The Astrophysical Journal, 544:L145–L148, 2000 December 1

EVIDENCE FOR A LONG-PERIOD PLANET ORBITING ϵ ERIDANI[1]

Artie P. Hatzes,[2] William D. Cochran,[2] Barbara McArthur,[2] Sallie L. Baliunas,[3] Gordon A. H. Walker,[4] Bruce Campbell,[5] Alan W. Irwin,[6] Stephenson Yang,[6] Martin Kürster,[7] Michael Endl,[7,8] Sebastian Els,[7,9] R. Paul Butler,[10] and Geoffrey W. Marcy[11]

Received 2000 August 22; accepted 2000 September 26; published 2000 November 20

ABSTRACT

High-precision radial velocity (RV) measurements spanning the years 1980.8–2000.0 are presented for the nearby (3.22 pc) K2 V star ϵ Eri. These data, which represent a combination of six independent data sets taken with four different telescopes, show convincing variations with a period of ≈7 yr. A least-squares orbital solution using robust estimation yields orbital parameters of period $P = 6.9$ yr, velocity amplitude $K = 19$ m s^{-1}, eccentricity $e = 0.6$, projected companion mass $M \sin i = 0.86\ M_{\rm Jupiter}$, and semimajor axis $a_2 = 3.4$ AU. Ca II H and K *S*-index measurements spanning the same time interval show significant variations with periods of 3 and 20 yr yet none at the RV period. If magnetic activity were responsible for the RV variations, then it produces a significantly different period than is seen in the Ca II data. Given the lack of Ca II variation with the same period as that found in the RV measurements, the long-lived and coherent nature of these variations, and the high eccentricity of the implied orbit, Keplerian motion due to a planetary companion seems to be the most likely explanation for the observed RV variations. The wide angular separation of the planet from the star (approximately 1″) and the long orbital period make this planet a prime candidate for both direct imaging and space-based astrometric measurements.

Subject headings: planetary systems — stars: individual (ϵ Eridani) — stars: low-mass, brown dwarfs — techniques: radial velocities

1. INTRODUCTION

Over the past 5 yr radial velocity (RV) surveys have had stunning success at finding the first giant gaseous planets ($M = 0.5$–$10\ M_{\rm Jupiter}$) in orbit around other stars. Although to date over 40 of these systems have been found, none qualify as “true Jupiters,” i.e., giant planets in low-eccentricity orbits with semimajor axes in excess of 3 AU.

ϵ Eri (HR 1084) is a bright ($V = 3.7$), nearby (3.22 pc) K2 V star exhibiting a high level of chromospheric activity (e.g., Gray & Baliunas 1995) that is consistent with its relatively young age of less than 1 Gyr (Soderblom & Däppen 1989). This star also has a dusty ring 60 AU from the star (Greaves et al. 1998).

The star ϵ Eri has been the subject of several RV planet searches. Walker et al. (1995), using measurements spanning 11 yr, found evidence for ≈10 yr variation with an amplitude of 15 m s^{-1}. These results were substantiated by Nelson & Angel (1998) using an analysis of the same data set. Cumming, Marcy, & Butler (1999) analyzed 11 yr of RV data on this star taken at Lick Observatory and found significant variations with comparable amplitude but with a shorter period of 6.9 yr. Because of the high level of magnetic activity for ϵ Eri, these RV variations were largely interpreted as arising from a stellar activity cycle.

The McDonald Observatory Planet Search Program (Cochran & Hatzes 1999) has been monitoring ϵ Eri since late 1988. In this Letter, these results in combination with other surveys are presented. We confirm the presence of long-period RV variations and demonstrate that they likely are due to the presence of a planetary companion.

2. THE RADIAL VELOCITY DATA SETS

The RV data represent measurements from four planet search groups. Data taken from late 1980 to late 1991 using the coudé spectrograph of the Canada-France-Hawaii 3.6 m telescope (CFHT set) utilized a hydrogen fluoride (HF) absorption cell for the velocity metric (Walker et al. 1995). Cumming et al. (1999) presented precise RV measurements for ϵ Eri taken with an iodine gas absorption cell spanning 1987.69–1999.99 using the Hamilton spectrograph of the 3 m Shane Telescope at Lick Observatory (Lick set). Observations of ϵ Eri spanning the time interval 1992.84–1998.02 were made as part of an ESO planet search program using the 1.4 m coudé auxiliary telescope + coudé echelle spectrometer at La Silla. Details of this program can be found in Kürster et al. (2000) and Endl, Kürster, & Els (2000).

The largest data set is based on observations made at the 2.7 m telescope at McDonald Observatory and comprises three subsets. From 1988.74 to 1994.81, observations of ϵ Eri were made using telluric O_2 as the wavelength reference (McD-O_2 set). From late 1990 to late 1998, an iodine absorption cell was used as the velocity metric (McD-I_2 set). Both of these data

[1] Based on observations collected at McDonald Observatory, Lick Observatory, European Southern Observatory at La Silla, and the Canada-France-Hawaii Telescope.

[2] McDonald Observatory, The University of Texas at Austin, Austin, TX 78712.

[3] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, MS 15, Cambridge, MA 02138.

[4] Physics and Astronomy Department, University of British Columbia, 6224 Agricultural Road, Vancouver, BC V6T 1Z4, Canada.

[5] BTEC Enterprises, Ltd.

[6] Department of Physics and Astronomy, University of Victoria, P.O. Box 3055, Victoria, BC V8W 3P6, Canada.

[7] European Southern Observatory, Casilla 19001, Vitacura, Santiago 19, Chile.

[8] Institut für Astronomie, Universität Wien, Türkenschanzstrasse 17, A-1180, Austria.

[9] Institut für Theoretische Astrophysik, Universität Heidelberg, Tiergartenstrasse 15, D-69121 Heidelberg, Germany.

[10] Department of Terrestrial Magnetism, Carnegie Institution of Washington, 5243 Broad Branch Road, NW, Washington, DC 20015-1305.

[11] Department of Astronomy, University of California, Berkeley, 601 Campbell Hall, Berkeley, CA 94720.

TABLE 1
THE DATA SETS

Data Set	Coverage (yr)	Technique	N	σ_{RV} (m s^{-1})
McD-O_2	1988.74–1994.81	Telluric	29	22.8
McD-I_2	1990.78–1998.07	Iodine cell	46	16.5
McD-2dC	1998.69–2000.03	Iodine cell	9	11.4
CFHT	1980.81–1991.88	HF cell	51	14.5
Lick	1987.69–1998.99	Iodine cell	62	14.0
ESO	1992.84–1998.02	Iodine cell	28	13.9

sets utilized the 6 foot camera of the coudé spectrograph, which isolated a single order of the echelle and thus had limited wavelength coverage (9 Å) but high spectral resolution (resolving power, $R = \lambda/\delta\lambda = 240{,}000$). Starting in 1998, the McDonald program switched to using the 2dcoudé spectrograph (McD-2dC set) of the 2.7 m telescope (Tull et al. 1995). This instrument allowed us to use the full spectral region having usable I_2 lines (~5000–6100 Å) but at a lower resolving power ($R = 60{,}000$). Analysis of the RV derived from the iodine (I_2) cell technique including modeling of the instrumental profile is outlined in Valenti, Butler, & Marcy (1995).

Table 1 summarizes the various data sets, the RV technique employed, the time interval of the observations, the number of observations, and the rms scatter σ of each set (from the fitted orbit; see § 4 for details). The number of observations represent nightly averages.

3. PERIOD SEARCH

A Lomb-Scargle periodogram (Scargle 1982) was used to search for periodic signals in the data. Each data set represents relative radial velocities that have different zero-point offsets with respect to the others. These offsets were determined in an unbiased manner from the orbital fitting (see below), which computed simultaneously all orbital elements as well as the relative velocity offsets (there is significant temporal overlap between the different sets). The top panel of Figure 1 shows the resulting periodogram of the combined data that exhibits significant power at a period of 7.13 yr (=2603 days). The false alarm probability (FAP) was estimated using equation (18) of Scargle (1982), and this yielded FAP $= 5 \times 10^{-9}$. This low FAP was confirmed using a bootstrap randomization scheme (e.g., Kürster et al. 1997). For comparison, false data sets with the same variance as the original observations were generated by randomly reassigning the RV values the times of the observations. This was done 5×10^5 times, and there was no instance where maximum power in the "random" periodogram exceeded that found in the data.

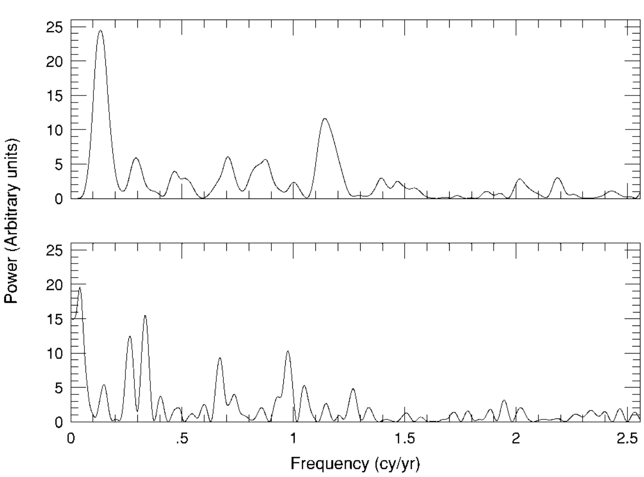

FIG. 1.—*Top*: Lomb-Scargle periodogram of the combined RV measurements for ϵ Eri. *Bottom*: Periodogram of the Ca II H and K *S*-index measurements.

TABLE 2
ORBITAL ELEMENTS OF THE PLANET AROUND ϵ ERIDANI

Element	Robust Estimation	Least Squares
Period (days)	2502.1 ± 20.1	2503.5 ± 27.1
T (JD)	2,449,194.8 ± 13.5	2,449,180.62 ± 17.2
Eccentricity	0.608 ± 0.041	0.584 ± 0.043
ω (deg)	48.9 ± 4.1	45.5 ± 4.3
$K1$ (m s^{-1})	19.0 ± 1.7	19.0 ± 1.6
$f(m)$ ($\times 10^{-9}$ $M_\odot$)	0.886 ± 0.248	0.943 ± 0.266
Slope (m s^{-1} yr^{-1})	0.42 ± 0.20	0.44 ± 0.19

4. THE ORBITAL SOLUTION

An orbital solution was performed using a GaussFit model (Jefferys, Fitzpatrick, & McArthur 1988; McArthur, Jefferys, & McCartney 1994). The relative velocity offsets of the different data sets were solved simultaneously with the orbital elements and a long-term trend in the RV measurements. Both standard least-squares and robust estimation analyses were performed.

Table 2 lists the orbital parameters from least squares and robust estimation. The solutions in Table 2 include a slight slope (0.4 m s^{-1} yr^{-1}) in the velocities. The orbital solution without the trend resulted in parameters consistent to within the errors of those listed in Table 2 but with larger standard deviations. The GaussFit results were independently verified using the ORBIT program (Forveille et al. 1999), which yielded orbital parameters to within the errors of the GaussFit solution. Assuming a mass of $M = 0.85\ M_\odot$ for ϵ Eri (Drake & Smith 1993) results in an $M \sin i = 0.86\ M_{\rm Jupiter}$. Figure 2 shows the robust estimation fit of the orbital solution RV measurements including the linear trend.

The rms scatter of the various data sets about the orbital curve are listed in Table 1. The average σ is about 14 m s^{-1}, excluding the O_2 data. (The telluric method suffers from larger systematic errors such as winds, pressure, temperature changes in the Earth's atmosphere, etc.) A large part of the scatter may

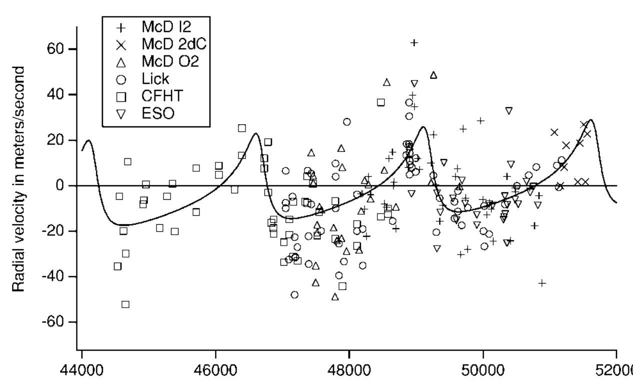

FIG. 2.—Orbital solution to the RV data using the robust estimation elements of Table 2.

TABLE 3
Ca II ANALYSIS

Parameter	Peak 1	Peak 2	Peak 3
Frequency (cycles day^{-1})	0.049 ± 0.004	0.334 ± 0.004	0.265 ± 0.005
Period (yr)	20.38	2.99	3.77
Power	18.5	15.6	12.8
FAP (%)	3.9×10^{-5}	0.0006	0.01
Amplitude	0.02	0.02	0.02

be related to magnetic activity. Saar & Donahue (1997) noted that stars as active as ϵ Eri should show activity-related RV "jitter" of 12–17 m s^{-1}. The scatter of our data is quantitatively consistent with expectations for star with the same age and activity level as ϵ Eri.

5. THE NATURE OF THE RV VARIATIONS: Ca II H and K MEASUREMENTS

Compared to the Sun, ϵ Eri is a modestly active star, and the 7 yr RV period is well within the range of periods expected for activity cycles. The Ca II H and K *S*-index has proved to be a powerful technique for discerning activity cycles and rotational modulation in magnetically active stars (see Baliunas et al. 1995 and references therein). If the RV variations of ϵ Eri were due to stellar activity, then one would expect to see the same period in the Ca II *S*-index variations, which would exclude the planet hypothesis.

Observations of the relative flux in the Ca II H and K emission cores in ϵ Eri have been made since 1966 at Mount Wilson Observatory with its 100 and 60 inch telescopes. Spectrophotometric records of about 100 lower main sequence stars show good long-term precision (rms = 1%–2%) and are described in a series of papers cited in Baliunas et al. (1995). Although the program of observations began with measurements made approximately monthly during the seasonal window of accessibility of each star for observations, by 1980 observations were made more frequently in order to record modulation of the Ca II flux by axial rotation owing to the uneven longitudinal distribution of Ca II–emitting regions.

The interval of Ca II spectrophotometric measurements that overlap with the RV data is approximately 1980–1999. The Ca II data were analyzed by one of us (S. L. B.) for sinusoidal periodicities according to the prescription for unevenly sampled data given in Horne & Baliunas (1986), and the results are given in Table 3. The periodogram analysis was made on data averaged over 30 day intervals. The lower panel of Figure 1 shows the Lomb-Scargle periodogram of the 30 day *S*-index averages.

Two significant periodicities, one of 20 yr (FAP = 4×10^{-7}) and one close to 3 yr (FAP = 6×10^{-6}), are present, suggesting multimode variations in surface magnetism, a not uncommon class of Ca II variability in younger stars like ϵ Eri. Both periods show strong and statistically significant normalized power in the periodogram. A third, weaker period of ~3.8 yr (FAP ~ 0.0001) is also possibly present.

The peak in the Ca II periodogram closest to the RV period is at 2476 days (= 6.78 yr; $\nu = 0.147 \pm 0.008$). However, this is only the sixth highest peak in the periodogram, and it has a very high FAP (16%), indicating the period's relative insignificance. Furthermore, a detailed investigation yielded no convincing correlation between the RV and Ca II data sets. We conclude that there is no significant periodicity in the Ca II spectrophotometric measurements near that of the Doppler RV variation.

6. DISCUSSION

We have provided convincing evidence for a 6.9 yr period in the RV variations of ϵ Eri based on six independent data sets taken at four telescopes using three different measurement techniques. Although these RV variations can be well fit with a Keplerian orbit, there might be some concern that RV variability may in fact be related to the high magnetic activity of this star.

A periodogram analysis of contemporaneous Ca II H and K *S*-index measurements revealed no significant periods at the one found in the RV analysis. This seems to exclude stellar activity as the cause of the observed RV variations. Since RV measurements provide an indirect planet detection and the exact relationship between Ca II and RV variability is poorly understood, we cannot absolutely exclude that photospheric motion related to magnetic activity is indeed responsible for the observed RV variations. However, this motion would have to be unrelated to the Ca II variability and *known* magnetic timescales on this star, which is counter to our current understanding of stellar activity. Furthermore, it is not clear whether activity-related RV variations can mimic Keplerian motion with a high orbital eccentricity over such a long timescale. Given all the available evidence, the planet hypothesis is the simplest, most likely explanation for the RV variability of this star.

This extrasolar planet is particularly interesting in light of the dusty ring around ϵ Eri. This ring is nonuniform, which may be evidence for other planets in the system (Greaves et al. 1998; Liou & Zook 1999), most likely at large orbital radii (~10–30 AU). It is not clear if the planet that we have detected can dynamically influence the dust ring, although inner planets may play some role in clearing out the inner parts of the dust disk (Liou & Zook 1999). Interestingly, we do detect a linear acceleration of the central star of about 0.4 m s^{-1} yr^{-1}, which is consistent with a 2 $M_{\rm Jupiter}$ planet orbiting at the inner radius of the ring (30 AU). Such a planet would produce an astrometric acceleration of 0.03 mas yr^{-2}, which can easily be confirmed by future space-based interferometry missions. ϵ Eri may be a good candidate star for multiple planets and is deserving of future studies.

Adopting a stellar inclination of $i = 30°$, which is consistent with $V \sin i$ measurements (Saar & Osten 1997) and the ring inclination (Greaves et al. 1998), and assuming that the orbital axis of the planet, stellar rotation axis, and ring axis are all aligned, we estimate the true mass of the planet to be 1.7 $M_{\rm Jupiter}$.

The candidate planet around ϵ Eri would qualify as the first "Jupiter analog" except for its high orbital eccentricity. Giant planets in eccentric orbits are a common phenomenon among extrasolar planets (Cochran et al. 1997; Korzenik et al. 2000; Vogt et al. 2000). Explanations include interactions with a binary companion (Holman, Touma, & Tremaine 1997), interaction with the disk (Artymowicz 1992), or mergers and scatterings between two or more giant planets (e.g., Lin & Ida 1997).

It seems unlikely that the eccentricity is due to interactions with a binary companion as there is scant evidence for ϵ Eri being a binary star. The claim of an astrometric perturbation to ϵ Eri with a 25 yr period by van de Kamp (1974) has been refuted by Heintz (1993). Wielen et al. (1999) compared ground-based proper-motion measurements of ϵ Eri to those of *Hipparcos* and found that this star was a binary "on the verge of detectability and significance." The "best-fit" orbit does have a slight linear trend that may be due to a long-period companion, but this is not compelling given that the slope amounts to a velocity change of less than 10 m s^{-1} over the course of our measurements or comparable to the RV rms scatter. Data covering a longer time base is needed to confirm this. At the present time, there is no strong evidence to support the hypothesis that the high eccentricity is caused by interactions with a stellar companion. Given the diversity of planets showing highly eccentric orbits (now with long orbital periods), there is probably a number of mechanisms at work producing the observed eccentricities of extrasolar planets.

With a period of nearly 7 yr and a velocity amplitude K of only 19 m s^{-1}, the planet of ϵ Eri has the longest orbital period and one of the lowest velocity amplitudes (for the central star) yet found. The rms scatter of the RV measurements about the orbital solution (due to measurement error and stellar activity) is comparable to the orbital amplitude K. In spite of this, the planet was detected with a high degree of confidence. This demonstrates that RV signals with amplitudes comparable to the noise level can be detected reliably given sufficient data. Ancillary measurements such as Ca II H and K emission measures are also extremely important for confirming planet discoveries, particularly long-period ones.

The stellar distance of 3.2 pc yields an angular separation between star and planet of about 1″. There is hope that we may one day be able to detect light from the planet using ground-based imaging with adaptive optics or space-based imaging. We searched the *Hubble Space Telescope* archives and found several images taken at 2 μm with the coronagraph of NICMOS, but no nearby companions were seen. However, the albedo of the planet at this wavelength is expected to be zero (Sudarsky, Burrows, & Pinto 2000). Furthermore, with an estimated effective temperature of ~100 K, the radiated flux from the planet would also be undetected by NICMOS in this bandpass. To detect the thermal radiation from the planet requires observations at wavelengths near 20 μm where the companion would have a magnitude ≈20. Searches for reflected light from the planet must be done in spectral regions where the planet albedo is expected to be high. For example, the theoretical albedo at 5500 Å for a gaseous giant planet with an effective temperature near 100 K is about 0.7 (Sudarsky et al. 2000). This results in a "reflected" magnitude for the planet about 21–22 mag fainter than the primary star.

The astrometric perturbation of the central star is estimated to be ≈2 mas. This is at the limit of ground-based measurements for this star (see Wielen et al. 1999) but should be measurable using space-based astrometric measurements with the *Hubble Space Telescope* (McArthur et al. 1999) or with future space-based or ground-based (Keck, Very Large Telescope Interferometer) astrometric measurements. These combined with the RV measurements should yield orbital inclination and thus the true mass of the companion. We note that either direct imaging or astrometric measurements would provide the best confirmation of this planet.

The discovery of the planet around ϵ Eri has now begun to push the parameter space of extrasolar planet discoveries to the long-period, solar system giant planet analogs. As RV searches lengthen their time base, more of these systems will undoubtedly be discovered.

A. P. Hatzes and W. D. Cochran acknowledge the support of NASA grants NAG5-4384 and NAG5-9227 and NSF grant AST 98-08980. B. McArthur receives support through NASA grant NAS5-1603. M. Endl acknowledges support by the Austrian Fond zur Förderung der wissenschaftlichen Forschung Nr. S7302. S. L. Baliunas is grateful to the dedication of M. A. Bradford, R. A. Donahue, K. Palmer, and W. H. Soon to the HK Project at Mount Wilson Observatory, which is operated by the Mount Wilson Institute under an agreement with the Carnegie Institution of Washington. Support for this research has been made possible through the generosity of the Richard C. Lounsbery Foundation. R. P. Butler and G. W. Marcy thank D. Fischer, E. Williams, S. Vogt, and C. McCarthy. Finally, we thank K. Dennerl and S. Döbereiner for help with the ESO observations.

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