Observationally Constraining the StarSpot Properties of Magnetically Active M67 Sub-subgiant S1063

Natalie M. Gosnell1, Michael A. Gully-Santiago2, Emily M. Leiner3, and Benjamin M. Tofflemire2,4

1 Department of Physics, Colorado College, 14 E. Cache La Poudre St., Colorado Springs, CO 80903, USA; ngosnell@coloradocollege.edu
2 Department of Astronomy, The University of Texas at Austin, Austin, TX 78712, USA
3 Center for Interdisciplinary Exploration and Research in Astrophysics (CIERA) and Department of Physics and Astronomy, Northwestern University, 1800 Sherman Ave., Evanston, IL 60201, USA

Received 2021 June 2; revised 2021 November 1; accepted 2021 November 2; published 2022 January 20

Abstract

Our understanding of the impact of magnetic activity on stellar evolution continues to unfold. This impact is seen in sub-subgiant stars, defined to be stars that sit below the subgiant branch and red of the main sequence in a cluster color–magnitude diagram. Here we focus on S1063, a prototypical sub-subgiant in open cluster M67. We use a novel technique combining a two-temperature spectral decomposition and light-curve analysis to constrain starspot properties over a multiyear time frame. Using a high-resolution near-infrared IGRINS spectrum and photometric data from K2 and ASAS-SN, we find a projected spot filling factor of 32% ± 7% with a spot temperature of 4000 ± 200 K. This value anchors the variability seen in the light curve, indicating the spot filling factor of S1063 ranged from 20% to 45% over a four-year time period with an average spot filling factor of 30%. These values are generally lower than those determined from photometric model comparisons but still indicate that S1063, and likely other sub-subgiants, are magnetically active spotted stars. We find observational and theoretical comparisons of spotted stars are nuanced due to the projected spot coverage impacting estimates of the surface-averaged effective temperature. The starspot properties found here are similar to those found in RS CVn systems, supporting classifying sub-subgiants as another type of active giant star binary system. This technique opens the possibility of characterizing the surface conditions of many more spotted stars than previous methods, allowing for larger future studies to test theoretical models of magnetically active stars.

Unified Astronomy Thesaurus concepts: Subgiant stars (1646); Stellar activity (1580); Starspots (1572); Spectroscopy (1558); Light curves (918); Open star clusters (1160); Near infrared astronomy (1093)

1. Introduction

Recent studies illuminate the important role stellar magnetic activity has on stellar structure, as the impact of stellar activity and magnetic fields is seen throughout the Hertzsprung–Russell (HR) Diagram. Magnetic activity biases isochronal ages of young clusters (Somers & Pinsonneault 2015a), inflates radii of active M-dwarfs (Morales et al. 2010; Torres 2010; Jackson et al. 2019), causes multiple redder turnoffs in stellar clusters (Bastian & de Mink 2009; Sun et al. 2019), and alters the pulsation modes of red giants (Gaumé et al. 2020). Our collective understanding of stellar structure has diverged from nonmagnetic theoretical expectations, thanks to careful observational studies of both magnetically active and inactive systems.

One increasingly conspicuous example of the impact of magnetic activity is the class known as sub-subgiant (SSG) stars. SSGs lie below the subgiant branch on a cluster optical color–magnitude diagram (CMD), but are too red to be on the main sequence. These anomalously underluminous subgiants stand out in evolved open clusters and globular clusters, with 65 sub-subgiants currently identified across 16 different clusters (Geller et al. 2017). Where orbital information is available, the majority of these cluster SSGs are single-lined spectroscopic binaries with short orbital periods of a few days. Many SSGs also exhibit moderate X-ray luminosities of 10^{30}–10^{31} erg s\(^{-1}\) (Geller et al. 2017, and references therein).

The existence of SSGs cannot be explained with typical single-star evolutionary pathways. Geller et al. (2017) and Leiner et al. (2017) put forth four possible formation scenarios for SSGs: mass transfer in a binary system, a collision between two main-sequence stars, removing material from a subgiant star envelope through a dynamical encounter, and reduced luminosity as a result of convection being inhibited due to the presence of strong magnetic fields. Leiner et al. (2017) conclude that mass transfer and dynamical formation pathways cannot account for the observed frequencies of SSGs in open clusters. The observed SSGs may instead be the result of strong magnetic fields and the affiliated starspot covering fractions suppressing convective energy transport. At the specific evolutionary stage of a subgiant star, this would result in the dramatic underluminosity apparent in the SSG population, although more work into the physics of this mechanism is necessary.

Observational evidence supports this interpretation, as hallmarks of activity such as H\(_\alpha\) and X-ray emission and optical variability (e.g., large spot modulation, flares) are seen throughout the known SSG population (Geller et al. 2017). This interpretation is further supported by theoretical work demonstrating strong internal magnetic fields can inhibit convective energy transport (Chabrier et al. 2007) and cause radius inflation (Feiden & Chaboyer 2013). Treatments of the surface properties of magnetically active spotted stars also exhibit an underluminosity in the SSG region of a CMD.

4 51 Pegasi b Fellow.
(Somers et al. 2020). However, comparison between these model predictions and observations can be difficult.

In order to characterize the impact of magnetic fields and stellar activity on stellar evolution, we would ideally directly measure the stellar radius and internal magnetic field strength to calibrate how the star inflates due to inhibited convective energy transport, thereby explaining the CMD positions of SSGs and other active stars. Although ensembles of stars show evidence for an average magnetic radius inflation of 10%–15% (Jackson et al. 2018; Kesseli et al. 2018), these quantities are difficult or impossible to measure at the precision required to demonstrate inflation for individual magnetically active systems.

Starspots have become a rich observational proxy for gauging the activity level of stars that may be magnetically inflated without needing to estimate magnetic field strengths. A full accounting of starspots requires careful consideration of geometrical degeneracies. Monochromatic light curves can indicate the presence of starspots (McQuillan et al. 2014), but only provide a lower limit on the differential spot coverage between the most- and least-spotted hemispheres. Longitudinally symmetric starspot geometries evade detection in monochromatic light curves alone (Luger et al. 2019). Disk-integrated covering fractions can be obtained from TiO band observations (O’Neal et al. 1996; Fang et al. 2016; Morris et al. 2019), but measuring the spot configuration typically requires Doppler imaging or interferometry studies restricted to only the brightest and most nearby sources (Roettenbacher et al. 2016).

Testing the next era of stellar activity models requires precision methodologies to measure spot covering fractions of a larger number of targets, including SSGs.

Starspots emit a spectrum of their own at a lower temperature and with distinct absorption features compared to the ambient photosphere. The observed spectrum is therefore a composite of the spot and photosphere spectra, which can be deconvolved. Gully-Santiago et al. (2017) extended the Starfish$^5$ (Czekala et al. 2015) spectral inference framework to support composite spectra and two-temperature probabilistic spectral decomposition. This deconvolution process constrains the spot covering fraction as well as the spot and photosphere temperatures. The resulting disk-average spot properties anchor a simultaneous light-curve flux to the starspot coverage fraction. This anchored value serves as a benchmark for interpreting long-term (multiyear) flux variability (Neff et al. 1995). This strategy only requires high-resolution near-infrared (near-IR) echelle spectroscopy and photometric monitoring, making it less demanding on telescope resources than either Doppler imaging or interferometry. The technique is amenable to sources with narrow to moderate width spectral lines and stars with any stellar inclination, a distinct advantage over Doppler imaging. These advantages dramatically increase the number of sources for which we can observationally constrain spot covering fractions.

In this paper, we demonstrate the power of this methodology by focusing on a single SSG system, S1063 (Sanders 1977; Mathieu et al. 2003) in the open cluster M67. This system is a prototypical SSG, with a single-lined spectroscopic orbital period of $P_{\text{orb}} = 18.38775 \pm 0.00009$ days, eccentricity $e = 0.207 \pm 0.009$, and a mass fraction of $1.4 \pm 0.04 \times 10^{-2} M_\odot$ (Geller et al. 2021). S1063 has an X-ray luminosity of $1.3 \times 10^{31}$ erg s$^{-1}$ (van den Berg et al. 1999), and a variable light curve in K2 and ASAS-SN (Section 2.4). Gaia DR2 astrometry (Gaia Collaboration et al. 2016, 2018) indicates a parallax $(1.17 \pm 0.025$ mas) and proper motion for S1063 (Gaia DR2 604921030968952832) consistent with other M67 members approaching 100% membership probability (Gao 2018). We present our observational data products in Section 2, and subsequent analysis in Section 3. Our results are given in Section 4, with a discussion in Section 5 including additional discussion of the possible systematic uncertainties that may bias our results. Finally, our conclusions are outlined in Section 6.

2. Observation and Data Reduction

2.1. IGRINS Observations

A high-resolution spectrum of S1063 was acquired with the $R \sim 45,000$ Immersion Grating Infrared Spectrograph (IGRINS; Park et al. 2014) at UT 2015 April 26 03$^{3}$29$^{s}$ at the 2.7 m Harlan J. Smith Telescope at McDonald Observatory. Eight 600 s individual exposures were acquired in an ABBA nod pattern at an airmass of 1.2. The sky emission lines and telluric lines were removed with the IGRINS Pipeline Package (PLP; Lee & Gullikson 2016) and a reference AOV star acquired nearby in time and airmass. The $H$-band spectra exhibited a signal-to-noise ratio (S/N) of approximately 50 per pixel. The $K$-band spectra possessed low $S/N$ and were excluded from further analysis. The observation occurred at a binary orbital phase of 0.148 (Geller et al. 2021), near an extreme of the RV variation.

2.2. K2 Superstamp Light Curves

The Kepler spacecraft targeted S1063 (EPIC 211414597) during the K2 mission (Howell et al. 2014) in Campaigns 5, 16, and 18 as part of the M67 superstamps. The instrumental point-spread function (PSF) of S1063 fell entirely within the oversized K2 target pixel files in Campaign 5 (K2 Custom Aperture ID 200008674, channel 13) and Campaign 18 (K2 Custom Aperture ID 200233338). Aperture photometry was conducted with interactively assigned custom apertures using the lightkurve.interact() feature (Barentsen et al. 2019). The apertures were chosen to minimize flux loss out of the aperture due to spacecraft-induced image motion, while avoiding low-$S/N$ pixels and the wings of adjacent PSFs (see Figure 1). The Campaign 16 source PSF overlapped the edge of Custom Aperture ID 200200534, therefore a mosaic of adjacent superstamps was assembled before conducting aperture photometry. We detrended motion-induced image artifacts with the Self Flat Field algorithm (Vanderburg & Johnson 2014) implemented in lightkurve.

2.3. Ground-based Photometric Monitoring

We retrieved All-Sky Automated Survey for Supernovae (ASAS-SN; Shappee et al. 2014) light curves from the Sky Portal (Kochanek et al. 2017). The light curves contained 758 epochs of $V$-band photometry spanning 2014–2018 (ASASSN-V J085113.44+115139.7) and 823 epochs of $g$-band photometry spanning mid-2017–2018. The $\sim 8"$ ASAS-SN pixels may cause some PSF blending of the nearby—albeit fainter—source seen at the bottom of Figure 1. The pixel images were not available to evaluate the extent of blending. Nearby sources were verified to be nonvariable in K2 data, so such blending

---

$^5$ https://github.com/Starfish-develop/Starfish
would be expected to subdue the overall ASAS-SN light-curve modulations while keeping the period and phase intact.

### 2.4. Intercampaign Relative Photometry with K2 Full Frame Images

Variation in stellar activity on S1063 can potentially change the stellar brightness on timescales comparable to the separation of the three campaigns of K2 observations. The comparison of flux levels among repeated K2 campaigns requires accounting for detector responsivity degradation on these same timescales. The absolute sensitivity of the Kepler detector pixels decays at approximately 1% yr$^{-1}$, due to sudden pixel sensitivity dropouts and other environmental lifetime factors (Montet et al. 2017).

To account for sensitivity changes, we calibrate the system-integrated throughput for Kepler detector channels including the M67 field for Campaigns 5, 16, and 18. We measure aperture photometry for approximately 2000 isolated reference stars from the Full Frame Images (FFIs), keeping only those stars that were observed in all three campaigns. Compared to Campaign 5, the reference stars have a median flux of 93.9% ± 4.2% in Campaign 16 and a median flux of 98.2% ± 2.8% in Campaign 18. Campaigns 5 and 18 were observed on the same detector channel, while a different detector channel was used for Campaign 16; therefore, the Campaign 16 offset is not a significant measure of detector degradation across campaigns. We use a Lomb–Scargle periodogram (Scargle 1982) on each campaign independently and find the rotation period to be consistent across all campaigns, with a mean rotation period of $P_{\text{rot}} = 23.5 \pm 0.2$ days. The rotation period is longer than the known binary period of $P_{\text{orb}} = 18.38775$ days because the slightly eccentric ($e = 0.2$) system is not yet fully synchronized. This is expected, as the tidal circulation period in M67 is approximately 11 days (Geller et al. 2021). The periodograms and phase-folded light curves are shown in Figure 2. We note that the light curves of all three campaigns exhibit flaring events.

### 3. Analysis

Characterizing the long-term starspot coverage of S1063 requires connecting coarse ground-based and precision space-based photometry—ASAS-SN and K2—alongside precision IGRINS spectroscopy. Here, we lay out the calibration of these data sets to accommodate their wide range in data quality.

#### 3.1. Joint Modeling of ASAS-SN and K2 Light Curves

We attempt to unify the ASAS-SN, K2 long-cadence, and K2 FFI data points into a single global light curve. The ASAS-SN V-band and K2 photometric system throughputs share significant, but not identical, wavelength coverage. We investigate the effect of bandpass differences in Section 4.1.1, and treat the Kepler and V bands as adequately similar for this purpose. Our methodology can be thought of as learning a bandpass or “notch” filter from the K2 data and applying it to the ASAS-SN data. The advantage of this approach is to combine near-in-time ASAS-SN data points in a way that preserves the correlation structure known from K2 without distorting the light-curve peaks and valleys through a binning procedure. A global light curve constructed in this way can guide the eye during times when K2 data is unavailable and ASAS-SN data are sparse but still informative.

We jointly modeled the ASAS-SN and K2 light curves as a damped, driven Simple Harmonic Oscillator (SHO) Gaussian Process (GP) with celerite (Foreman-Mackey et al. 2017). We tuned a two-period GP model with the harmonic component possessing roughly half the period $P_H \sim 12.5$ days of the fundamental period $P_0 = 23.5$ days. The harmonic overtone frequency can be seen by eye in Figure 3, as the K2 light curves appear more structured than a pure sine wave.
We fit for a correlation amplitude and SHO quality factor for each periodic GP term. We found consistent best-fit values when K2 light curves were fitted on a per-campaign basis. We then fit the three campaigns simultaneously by adding an additional nonperiodic secular trend GP component to capture the campaign-to-campaign mean-level variation. We set the overall vertical registration of the K2 light curves such that the ASAS-SN and Campaign 16 trends match, since M67 was contemporaneously observable from the ground for the entire duration of Campaign 16. The uncertainty in the intercampaign offsets calculated in Section 2.4 is larger than the internal precision of the K2 photometry, so we adjust the Campaign 5 data within the offset uncertainty to match the approximately one week of temporal overlap with ASAS-SN.

Finally, we transfer the model parameters pretrained from the K2 fit to a GP based on the ASAS-SN photometry. We attempted to apply a GP to the K2 and ASAS-SN data simultaneously, but the result had numerical artifacts due to quality and cadence differences between the data sets. We evaluate the ASAS-SN GP at all time points in Figure 3 including the seasonal data gaps. This trend appears in Figure 3 as the dark orange line with an orange shaded standard confidence region. This trendline guides the eye to see broad secular changes to the amplitude encoded in the noisy ASAS-SN data, with a global maximum peak-to-valley amplitude of 17% occurring near 2017 January, and global minimum peak-to-valley of 3% occurring shortly before the IGRINS measurement.

3.2. IGRINS Spectral Analysis
3.2.1. Broadening Function Analysis

To measure the radial velocity of S1063 and to search for spectroscopic signatures of its binary companion at NIR wavelengths, we compute a spectral-line broadening function (BF) for the IGRINS spectrum (e.g., Tofflemire et al. 2019). The BF is a linear inversion of the observed spectrum with a narrow-lined spectral template. It is a profile that, when
convolved with the narrow-lined template, reproduces the observed spectrum. As a result, the BF represents the average absorption line profile of stellar components present in the spectrum, carrying information on their radial velocities and rotational broadening (i.e., $v \sin i$).

Using a 5000 K, log $g = 4.0$ precomputed PHOENIX model (Husser et al. 2013) as our narrow-lined template, we compute the BF for each spectral order considered in Section 3.2.2 below (nine in total). We then combine them into a single, high signal-to-noise BF. The resultant BF contains only one significant peak (>3σ), indicating that we do not detect the binary companion.

We fit a rotationally broadened line profile (Gray 2008) to the S1063 component, measuring a barycentric radial velocity of $14.6 \pm 0.2$ km s$^{-1}$ and a $v \sin i$ of $13.7 \pm 0.9$ km s$^{-1}$. The radial velocity agrees with the Geller et al. (2021) orbital solution for the given orbital phase.

### 3.2.2. Two-temperature Spectral Decomposition

The IGRINS observation epoch can be seen as the vertical blue line in Figure 3. The filling factor derived at this moment will serve as the anchor for the filling factor projected forward and backward in time.

We performed a two-temperature probabilistic spectral decomposition on the IGRINS H-band spectrum. We applied the spectral inference framework Starfish (Czekala et al. 2015), recently extended to support composite spectra comprised of mixtures of two distinct photospheric components (Gully-Santiago et al. 2017). Here, the two temperature components are labeled as $T_{\text{spot}}$ and $T_{\text{amb}}$ for the starspot and ambient photospheric emission, respectively, with a filling factor $f$ defined as the ratio of disk-integrated projected surface area of the spot groups to the projected area of the star. Given that we do not detect the binary companion in the BF above, and at the observed binary phase we expect the primary and secondary to have an RV separation of more than 50 km s$^{-1}$, we are confident our single-velocity spectral decomposition of S1063 is not systematically impacted by the secondary.

We employed the PHOENIX precomputed synthetic model grid (Husser et al. 2013) with grid ranges of $3000 < T_{\text{eff}} (K) < 5300$, $3 < \log g (\text{cm s}^{-2}) < 4$, and $-0.5 < [\text{Fe/H}] < 0.5$. We trained the spectral emulator (Czekala et al. 2015) on this grid range, while preserving the absolute model mean fluxes to enable accurate flux comparison between two spectra of disparate characteristic temperatures. This new approach offers improved accuracy over the scalar flux interpolated approach introduced in Appendix A of Gully-Santiago et al. (2017), especially for such a large dynamic range in effective temperature. The spectral emulator approach also propagates the uncertainty attributable to the coarsely sampled PHOENIX models.

The predefined grid ranges place uniform priors over their domain. Additionally, a threshold of 4500 K separated the allowed domains for the spot and ambient temperatures, yielding uniform priors $3000 < T_{\text{spot}} (K) < 4500$ and $4500 < T_{\text{amb}} (K) < 5300$.

Each IGRINS H-band spectral order was fit independently, yielding over 20 individual sets of MCMC posteriors. We employed emcee (Foreman-Mackey et al. 2013) with 5000 samples and 40 walkers, spot-checking the MCMC chains for signatures of steady-state posterior probability distributions suggestive of convergence. Some orders did not pass our convergence criteria, usually due to poor initialization of nuisance parameters or overfitting. Furthermore, the radial velocity $v_r$ and projected rotational broadening $v \sin i$ were spot-checked to verify consistent values among spectral orders as well as posterior distributions indicative of information-rich spectral orders. Some relatively feature-free spectral orders did not offer enough constraining power to derive meaningful results in the face of multiple sources of degeneracy. Collectively, these discrepant or uninformative spectral orders were removed from future analysis, yielding a total of nine preserved spectral orders, shown in Figure 4. The per-order estimates for radial velocity are all consistent with $v_r = 44$ km s$^{-1}$ at the measurement epoch, uncorrected for barycentric motion. All spectral orders except for $m = 106$ are consistent with a $v \sin i = 10$ km s$^{-1}$, with typical per-order 1σ uncertainties of 0.2–1.0 km s$^{-1}$. The fit to order 106 finds $v \sin i = 15 \pm 3$ km s$^{-1}$. As can be seen in Figure 4, this particular order contains few significant spectral lines. Although the fit converged and is included in our subsequent analysis, this order in particular demonstrates some of the systematic uncertainties in this process.

### 4. Results

#### 4.1. Spot Temperature and Filling Factor

Using the Starfish spectral inference results, we investigate the joint constraints on spot temperature and filling factor, marginalized over all other uncertainties in stellar properties and fitting hyperparameters (such as Starfish-derived Gaussian Process correlation length and amplitude and continuum fitting polynomials). In Figure 5, we show two-dimensional posterior distributions of filling factor and spot temperature of the last 1000 samples thinned by a factor of 10 from all 40 emcee walkers for the nine orders with accepted fits. The orders show broad agreement between spot temperature and filling factor. Across all nine orders, the median filling factor value is 32% with a standard deviation of 7%, with a corresponding spot temperature of 4000 ± 200 K. We note that, although the fit results for order 106 appear disparate in Figure 5, likely due to systematic effects, excluding order 106 from the analysis does not change the median filling factor or spot temperature values. The ambient photosphere temperature associated with this spot signature varies from order to order, and is in the range of 5000–5300 K, with a median value of 5200 K. These values are broadly consistent with a spectroscopic temperature of 5000 K for S1063, determined by Mathieu et al. (2003) from visible-wavelength spectra.

#### 4.1.1. Light-curve Interpretation

The ASAS-SN and K2 Campaign 5 data of S1063 (Figure 3) indicate that the IGRINS observation was coincidently acquired near the modest local maximum at an overall flux level of 91.2%. This is close to the overall 89.5% mean flux level, where the 100% flux level is defined as the global maximum over the four-year period covered by ASAS-SN and K2. The light curve exhibits relatively modest variability just before the time of the IGRINS observation, with merely 3% peak-to-valley variation compared to the largest global variation of almost 17% as observed around 2017 January.

For a first-order interpretation of light-curve amplitudes, we posit that the light curve is starspot-dominated as opposed to facula-dominated. Under this assumption, minimum light corresponds to the largest blockage of ambient flux—and therefore the largest starspot coverage on the instantaneous
Figure 4. Nine $H$-band IGRINS echelle orders showing two-component spectral decomposition of collective starspot photospheric emission, labeled with the corresponding order number $m$. The starspot spectrum (thick red line) and ambient photosphere spectrum (dotted blue line) combine to form the composite spectrum (solid purple line) that resembles the observed spectrum (thick gray line). The starspot and ambient components can share similar spectral structure, leading to a range of filling factors and temperatures ranges with nearly equivalent composite spectra; here, we present a single random draw from the MCMC posterior, not a “best fit.” The cool and hot temperatures $T_s$ and $T_{amb}$ for each draw show variety consistent with the fitting uncertainty. The corresponding spot filling factor, $f_s$, is also shown for each specific random draw. Unexplained spectral structure and over- and underfitting of spectral lines arise from a combination of PHOENIX model imperfections, possible magnetic Zeeman broadening, and other model mis-specifications.

If S1063 was spot-free at the time of the global light-curve maximum, the epoch of IGRINS observation would correspond to starspots blocking 8.8% of the total instantaneous stellar flux (100% − 91.2% = 8.8% blocked flux at the time of observation), assuming nonemitting starspots. However, starspots are emitting and effectively filling in some of the light that is “blocked.” This nonzero starspot emission demands that the spot covering fraction must be greater than 8.8% at the time of the IGRINS observation. Adopting an ambient photosphere temperature of 5200 K and a spot temperature of 4000 K, the projected spot coverage of S1063 must be at least 13% to account for the 8.8% flux loss in the ASAS-SN optical band. This 13% spot coverage is a minimum value based on an assumption that the global maximum light-curve flux results from an unspotted star. Our spectral inference results indicate the spot coverage at the time of the IGRINS observation was 32% ± 7%. Therefore, the spot coverage of S1063 was...
approximately 20% at maximum light over this four-year period, and not zero as a first-order interpretation of the light curve would imply.

The presence of starspots at the light-curve maximum acts as a starspot baseline for interpreting the light curve. Over the four years shown in Figure 3, the average flux variation is approximately 5%, corresponding to an average spot covering fraction variation between each observed hemisphere of ±8%. The light curve exhibits a global flux minimum 10% lower than the flux at the time of the IGRINS observation, requiring a spot filling factor close to 45% on the projected hemisphere at that time.

We therefore determine that, over the time period from 2014–2018, S1063 possessed a range of 20%–45% spot coverage fraction on the projected hemisphere, with an average close to 30%. The IGRINS observation occurring near the mean global flux level fortuitously allows a robust characterization of the average state of S1063. These numbers possess formal uncertainties in the few percent range, and additional systematic uncertainties from our reliance on spectral models. But broadly speaking, our result is firm under our assumptions—S1063 has a large persistent starspot population that ebb and flows in its longitudinal symmetry, resulting in variation in the peak-to-valley modulation, but routinely possessing an approximately 30% spot covering fraction.

Finally, we investigate how bandpass differences between the broad K2-bandpass and the ASAS-SN V-band may impact our light-curve analyses. The V-band is bluer on average than the wider and red-weighted K2-bandpass, so we expect the presence of starspots to result in slightly more contrast in V than in the K2-band, as more spot coverage results in less blue flux. We confirm this by integrating spotted spectra (assuming 5200 K ambient photosphere and 4000 K spots) over a range of filling factors against both transmission curves. We find that a 1% change in filling factor results in a 0.78% loss of flux in K2 and a 0.83% loss of flux in the V band. This could result in an approximately 6% higher light-curve amplitude observed in the V band than would be observed with K2. However, we

Figure 5. Two-dimensional distributions of filling factor and spot temperature for the nine accepted IGRINS orders for S1063, including 1000 samples of the emcee chains thinned by a factor of 10. Some orders demonstrate a stronger ability to constrain the spot characteristics than others; however, all are consistent with the detection of a moderate covering fraction of spots. The median filling factor across these nine orders is 32% ± 7%, with a spot temperature of 4000 ± 200 K.
emphasize that our global light-curve trends are determined using only the ASAS-SN V-band photometry, therefore the slight discrepancy does not impact our results. The quality of the ASAS-SN data is not sufficient to confirm this expected ~6% amplitude difference between the V-band and K2 photometry.

4.2. Comparison to Evolutionary Models of Active Stars

Current theoretical modeling of active stars takes several different approaches, including surface treatments of spots at nonzero temperatures that suppress convective energy transport (Somers et al. 2020), direct treatments of the interior magnetic field (Feiden & Chaboyer 2013), and reduced mixing length models with nonemitting spots (Chabrier et al. 2007). Comparing observationally constrained spot filling factors with those from theoretical predictions can highlight current gaps in our knowledge, and therefore direct future studies.

Here, we compare the photometry of S1063 to spotted SPOTS evolutionary tracks (Somers et al. 2020). SPOTS models assume the presence of starspots inhibits local flux that must instead escape through ambient (nonspotted) regions of the stellar surface. To determine photometric conversions from the stellar structure models, all SPOTS evolutionary tracks adopt a two-temperature surface with a fixed ratio of spot to ambient temperature of 0.8. To compare these models against S1063, we use optical photometry from Gaia (Gaia Collaboration et al. 2016, 2018) and near-IR photometry from 2MASS (Skrutskie et al. 2006). In Figure 6, we show CMDs of M67 members (Geller et al. 2015) compared to the shaded region in each CMD populated by SPOTS tracks. As expected, spotted subgiant models appear redder and fainter than the subgiant branch in both CMDs. We also show the unspotted SPOTS evolutionary track in each CMD as a black solid line. This unspotted model generally fits the typical subgiant branch of M67 in the 2MASS CMD; however, this is not true when using Gaia photometry. In the Gaia CMD, the unspotted SPOTS model has a more extended subgiant branch and redder giant branch than observed in the cluster. This discrepancy is not resolvable by changing cluster parameters (i.e., reddening, distance, turnoff mass, metallicity). It may be due to internal model physics (e.g., choice of mixing length) or an error introduced when calculating model colors in the Gaia bandpasses.

Photometry for S1063 from both Gaia and 2MASS is roughly consistent with the region populated by SPOTS evolutionary tracks. Generally, the spot covering fraction adopted from this model comparison would result in larger spot filling factors of approximately 50%–85%, depending on the photometry used. Leiner et al. (2017) also conclude similarly large filling factors would be necessary to reproduce the spectral energy distribution of S1063, compared to the 32% ± 7% filling factor found in this work.

Observational biases may impact the filling factors determined through spectroscopic and photometric methods. Our near-IR spectral decomposition technique is most sensitive to detecting a “sweet spot” in starspot contrast: cool enough to exhibit a spectrum that is qualitatively distinct from the ambient photosphere, but not so cool as to possess vanishing specific intensity. As a result, spectral decomposition techniques are more sensitive to warmer spot components and may therefore be constraining the penumbra rather than umbra filling factor (Vogt 1981). Depending on the ratio of penumbra to umbra, this could lead our technique to systematically underestimate the total starspot coverage, placing our filling factor constraint as a lower limit.

Other second-order effects could be at play. Spot boundaries could hypothetically exhibit a perceived wavelength dependence, leading to apparent discrepancies in spot filling factors across photometric and spectroscopic determinations at different wave bands. Such effects are not well-understood for stars other than the Sun, where the exact boundaries of active regions can be examined in different filters. We note that photometry collected at different epochs can also degrade the precision of SED-based photometric filling factors. Given our light-curve analysis of S1063, we expect SED-based filling factor uncertainties could be as large as ~20% if the individual photometry observations span peaks and troughs of the light curve.

Figure 6. On the left is a Gaia color–magnitude diagram (CMD) that shows members of M67 (gray points) with SSG S1063 highlighted (red square). In comparison, we show SPOTS evolutionary tracks (Somers et al. 2020) for a 1.3 M_☉ star (black lines). The shaded blue area between the tracks indicates the region occupied by stars with spot covering fractions between 0% and 85% according to the SPOTS models. On the right is a similar CMD using photometry from 2MASS.
A summary of the surface and stellar parameters for S1063 are given in Table 1, comparing our work here with parameters for S1063 determined in Mathieu et al. (2003), Leiner et al. (2017), and the SPOTS model comparison above. As the closest SPOTS model depends on the comparison photometry used (see Figure 6), the stellar parameters for both models are given. Fully resolving the complexities of photometric and spectroscopic constraints of spot filling factors likely requires careful photometric and atmospheric modeling of a multi-temperature stellar surface, which is beyond the scope of this paper.

5. Discussion

The spot coverage fraction for S1063 determined in this work is consistent with the range of spot coverage seen on RS CVn systems of 30%–40% from measuring TiO band strength (O’Neal et al. 1996, 1998, 2004) and Doppler imaging (Hackman et al. 2012). The collective evidence supports the interpretation that S1063, and by extension other SSGs, have magnetic activity significant enough to alter their positions in the HR diagram, although continued work is needed in the photometric modeling of these sources (see Section 4.2). This interpretation is further supported by the fact that flares are present in the K2 light curves (see Figure 2), which is a clear indicator of magnetic activity.

Strong magnetic fields and starspots reduce convective energy transport efficiency, which in turn alters theoretical evolutionary model tracks from their unspotted/nonmagnetic counterparts (Feiden & Chaboyer 2013; Somers & Pinsonneault 2015a, 2015b; Somers et al. 2020). Understanding the physical nature of magnetic activity and the impact it has on stellar structure and evolution requires comparison of high-fidelity observations with these theoretical models. An accurate HR diagram position requires a determination of the effective temperature ($T_{\text{eff}}$) having accounted for spots, as well as the stellar luminosity.

5.1. Effective Temperature of Spotted Stars

The radius and luminosity of a star provide an effective temperature through the Stefan–Boltzmann Law. The radius of S1063 remains constant over thermal timescales much longer than the span of available data. We assume the time-averaged luminosity also remains constant, as starspots come and go on the surface but have a near-constant time-averaged filling factor. This is supported by Figure 3 showing a relatively constant mean flux level of 89.5% compared to the maximum global flux. With these assumptions, there theoretically exists a well-defined $T_{\text{eff}}$ that conventionally relates the time-averaged bolometric luminosity and radius. For example, Leiner et al. (2017) fit the multiband spectral energy distribution for S1063 with a single Castelli–Kurucz spectrum (Castelli & Kurucz 2004) and find a best-fit single-temperature $T_{\text{eff}}$ of 4500 K. Our results, however, indicate that S1063 has a multi-temperature surface. Therefore, we can calculate a surface-averaged temperature:

\[ T_{\text{eff}}^4 = f_s T_s^4 + (1 - f_s) T_{\text{amb}}^4 \]  

(1)

where $f_s$ is the spot covering fraction, $T_s$ is the spot temperature, and $T_{\text{amb}}$ is the ambient photosphere temperature. This surface-averaged $T_{\text{eff}}$ can be calculated for either a specific epoch of observation or using time-averaged values.

At the epoch of the IGRINS observation, the $T_{\text{eff}}$ of S1063 derived with Equation (1) is 4900 ± 100 K. This temperature is inconsistent with the 4500 K temperature determined via single-temperature SED fitting in Leiner et al. (2017), possibly indicative of the discrepancies between the spectral and photometric constraints outlined in Section 4.2, although we note that the previous temperature of 4500 K is between the measured spot and ambient photosphere temperatures determined in this work.

The instantaneously derived $T_{\text{eff}}$ value varies based on the spot covering fraction at the time of observation. We know from the variable light curve (Figure 3) that stars such as S1063 have differing spot covering fractions on opposite observable hemispheres of the star. For example, at the four-year light-curve maximum, S1063 had approximately a 20% spot covering fraction and therefore an instantaneously derived surface-averaged $T_{\text{eff}}$ (for the observed hemisphere of the star) of 5000 K. At the light-curve minimum with a 45% spot covering fraction, the surface-averaged $T_{\text{eff}}$ for the observed hemisphere would only be 4700 K.

The true surface-averaged $T_{\text{eff}}$ includes the entire stellar surface. Observationally constraining the surface-averaged $T_{\text{eff}}$ requires either multi-epoch spectrum observations at both the light-curve maximum and minimum, or a single observation at the mean flux level. The date of the IGRINS observation corresponds to a flux level of 91.2% compared to the global

---

### Table 1

| S1063 Surface and Stellar Parameters | Spot Temp (K) | Filling Factor (%) | Ambient Temp (K) | Radius ($R_\odot$) |
|-------------------------------------|--------------|--------------------|-----------------|-------------------|
| Spectroscopic Constraints:          |              |                    |                 |                   |
| This work                           | 4000 ± 200   | 32 ± 7             | 5200            | 3.7–4.6*          |
| Mathieu et al. (2003)               | ...          | ...                | 5000            | 2.4               |
| Photometric Constraints:            |              |                    |                 |                   |
| Gaia SPOTS models                   | 4100         | 51                 | 5100            | 3.0               |
| 2MASS SPOTS models                  | 4200         | 85                 | 5300            | 3.1               |
| Leiner et al. (2017)                | ...          | ...                | 4500            | 2.8–3.1           |
|                                    | 3500*        | 40                 | 4750            | 3.4               |

Notes.

* $R \sin i$, determined from $v \sin i$, see Section 5.2.

* Section 4.2, from Somers et al. (2020).

* Unspotted model.

* Model assuming 40% spot coverage with a spot temperature contrast of ~1000 K.
maximum, suggesting that observed spot coverage is a close proxy for the mean state of S1063 with a flux level of 89.5%. Therefore, we conclude that the total surface-averaged $T_{\text{eff}}$ of S1063 is consistent with the observed surface-averaged $T_{\text{eff}}$ of 4900 ± 100 K. We stress, however, that determining a single $T_{\text{eff}}$ value for spotted stars makes model comparisons exceedingly nuanced.

5.2. Radius of S1063

The radius of S1063, important for determining the bolometric luminosity, is encoded into data in three ways: via surface gravity-sensitive spectral lines, in the SED and HR diagram position through the luminosity, and embedded within the $v \sin i$ measurement. Measuring the radius of a spotted star would help constrain magnetic inflation models, especially in light of the $T_{\text{eff}}$ nuances elaborated above.

Our weak constraints on surface gravity from the IGRINS spectra cannot meaningfully inform the radius without an independent measurement of the stellar mass. Previously determined SED-based photometric results suggest a radius of $R_\ast = 2.8$–3.4 $R_\odot$ (see Table 1). We elaborate on constraining the radius from $v \sin i$ here.

The stellar radius $R_\ast$ contributes to the observed magnitude of the equatorial velocity $v$ given a rotation rate $P_{\text{rot}}$ and projected stellar inclination angle $i$:

$$R_\ast \sin i = \frac{v \sin i \cdot P_{\text{rot}}}{2\pi}.$$  \hspace{1cm} (2)

Our Starfish/IGRINS-derived $v \sin i = 10.0 \pm 1.0$ km s$^{-1}$ and celerite/K2-derived period $P_{\text{rot}} = 23.5 \pm 0.2$ days constrain $R \sin i = 4.6$ $R_\odot$, with a formal statistical uncertainty of ±0.5 $R_\odot$. For stars viewed at an inclination other than perfectly edge-on, the typical inferred stellar radius $R_\ast$ must exceed 4.6 $R_\odot$. If we instead adopt the optically determined $v \sin i = 8$ km s$^{-1}$ from Mathieu et al. (2003), the radius must exceed 3.7 $R_\odot$. In either case, this kinematically inferred radius is larger than most active stars more generally—must exhibit a range of apparent surface features attributable to umbra, penumbra, faculae, chromospheric emission, and other phenomena unaccounted for in this work (Berdyugina 2005; Strassmeier 2009). These phenomena all have different temperatures and wavelength-dependent flux contrasts with the ambient photosphere.

Another possibility is that S1063 could hypothetically be much larger than SED-based estimates, meaning a one- or two-temperature fit to the SED is understating the total luminosity. In this work, we assume a two-temperature stellar surface to derive our estimates for spot filling factor and effective temperature. In reality, this star—and most active stars more generally—must exhibit a range of apparent surface features attributable to umbra, penumbra, faculae, chromospheric emission, and other phenomena unaccounted for in this work (Berdyugina 2005; Strassmeier 2009). These phenomena all have different temperatures and wavelength-dependent flux contrasts with the ambient photosphere.

The prospect of undercounting umbra suggests yet another candidate interpretation of the SED-R sin$i$ tension: S1063 really has a radius of 3.7–4.6 $R_\odot$ or larger, but has a profound coverage of imperceptibly dark umbra that is undetected with our methodology. This scenario is oddly self-consistent: painting a surface with dark umbra dramatically impedes the ability of the star to transport away internal energy, demanding a dramatic increase in radius in order to reach energy balance. The SED would mask the existence of these dark umbral regions, as would our spectroscopic methods presented here.

Studying SSGs in eclipsing binaries would provide strong constraints on the stellar radius as well as provide a stringent test to discern a significant presence of dark umbra, wherein an ensemble of SSG eclipsing binaries would reveal a pattern of primary stars with shallow eclipse depths. If SSG starspots are small and distributed quasi-isotropically, eclipses would also show dramatic spot-crossing events, as eclipse chords contain gigantic black patches surrounded by brighter ambient photosphere. Future large samples of SSG eclipsing binaries may help investigate these scenarios while providing crucial radius measurements necessary for confident comparisons of this class of stars to theoretical stellar evolutionary models.

5.3. Additional Sources of Systematic Uncertainty

Compared to umbra, faculae and plage act to add a hotter-than-average surface component. Our two-component model cannot accurately account for the coexistence of spots and faculae with an ambient photosphere (Solanki & Unruh 1998). Specifically, faculae may act to either increase or decrease starspot coverage estimates insofar as they act to boost the perceived ambient photosphere features and accordingly bias the derived temperature (Wakeford et al. 2019). The existence of large and hot faculae can be ruled out to some extent by the fact that they would dominate the temperature determination in visible wavelength spectra. The adequate agreement in ambient temperature derived from visible (Mathieu et al. 2003) and near-IR spectra of S1063 in this work suggests that faculae may be negligible. Chromospheric emission should mostly perturb individual lines that are known to be chromospherically active. Our IGRINS-based technique analyzed the majority of the H band with whole-spectrum fitting, where such isolated chromospherically active lines would have negligible impact.

Our reliance on PHOENIX synthetic spectra adds a model-dependent systematic to our entire approach. The current lack of numerous spot-free high-precision and high-resolution empirical template spectra across all of H-band demands the use of these models in order to compare to IGRINS data. The ability of such synthetic spectra to resemble starspots remains an unknown. We can examine fit residuals to explore the performance of the synthetic spectra by comparing the purple
two-component composite spectrum to the gray IGRINS spectrum in Figure 4. We see that the observed IGRINS spectrum has lines that do not appear in the model, and the model has lines that do not appear in the observed spectrum. The Gaussian process “Global Kernels” employed in Starfish accounts for some degree of correlated data-model residual mismatching. We did not employ the “Local kernels” approach, which would otherwise have corrected for a systematic bias of up to 30 K in comparable-quality spectra of WASP-14 also compared to the PHOENIX models (Czekala et al. 2015). We therefore assign at least a 30 K systematic bias in our temperature estimates based on the prospect of individual line outliers polluting our fit residuals. We co-assign a coarse estimate of 100–200 K to so-called “label noise,” associated with the alignment of a best-fit PHOENIX-provided temperatures and an unseen ground-truth label for the “True” temperature of the spots. New studies of the Sun based on DKIST may offer the best future avenue for testing such assumptions and refining the ability to distinguish starspot emission from ambient photosphere.

6. Conclusions

We use a novel combination of a light-curve analysis and a near-IR spectral decomposition technique to constrain the starspot filling factor and spot temperature of SSG S1063 in open cluster M67. Previous work suggested that the under-luminosity apparent in SSGs could be caused by inhibited convective energy transport due to high magnetic activity (Leiner et al. 2017). Constraining the starspot filling factor is a helpful proxy for determining stellar magnetic activity, allowing us to directly compare observed photometry to model predictions for active stars. Additionally, our technique allows for constraints on a much larger sample of stars than can be studied with Doppler imaging or interferometry.

Assuming a two-temperature surface, we find a spot filling factor for S1063 of 32% ± 7% at the time of the IGRINS observation, with a spot temperature of 4000 ± 200 K, compared to the ambient photosphere temperature of 5200 K. We use this constraint to interpret the long-term variability observed in a four-year light curve combining ground-based ASAS-SN data with space-based K2 campaigns, with minimum and maximum projected spot covering fractions of 20%–45%, respectively. Importantly, this technique reveals that the maximum light during this time period does not correspond to an unspotted star.

Although the instantaneous spot filling factor changes based on the observation epoch, the time of the IGRINS observation happens to approximate the mean state of the star over this four-year time period. This spot filling factor is consistent with those determined for RS CVn systems through other methods, suggesting that SSGs are another type of active giant star binary system.

Careful comparison of observational constraints and theoretical predictions is necessary to understand the physical mechanisms responsible for how magnetic activity alters stellar evolution in stars such as SSGs, but this comparison can be fraught. We find that reporting a single “$T_{\text{eff}}$” for active spotted stars is a complicated prospect, possibly leading to unclear or possibly incorrect observational and model comparisons. The surface-averaged $T_{\text{eff}}$ derived from our results is not consistent with a single SED-fit temperature for S1063. Additionally, the instantaneously observed surface-averaged $T_{\text{eff}}$ for S1063 varies from 4700 to 5000 K depending on the epoch of observation, as only one hemisphere of the star can be observed at a time. We also find a wide range of observational constraints on the radius of S1063, and suggest that surface conditions of SSGs may inflate $R \sin i$ values. We encourage future work to be as explicit as possible when reporting temperatures and radii for active stars, to enable the most accurate comparisons between observational and theoretical efforts.

There is still much to learn about spot morphologies and temperature profiles, the observational biases impacting constraints of spot filling factors, and how to connect measurements of the stellar surface to the internal structure. SSGs serve as an important sample for furthering our knowledge in these areas, as they exhibit dramatic offsets from typical stellar evolutionary pathways. Focused studies such as this one serve as important benchmarks for technique development. Future larger studies of SSGs will provide important test samples for observational and theoretical comparisons to further untangle the impact of stellar activity on stellar evolution.

We thank the referee for helpful comments that improved this paper. N.M.G. is a Cottrell Scholar receiving support from the Research Corporation for Science Advancement under grant ID 27528. E.M.L. is supported by an NSF Astronomy and Astrophysics Postdoctoral Fellowship under award AST-1801937.

The custom project files, including Jupyter Notebooks, raw and reduced data, Starfish configuration files, reproducible Python environment files, and the entire project revision history are publicly available as a Git repository at https://github.com/BrownDwarf/subsub.

This research has made use of the NASA Astrophysics Data System. This work used the Immersion Grating Infrared Spectrometer (IGRINS) that was developed under a collaboration between the University of Texas at Austin and the Korea Astronomy and Space Science Institute (KASI) with the financial support of the US National Science Foundation under grant AST-1229522, of the University of Texas at Austin, and of the Korean GMT Project of KASI. This paper includes data collected by the Kepler mission. Funding for the Kepler mission is provided by the NASA Science Mission directorate. Some of the data presented in this paper were obtained from the Mikulski Archive for Space Telescopes (MAST). STScI is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555.

This work has made use of data from the European Space Agency (ESA) mission Gaia (https://www.cosmos.esa.int/gaia), processed by the Gaia Data Processing and Analysis Consortium (DPAC, https://www.cosmos.esa.int/web/gaia/dpac/consortium). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the Gaia Multilateral Agreement.

Facilities: Smith (IGRINS), ASAS, Kepler, Gaia, PS1.
Software: pandas ( McKinney 2010), emcee (Foreman-Mackey et al. 2013), celerite ( Foreman-Mackey et al. 2017), matplotlib ( Hunter 2012), numpy (Harris et al. 2020), scipy (Virtanen et al. 2020), ipython ( Pérez & Granger 2007), starfish ( Czekala et al. 2015), seaborn ( Waskom et al. 2014), lightkurve ( Barentsen et al. 2019), saphires ( Tofflemire et al. 2019).
References

Barentsen, G., Hedges, C., Vincius, Z., et al. 2019, KeplerGO/lightkurve: Lightkurve v1.0b29, Zenodo, doi:10.5281/zenodo.2565212

Basri, G. 2018, ApJ, 865, 142

Bastian, N., & de Mink, S. E. 2009, MNRAS, 398, L11

Berdyugina, S. V. 2005, LRSP, 2, 8

Castelli, F., & Kurucz, R. L. 2004, arXiv:astro-ph/0405087

Chabrier, G., Gallardo, J., & Baraffe, I. 2007, A&A, 472, L17

Czekala, I., Andrews, S. M., Mandel, K. S., Hogg, D. W., & Green, G. M. 2015, ApJ, 812, 128

Fang, X.-S., Zhao, G., Zhao, J.-K., Chen, Y.-Q., & Bharat Kumar, Y. 2016, MNRAS, 463, 249

Gaulme, P., Jackiewicz, J., Spada, F., et al. 2020, A&A, 639, A63

Gray, D. F. 2008, The Observation and Analysis of Stellar Photospheres (Cambridge: Cambridge Univ. Press)

Gully-Santiago, M. A., Herczeg, G. J., Czekala, I., et al. 2017, ApJ, 840, A19

Geller, A. M., Latham, D. W., & Mathieu, R. D. 2015, ApJ, 150, 97

Geller, A. M., Leiner, E. M., Bellini, A., et al. 2017, ApJ, 840, 66

Geller, A. M., Mathieu, R. D., Latham, D. W., et al. 2021, AJ, 161, 190

Gray, D. F. 2008, The Observation and Analysis of Stellar Photospheres (Cambridge: Cambridge Univ. Press)

Husser, T., Mantere, M. J., Lindborg, M., et al. 2012, A&A, 538, A126

Harris, C. R., Millman, J. J., van der Walt, S. J., et al. 2020, Nature, 585, 357

Howell, S. B., Sobeck, C., Haas, M., et al. 2014, PASP, 126, 398

Hunter, J. D. 2007, CSE, 9, 90

Jackson, R. J., Jeffries, R. D., Deliyannis, C. P., Sun, Q., & Douglas, S. T. 2019, MNRAS, 483, 1125

Kesseli, A. Y., Muirhead, P. S., Mann, A. W., & Mace, G. 2018, AJ, 155, 225

Kochanek, C. S., Shappee, B. J., Stanek, K. Z., et al. 2017, PASP, 129, 104502

Lee, J.-J., & Gullikson, K. 2016, plp: v2.1 alpha 3, Zenodo, doi:10.5281/zenodo.56067

Leiner, E., Mathieu, R. D., & Geller, A. M. 2017, ApJ, 840, 67

Luger, R., Agol, E., Foreman-Mackey, D., et al. 2019, AJ, 157, 64

Mathieu, R. D., van den Berg, M., Torres, G., et al. 2003, AJ, 125, 246

McKinney, W. 2010, in Proc. of the 9th Python in Science Conf., Vol. 445, ed. S. van der Walt & J. Millman, 56

McQuillan, A., Mageh, T., & Aigrain, S. 2014, ApJS, 211, 24

Montet, B. T., Tovar, G., & Foreman-Mackey, D. 2017, ApJ, 851, 116

Morales, J. C., Gallardo, J., Ribas, I., et al. 2010, ApJ, 718, 502

Morris, B. M., Curtis, J. L., Sakari, C., Hawley, S. L., & Agol, E. 2019, AJ, 158, 101

Neff, J. E., O’Neal, D., & Saar, S. H. 1995, ApJ, 452, 879

O’Neal, D., Neff, J. E., Saar, S. H., & Cuntz, M. 2004, AJ, 128, 1802

O’Neal, D., Saar, S. H., & Neff, J. E. 1996, ApJ, 463, 766

O’Neal, D., Saar, S. H., & Neff, J. E. 1998, ApJL, 501, L73

Park, C., Jaffe, D. T., Yuk, I.-S., et al. 2014, Proc. SPIE, 9147, 91471D

Pérez, F., & Granger, B. E. 2007, CSE, 9, 90

Pettersen, R., Monnier, J. D., Horrione, D., et al. 2016, Natur, 533, 217

Sanders, W. L. 1977, A&AS, 27, 89

Scargle, J. D. 1982, ApJ, 263, 835

Shappee, B. J., Prieto, J. L., Grupe, D., et al. 2014, ApJ, 788, 48

Skrutskie, M. F., Cutri, R. M., Stiening, R., et al. 2006, AJ, 131, 1163

Solanki, S. K., & Unruh, Y. C. 1998, A&A, 329, 747

Somers, G., Cao, L., & Pinesseau, M. H. 2020, ApJ, 891, 29

Somers, G., & Pinesseau, M. H. 2015a, ApJ, 807, 174

Somers, G., & Pinesseau, M. H. 2015b, MNRAS, 449, 4131

Strassmeier, K. G. 2009, A&ARv, 17, 251

Sun, W., de Grijs, R., Deng, L., & Albrow, M. D. 2019, ApJ, 876, 113

Tofflemire, B. M., Mathieu, R. D., & Johns-Krull, C. M. 2019, AJ, 158, 245

Torres, G. 2010, AJ, 140, 1158

van den Berg, M., Verbunt, F., & Mathieu, R. D. 1999, A&A, 347, 866

Vanderburg, A., & Johnson, J. A. 2014, PASP, 126, 948

Virtanen, P., Gommers, R., Oliphant, T. E., et al. 2020, NatMe, 17, 261

Waskom, M., Botvinnik, O., Hobson, P., et al. 2014, seaborn: v0.5.0 (2014 November), Zenodo, doi:10.5281/zenodo.127710