MAGNETIC ACTIVITY CYCLES IN THE EXOPLANET HOST STAR ϵ ERIDANI

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ABSTRACT

The active K2 dwarf ϵ Eri has been extensively characterized, both as a young solar analog and more recently as an exoplanet host star. As one of the nearest and brightest stars in the sky, it provides an unparalleled opportunity to constrain stellar dynamo theory beyond the Sun. We confirm and document the 3 year magnetic activity cycle in ϵ Eri originally reported by Hatzes and coworkers, and we examine the archival data from previous observations spanning 45 years. The data show coexisting 3 year and 13 year periods leading into a broad activity minimum that resembles a Maunder minimum-like state, followed by the resurgence of a coherent 3 year cycle. The nearly continuous activity record suggests the simultaneous operation of two stellar dynamos with cycle periods of 2.95 ± 0.03 years and 12.7 ± 0.3 years, which by analogy with the solar case suggests a revised identification of the dynamo mechanisms that are responsible for the so-called "active" and "inactive" sequences as proposed by Böhm-Vitense. Finally, based on the observed properties of ϵ Eri we argue that the rotational history of the Sun is what makes it an outlier in the context of magnetic cycles observed in other stars (as also suggested by its Li depletion), and that a Jovian-mass companion cannot be the universal explanation for the solar peculiarities.

Subject headings: stars: activity—stars: chromospheres—stars: individual(HD 22049)—surveys

1. BACKGROUND

The study of stellar magnetic activity cycles dates back to the 1960's, when Olin Wilson began monitoring Ca II H and K (Ca HK) emission for a sample of stars from the Mount Wilson Observatory (MWO) to provide some context for our understanding of the 11 year sunspot cycle (Wilson 1978). The Mount Wilson survey continued for several decades (see Baliunas et al. 1995, and references therein), and ultimately documented activity cycles and rotation periods for dozens of stars (Saar & Brandenburg 1999). These observations revealed two distinct relationships between the activity cycle period and the rotation period, with an active "A" sequence including stars rotating more than 300 times for each activity cycle, and an inactive "I" sequence with stars rotating fewer than 100 times per activity cycle. This pattern led Böhm-Vitense (2007) to suggest that there may be two different dynamos operating inside the stars, with the active sequence representing a dynamo driven by rotational shear in the near-surface layers, and the inactive sequence driven by a so-called *tachocline* at the base of the outer convection zone. Some stars in the Mount Wilson sample exhibit two distinct cycle periods, suggesting that the two dynamos can operate simultaneously.

The K2V star ϵ Eridani (ϵ Eri $\equiv$ HD 22049, V=3.7, B−V=0.88) is a young solar analog with a stellar activity record that stretches back to 1968. The first 24 years of observations were published in Gray & Baliunas (1995), who determined a rotation period of 11.1 days and found evidence of a 5 year activity cycle. This cycle period was confirmed by Buccino & Mauas (2008) from a joint analysis of the Mg II h and k lines in archival IUE spectra and more recent Ca HK observations from the Complejo Astronómico El Leoncito (CASLEO) in Argentina. Additional Ca HK data were obtained by Hall et al. (2007) with the Solar-Stellar Spectrograph at Lowell Observatory, though with less regularity because the star is slightly cooler than the close solar analogs that dominate their sample. As a bright nearby star (d = 3.2 pc; van Leeuwen 2007), ϵ Eri also has a precisely measured radius from interferometry ($R = 0.74 \pm 0.01 R_{\odot}$; Baines & Armstrong 2012). A further constraint for stellar dynamo modeling comes from a measurement of surface differential rotation, derived from 35 days of photometry by the *MOST* satellite (Croll et al. 2006).

Observations of the variable radial velocity (RV) of ϵ Eri were first reported by Campbell et al. (1988). Early claims by Walker et al. (1995) of periodic variations were eventually corroborated by Cumming et al. (1999), who identified a period near 7 years. Hatzes et al. (2000) used additional RV data to confirm the $\sim$7 year period, interpreting it as the reflex motion from an eccentric Jovian-mass exoplanet; they ruled out stellar activity as the source of the variations from an analysis of Mount Wilson data between 1980-1999. The Ca HK observations revealed periodic signals near 20 years (the length of the data set) and 3 years, but nothing at the orbital period of the presumed planet. The planetary nature of the companion was later confirmed by Benedict et al. (2006) who measured the astrometric orbit using the *Hubble Space Telescope*, yielding an inclination angle $i = 30.^{\circ}1 \pm 3.^{\circ}2$ (consistent with that

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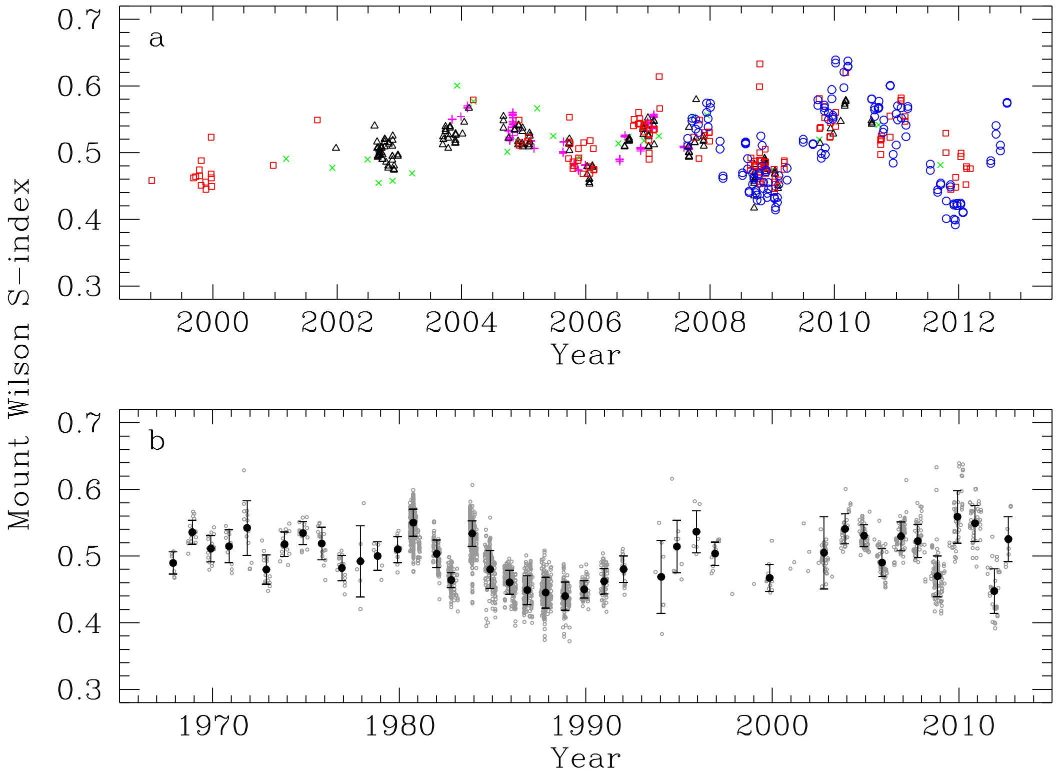

Figure 1. Chromospheric activity measurements of the K2V star ϵ Eri. **a:** Recent data from SMARTS (○), Lowell Observatory (□), and CASLEO (×), along with previously published measurements from CPS (△, Isaacson & Fischer 2010) and HARPS (+, Anglada-Escudé & Butler 2012). **b:** Archival data from Mount Wilson (1968-1992; Gray & Baliunas 1995) and the more recent observations (grey points) with seasonal means (•) and uncertainties reflecting the standard deviation within each season.

of an observed dust ring; Greaves et al. 2005) and determining the absolute mass of the planet, $M = 1.5\ M_J$. More recent RV measurements from the HARPS spectrograph imply that the properties of the planet may need to be revised, but still support a period near 7 years (Anglada-Escudé & Butler 2012).

We present new observations of the magnetic activity variations in ϵ Eri from synoptic Ca HK measurements obtained since 2007 with the Small and Moderate Aperture Research Telescope System (SMARTS) 1.5-m telescope at Cerro Tololo Interamerican Observatory (CTIO). We provide an overview of our data as well as corroborating measurements from other surveys in section 2, and in section 3 we evaluate the dominant periodicities over time using archival observations spanning 45 years. We conclude in section 4 with a discussion of the implications of these results for stellar dynamo modeling and future observations.

2. OBSERVATIONS & ARCHIVAL DATA

The SMARTS southern HK project (Metcalfe et al. 2009, 2010) began in August 2007 with the primary objective of characterizing magnetic activity cycles for the brightest stars (V<6) in the southern hemisphere. The 58 solar-type stars in the sample, defined as a subset of the Henry et al. (1996) sample, included all of the most likely future asteroseismic targets of the Stellar Observations Network Group (SONG; Grundahl et al. 2008). Several targets near the celestial equator, including ϵ Eri, provided an overlap with the Mount Wilson and Lowell surveys, allowing the calibration of derived Ca HK S-indices onto the Mount Wilson system.

Since August 2007, we have used the *RC Spec* instrument on the SMARTS 1.5-m telescope to obtain 141 low-resolution spectra ($R \sim 2500$) of ϵ Eri on 69 distinct epochs. Standard IRAF[11] routines were used on the 60 s integrations to apply bias and flat field corrections, and a wavelength calibration was applied using a reference He-Ar spectrum obtained just prior to each pair of stellar exposures. Following Duncan et al. (1991), we integrated the calibrated spectra in 1.09 Å triangular bandpasses centered on the cores of the Ca H (396.8 nm) and K (393.4 nm) lines and compared them to 20 Å continuum regions from the wings of the lines to generate a CTIO chromospheric activity index, $S_{\rm CTIO}$. We used data for 26 targets that were observed contemporaneously with the Solar-Stellar Spectrograph at Lowell Observatory to make the conversion to Mount Wilson indices ($S_{\rm MWO}$). Our SMARTS observations of ϵ Eri are listed in Table 1, where the quoted uncertainties represent the internal errors and do not include the systematic uncertainty ($\sigma_{\rm sys} \sim +0.007$) from the conversion between the CTIO and MWO indices.

We used additional observations of ϵ Eri from previously published surveys to corroborate our recent SMARTS measurements and to extend the time baseline of our analysis. The MWO data from 1968–1992 were published by Gray & Baliunas (1995). Although observations were collected at Mount Wilson for nearly an additional decade beyond 1992, those data have never been released. Fortunately, the data from Lowell Observatory begin in 1994 and continue to the present (see Hall et al. 2007). As the Lowell series is the longest among the recent measurements, we used these observations to rescale the other data to the MWO system. The southern survey at CASLEO includes

[11] IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA) under cooperative agreement with the National Science Foundation.

measurements of ϵ Eri from 2001–2011 (Mauas et al. 2012). Additional published data between 2002–2010 are available from the California Planet Search (CPS; Isaacson & Fischer 2010), and between 2004–2008 from the HARPS spectrograph (Anglada-Escudé & Butler 2012). In each case we placed the S-index measurements on the Mount Wilson system from their overlap with the Lowell data, yielding multiplicative scale factors of 1.04 (CASLEO), 1.09 (CPS), and 1.32 (HARPS). The results presented in section 3 are insensitive to small changes in these factors. From the combined data we calculated seasonal means for each year that had more than three observations, including uncertainties that reflect the standard deviation within each season. The observed scatter is dominated by actual variations in the S-index caused by rotational modulation of individual active regions, but it also contains a small contribution from the statistical uncertainties of the individual measurements (cf. Table 1).

The chromospheric activity measurements of ϵ Eri are shown in Figure 1. The top panel includes the recent measurements from SMARTS (○, see Table 1), as well as the data from Lowell (□), CASLEO (×), CPS (△), and HARPS (+). The bottom panel includes all of the recent data as well as the archival measurements from Mount Wilson (grey points) along with our calculated seasonal means and those from Gray & Baliunas (1995).

3. RESULTS & INTERPRETATION

We determined the significant periodicities in our chromospheric activity measurements by passing both the seasonal and nightly mean S-indices through a Lomb-Scargle periodogram (Lomb 1976; Scargle 1982). In each case, we also performed the analysis on two subsets of the data, between 1968–1992 from MWO and on the more recent measurements between 1994–2012, to understand the dominant source of various periodicities. The results are shown in Figure 2, where the top and bottom panels show the periodogram of the seasonal and nightly means, respectively. The early data from MWO (dotted lines) reveals a primary periodicity near 13 years and smaller peaks near 3 years and 5 years. The 13 year period appears to be rooted in the broad activity minimum between 1985–1992 in the MWO data, but it is also evident in the declining activity level of successive minima since 2006 (see Figure 1). The more recent data (dashed lines) are dominated by a period near 3 years, but they also show a weak signal near 7 years which corresponds to the orbital period of the exoplanet. This 7 year period is present in the individual observations of the longer time series measurements from both Lowell and CPS, while the 3 year signal is present in each of the recent data sets individually. The longest time series from Lowell resolves the power between 3–5 years into multiple components, among which the 3 year signal is the strongest. This is also reflected in the periodogram of the full data set (solid lines), which shows significant periodicities at 2.95 ± 0.03 years and 12.7 ± 0.3 years (both with false alarm probability $< 10^{-6}$ from the nightly means) along with several weaker peaks between 3–7 years. Simulations of the two dominant periods reveal all of these peaks to be artifacts of the time sampling. An additional peak at longer periods of 20–35 years is present in both periodograms, but we exclude it from our analysis because it is correlated with the length of the adopted data set.

To investigate the strength of these periodic signals over time, we performed a wavelet analysis of the seasonal mean S-index measurements (Torrence & Compo 1998). Such an

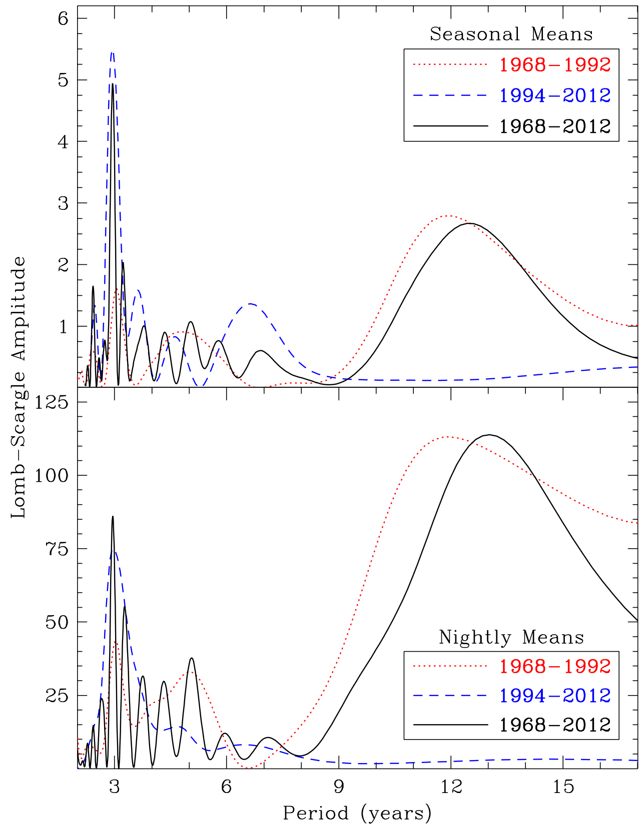

Figure 2. Lomb-Scargle periodograms of the seasonal (top panel) and nightly (bottom panel) mean S-index measurements from the MWO data 1968-1992 (dotted), the recent data 1994-2012 (dashed) and the full data set 1968-2012 (solid). Significant variations are detected in the complete time series with periods near 3 years and 13 years, corresponding to cycles on the inactive and active sequence respectively for a star with a rotation period near 11 days (Böhm-Vitense 2007).

analysis essentially calculates a periodogram for overlapping subsets of the time series, where the length of the subset must be proportional to the periodicity under investigation. Consequently, there are regions of the wavelet spectrum (outside of the so-called "cone of influence") that suffer from edge effects, where the signal is attenuated. The results are shown in Figure 3, where the border of the cone of influence is indicated with a hatched region and the significance of the signal is shown with a color scale going from the weakest (white and blue) to the strongest (black and red). The 2.95 year and 12.7 year periods are indicated with dashed horizontal lines. The 2.95 year period maintains its strength through most of the duration of the time series, with the exception of the late 1980's to early 1990's through the broad activity minimum. During this interval, the signal is dominated by the 12.7 year periodicity, which remains strong inside the cone of influence. The spurious 5 year signal in the MWO data appears only in the early observations, while the 7 year artifact in the recent data is also transient and even less prominent. Due to the limited time-resolution of the wavelet analysis for longer periods, it is difficult to determine whether the 2.95 year and 12.7 year periods coexist simultaneously, or if they alternate instead. If the 2.95 year period actually disappeared during the broad activity minimum, it may represent the first observation of another star entering (and later emerging from) a Maunder minimum-like state for the short cycle.

It is striking that ϵ Eri displays such short magnetic activity cycles. Many models of the solar dynamo favor a

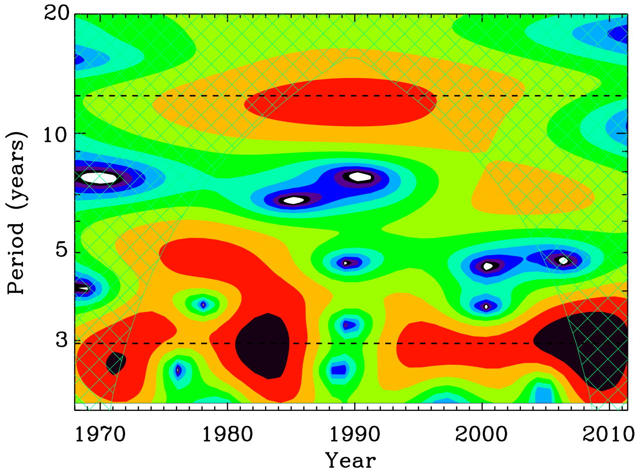

Figure 3. Wavelet spectrum of the seasonal mean S-index measurements from 1968-2012, showing the relative strength of the cycle periods over time. The hatched region marks the area outside of the cone of influence where signals can be reliably measured with the method, while the color scale indicates the significance of the signal from the weakest (white and blue) to the strongest (black and red).

flux-transport paradigm, and typically the slow meridional circulations set the cycle timescale for a dynamo operating in the tachocline at the base of the outer convection zone (e.g., Dikpati & Gilman 2006). From three-dimensional (3-D) models of stellar convection, we expect that the meridional circulations should be weaker in lower mass stars and at faster rotation rates (Brown et al. 2008; Matt et al. 2011; Augustson et al. 2012). In Babcock-Leighton flux-transport models, this should lead to long activity cycles (Jouve et al. 2010). To test this assertion, we used the MESA code (Paxton et al. 2011) to generate a stellar structure model for ϵ Eri assuming a mass of 0.85 $M_\odot$ and an age of 0.8 Gyr. The radius, luminosity and $T_{\rm eff}$ of this model agree with the interferometric observations (Baines & Armstrong 2012), and the convective velocities v_c are roughly half as fast as in the solar convection zone. From angular momentum transport arguments ($v_m \sim v_c^2/\Omega$), this suggests that the meridional flow speed v_m might be as small as 10% of the solar value (or about 2–3 m s^{-1} at the photosphere), making ϵ Eri a challenging case for flux-transport dynamos. Recently, 3-D simulations of convectively driven dynamos in rapidly rotating stars have achieved large-scale organization and cyclic behavior in stellar convection zones (Brown et al. 2011). These dynamos do not rely on the slow meridional circulations, and can exhibit short cycles even in rapidly rotating lower mass stars, with the cycle period determined by the rotation rate and the convective properties (Nelson et al. 2013). Of relevance to ϵ Eri, these convection zone dynamos show both short-period and long-period variations in the global-scale magnetism.

4. DISCUSSION

The long-term behavior of the magnetic activity cycles observed in ϵ Eri qualitatively resembles the interaction of the 11 year solar cycle with the quasi-biennial ($\sim$2 year) variations analyzed by Fletcher et al. (2010, their Fig. 1). The amplitude of the shorter (2.95 year) cycle in ϵ Eri appears to be modulated by the longer (12.7 year) cycle. During the broad minimum of the long cycle in 1985–1992, there is no evidence of the short-period variations. Fletcher et al. documented similar behavior in the Sun from helioseismic observations, with the quasi-biennial variations almost disappearing during the minimum of the 11 year solar cycle but gradually returning during the rise to solar maximum. They attributed this behavior to buoyant magnetic flux, generated near the tachocline during periods of high activity in the 11 year cycle, rising through the outer convection zone and episodically pumping up the amplitude of the quasi-biennial cycle. Support for this interpretation has emerged recently from efforts to localize the source of the quasi-biennial variations, placing them firmly in the near-surface regions of the Sun (Broomhall et al. 2012).

If we assume that the 2.95 year/12.7 year cycles in ϵ Eri are analogous to the 2 year/11 year cycles in the Sun, then the localization of the two signals has interesting consequences for the identification of the dynamos that are responsible for the active and inactive sequences as proposed by Böhm-Vitense (2007). She suggested that "differential rotation near the surface mainly feeds [the A-sequence] dynamos", while "interface dynamos in the stars with deep [outer convection zones] are the important ones for the I-sequence stars". This is precisely the opposite identification as that suggested by the helioseismic observations, which support a short cycle on the I-sequence localized in the near-surface regions and a long cycle on the A-sequence attributed to an interface dynamo at the tachocline. On the other hand, the Sun appears to be an outlier when compared to the A and I sequences established by observations of other stars. With the solar-like magnetic cycles observed in ϵ Eri, we are now in a better position to evaluate the specific property of the Sun that might make it peculiar in the context of other stars. Despite the fact that the Sun rotates less than half as fast as ϵ Eri, the stars each appear to have two interacting dynamos that operate on very similar timescales. This leads us to speculate that the rotational history of the Sun may be what makes it an outlier in the analysis of Böhm-Vitense (2007).

A complementary indication of the rotational history of a star can be found in its Li abundance. A stronger than usual rotational shear at the base of the outer convection zone can induce additional mixing below the tachocline where the temperature is sufficient to destroy Li. The solar Li abundance is anomalously low compared to some well-characterized solar twins such as 18 Sco (Meléndez & Ramírez 2007; Bazot et al. 2011), suggesting that the Sun may have been subjected to some additional mixing during its evolution. One way to explain a non-standard rotational history for the Sun is to blame Jupiter. Bouvier (2008) suggested that a necessary condition for the formation of Jovian-mass planets is a long-lived proto-planetary disk, which then has sufficient time to interact with the stellar convection zone and induce a strong rotational shear between the radiative zone and the surface layers. This model predicts enhanced Li depletion among stars like the Sun and ϵ Eri which have Jovian-mass planets, compared to stars like 18 Sco which do not. The Li abundance of ϵ Eri ($\log\epsilon$(Li)=0.36$\pm$0.07) is a factor of five below the solar value ($\log\epsilon$(Li)=1.05$\pm$0.10; Asplund et al. 2009), but it falls on the upper end of the distribution for stars with similar $T_{\rm eff}$ (Gonzalez et al. 2010). Thus, if a Jovian-mass companion is responsible for the relatively low solar Li abundance, the underlying mechanism must not be effective in all cases.

Additional constraints on the interior structure and dynamics of ϵ Eri could come from future asteroseismic observations by the SONG network (Grundahl et al. 2008). Even without a dedicated network of telescopes, ground-based RV observations have already revealed solar-like oscillations in α Cen B (Kjeldsen et al. 2005), which is only slightly more luminous than ϵ Eri. If solar-like oscillation amplitudes scale like

$[L/M]^s$ (Kjeldsen & Bedding 1995), then the signal in ϵ Eri should be between 64% (s=1.5; Houdek et al. 1999) and 81% (s=0.7; Samadi et al. 2007) as strong as that seen in α Cen B. Assuming comparable mode lifetimes for the two stars and using a more recent scaling relation that includes a dependence on $T_{\rm eff}$ (Kjeldsen & Bedding 2011), the estimate rises to 85%. However, the relatively strong magnetic activity of ϵ Eri may suppress the oscillation amplitudes (Chaplin et al. 2011). Nearly uninterrupted RV measurements from SONG that span several months are expected to have the precision necessary to measure the depth of the surface convection zone (Verner et al. 2006) and to reveal possible signatures of strong radial differential rotation (Gough & Kosovichev 1993). When combined with constraints on surface differential rotation from *MOST* (Croll et al. 2006) and our detailed characterization of the interacting magnetic cycles, ϵ Eri may represent the best opportunity beyond the Sun to test stellar dynamo theory.

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Table 1
Journal of SMARTS observations for ϵ Eri.

DATE	UT	BJD (2450000+)	$S_{\rm MWO}$	σ_S	DATE	UT	BJD (2450000+)	$S_{\rm MWO}$	σ_S
2007 Aug 22	08:37:02	4334.86078	0.5213	0.0023	2009 Nov 8	02:33:33	5143.61246	0.4971	0.0024
2007 Aug 22	08:37:56	4334.86141	0.5097	0.0022	2009 Nov 27	02:31:27	5162.61077	0.5497	0.0024
2007 Sep 17	07:11:59	4360.80377	0.5517	0.0027	2009 Nov 27	02:32:41	5162.61163	0.5592	0.0025
2007 Sep 17	07:13:03	4360.80451	0.5474	0.0027	2009 Dec 18	04:42:19	5183.70078	0.5807	0.0033
2007 Oct 8	07:51:16	4381.83230	0.5354	0.0021	2009 Dec 18	04:43:33	5183.70163	0.5944	0.0032
2007 Oct 8	07:53:28	4381.83383	0.5498	0.0020	2009 Dec 24	04:33:04	5189.69400	0.5532	0.0032
2007 Oct 25	03:50:35	4398.66577	0.5421	0.0017	2009 Dec 24	04:34:18	5189.69486	0.5559	0.0031
2007 Oct 25	03:52:49	4398.66732	0.5299	0.0020	2009 Dec 24	04:36:07	5189.69612	0.5502	0.0038
2007 Dec 12	02:25:59	4446.60645	0.5602	0.0015	2010 Jan 9	03:43:50	5205.65868	0.6342	0.0028
2007 Dec 12	02:28:13	4446.60800	0.5743	0.0016	2010 Jan 9	03:45:04	5205.65954	0.6392	0.0028
2007 Dec 20	06:08:27	4454.76051	0.5509	0.0017	2010 Feb 26	01:29:54	5253.56154	0.5974	0.0076
2007 Dec 20	06:10:41	4454.76206	0.5383	0.0020	2010 Feb 26	01:31:08	5253.56240	0.6209	0.0075
2008 Jan 3	02:01:24	4468.58805	0.5740	0.0016	2010 Mar 21	23:47:25	5277.48855	0.6373	0.0029
2008 Jan 3	02:03:18	4468.58937	0.5675	0.0015	2010 Mar 21	23:48:39	5277.48941	0.6298	0.0030
2008 Feb 29	01:06:20	4525.54498	0.5170	0.0024	2010 Mar 21	23:50:03	5277.49038	0.6285	0.0030
2008 Feb 29	01:07:34	4525.54583	0.5054	0.0024	2010 Aug 9	10:05:13	5417.92090	0.5800	0.0028
2008 Mar 17	00:01:35	4542.49871	0.4615	0.0021	2010 Aug 9	10:06:27	5417.92176	0.5806	0.0026
2008 Mar 17	00:02:49	4542.49956	0.4649	0.0024	2010 Aug 26	07:04:31	5434.79687	0.5639	0.0058
2008 Jul 9	09:30:20	4656.89418	0.4698	0.0038	2010 Aug 26	07:05:46	5434.79774	0.5539	0.0059
2008 Jul 9	09:31:34	4656.89503	0.4657	0.0038	2010 Aug 26	07:07:15	5434.79877	0.5675	0.0054
2008 Jul 27	09:36:41	4674.90003	0.5161	0.0027	2010 Sep 16	06:19:23	5455.76716	0.5674	0.0050
2008 Jul 27	09:37:55	4674.90088	0.5127	0.0027	2010 Sep 16	06:20:37	5455.76802	0.5662	0.0055
2008 Jul 27	09:39:09	4674.90174	0.5144	0.0027	2010 Sep 21	07:45:46	5460.82750	0.5768	0.0054
2008 Aug 8	08:14:46	4686.84416	0.4753	0.0049	2010 Sep 21	07:47:00	5460.82836	0.5676	0.0053
2008 Aug 8	08:16:00	4686.84502	0.4911	0.0064	2010 Oct 15	07:07:37	5484.80228	0.5304	0.0024
2008 Aug 18	10:05:14	4696.92175	0.4422	0.0018	2010 Oct 20	03:44:13	5489.66119	0.5487	0.0029
2008 Aug 18	10:06:28	4696.92261	0.4399	0.0017	2010 Oct 20	03:45:27	5489.66205	0.5353	0.0028
2008 Sep 7	05:48:54	4716.74537	0.4525	0.0060	2010 Nov 26	04:34:25	5526.69619	0.6010	0.0029
2008 Sep 7	05:50:08	4716.74623	0.4688	0.0029	2010 Nov 26	04:35:39	5526.69704	0.5999	0.0030
2008 Sep 15	06:25:08	4724.77113	0.4634	0.0020	2010 Dec 13	05:41:53	5543.74241	0.4972	0.0031
2008 Sep 15	06:26:22	4724.77199	0.4604	0.0020	2010 Dec 13	05:43:07	5543.74326	0.4843	0.0025
2008 Sep 25	05:08:51	4734.71882	0.4396	0.0018	2010 Dec 31	03:01:03	5561.62965	0.5582	0.0099
2008 Sep 25	05:10:05	4734.71968	0.4430	0.0018	2010 Dec 31	03:02:17	5561.63050	0.5112	0.0111
2008 Oct 4	05:39:08	4743.74037	0.4288	0.0026	2011 Jan 8	03:28:43	5569.64827	0.5704	0.0030
2008 Oct 4	05:40:22	4743.74122	0.4363	0.0026	2011 Jan 8	03:29:57	5569.64913	0.5492	0.0028
2008 Oct 12	05:37:24	4751.73953	0.4681	0.0050	2011 Jan 30	03:25:41	5591.64433	0.5673	0.0067
2008 Oct 12	05:38:37	4751.74038	0.4657	0.0052	2011 Jan 30	03:26:55	5591.64519	0.5520	0.0058
2008 Oct 25	06:23:37	4764.77205	0.5247	0.0159	2011 Feb 26	00:42:39	5618.52875	0.5410	0.0068
2008 Oct 25	06:24:51	4764.77291	0.4274	0.0085	2011 Feb 26	00:43:53	5618.52960	0.5237	0.0058
2008 Nov 2	07:06:32	4772.80199	0.4799	0.0031	2011 Mar 9	00:41:04	5629.52675	0.5690	0.0033
2008 Nov 2	07:07:46	4772.80285	0.5108	0.0033	2011 Mar 9	00:42:18	5629.52761	0.5662	0.0028
2008 Nov 10	05:37:51	4780.74045	0.4464	0.0020	2011 Jul 20	09:47:19	5762.90675	0.4732	0.0056
2008 Nov 10	05:39:05	4780.74130	0.4558	0.0020	2011 Jul 20	09:48:33	5762.90761	0.4827	0.0050
2008 Nov 26	06:30:29	4796.77678	0.4713	0.0027	2011 Sep 1	08:21:44	5805.85096	0.4406	0.0038
2008 Nov 26	06:31:42	4796.77763	0.4737	0.0027	2011 Sep 1	08:22:58	5805.85182	0.4442	0.0037
2008 Dec 2	04:34:49	4802.69628	0.4392	0.0021	2011 Sep 18	07:54:44	5822.83350	0.4520	0.0030
2008 Dec 2	04:36:03	4802.69714	0.4329	0.0021	2011 Sep 18	07:55:58	5822.83436	0.4542	0.0033
2008 Dec 10	01:06:35	4810.55136	0.4552	0.0046	2011 Oct 22	07:49:41	5856.83171	0.4010	0.0066
2008 Dec 10	01:07:49	4810.55222	0.4456	0.0071	2011 Oct 22	07:50:55	5856.83257	0.4276	0.0061
2009 Jan 13	03:18:41	4844.64089	0.4327	0.0020	2011 Nov 14	06:25:34	5879.77356	0.4517	0.0024
2009 Jan 13	03:19:55	4844.64175	0.4310	0.0019	2011 Nov 14	06:26:48	5879.77441	0.4486	0.0024
2009 Jan 20	02:31:57	4851.60786	0.4137	0.0024	2011 Dec 4	03:03:34	5899.63286	0.4001	0.0020
2009 Jan 20	02:33:11	4851.60872	0.4178	0.0025	2011 Dec 5	02:45:36	5900.62034	0.4231	0.0021
2009 Jan 31	02:45:28	4862.61629	0.4327	0.0020	2011 Dec 5	02:46:50	5900.62120	0.4212	0.0021
2009 Jan 31	02:46:42	4862.61715	0.4254	0.0020	2011 Dec 14	03:04:15	5909.63290	0.3987	0.0020
2009 Feb 8	01:34:25	4870.56624	0.4655	0.0021	2011 Dec 14	03:05:29	5909.63376	0.3916	0.0019
2009 Feb 8	01:35:39	4870.56710	0.4519	0.0020	2011 Dec 23	02:35:50	5918.61267	0.4203	0.0039
2009 Mar 28	23:49:25	4919.48951	0.4767	0.0043	2011 Dec 23	02:37:04	5918.61353	0.4240	0.0049
2009 Mar 28	23:50:39	4919.49036	0.4586	0.0024	2012 Jan 14	04:11:35	5940.67758	0.4219	0.0021
2009 Jul 1	10:03:32	5013.91665	0.5200	0.0025	2012 Jan 14	04:12:49	5940.67844	0.4243	0.0021
2009 Jul 1	10:04:46	5013.91751	0.5155	0.0027	2012 Jan 28	02:34:39	5954.60909	0.4097	0.0032
2009 Aug 28	07:19:32	5071.80750	0.5136	0.0023	2012 Jan 28	02:35:53	5954.60994	0.4111	0.0031
2009 Aug 28	07:20:46	5071.80835	0.5121	0.0027	2012 Jul 9	10:28:07	6117.93430	0.4836	0.0023
2009 Sep 27	07:00:06	5101.79619	0.5792	0.0027	2012 Jul 9	10:29:22	6117.93517	0.4877	0.0023
2009 Sep 27	07:01:22	5101.79707	0.5707	0.0028	2012 Aug 9	09:18:52	6148.88876	0.5407	0.0033
2009 Oct 17	05:08:16	5121.71948	0.4986	0.0030	2012 Aug 9	09:20:07	6148.88963	0.5278	0.0032
2009 Oct 17	05:09:30	5121.72034	0.4916	0.0030	2012 Sep 3	08:59:35	6173.87748	0.5024	0.0031
2009 Nov 3	05:31:51	5138.73625	0.5710	0.0036	2012 Sep 3	09:00:50	6173.87835	0.5111	0.0031
2009 Nov 3	05:33:05	5138.73710	0.5670	0.0032	2012 Oct 13	07:16:28	6213.80837	0.5753	0.0042
2009 Nov 3	05:34:28	5138.73806	0.5624	0.0036	2012 Oct 13	07:17:42	6213.80923	0.5738	0.0040
2009 Nov 8	02:32:20	5143.61161	0.5069	0.0024	···	···	···	···	···