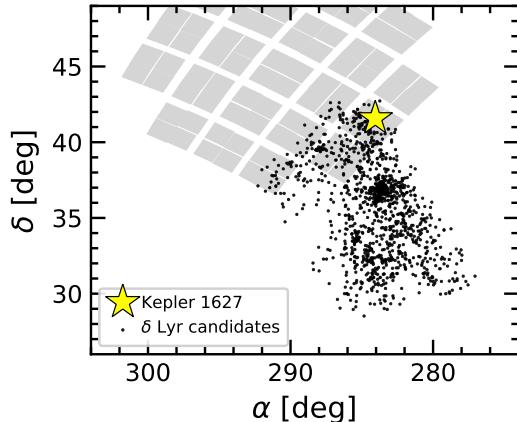


Figure 2. Kepler's view of the δ Lyr cluster, shown in equatorial coordinates. Each black circle is a candidate cluster member selected based on its position and kinematics (Figure 1). Of the 1,201 candidate cluster members, 58 have at least one quarter of Kepler data. TESS has also observed most of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

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

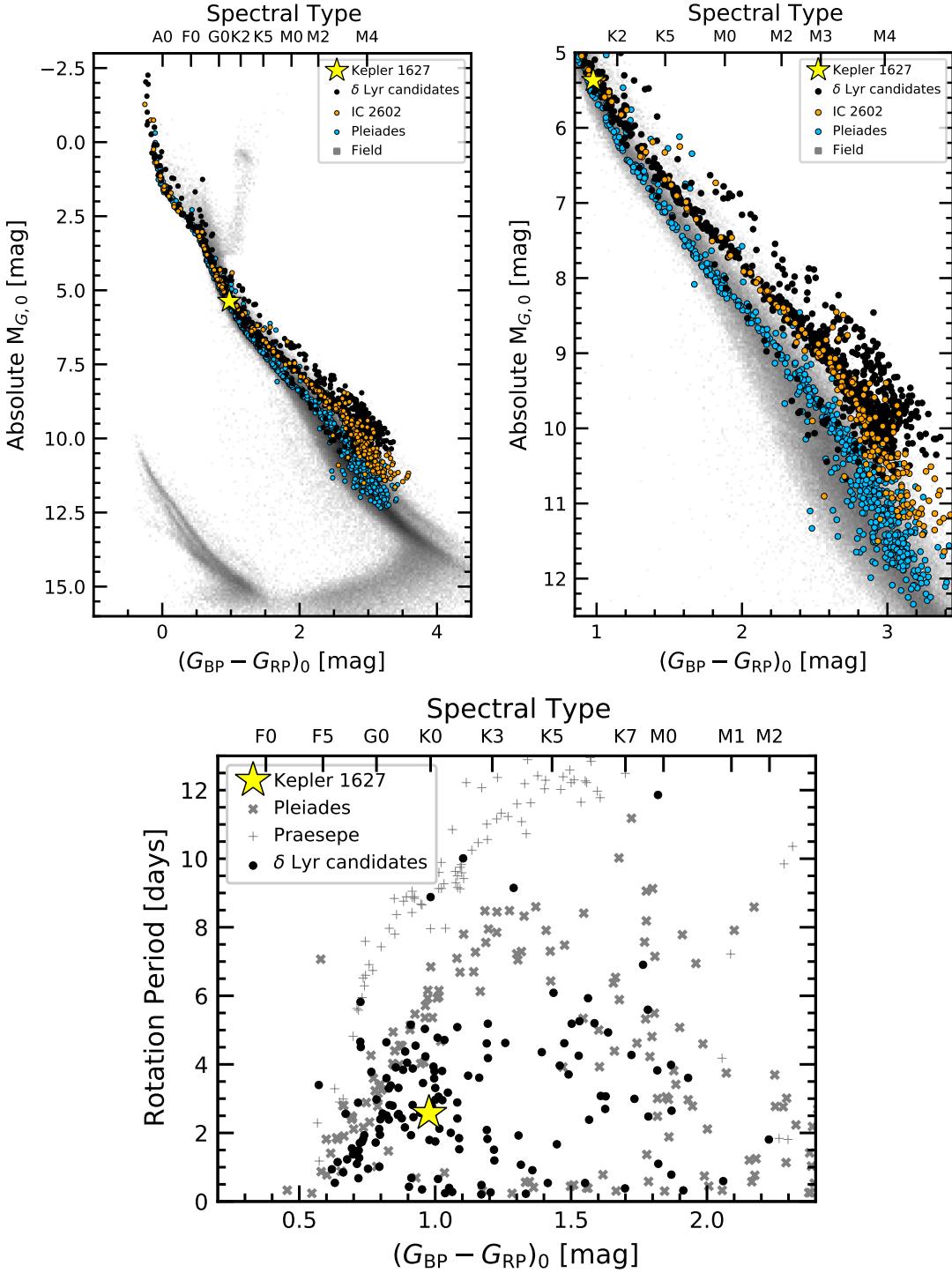


Figure 3. The δ Lyr cluster is 38^{+6}_{-5} Myr old. *Top:* Color-absolute magnitude diagram of candidate δ Lyr cluster members, in addition to stars in IC 2602 (≈ 38 Myr), the Pleiades (≈ 115 Myr), and the Gaia EDR3 Catalog of Nearby Stars (gray background). The zoomed right panel highlights the pre-main-sequence. 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.

$E(B-V) = \{0.084 \pm 0.041, 0.020 \pm 0.003, 0.045 \pm 0.008, 0.032 \pm 0.006\}$. 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 & Hillenbrand 2015; Bossini et al. 2019). If we were

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.

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 one-tenth of the target star in a 21.⁰ radius. There

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.

were 192 stars that met these crowding requirements, and that had TESS data available. For plotting purposes we then imposed a selection based on the strength of the signal itself: we required the Lomb Scargle power to exceed 0.2, and the period to be below 15 days.

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

3. THE STARS

3.1. Kepler 1627A

3.1.1. Age

Based on the spatial and kinematic association of Kepler 1627 with the δ Lyr cluster, and the assumption that the planet formed shortly after the star, it seems likely that Kepler 1627 is the same age as the cluster. There are two consistency checks on whether this is true: rotation and lithium. Based on the Kepler light curve, the rotation period is 2.642 ± 0.042 days, where the quoted uncertainty is based on the scatter in rotation periods measured from each individual Kepler quarter. This is consistent with comparable cluster members (Figure 3).

To infer the amount of Li I from the 6708 Å doublet (*e.g.*, Soderblom et al. 2014), we acquired an iodine-free spectrum from Keck/HIRES on the night of 2021 March 26 using the standard setup and reduction techniques of the California Planet Survey (Howard et al. 2010). Following the equivalent width measurement procedure described by Bouma et al. (2021), we find $\text{EW}_{\text{Li}} = 233^{+5}_{-7}$ mÅ. This value does not correct for the Fe I blend at 6707.44 Å. Nonetheless, given the stellar effective temperature (Table 1), this measurement is in agreement with expectations for a ≈ 40 Myr star (*e.g.*, as measured in IC 2602 by Randich et al. 2018). It is also larger than any lithium equivalent

widths measured by Berger et al. (2018) in their analysis of 1,301 Kepler-star spectra.

3.1.2. Stellar Properties

The adopted stellar parameters are listed in Table 1. The stellar mass, radius, and effective temperature are found by interpolating against a 38 Myr MIST isochrone (Choi et al. 2016). The statistical uncertainties are propagated from the absolute magnitude (mostly originating from the parallax uncertainty) and the color; the systematic uncertainties are taken to be the difference between the PARSEC (Bressan et al. 2012) and MIST isochrones. Reported uncertainties are a quadrature sum of the statistical and systematic components. As a consistency check, we analyzed the aforementioned Keck/HIRES spectrum from the night of 2021 March 26 using a combination of SpecMatch-Emp for stellar properties, and SpecMatch-Synth for $v\sin i$ (Yee et al. 2017). This procedure yielded $T_{\text{eff}} = 5498 \pm 100$ K, $\log g = 4.6 \pm 0.1$, $[\text{Fe}/\text{H}] = 0.15 \pm 0.10$ from SpecMatch-Emp, and $v\sin i = 18.9 \pm 1.0$ from SpecMatch-Synth. These values are within the $1-\sigma$ uncertainties of our adopted values from the isochrone interpolation.

3.2. Kepler 1627B

We first noted the presence of a close neighbor in the Kepler 1627 system on 2015 July 22 when we acquired adaptive optics imaging using the NIRC2 imager on Keck-II. We used the narrow camera (FOV = 10.2'') to obtain 8 images in the K' filter ($\lambda = 2.12 \mu\text{m}$) with a total exposure time of 160 s. We analyzed these data following Kraus et al. (2016), which entailed using PSF-fitting to measure the separation, position angle, and contrast of the candidate companion. The best-fitting empirical PSF template was identified from among the near-contemporaneous observations of single stars in the same filter. The mean values inferred from the 8 images are reported in Table 1. To estimate the detection limits, we analyzed the residuals after subtracting the empirical PSF template. Within each residual image, the flux was measured through 40 mas apertures centered on every pixel, and then the noise as a function of radius was estimated from the RMS within concentric rings. Finally, the detection limits were estimated from the strehl-weighted sum of the detection significances in the image stack, and we adopted the $6-\sigma$ threshold as the detection limit for ruling out additional companions.

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

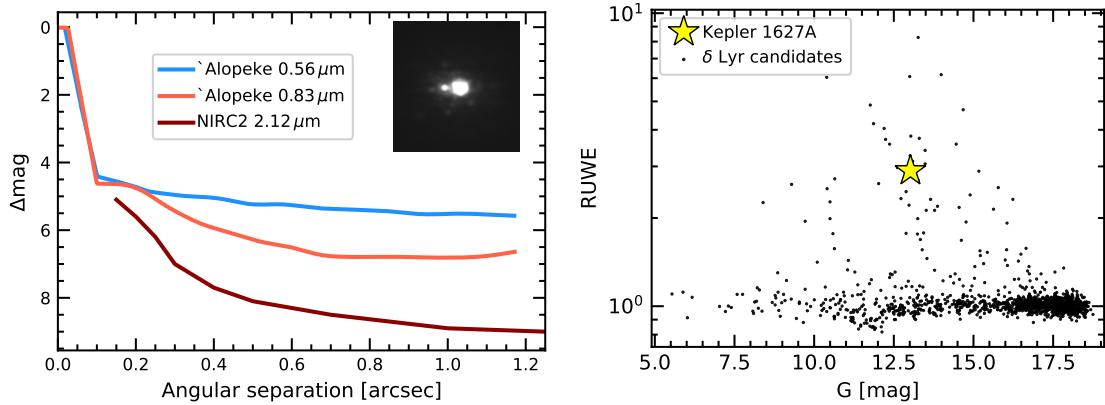


Figure 4. Kepler 1627 is a binary. *Left:* High-resolution imaging from Gemini-North/‘Alopeke and Keck/NIRC2 shows an \approx M2.5V companion at $\rho \approx 0.^{\prime\prime}16$, which corresponds to a projected separation of 53 ± 4 AU. The inset shows a cutout of the stacked NIRC2 image (North is 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 ply a companion mass of $M_B \approx 0.33M_{\odot}$ and com-
 451 panion temperature of $T_{\text{eff},B} \approx 3450$ K. The corre-
 452 sponding spectral type is roughly M2.5V (Pecaut
 453 & Mamajek 2013). These models combined with

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

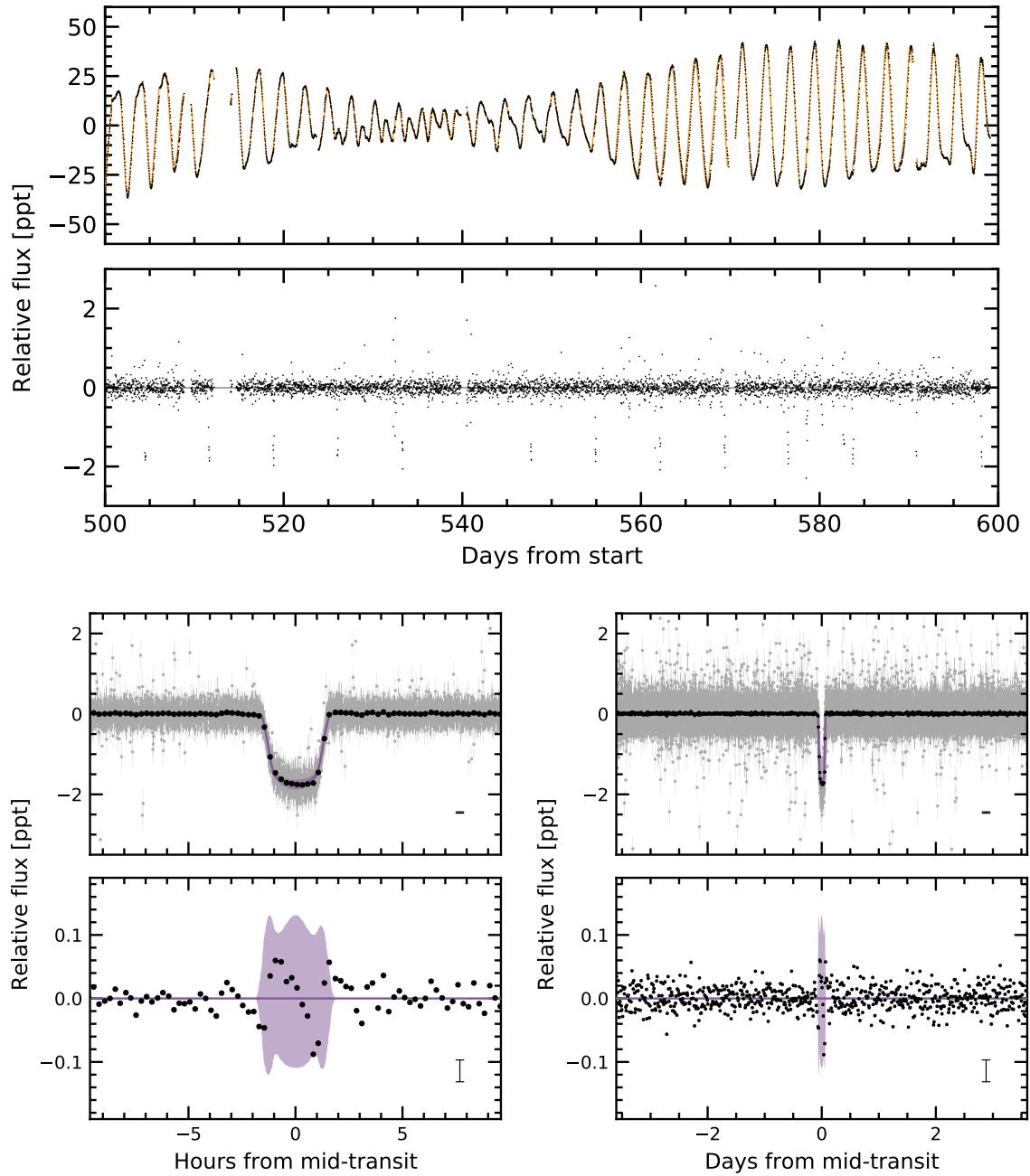


Figure 5. The light curve of Kepler 1627. *Top:* The Kepler data span 1,437 days (3.9 years), sampled at 30 minute cadence; a 100 day segment is shown. The top panel shows the PDCSAP median-subtracted flux in units of parts-per-thousand ($\times 10^{-3}$). The dominant signal is induced by starspots. 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**

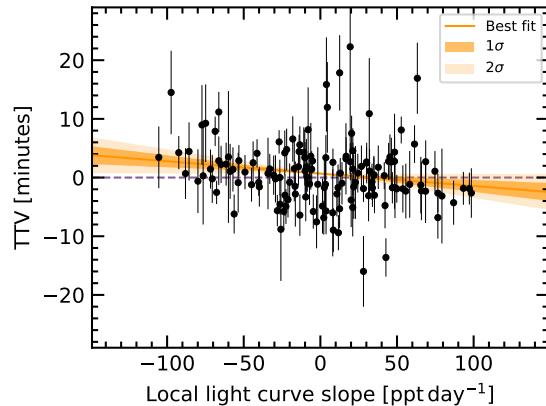
489 We fitted the Kepler long cadence time series with a model that simultaneously included
 490 the planetary transit and the stellar variability. The stellar variability was modeled with
 491 the RotationTerm Gaussian Process kernel in `exoplanet` (Foreman-Mackey et al. 2020). This
 492 kernel assumes 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).

498 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).

500 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



501 **Figure 6. Possible 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 are weakly anti-correlated ($\approx 2-\sigma$), which might 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).

502 the second half. The semi-amplitude of this deviation
 503 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 2- σ 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.

504 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 2- σ ; 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).

One 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 Kepler mission.⁵ Could the transit be produced by anything other than a planet orbiting this near-solar analog? Morton et al. (2016) validated the planet based on the transit shape, arguing that the

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).

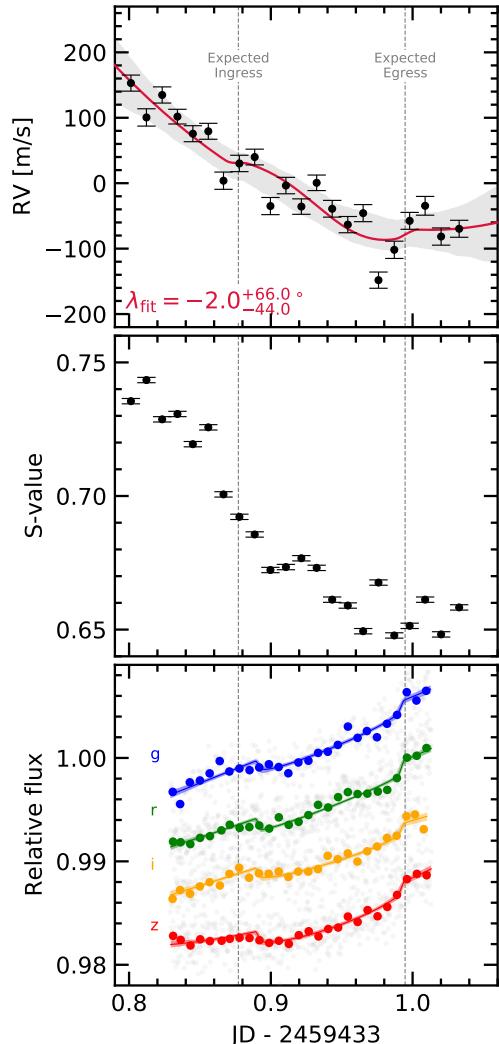


Figure 7. Keck/HIRES radial velocities and MuSCAT3 photometry from the transit of 2021 Aug 7. Top: The radial velocity jitter across the 15 minute exposures ($\sigma_{\text{RV}} \approx 30$ m s $^{-1}$) prevented us from detecting the RM effect; a model including the RM anomaly and a quadratic trend in time to fit the spot-induced ≈ 250 m s $^{-1}$ trend is shown (see Appendix C). Shaded bands show $2-\sigma$ 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.

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.

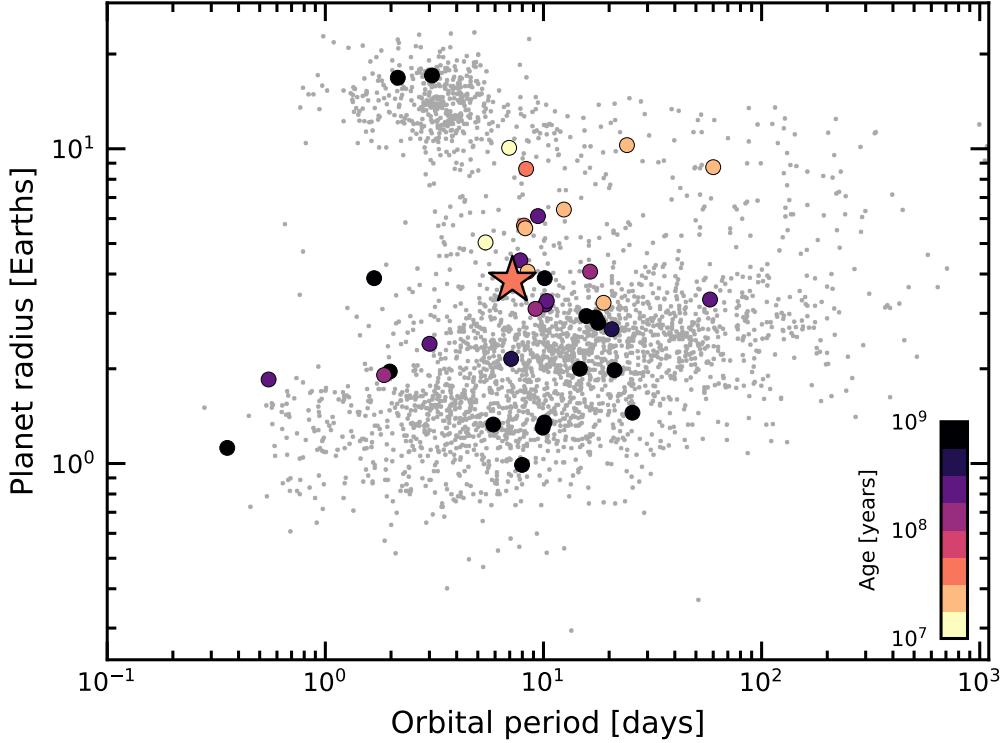


Figure 8. Radii, orbital periods, and ages of transiting exoplanets. Planets younger than a gigayear with $\tau/\sigma_\tau > 3$ are emphasized, where τ is the age and σ_τ is its uncertainty. Kepler 1627Ab is shown with a star. The large sizes of the youngest transiting planets could be explained by 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).

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 is \approx

4.6 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 $10-\sigma$. 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 lat-

682 ter assumption to be reasonably secure (Shapiro
683 et al. 2016; Montet et al. 2017; Reinhold & Hekker
684 2020).

685 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
686 spectroscopically with HIRES at the Keck-I telescope and photometrically in *griz* bands with MuS-
687 CAT3 at Haleakala Observatory. Details of the ob-
688 servation sequence are discussed in Appendix C;
689 Figure 7 shows the results. Although we did not
690 detect the Rossiter-McLaughlin (RM) anomaly, the
691 multi-band MuSCAT3 light curves show that the
692 transit is achromatic. Quantitatively, when we fit-
693 ted the MuSCAT3 photometry with a model that
694 lets the transit depths vary across each bandpass,
695 we found *griz* depths consistent with the Kepler
696 depth at 0.6, 0.3, 0.3, and 1.1- σ respectively. The
697 achromatic transits strongly favor Kepler 1627A as
698 the transit host, since Kepler 1627B is a much re-
699 dder star. Conditioned on the ephemeris and tran-
700 sit depth from the Kepler data, the MuSCAT3 ob-
701 servations also suggested a transit duration $17.3 \pm$
702 4.3 min shorter than the Kepler transits. However,
703 given both the lack of TDVs in the Kepler data
704 and the relatively low signal-to-noise of the MuS-
705 CAT3 transit, further photometric follow-up would
706 be necessary to determine whether the transit dura-
707 tion is actually changing.

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

717 5. DISCUSSION & CONCLUSIONS

718 Kepler 1627Ab provides a new extremum in the
719 ages of the Kepler planets, and opens multiple
720 avenues for further study. Observations of spec-
721 troscopic transits at greater signal-to-noise should
722 yield a measurement of the stellar obliquity, which
723 would confirm or refute the prograde orbital ge-
724 ometry suggested by the TTV-local slope corre-
725 lation. Separately, transit spectroscopy aimed at
726 detecting atmospheric outflows could yield insight
727 into the evolutionary state of the atmosphere (e.g.,
728 Ehrenreich et al. 2015; Spake et al. 2018; Vissapra-
729 gada et al. 2020). Observations that quantify the
730 amount of high-energy irradiation incident on the
731 planet would complement these efforts, by helping
732 to clarify the expected outflow rate (e.g., Poppens-
733 haeger et al. 2021). Finally, a challenging but infor-
734 mative quantity to measure would be the planet’s
735 mass. Measured at sufficient precision, for instance

736 through a multi-wavelength radial velocity cam-
737 paign, the combination of the size, mass, and age
738 would yield constraints on both the planet’s com-
739 position and its initial entropy (Owen 2020).

740 More immediately, the Kepler data may yet con-
741 tain additional information. For instance, one pos-
742 sible explanation for the transit asymmetry shown
743 in Figure 5 is that of a dusty asymmetric out-
744 flow. Dusty outflows are theoretically expected
745 for young mini-Neptunes, and the amplitude of the
746 observed asymmetry is consistent with predictions
747 (Wang & Dai 2019). A second possibility is that
748 the planetary orbit is slightly misaligned from the
749 stellar spin axis, and tends to transit starspot groups
750 at favored stellar latitudes. This geometry would
751 be necessary in order to explain how the starspot
752 crossings could add up coherently, given that the
753 planetary orbital period (7.203 days) and the stel-
754 lar rotation period (2.642 days) are not a rational
755 combination. Other possibilities including gravity
756 darkening or TTVs causing the asymmetry are dis-
757 favored (see Appendix B).

758 Beyond the asymmetric transits, Appendix D
759 highlights an additional abnormality in the short-
760 cadence Kepler data, in the arrival time distribu-
761 tion of stellar flares. We encourage its exploration
762 by investigators more versed in the topic than our-
763 selves.

764 In the context of the transiting planet population,
765 Kepler 1627Ab is among the youngest known (Fig-
766 ure 8). Comparable systems with precise ages in-
767 clude K2-33 (Mann et al. 2016; David et al. 2016),
768 DS Tuc (Benatti et al. 2019; Newton et al. 2019),
769 HIP 67522 (Rizzuto et al. 2020), TOI 837 (Bouma
770 et al. 2020; Martioli et al. 2021) and the four-planet
771 V1298 Tau (David et al. 2019). Kepler 1627Ab is
772 one of the smaller planets in this sample ($3.82 \pm$
773 $0.16 R_\oplus$), which could be linked to the selection
774 effects imposed by spot-induced photometric vari-
775 ability at very young ages (e.g., Zhou et al. 2021).
776 However, it seems that smaller planets could have
777 been detected: based on the per-target detection
778 contours, the Kepler pipeline’s median complete-
779 ness extended to $1.6 R_\oplus$ at 10 day orbital peri-
780 od, and $3.3 R_\oplus$ at 100 days (Burke & Catanzarite
781 2021). These limits account for the spot-
782 induced variability in the system through a cor-
783 rection based on the Combined Differential Photo-
784 metric Precision (CDPP) in the Kepler 1627 light
785 curve over the relevant transit timescales (Burke
786 & Catanzarite 2017). The large size of Ke-
787 pler 1627Ab relative to most Kepler mini-Neptunes
788 might therefore support a picture in which the typ-
789 ical $5 M_\oplus$ mini-Neptune (Wu 2019) loses a signif-
790 icant fraction of its primordial atmosphere over its
791 first gigayear (Owen & Wu 2013; Ginzburg et al.
792

796 2018). It could also be consistent with a scenario
 797 in which an earlier “boil-off” of the planet’s atmosphere during disk dispersal decreases the
 798 entropy of the planetary interior, leading to a
 799 $\sim 10^8$ year Kelvin-Helmholtz cooling and contraction
 800 timescale (Owen 2020). Confirming either of
 801 these scenarios would require a measurement of
 802 the planetary mass; otherwise, alternative explanations
 803 for its large size also include that it is abnor-
 804 mally massive, or that it has an abnormally large
 805 envelope to core mass ratio.

806 Ultimately, the main advance of this work is a
 807 precise measurement of the age of Kepler 1627Ab.
 808 This measurement was enabled by identifying the
 809 connection of the star to the δ Lyr cluster using
 810 Gaia kinematics, and by then using the Gaia color-
 811 absolute magnitude diagram and TESS stellar ro-
 812 tation periods to verify the cluster’s existence. Ta-
 813 ble 3 enables similar cross-matches for both known
 814 and forthcoming exoplanet systems (*e.g.*, Guerrero
 815 et al. 2021). Confirming these candidate associa-
 816 tions using independent age indicators is essential
 817 because their false positive rates are not known. A
 818 related path is to identify new kinematic associa-
 819 tions around known exoplanet host stars using po-
 820 sitions and tangential velocities from Gaia, and to
 821 verify these associations with stellar rotation per-
 822 iodis and spectroscopy (*e.g.*, Tofflemire et al. 2021).
 823 Each approach seems likely to expand the census
 824 of planets with precisely measured ages over the
 825 coming years, which will help in deciphering the
 826 early stages of exoplanet evolution.

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875 **Software:** `altaipony` (Ilin et al. 2021),
 876 `astrobase` (Bhatti et al. 2018), `astropy` (As-
 877 trophy Collaboration et al. 2018), `astroquery`
 878 (Ginsburg et al. 2018), `corner` (Foreman-Mackey
 879 2016), `exoplanet` (Foreman-Mackey et al.
 880 2020), and its dependencies (Agol et al. 2020; Kip-
 881 ping 2013; Luger et al. 2019; Theano Develop-
 882 ment Team 2016), `PyMC3` (Salvatier et al. 2016),
 883 `scipy` (Jones et al. 2001), `TESS-point` (Burke
 884 et al. 2020), `wotan` (Hippke et al. 2019).

885 **Facilities:** *Astrometry:* Gaia (Gaia Col-
 886 laboration et al. 2018b, 2021a). *Imaging:*
 887 Second Generation Digitized Sky Survey.
 888 Keck:II (NIRC2; [www2.keck.hawaii.edu/inst/
 889 nirc2](http://www2.keck.hawaii.edu/inst/nirc2)). Gemini:North ('Alopeke; Scott et al. 2018,
 890 2021). *Spectroscopy:* Keck:I (HIRES; Vogt et al.
 891 1994). *Photometry:* Kepler (Borucki et al. 2010),
 892 MuSCAT3 (Narita et al. 2020), TESS (Ricker et al.
 893 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 (NIRC2 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), ⁵HIRESS 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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1232

APPENDIX

1233

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

1234 The v0.6 CDIPS target catalog (Table 3) includes stars that are young, age-dated, and age-dateable. By
 1235 “age-dateable”, we mean that the stellar age should be measurable at greater precision than that of a typical
 1236 FGK field star, through either isochronal, gyrochronal, or spectroscopic techniques. As in Bouma et al.
 1237 (2019), we collected stars that met these criteria from across the literature. Table 4 gives a list of the studies
 1238 included, and brief summary statistics. The age measurement methodologies adopted by each study differ: in
 1239 many, spatial and kinematic clustering has been performed on the Gaia data, and ensemble isochrone fitting
 1240 of the resulting clusters has been performed (typically focusing on the turn-off). In other studies however,
 1241 the claim of youth is based on the location of a single star in the color-absolute magnitude diagram, or on
 1242 spectroscopic information.

1243 One major change in Table 3 relative to the earlier iteration from Bouma et al. (2019) is that the extent
 1244 of Gaia-based analyses has now matured to the point that we can neglect pre-Gaia cluster memberships,
 1245 except for a few cases with spectroscopically confirmed samples of age-dated stars. The membership lists for
 1246 instance of Kharchenko et al. (2013) and Dias et al. (2014) (MWSC and DAML) are no longer required. This
 1247 is helpful for various post-processing projects, since the field star contamination rates were typically much
 1248 higher in these catalogs than in the newer Gaia-based catalogs.

1249 The most crucial parameters of a given star for our purposes are the Gaia DR2 `source_id`, the cluster or
 1250 group name (`cluster`), and the age. Given the hierarchical nature of many stellar associations, we do not
 1251 attempt to resolve the cluster names to a single unique string. The Orion complex for instance can be divided
 1252 into almost one hundred kinematic subgroups (Kounkel et al. 2018). Based on Figure 1, the δ Lyr cluster may
 1253 also be part of a similar hierarchical association. Similar complexity applies to the problem of determining
 1254 homogeneous ages, which we do not attempt to resolve. Instead, we simply merged the cluster names and
 1255 ages reported by various authors into a comma-separated string.

1256 This means that the `age` column can be null, for cases in which the original authors did not report an age,
 1257 or for which a reference literature age was not readily available. Nonetheless, since we do prefer stars with
 1258 known ages, we made a few additional efforts to populate this column. When available, the age provenance
 1259 is from the original analysis of the cluster. In a few cases however we adopted other ages when string-
 1260 based cross-matching on the cluster name was straightforward. In particular, we used the ages determined
 1261 by Cantat-Gaudin et al. (2020) to assign ages to the clusters from Gaia Collaboration et al. (2018a), Cantat-
 1262 Gaudin et al. (2018), Castro-Ginard et al. (2020), and Cantat-Gaudin & Anders (2020).

1263 The catalogs we included for which ages were not immediately available were those of Cotten & Song
 1264 (2016), Oh et al. (2017), Zari et al. (2018), Gagné et al. (2018a), Gagné et al. (2018b), Gagné & Faherty
 1265 (2018), and Ujjwal et al. (2020). While in principle the moving group members discussed by Gagné et al.
 1266 (2018a,b); Gagné & Faherty (2018) and Ujjwal et al. (2020) have easily associated ages, our SIMBAD cross-
 1267 match did not retain the moving group identifiers given by those studies, which should therefore be recovered
 1268 using tools such as BANYAN Σ (Gagné et al. 2018b). We also included the SIMBAD object identifiers `TT*`,
 1269 `Y*O,Y*?`, `TT?`, and `pMS*`. Finally, we included every star in the NASA Exoplanet Archive planetary system
 1270 (`ps`) table that had a Gaia identifier available (Akeson et al. 2013). If the age had finite uncertainties, we also
 1271 included it, since stellar ages determined through the combination of isochrone-fitting and transit-derived
 1272 stellar densities typically have higher precision than from isochrones alone.

1273 For any of the catalogs for which Gaia DR2 identifiers were not available, we either followed the spatial
 1274 (plus proper-motion) cross-matching procedures described in Bouma et al. (2019), or else we pulled the
 1275 Gaia DR2 source identifiers associated with the catalog from SIMBAD. We consequently opted to drop the
 1276 `ext_catalog_name` and `dist` columns maintained in Bouma et al. (2019), as these were only popu-
 1277 lated for a small number of stars. The technical manipulations for the merging, cleaning, and joining were
 1278 performed using pandas (McKinney 2010). The eventual cross-match (using the Gaia DR2 `source_id`)
 1279 against the Gaia DR2 archive was performed asynchronously on the Gaia archive website.

1280

B. THE TRANSIT ASYMMETRY

1281

B.1. How Robust is the Asymmetric Transit?

1282 As a means of exploring the robustness of the transit asymmetry, Figures 9, 10, and 11 show the Kepler data
 1283 binned in three ways: over Kepler quarters, Julian years, and quartiles of local slope. Over Kepler quarters
 1284 (Figure 9), Quarter 6 shows the strongest asymmetry: a deviation of about 3 ppt from expectation. Quarter

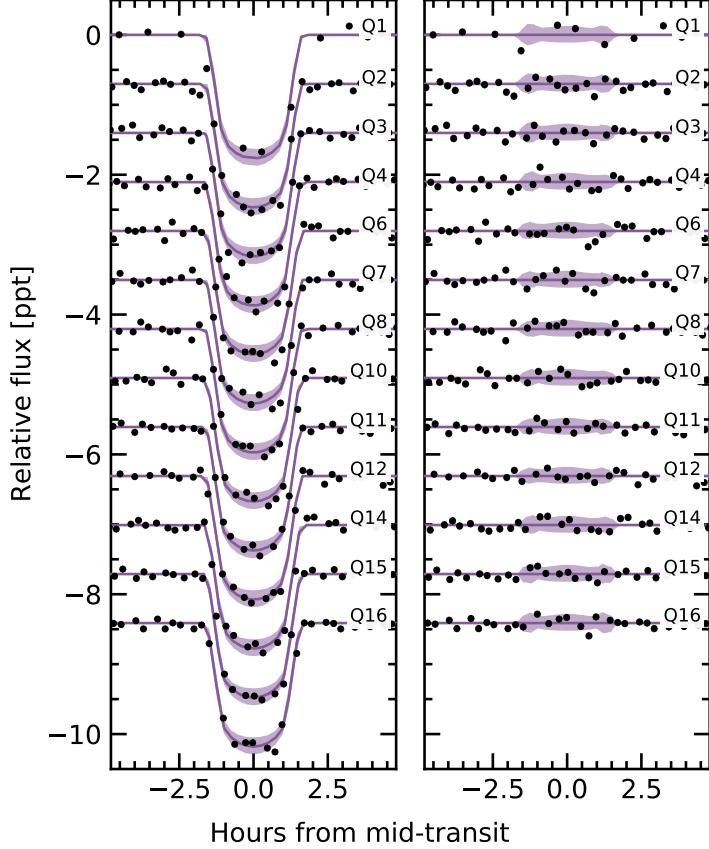


Figure 9. Transit model residuals through time (binned by Kepler quarter). *Left:* Phase-folded transit of Kepler 1627b, with stellar variability removed. Black points are binned to 20 minute intervals. The 2σ model uncertainties and the maximum *a posteriori* model are shown as the faint purple band,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

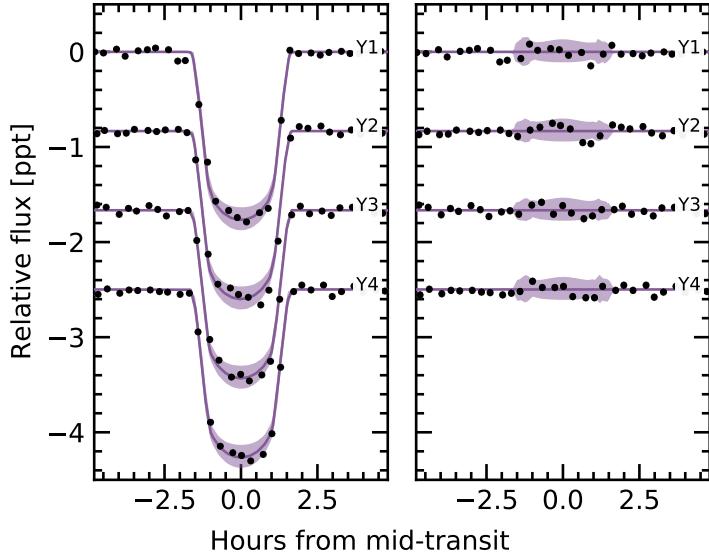


Figure 10. Transit model residuals through time (binned by year of observation). *Left:* Phase-folded transit of Kepler 1627b, with stellar variability removed. Points and models are as in Figure 9. *Right:* As on the left, with the transit removed.

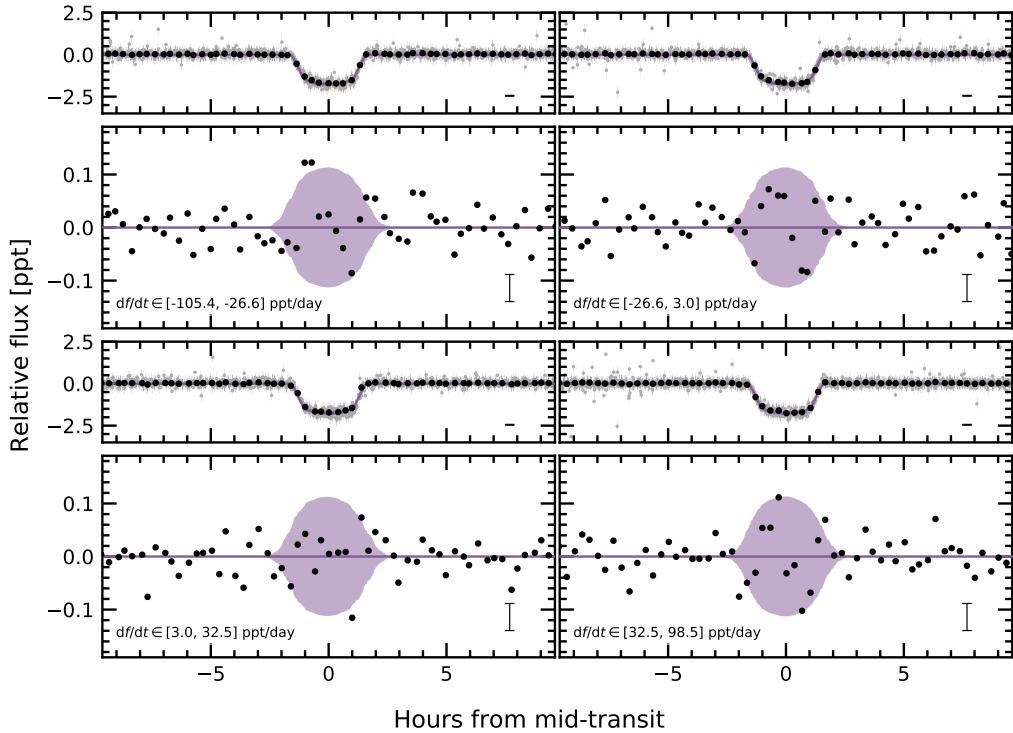


Figure 11. Transit models and residuals, binned by quartiles in the local slope of the light curve. Representative uncertainties for the black points (binned at 20 minute intervals) are shown in the lower right of each panel. A similar transit asymmetry to that shown in Figure 5 seems to be present in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

1285 7 shows an anomaly at roughly the same transit phase. Year 2 correspondingly shows the strongest anomaly
 1286 out of any year in Figure 10; the asymmetry is visually apparent however in each of the four years.

1287 To bin by quartiles in local slope, we used our measurements of the local linear slopes in each of the
 1288 observed transit windows (144 transits total). Four outlier transits were removed, leaving 140 transits. These
 1289 were then divided into quartiles, so that each panel shows 35 transits binned together. The exact light curve
 1290 slope intervals are listed in the lower left panels of Figure 11. Binned by local slope quartiles (Figure 11),
 1291 the asymmetry is visually present in three of the four quartiles: the only bin in which it does not appear is
 1292 $df/dt \in [3.0, 32.5] \text{ ppt day}^{-1}$.

1293 Within the theory presented by Mazeh et al. (2015), unresolved starspot crossings cause the weak correlation
 1294 between TTVs and the local light curve slope (Figure 6). In this model, we would expect the light curves
 1295 with the most negative local slopes to have the largest positive TTVs, due to spot crossing events during the
 1296 latter half of transit. The upper-left panel of Figure 11 agrees with this expectation. However, we would also
 1297 expect the sign of the effect to reverse when considering the most positive local slopes (most negative TTVs).
 1298 The lower-right panel of Figure 11 contradicts this expectation: the residual in both cases maintains the same
 1299 parity! On the one hand, this shows that the residual is not dependent on the local light curve slope, which
 1300 lowers the likelihood that it might be an artifact of our detrending methods. On the other, it raises the question
 1301 of whether unresolved starspot crossings are indeed the root cause of the correlation shown in Figure 6. While
 1302 we do not have a solution to this contradiction, the injection-recovery tests discussed in Section 4.1.3 provide
 1303 some assurance that the TTV-slope correlation is not simply a systematic artifact.

1304

B.2. Interpretation

1305 The transit asymmetry seems robust against most methods of binning the data, though with some caveats
 1306 (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).
 1307 Nonetheless, if the asymmetric were systematic we might expect its parity to reverse as a function of the sign
 1308 of the local slope, and it does not. We therefore entertained four possible astrophysical explanations: gravity
 1309 darkening, transit timing variations, spot-crossing events, and a persistent asymmetric dusty outflow.

1310 Gravity darkening is based on the premise that the rapidly rotating star is oblate, and brighter near the
 1311 poles than the equator (e.g., Masuda 2015). The fractional transit shape change due to gravity darkening
 1312 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 MuSCAT3 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

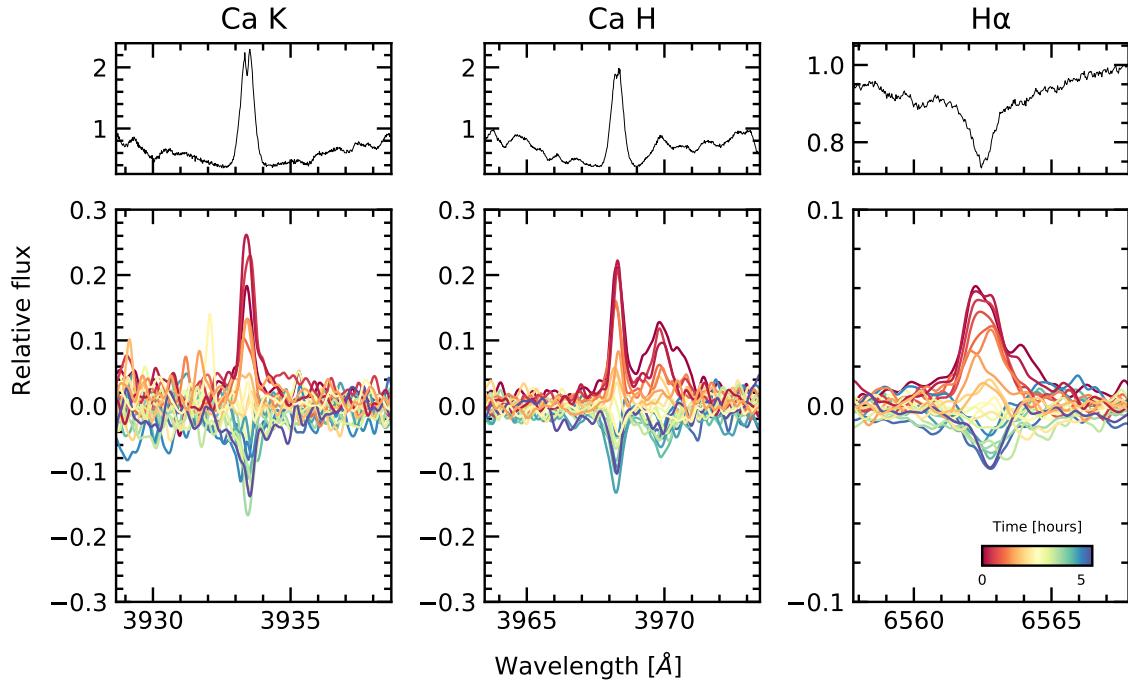


Figure 12. Spectroscopic activity indicators during the transit of 2021 Aug 7. The *top panels* show the median line profiles Ca K, Ca H, and H α line profiles from the HIRES spectra. The *lower panels* show the differences of each individual spectrum relative to the median spectrum. The bump in the 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 $0.5 P_{\text{rot}}$ or $0.25 P_{\text{rot}}$ (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

¹³⁹⁵ 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
¹³⁹⁶ 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.

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

¹³⁹⁷ There is therefore no evidence to prefer the model with the RM effect against a model that only accounts
¹³⁹⁸ for the stellar variability. The “only quadratic” model does particularly well because it can inflate the jitter
¹³⁹⁹ term to account for scatter during the transit (even if the scatter contains astrophysics!), and it has fewer free
¹⁴⁰⁰ parameters. However, we cannot justify a physical prior on the jitter term, because we do not understand
¹⁴⁰¹ the origin of the exposure-to-exposure scatter. As noted above, the velocity deviations from starspots are
¹⁴⁰² expected to have contributions at the stellar rotation frequency, or harmonics thereof. This jitter is present on
¹⁴⁰³ the exposure timescale (15 minutes), which is only 0.4% of the stellar rotation period; it is not obvious that
¹⁴⁰⁴ starspots would be the culprit.

¹⁴⁰⁵ The amplitude of both the spot-induced trend and the jitter are somewhat larger than recent comparable
¹⁴⁰⁶ measurements in systems such as AU Mic (Palle et al. 2020), DS Tuc (Montet et al. 2020; Zhou et al. 2020)
¹⁴⁰⁷ and TOI 942 (Wirth et al. 2021). One possible explanation for the jitter is that it is astrophysical in origin,
¹⁴⁰⁸ and that it is caused by some novel process operating on the surface of Kepler 1627A. Another possibility
¹⁴⁰⁹ is that our RV analysis underestimates our measurement uncertainties; in order to achieve the requisite time-
¹⁴¹⁰ sampling the S/N per resolution element in our spectra was 70 to 80, which is lower than desired for deriving
¹⁴¹¹ high-precision velocities. In addition, the rapid rotation of the star could affect accuracy of the uncertainties
¹⁴¹² from the velocity extraction. Observations at higher S/N are necessary to distinguish these two possibilities,
¹⁴¹³ and remain worthwhile in order to clarify the orbital geometry of Kepler 1627Ab. Useful next steps would
¹⁴¹⁴ include transit observations with a stabilized spectrograph in the optical (e.g., Gibson et al. 2016; Seifahrt
¹⁴¹⁵ 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

¹⁴¹⁶
¹⁴¹⁷ In addition to the 3.9 years of long cadence data,
¹⁴¹⁸ short cadence (1-minute) Kepler observations were
¹⁴¹⁹ acquired over 97.7 days during Quarter 15. The

¹⁴²⁰ short cadence light curve shows a higher rate of
¹⁴²¹ flaring than visible in the long cadence data (Figure 13). We analyzed the short cadence light curve
¹⁴²² and its flares according to the following procedure.
¹⁴²³

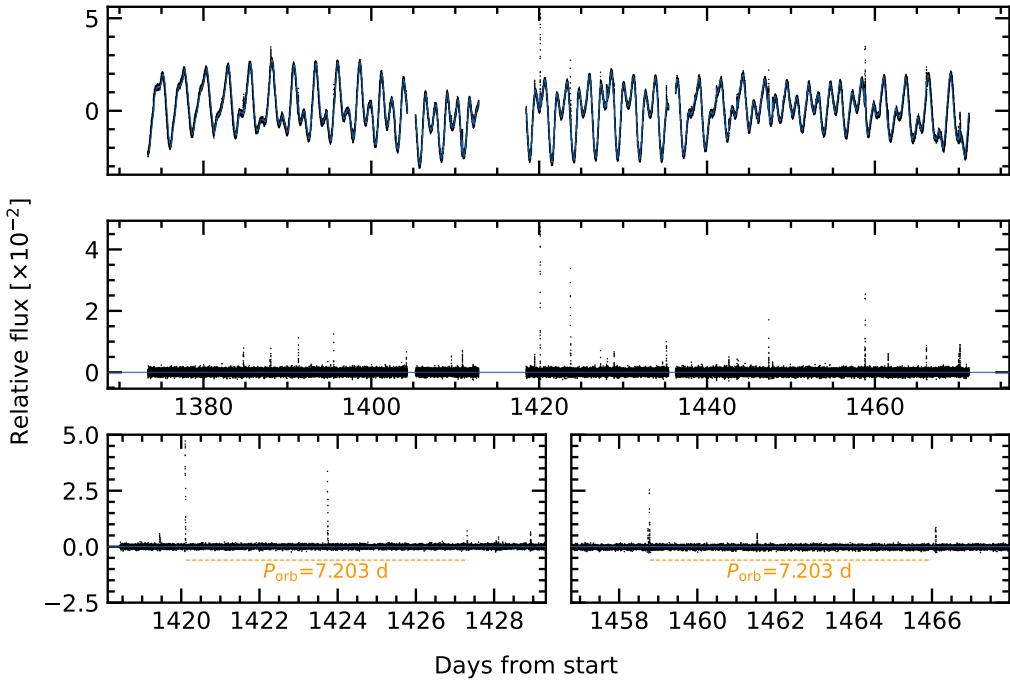


Figure 13. Flares in Kepler 1627. *Top:* The 1-minute cadence Kepler data (black points) is shown with a stellar variability model superposed (blue line). *Middle:* Residual after subtracting the stellar variability model. Flares appear as spikes. *Bottom:* Zooms of the brightest, and third-brightest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

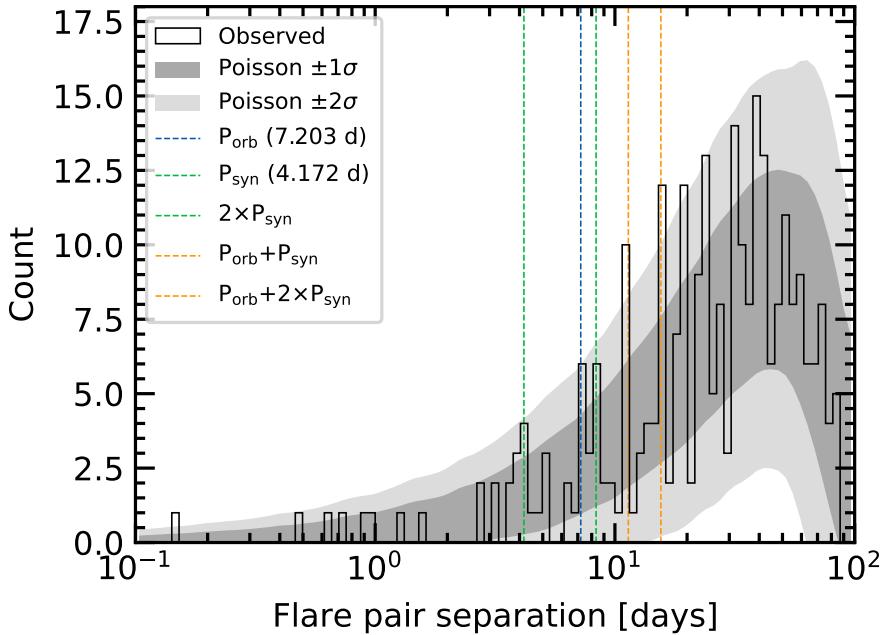


Figure 14. Statistics of inter-flare arrival times. 24 flares were recorded with amplitudes exceeding 0.5% over the 97.7 days of short cadence observations. The histogram of the time intervals between every possible pair of flares is shown in black. Some plausibly important timescales for star-planet 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 5- σ threshold.

- 1424 1. Fit the starspot-induced variability using a
 1425 Gaussian Process with a SHOTerm kernel,
 1426 a white-noise jitter term, and the mean flux.
 1427 2. Select points more than twice the median ab-
 1428 solute deviation from the residual, and ex-
 1429 clude them from the light curve (these points
 1430 include the flares). Repeat Step 1.
 1431 3. Using the residual from Step 2, identify all
 1432 flares, requiring them to be at least 20 ca-
 1433 dences apart, at least 7 median absolute de-
 1434 viations above the median baseline, and last-
 1435 ing at least 2 cadences in duration. Build the
 1436 mask spanning these times, from 5 minutes
 1437 before each flare begins to 2.5 minutes after
 1438 the final flare cadence. Repeat Step 1 a final
 1439 time.

1440 The final step of flare identification and fitting was
 1441 performed using `altaipony` (Davenport 2016;
 1442 Ilin et al. 2021). The analytic flare model is from
 1443 Davenport et al. (2014) and it parametrizes the flare
 1444 with a start time, an exponential lag time, and an
 1445 amplitude.

1446 There were $N_f = 24$ flares that exceeded 0.5% in
 1447 relative flux during the short cadence observations.
 1448 These 24 flares spanned a total of 6.5 hours (~ 15
 1449 minutes per flare). Inspecting the data, we noticed
 1450 a coincidence in the flare arrival times. The co-
 1451 incidence is that despite the low flare duty cycle,
 1452 one orbital period after the brightest flare, a second
 1453 flare followed. This and a similar event are shown
 1454 in Figure 13. The timing error is good to a $\approx 0.2\%$
 1455 difference from the orbital period, which given the
 1456 duty cycle seems *a priori* unlikely. If we consider
 1457 flares falling within 2% of the planet’s orbital pe-
 1458 riod after a previous flare, then 4 of the 24 flare
 1459 events have candidate “successors”.

1460 As with any coincidence, if one does not have a
 1461 firm prediction, it is difficult to assess whether a
 1462 surprise is statistically significant. Since our sur-
 1463prise was specifically at the inter-arrival time of
 1464 certain flares coinciding with special time inter-
 1465 vals, we performed the following analysis. First,
 1466 we considered all unordered pairs of flares. For
 1467 N flares there are $\binom{n}{2}$ such pairs (for our case,
 1468 276 pairs). We then compared the distribution of
 1469 the pair separations against that of a Poisson dis-
 1470 tribution. Specifically, we drew $N_f = 24$ samples
 1471 from a Poisson distribution with $\lambda = \Delta t / N_f$, for
 1472 $\Delta t = 97.7$ days the total duration of the observa-
 1473 tions, and repeated the draw 10^3 times with unique
 1474 random seeds.

1475 Figure 14 shows the results. The vertical lines
 1476 in the figure show the planetary orbital period,
 1477 the synodic period $P_{\text{syn}} = (P_{\text{rot}}^{-1} - P_{\text{orb}}^{-1})^{-1}$, and lin-
 1478 ear combinations thereof. The tidal period (half
 1479 the synodic period) is not shown. The bins are

1480 logarithmically spaced to give 100 bins between
 1481 the minimum and maximum ordinate values. The
 1482 gray bands express the range of values observed
 1483 from the Poissonian draws. While it does seem
 1484 like an odd coincidence for peaks in the observed
 1485 flare arrival time distribution to coincide with the
 1486 locations of these “special intervals”, the statisti-
 1487 cal evidence for a non-Poissonian process driving
 1488 the flares does not seem especially overwhelming.
 1489 More quantitatively, the peaks observed at the or-
 1490 bital and synodic periods are within the $\pm 2\sigma$ range
 1491 of a Poissonian process, and those at $P_{\text{orb}} + P_{\text{syn}}$ and
 1492 $P_{\text{orb}} + 2P_{\text{syn}}$ are only slightly above this range. With
 1493 that said, future analyses of these data by investiga-
 1494 tors with more knowledge of this topic could very
 1495 well yield more quantitative insights. Such analy-
 1496 ses should keep in mind an important caveat: the
 1497 amplitude distribution of M-dwarf flares extends
 1498 up to many times the quiescent flux (see Figure 7 of
 1499 Günther et al. 2020). A flare on Kepler 1627B pro-
 1500 ducing double its quiescent white-light flux would
 1501 yield a $\approx 1\%$ apparent amplitude. Such flares could
 1502 represent a significant fraction of those in the Ke-
 1503 pler observations.