THE EXTRASOLAR PLANET $\epsilon$ ERI DANI b: ORBIT AND MASS

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ABSTRACT

Hubble Space Telescope (HST) observations of the nearby (3.22 pc) K2 V star $\epsilon$ Eridani have been combined with ground-based astrometric and radial velocity data to determine the mass of its known companion. We model the astrometric and radial velocity measurements simultaneously to obtain the parallax, proper motion, perturbation period, perturbation inclination, and perturbation size. Because of the long period of the companion, $\epsilon$ Eri b, we extend our astrometric coverage to a total of 14.94 yr (including the 3 yr span of the HST data) by including lower precision ground-based astrometry from the Allegheny Multichannel Astrometric Photometer. Radial velocities now span 1980.8–2006.3. We obtain a perturbation period, $P = 6.85 \pm 0.03$ yr, semimajor axis $a = 1.88 \pm 0.20$ mas, and inclination $i = 30.1 \pm 3.8$. This inclination is consistent with a previously measured dust disk inclination, suggesting coplanarity. Assuming a primary mass $M_\star = 0.83 M_\odot$, we obtain a companion mass $M = 1.55 M_J \pm 0.24 M_J$. Given the relatively young age of $\epsilon$ Eri (~800 Myr), this accurate exoplanet mass and orbit can usefully inform future direct-imaging attempts. We predict the next periastron at 2007.3 with a total separation $\rho = 0.053$ at position angle P.A. = $-27^\circ$. Orbit orientation and geometry dictate that $\epsilon$ Eri b will appear brightest in reflected light very nearly at periastron. Radial velocities spanning over 25 yr indicate an acceleration consistent with a Jupiter-mass object with a period in excess of 50 yr, possibly responsible for one feature of the dust morphology, the inner cavity.

Key words: astrometry — stars: distances — stars: individual ($\epsilon$ Eridani b) — stars: late-type — techniques: interferometric — techniques: radial velocities

Online material: color figures

1. INTRODUCTION

With a spectral type of K2 V, $\epsilon$ Eridani (=HD 22049, HIP 16537, HR 1084, PLX 742) is one of the nearest solar-type stars, with a distance of about 3.2 pc. It is slightly metal-poor (Fe/H = $-0.13 \pm 0.04$; Santos et al. 2004; Laws et al. 2003). Its proximity makes it a prime target for future extrasolar planet direct-imaging efforts. The success of these efforts will depend on knowing exactly where to look, requiring accurate orbital elements for the companion. It will depend on the mass of the planetary companion and on the age of the system. Younger and more massive gas giant planets are predicted to be brighter (Hubbard et al. 2002). If young enough, the intrinsic luminosity of $\epsilon$ Eri b might be greater than its brightness in reflected light. However, planetary-mass objects with the age of $\epsilon$ Eri change intrinsic luminosity by a factor of nearly 100 between $1 M_J$ and $7 M_J$, hence the need for a more precise companion mass.

The star $\epsilon$ Eri has been the subject of multiple radial velocity planet searches. Walker et al. (1995), using measurements spanning 11 yr, found evidence for $\approx 10$ 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 et al. (1999) analyzed 11 yr of radial velocity 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 $\epsilon$ Eri (inferred from chromospheric activity), these radial velocity variations were largely interpreted as arising from a stellar activity cycle. The McDonald Observatory Planet Search Program (Cochran & Hatzes 1999) has monitored $\epsilon$ Eri since late 1988. The McDonald results in combination with these other surveys, along with data from ESO (Endl et al. 2002), confirmed the presence of a long-period radial velocity variations and demonstrated that the most likely explanation for the observed radial velocity variations was the presence of a planetary companion with a period $P = 6.9$ yr. Details of this analysis are given in Hatzes et al. (2000).

We obtained 3 years of astrometry with the Hubble Space Telescope (HST) with milliarcsecond precision which we combined with radial velocity data as we have in previous planetary mass studies (Benedict et al. 2002; McArthur et al. 2004). Just as in the case of the Hatzes et al. (2000) radial velocity analysis, in which the less precise data extended the observation span and allowed a companion detection, we anticipated that less precise astrometry with a 14 yr baseline from the Allegheny Multichannel Astrometric Photometer (MAP) astrometry project would improve the astrometric result. Gatewood (2000) reported in a meeting abstract an inclination $i = 46^\circ \pm 17^\circ$ and a companion mass $M_b = 1.2 M_J \pm 0.3 M_J$ obtained with the MAP data alone. In this study we combine the MAP data with the HST data only to improve the determination of the proper motion of $\epsilon$ Eri. The parallax and proper motion must be removed as accurately as possible to determine the perturbation orbit of $\epsilon$ Eri,
which, when combined with an estimate of the mass of \( \epsilon \) Eri, provides the mass of the companion \( \epsilon \) Eri b.

This paper presents the mass of the planet orbiting \( \epsilon \) Eri discussed in Hatzes et al. (2000), not the far longer period object inferred from dust-disk morphology (Quillen & Thorndike 2002). Our mass is derived from combined astrometric and radial velocity data, continuing a series presenting accurate masses of planetary companions to nearby stars. Previous results include the mass of Gl \( 876b \) (Benedict et al. 2002) and of \( \rho \) Cnc d (McArthur et al. 2004).

In §2 we briefly review the astrometers, discuss the data sets coming from each, and identify our many sources for radial velocities. In §3 we present the results of extensive spectrophotometry of the astrometric reference stars, information required to correct relative parallax to absolute. In §4 we briefly discuss our astrometric modeling and the quality of our results as determined by residuals. In §5 we review our radial velocity data. In §6 we derive an absolute parallax and relative proper motion for \( \epsilon \) Eri, those nuisance parameters that must be removed to determine the perturbation orbital parameters. We finally establish the perturbation orbital parameters and, combined with an estimate of the mass of \( \epsilon \) Eri, estimate a mass for \( \epsilon \) Eri b. We discuss system age, dust, and companion detectability in §7 and summarize our conclusions in §8.

2. THE ASTROMETERS AND OBSERVATIONAL DATA

2.1. HST FGS1r

We used \( HST \) Fine Guidance Sensor 1r (FGS1r) to carry out our space-based astrometric observations. Nelson et al. (2003) provided a detailed overview of FGS1r as a science instrument. Benedict et al. (2000) described the FGS3 instrument’s astrometric capabilities along with the data acquisition and reduction strategies used in the present study. We use FGS1r for the present study because it provides superior fringes from which to obtain target and reference-star positions (McArthur et al. 2002).

Table 1 presents a log of \( HST \) FGS observations. Epochs 2–4 contain multiple data sets acquired continguously, the time span being less than a day. Each time is that of the first observation within each epoch. Each distinct observation set typically contains five measurements of \( \epsilon \) Eri. The field was observed at multiple spacecraft roll values, and \( \epsilon \) Eri had to be placed in different, noncentral locations within the FGS1r field of view (FOV) to accommodate the less-than-optimal distribution of reference stars. FGS photometric sensitivity depends on location within the FOV (e.g., Benedict et al. 1998) and on time, as the FGS photomultiplier tubes age. Given the faintness of our reference stars, we could not use them to provide a high-precision flat field. Hence, we could not extract millimagnitude photometry (cf. Benedict et al. 2000) to monitor \( \epsilon \) Eri stellar activity.

2.2. The Allegheny MAP

The MAP and associated observation and reduction procedures are described by Gatewood (1987). The observational program using the MAP began in 1986, but reluctance to observe at the low declination of \( \epsilon \) Eri over the city of Pittsburgh delayed initiation of its observation until 1989 January. Despite the reduced precision and rate of successful observation, the field remained on the MAP program until the installation of new instrumentation early in 2004 (Gatewood 2004).

MAP observations of the brightest stars use either a specially filtered 12th channel (e.g., Gatewood & Han 2006) or a divide-by-16 feature on channel 2, which reduces the count sufficiently for the 16 bit counters. With an \( R \) magnitude of 3.0 \( \epsilon \) Eri could be placed on channel 2 without counter flooding. The other 10 channels were assigned to the MAP reference stars noted below. An observation consists of 4 \( \times \) 11 minute sweeps of the ruling across the field, with probe rotations and ruling rotations to reduce systematic error (Gatewood 1987). Thus, each observation consists of approximately 22 minutes of integration on each axis. Table 2 presents a log of MAP observations.

2.3. Radial Velocities

The radial velocity data used include all data described in Hatzes et al. (2000) in addition to more recent data from McDonald.
| Epoch | MJD  | Year   |
|-------|------|--------|
| 47,544.0781 | 1989.0474 |
| 47,772.4045 | 1989.6726 |
| 47,790.3559 | 1989.7217 |
| 47,822.2920 | 1990.8091 |
| 47,826.2622 | 1990.8200 |
| 47,829.2503 | 1990.8282 |
| 47,905.0385 | 1990.9357 |
| 47,923.0024 | 1990.9849 |
| 47,933.0142 | 1990.1123 |
| 48,209.2163 | 1990.8685 |
| 48,213.2052 | 1990.8794 |
| 48,234.1406 | 1990.9367 |
| 48,281.0559 | 1991.0652 |
| 48,290.0135 | 1991.0897 |
| 48,528.3413 | 1991.7422 |
| 48,547.2948 | 1991.7941 |
| 48,901.3066 | 1992.7633 |
| 48,915.2816 | 1992.8016 |
| 49,007.9990 | 1993.0554 |
| 49,022.0066 | 1993.0938 |
| 49,027.0066 | 1993.1075 |
| 49,268.2733 | 1993.7680 |
| 49,274.2691 | 1993.7844 |
| 49,283.2309 | 1993.8145 |
| 49,302.2240 | 1993.8610 |
| 49,312.1545 | 1993.8882 |
| 49,334.1448 | 1993.9484 |
| 49,372.9997 | 1994.0548 |
| 49,597.4087 | 1994.6692 |
| 49,600.4003 | 1994.6773 |
| 49,640.3052 | 1994.7866 |
| 49,653.2205 | 1994.8220 |
| 49,668.1733 | 1994.8629 |
| 49,708.0587 | 1994.9721 |
| 49,747.0052 | 1995.0787 |
| 49,748.0476 | 1995.0816 |
| 50,362.2622 | 1996.7632 |
| 50,371.2538 | 1996.7878 |
| 50,719.3260 | 1997.7408 |
| 50,736.3129 | 1997.7873 |
| 50,741.3281 | 1997.8010 |
| 50,798.1108 | 1997.9565 |
| 50,799.1316 | 1997.9939 |
| 51,079.3615 | 1998.7276 |
| 51,100.3219 | 1998.7839 |
| 51,145.1372 | 1998.9066 |
| 51,209.0010 | 1999.0815 |
| 51,829.2788 | 2000.7797 |
| 52,183.3115 | 2001.7490 |
| 52,185.2774 | 2001.7544 |
| 52,219.1969 | 2001.8472 |
| 52,219.3080 | 2001.8475 |
| 52,220.2115 | 2001.8500 |
| 52,225.1816 | 2001.8636 |
| 52,226.1899 | 2001.8664 |
| 52,226.2573 | 2001.8665 |
| 52,227.2226 | 2001.8692 |
| 52,265.0691 | 2001.9728 |
| 52,893.3497 | 2003.6929 |
| 52,924.2726 | 2003.7776 |
| 52,925.2747 | 2003.7804 |
| 52,925.3420 | 2003.7805 |
| 52,937.2087 | 2003.8130 |
| 52,946.2240 | 2003.8377 |
| 53,000.0580 | 2003.9851 |
| 53,001.0760 | 2003.9887 |
| 50,362.2622 | 1996.763 |
TABLE 3

| Data Set | Coverage | Technique | N | rms (m s$^{-1}$) |
|----------|----------|-----------|---|-----------------|
| CFHT     | 1980.81–1991.88 | HF cell   | 48 | 10.5            |
| Lick     | 1987.69–1998.99 | I$_2$ cell | 54 | 11.5            |
| McD dH   | 1988.74–1994.81 | Telluric  | 27 | 15.2            |
| ESO dI   | 1990.78–1998.87 | I$_2$ cell | 42 | 11.7            |
| McD dII  | 1992.84–1998.02 | I$_2$ cell | 36 | 9.6             |
| Total    | 1998.69–2004.86 | I$_2$ cell | 28 | 7.4             |

| MJD       | RV$_{eff}$ (m s$^{-1}$) |
|-----------|-------------------------|
| 51,066.4339 | –3.6 ± 6.4             |
| 51,212.1671 | 13.6 ± 5.0             |
| 51,239.1133 | 1.7 ± 8.6              |
| 51,449.4333 | 6.5 ± 5.0              |
| 51,503.3574 | 14.7 ± 5.1             |
| 51,529.1986 | –3.5 ± 7.4             |
| 51,555.1645 | –0.2 ± 5.2             |
| 51,775.4643 | 1.3 ± 5.9              |
| 51,809.4033 | –2.7 ± 4.8             |
| 51,917.2260 | 2.9 ± 5.5              |
| 52,142.4227 | –0.7 ± 6.2             |
| 52,142.4264 | –0.4 ± 6.1             |
| 52,248.2921 | –14.0 ± 5.9            |
| 52,303.1266 | –16.1 ± 7.7            |
| 52,328.1208 | 2.1 ± 5.6              |
| 52,330.1064 | –0.9 ± 5.7             |
| 52,539.4226 | –16.4 ± 6.4            |
| 52,576.4378 | 2.0 ± 5.5              |
| 52,661.1445 | –11.8 ± 5.2            |
| 52,931.3912 | –13.9 ± 6.4            |
| 52,958.2499 | –0.4 ± 5.4             |
| 52,958.2481 | 0.0 ± 6.0              |
| 53,016.2424 | 2.9 ± 6.0              |
| 53,016.2456 | 2.1 ± 6.0              |
| 53,035.1757 | –5.2 ± 5.6             |
| 53,075.0940 | 3.0 ± 5.7              |
| 53,318.3124 | –10.1 ± 6.6            |
| 53,632.4520 | –1.2 ± 5.3             |
| 53,632.4550 | 0.4 ± 5.5              |
| 53,689.3900 | –3.0 ± 5.2             |
| 53,745.2110 | 6.3 ± 5.1              |
| 53,809.0850 | 9.0 ± 5.5              |

Observatory and ESO. These data now span over 25 years. All sources are listed in Table 3. Briefly, McDonald phases I, II, and III are all data obtained with the 2.7 m Smith telescope. The phases correspond to (I) early velocities referenced to atmospheric O$_2$, (II) velocities obtained with an I$_2$ cell, and (III) velocities obtained with the McDonald 2d-Coude spectrograph (Tull et al. 1995) and an I$_2$ cell. The only new radial velocity data included in this new study are from the McDonald Observatory phase III 2.7 m program. They are listed in Table 4. Note that the errors associated with these data are larger than typically produced by this telescope/spectrograph combination (Endl et al. 2006) due to high levels of $\epsilon$ Eri stellar activity.

3. $\epsilon$ ERI ASTROMETRIC REFERENCE FRAMES

Any prior knowledge concerning the 15 stars included in our reference frame (listed in Table 5) eventually enters our modeling as observations with error and yields the most accurate parallax and proper motion for the prime target, $\epsilon$ Eri. These periodic and nonperiodic motions must be removed as accurately and precisely as possible to obtain the perturbation inclination and size caused by $\epsilon$ Eri b.

3.1. The MAP Reference Frame

Figure 1 shows the distribution of the 10 reference stars in the 130 MAP $\epsilon$ Eri observation sets (Table 2). Note that the areal coverage is approximately $0^\circ.6 \times 0^\circ.6$, allowing for the use of relatively bright reference stars, well distributed around the prime target $\epsilon$ Eri, in contrast to the case for the HST FGS (below).

3.2. The FGS Reference Frame

Figure 2 shows the distribution in FGS1r Pickle coordinates of the 52 sets of five reference-star measurements for the $\epsilon$ Eri field. The arcing pattern is enforced by the requirement that HST must roll to keep its solar panels fully illuminated throughout the year. To ensure access to all reference stars for every observation set, it was not possible to keep $\epsilon$ Eri (cross) located in the center of the FGS1r FOV. At each epoch we measured each reference star two to four times and $\epsilon$ Eri four to five times.

3.3. Absolute Parallaxes for the Reference Stars

Because the parallax determined for $\epsilon$ Eri is measured with respect to reference frame stars that have their own parallaxes, we must either apply a statistically derived correction from relative to absolute parallaxes (Yale Parallax Catalog; van Altena et al. 1995; hereafter YPC95) or estimate the absolute parallaxes of the reference-frame stars. In principle, the colors, spectral type, and luminosity class of a star can be used to estimate the absolute magnitude, $M_V$, and $J$-band absorption, $A_J$. The absolute parallax is then simply

\[ \pi_{abs} = 10^{-\left(m_V - M_V + 5 - A_V\right)/5}. \]  

3.3.1. Reference-Star Photometry

Our bandpasses for reference-star photometry include $V$ (from FGS1r) and $JHK$ from 2MASS. The $JHK$ values have been transformed to the Bessell & Brett (1988) system using the transformations provided in Carpenter (2001). Table 6 lists $VJK$ photometry for the target and reference stars indicated in Figures 1 and 2. Figure 3 contains a ($J - K$) versus ($V - K$) color-color diagram with reference stars and $\epsilon$ Eri labeled. Schlegel et al. (1998) found an upper limit $A_K \sim 0.1$ toward $\epsilon$ Eri. In the following we adopt $A_J = 0.0$ but increase the error on reference-star distance moduli by 0.1 mag to account for absorption uncertainty.

The derived absolute magnitudes are critically dependent on the assumed stellar luminosity, a parameter impossible to obtain for all but the latest type stars using only Figure 3. To confirm the luminosity classes we obtain UCAC2 proper motions (Zacharias et al. 2004) for a 1 deg$^2$ field centered on $\epsilon$ Eri and then iteratively

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11 The Two Micron All Sky Survey is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center, California Institute of Technology.
employ the technique of reduced proper motion (Yong & Lambert 2003; Gould & Morgan 2003) to discriminate between giants and dwarfs. The end result of this process is contained in Figure 4.

3.3.2. Adopted Reference-Frame Absolute Parallaxes

We derive absolute parallaxes using our estimated spectral types and luminosity classes and $MV$ values from Cox (2000). Our adopted input errors for distance moduli, $(m - M)_0$, are 0.4 mag for all reference stars (except ref-2 and ref-6, as discussed below). Contributions to the error are a small but undetermined $AV$, and errors in $MV$ are due to uncertainties in color–to–spectral-type mapping. We estimate a spectral type for reference star ref-6 only through its apparent magnitude, hence the larger error in its distance modulus. Ref-2, which in Figure 3 straddles the gap between giants and dwarfs, was finally typed K4 V, because the $\chi^2$ (from modeling of the reference frame) significantly decreased using that typing. Its input parallax error was also increased. All reference-star absolute parallax estimates are listed in Table 7. Individually, no reference-star absolute parallax is better determined than $\pm 18\%$. The average input absolute parallax for the reference frame is $\pi = 4.9$ mas, a quantity known to $\pm 5\%$ (standard deviation of the mean of 15 reference stars). We compare this to the correction to absolute parallax discussed and presented in YPC95 (§ 3.2, Fig. 2). Entering YPC95, Figure 2, with the Galactic latitude of $b = -48^\circ$ and average magnitude for the reference frame ($V_{\text{ref}} = 12.2$), we obtain a correction to the absolute parallax of 2.3 mas, considerably different. Rather than apply a model-dependent correction to the absolute parallax we introduce our

### Table 5

| ID  | Catalog       | R.A. (J2000.0) | Decl. (J2000.0) | $\pi^b$ | 2MASS       |
|-----|---------------|---------------|----------------|---------|-------------|
| 1   | $\epsilon$ Eri | 53.232961     | -9.458295      | 3.82    | 03325591–0927298 |
| 2   | ...           | 53.325845     | -9.467569      | 15.61   | 03331820–0928032 |
| 3   | ...           | 53.312638     | -9.434314      | 15.58   | 03331503–0926035 |
| 4   | ...           | 53.295306     | -9.421752      | 16.12   | 03331087–0925183 |
| 5   | ...           | 53.269681     | -9.418811      | 16.41   | 03330472–0925077 |
| 6   | ...           | 53.207917     | -9.449667      | 16.48   | ...         |
| 7   | GEN +6.10280864 | 53.374062    | -9.504524      | 11.36   | 03323977–0930162 |
| 8   | HD 22130      | 53.401866     | -9.349848      | 9.52    | 03333644–0920594 |
| 9   | BD –10 699    | 53.164328     | -9.267778      | 10.69   | 03323943–0916040 |
| 10  | GEN +6.10280861 | 53.032108    | -9.514245      | 11.60   | 03320770–0930512 |
| 11  | BD –10 699    | 53.399013     | -9.586081      | 10.24   | 03333576–0935098 |
| 12  | HD 21951      | 53.001248     | -9.385150      | 9.69    | 03320209–0923065 |
| 13  | BD –10 695    | 53.320908     | -9.696887      | 9.78    | 03331701–0941487 |
| 14  | BD –10 700    | 53.466004     | -9.641330      | 9.94    | 0335184–0938287 |
| 15  | BD –10 699    | 53.429559     | -9.232722      | 11.20   | 0334309–0913577 |
| 16  | 2MASS 03320556–0945292 | 53.023188     | -9.758118      | 11.15   | 03320556–0945292 |

| a Positions in degrees from 2MASS, except for ID 6, which was obtained from applying STScI Visual Target Tuner to the Digital Sky Survey. |
| b Magnitudes from FGS1r (ID 2–6), SIMBAD (ID 1), or MAP (ID 7–16). |

![Fig. 1.—MAP and $\epsilon$ Eri reference stars on the sky. Each star is identified by the number listed in Table 5. The inner box indicates the FGS1r reference-frame coverage for epoch 2 in Table 1.](image1)

![Fig. 2.—HST $\epsilon$ Eri and reference-frame observations in FGS1r Pickle coordinates. The symbol shape identifies each star listed in Table 5. Note that the position of $\epsilon$ Eri (cross) within the FGS1r FOV is not fixed at the center.](image2)
spectrophotometrically estimated reference-star parallaxes into our reduction model as observations with error.

4. THE ASTROMETRIC MODEL

The ε Eri reference frame contains 15 stars and has been measured by two different astrometers, FGS1r and MAP. The only object in common is ε Eri. From these positional measurements we determine the scale, rotation, and offset “plate constants” relative to an arbitrarily adopted constraint epoch for each observation set. As for all our previous astrometric analyses we employ GaussFit (Jefferys et al. 1988) to minimize $\chi^2$. The solved equations of condition for the ε Eri field are

$$x' = x + l c_\theta (B - V) - \Delta X F x,$$

TABLE 6
$\textit{V} \text{ and Near-IR Photometry}$

| ID | $V$ | $K$ | $(J - H)$ | $(J - K)$ | $(V - K)$ |
|----|-----|-----|-----------|-----------|----------|
| 1  | 3.82 ± 0.01 | 1.82 ± 0.05 | 0.40 ± 0.28 | 0.48 ± 0.07 | 2.00 ± 0.05 |
| 2  | 15.61 ± 0.03 | 13.01 ± 0.03 | 0.58 ± 0.04 | 0.72 ± 0.04 | 2.60 ± 0.04 |
| 3  | 15.58 ± 0.03 | 14.09 ± 0.06 | 0.41 ± 0.05 | 0.44 ± 0.07 | 1.50 ± 0.06 |
| 4  | 16.12 ± 0.03 | 13.88 ± 0.05 | 0.51 ± 0.04 | 0.59 ± 0.06 | 2.24 ± 0.06 |
| 5  | 16.41 ± 0.03 | 14.21 ± 0.08 | 0.46 ± 0.07 | 0.62 ± 0.09 | 2.20 ± 0.08 |
| 6  | 16.48 | ... | ... | ... | ... |
| 7  | 11.36 ± 0.03 | 9.93 ± 0.02 | 0.29 ± 0.03 | 0.33 ± 0.03 | 1.43 ± 0.04 |
| 8  | 9.52 ± 0.01 | 8.63 ± 0.02 | 0.21 ± 0.06 | 0.24 ± 0.03 | 0.89 ± 0.02 |
| 9  | 10.69 ± 0.03 | 8.85 ± 0.02 | 0.48 ± 0.04 | 0.54 ± 0.03 | 1.84 ± 0.04 |
| 10 | 11.60 ± 0.03 | 10.43 ± 0.02 | 0.33 ± 0.03 | 0.41 ± 0.03 | 1.17 ± 0.04 |
| 11 | 10.24 ± 0.03 | 8.73 ± 0.02 | 0.40 ± 0.06 | 0.43 ± 0.04 | 1.51 ± 0.04 |
| 12 | 9.69 ± 0.03 | 8.98 ± 0.02 | 0.13 ± 0.03 | 0.18 ± 0.03 | 0.71 ± 0.04 |
| 13 | 9.78 ± 0.01 | 7.87 ± 0.02 | 0.47 ± 0.03 | 0.55 ± 0.02 | 1.91 ± 0.02 |
| 14 | 9.94 ± 0.03 | 7.69 ± 0.03 | 0.57 ± 0.06 | 0.66 ± 0.04 | 2.25 ± 0.04 |
| 15 | 11.20 ± 0.03 | 8.13 ± 0.03 | 0.62 ± 0.05 | 0.74 ± 0.03 | 3.07 ± 0.04 |
| 16 | 11.15 ± 0.03 | 9.43 ± 0.02 | 0.45 ± 0.03 | 0.49 ± 0.03 | 1.72 ± 0.04 |

![Fig. 3.—(J − K) vs. (V − K) color-color diagram for stars identified in Table 5. The dashed line is the locus of dwarf (luminosity class V) stars of various spectral types; the dot-dashed line is for giants (luminosity class III). The reddening vector indicates $A_V = 1.0$ for the plotted color systems. Along this line of sight maximum extinction is $A_V \sim 0.1$ (Schlegel et al. 1998). [See the electronic edition of the Journal for a color version of this figure.]](image1)

![Fig. 4.—Reduced proper-motion diagram for 9041 stars in a 6′ field centered on ε Eri. Star identifications are in Table 5. For a given spectral type, giants and subgiants have more negative $H_K$ values and are redder than dwarfs in $(J − K)$. $H_K$ values are derived from the “final” proper motions in Table 9. The small plus sign at the lower left represents a typical $(J − K)$ error of 0.04 mag and $H_K$ error of 0.17 mag. The horizontal dashed line is a giant-dwarf demarcation derived from a statistical analysis of the Tycho input catalog (D. Ciardi 2004, private communication). Ref-14 and ref-15 are likely luminosity class III.](image2)
\[ y' = y + lcy(B - V) - \Delta XFy, \]  
\[ \xi = Ax' + By' + C - \mu_\alpha \Delta t - P_\alpha \pi, \]  
\[ \eta = Dx' + Ey' + F - \mu_\delta \Delta t - P_\delta \pi \]  
for FGS1r data and
\[ \xi = Ax + By + C - P_\alpha \pi - \mu_\alpha \Delta t, \]  
\[ \eta = Dx + Ey + F - P_\delta \pi - \mu_\delta \Delta t \]  
for the MAP data. Identifying terms, \( x \) and \( y \) are the measured coordinates from HST and the MAP; \( (B - V) \) represents the \( (B - V) \) color of each star, estimated from its spectral type, \( A, B, D, \) and \( E \) are scale and rotation-plate constants; \( C \) and \( F \) are offsets; \( \Delta t \) is the epoch difference from the mean epoch; \( P_\alpha \) and \( P_\delta \) are parallax factors; and \( \pi \) is the parallax. We obtain the parallax factors from a JPL Earth orbit predictor (Standish 1990) upgraded to version DE405. Orientation to the sky for the FGS1r data is obtained from ground-based astrometry (2MASS catalog) with uncertainties of 0.01.

### 4.1. Assessing Reference-Frame Residuals

Histograms of the MAP residuals (Fig. 5) indicate per-observation precision of \( \sim 7 \) mas. Because we are seeking the signature of a perturbation over 3 times smaller than that per-observation precision, the MAP data were only used to lower the errors on parallax and proper motion, not to establish any perturbation parameters. As for the FGS data, the Optical Field Angle Distortion calibration (McArthur et al. 2002) reduces as-built HST telescope and FGS1r distortions with magnitude \( \sim 1'' \) to below 2 mas over much of the FGS1r field of regard. From histograms of the FGS astrometric residuals (Fig. 6) we conclude that we have obtained correction at the \( \sim 1 \) mas level. The reference frame “catalogs” for MAP and FGS1r in \( \xi \) and \( \eta \)

---

| ID | Spectral Typea | \( V \) | \( M_r \) | \( m - M \) | \( \pi_{\text{abs}} \) (mas) |
|----|----------------|-------|--------|----------|-----------------|
| 2  | K4 V           | 15.6  | 7.1    | 8.5 ± 1  | 1.9 ± 1.0       |
| 3  | G8 V           | 15.6  | 5.6    | 10.0 ± 0.4 | 1.0 ± 0.2   |
| 4  | K2 V           | 16.1  | 6.5    | 9.6 ± 0.4 | 1.2 ± 0.2     |
| 5  | K2 V           | 16.4  | 6.5    | 9.9 ± 0.4 | 1.0 ± 0.2     |
| 6  | K2 V           | 16.4  | 6.5    | 9.9 ± 2  | 1.0 ± 0.9     |
| 7  | G0 V           | 11.4  | 4.4    | 7.0 ± 0.4 | 4.1 ± 0.7     |
| 8  | F5 V           | 9.5   | 3.5    | 6.0 ± 0.4 | 6.3 ± 1.2     |
| 9  | K0 V           | 10.7  | 5.9    | 4.8 ± 0.4 | 11.0 ± 2.0    |
| 10 | G5 V           | 11.6  | 5.1    | 6.5 ± 0.4 | 5.0 ± 0.9     |
| 11 | G8 V           | 10.2  | 5.9    | 4.6 ± 0.4 | 11.8 ± 2.2    |
| 12 | F0 V           | 9.7   | 2.7    | 7.0 ± 0.4 | 4.0 ± 0.7     |
| 13 | K0 V           | 9.8   | 5.9    | 3.9 ± 0.4 | 16.7 ± 3.1    |
| 14 | K0 III         | 9.9   | 0.7    | 9.2 ± 0.4 | 1.4 ± 0.3     |
| 15 | K2 III         | 11.2  | 2.7    | 8.5 ± 0.4 | 2.0 ± 0.4     |
| 16 | G8 V           | 11.2  | 5.6    | 5.6 ± 0.4 | 7.8 ± 1.4     |

* Spectral types and luminosity classes estimated from colors and the reduced proper-motion diagram.
tributions are fit with Gaussian profiles. Observations of \( \pm C15 \) standard coordinates (Table 8) were determined with and \( \pm C27 /C17 \) the aggregate data. This improved our goodness of fit (total number of observations so discarded was less than 1% of reweighted, but they were later discarded as spurious data. The discarded for this solution. Initially these points were merely provided by degrees of freedom) measurement of the modeling for significant outliers were filtered. For example, if five data points of these observations. The weighting of the radial velocity data set from 0.94 in the announcement paper provided to 0.30 in the current analysis.

5. RADIAL VELOCITIES

Measurements from four planet-search groups were included in our modeling. Table 3 lists the source, coverage, technique, number of observations, and rms deviation from the final orbit of these observations. The weighting of the radial velocity data was carefully evaluated with independent modeling, and significant outliers were filtered. For example, if five data points were taken in succession, all assigned with the same weight, and one point was 50 m s\(^{-1}\) offset from the others, that point was discarded for this solution. Initially these points were merely reweighted, but they were later discarded as spurious data. The total number of observations so discarded was less than 1% of the aggregate data. This improved our goodness of fit (\( \chi^2 \) divided by degrees of freedom) measurement of the modeling for the radial velocity data set from 0.94 in the announcement paper to 0.30 in the current analysis.

Fig. 6.—Histograms of \( x \)- and \( y \)-residuals obtained from modeling the FGS observations of \( \pm C15 \) Eri and the FGS reference frame with eqs. (4) and (5). Distributions are fit with Gaussian profiles.

standard coordinates (Table 8) were determined with \( \langle \sigma_x \rangle = 1.0 \) and \( \langle \sigma_y \rangle = 1.3 \) mas (MAP) and \( \langle \sigma_x \rangle = 0.3 \) and \( \langle \sigma_y \rangle = 0.2 \) mas (FGS).

6. \( \pm C15 \) ERI PARALLAX, PROPER MOTION, AND PERTURBATION ORBIT FROM ASTROMETRY AND RADIAL VELOCITIES

Solving for relative parallax, proper motion, and orbital motion (see Tables 9 and 10), using astrometry and radial velocities simultaneously, the model now becomes,

\[
\xi = ax' + by' + c - P_x \pi - \mu_x t - \text{ORBIT}_x, \tag{8}
\]

\[
\eta = -bx' + ay' + f - P_y \pi - \mu_y t - \text{ORBIT}_y, \tag{9}
\]

where ORBIT is a function (through Thiele-Innes constants) of the traditional astrometric and radial velocity orbital elements listed in Table 11.

The period \( P \), the epoch of passage through periastron in years \( (T) \), the eccentricity \( (e) \), and the angle in the plane of the true orbit between the line of nodes and the major axis \( (\omega) \) are constrained to be equal for the radial velocity and astrometry portions of the model. Only radial velocity provides information with which to determine the half-amplitudes \( K_1 \) and the systemic velocity \( \gamma \). Combining radial velocity observations from different sources is possible with GaussFit, which has the ability to simultaneously solve for many separate velocity offsets (because velocities from different sources are relative, having differing zero points) along with the other orbital parameters.

We force a relationship between the astrometry and the radial velocity by a constraint from Pourbaix & Jorissen (2000),

\[
\frac{\alpha_A \sin i}{\pi_{\text{abs}}} = \frac{PK_1(1 - e^2)}{2\pi(4.7405)^{1/2}}, \tag{10}
\]

where quantities derived only from astrometry (parallax, \( \pi_{\text{abs}} \), primary perturbation orbit size \( \alpha_A \), and inclination \( i \)) are on the left and quantities derivable from both (the period \( P \) and eccentricity \( e \) or radial velocities only (the radial velocity amplitude for the primary, \( K_1 \)) are on the right.
Combining radial velocity measurements complete through 2006.3 (Table 3), all the astrometric measurements, and the equation (10) constraint, we solve for parallax, proper motion, semimajor axis, orbit orientation, and orbit inclination for the perturbation caused by the companion. For the parameters critical in determining the mass of ε Eri we find a parallax \( \pi_{\text{abs}} = 311.37 \pm 0.10 \) mas and a proper motion \( 976.54 \pm 0.1 \) mas yr\(^{-1} \) in position angle \( 269.0 \pm 0.6 \). Table 10 compares values for the parallax and proper motion of ε Eri from HST and Hipparcos. We note satisfactory agreement. Our precision and extended study duration have significantly improved the accuracy and precision of the parallax and proper motion of ε Eri.

At this stage we can assess the reality of any ε Eri perturbation by plotting residuals to a model that does not include an orbit. Figure 7 shows the \( \xi \)- and \( \eta \)-components of only the higher precision astrometry FGS residuals plotted as gray dots. The lower precision MAP data were not considered in the determination of the orbital parameters. We also plot normal points formed from those dots at nine epochs. Finally, each plot contains as a dashed line the \( \xi \)- and \( \eta \)-components of the perturbation we find by including an orbit in our modeling.

We find a perturbation size \( \alpha_\delta = 1.88 \pm 0.19 \) mas and an inclination \( i = 30.1 \pm 3.8 \). These and the other orbital elements for the perturbation are listed in Table 11 with \( 1 \sigma \) errors. Errors generated by GaussFit (Jefferys et al. 1988) come from a maximum likelihood estimation that is an approximation to a Bayesian maximum a posteriori estimator with a flat prior (Jefferys 1990). Figure 8 illustrates the Pourbaix & Jorissen (2000) relation (eq. [10]) between parameters obtained from astrometry (left-hand side) and radial velocities (right-hand side) and our final estimates for \( \alpha_\delta \) and \( i \). As seen in Tables 10 and 11, most of the errors of the terms in equation (10) are quite small. In essence, our simultaneous solution uses the Figure 8 curve as a quasi-Bayesian prior, sliding along it until the astrometric and radial velocity residuals are minimized. Gross deviations from the curve are minimized by the high precision of many of the terms in equation (10). Figure 9 contains all radial velocity measures and the predicted velocity curve from the simultaneous solution. Compared to the typical perturbation radial velocity curve (e.g., Hatzes et al. 2005; McArthur et al. 2004; Cochrane et al. 2004), Figure 9 exhibits far more scatter about the derived orbit. There are two reasons for this. The perturbation amplitude is small (\( K_1 = 18.5 \) m s\(^{-1} \), and ε Eri is an active star, as discussed in Hatzes et al. 2000). Reiterating their conclusions, none of the activity cycles have periods commensurate with the planetary perturbation period. Figure 10 presents the astrometric residuals and the derived

### Table 11: Orbital Elements of ε Eri Perturbation Due to ε Eri

| Parameter                     | Value                          |
|-------------------------------|-------------------------------|
| \( \alpha_\delta \)           | \( 1.88 \pm 0.20 \) mas        |
| \( \alpha_\delta \sin i \)    | \( 3.02e-3 \pm 0.32e-3 \) AU   |
| \( P \)                       | \( 2502 \pm 10 \) days        |
| \( P \)                       | \( 6.85 \pm 0.03 \) yr        |
| \( T_0 \)                     | \( 54,207 \pm 7 \) MJD        |
| \( T_0 \)                     | \( 2007.29 \pm 0.02 \) yr     |
| \( \epsilon \)                | \( 0.702 \pm 0.039 \)         |
| \( \omega \)                  | \( 30.1 \pm 3.8 \)            |
| \( \Omega \)                  | \( 74.7^\circ \)             |
| \( \omega \)                  | \( 47^\circ \)                |
| \( K_1 \)                     | \( 18.5 \pm 0.2 \) m s\(^{-1} \) |
| \( M_e \)                     | \( 0.83 \pm 0.05 \) \( M_\odot \) |
p perturbation orbit for the primary star $\epsilon$ Eri. Stellar activity has even less of an effect on astrometry at our level of precision. A starspot covering 30% of the surface would induce a photocenter shift of less than 0.2 mas (Sozzetti 2005). The astrometry confirms the existence of the companion.

Our analysis of the radial velocities (now spanning over 25 years, all shown in Fig. 9) included a linear-drift term, a change in velocity as a function of time. This drift is clearly seen 25 years, all shown in Fig. 9) included a linear-drift term, a change in velocity as a function of time. This drift is clearly seen.

for each set. Typical offset random error is $\sim1$ m s$^{-1}$. While this acceleration is not a detection of the longer period companion (40 AU $< a <$ 60 AU) invoked by Quillen & Thorndike (2002) and Ozernoy et al. (2000) to modify the dust distribution as discussed below in $\S$ 7, it may (with a semimajor axis 10–20 AU) be at least partially responsible for the inner cavity in the dust disk distribution imaged by Greaves et al. (2005). The astrometric motion over 15 yr due to this possible tertiary would be of order 3 mas and difficult to separate from proper motion (e.g., Black & Scargle 1982).

The planetary mass depends on the mass of the primary star, for which we have adopted $M_\star = 0.83 \pm 0.05 M_\odot$ (Di Folco et al. 2004). For this $M_\star$ we find $M_b = 1.55 M_\oplus \pm 0.24 M_\oplus$. The companion is clearly an extrasolar giant planet. In Table 12 the mass value $M_b$ incorporates the present uncertainty in $M_\star$. Until $\epsilon$ Eri b is directly detected, its radius will be unknown. From a review of exoplanets masses and radii (Guillot 2005), a radius of $R = 1 R_\oplus$ seems reasonable.

Our eccentricity value, $e = 0.70$, allows for a significant difference in separation between star and exoplanet at apastron compared to periastron. At the time of periastron passage, $T_0 = 2007.29$, we predict a separation $0.3 \pm 0.1$ at a position angle of $-27^\circ$. At the next apastron, to occur at 2010.71, the separation should be $1.8 \pm 0.4$ at a position angle of $153^\circ$. The dominant sources of error for the separations are the eccentricity (6%) and the $\epsilon$ Eri b planet mass (15%).

7. DISCUSSION

Our accurate mass and orbital parameters for this planetary companion have value for future direct-imaging projects. We now know where near $\epsilon$ Eri to look for $\epsilon$ Eri b. We would now like to know when to look, what bandpass is best, and what we can expect to see. As stated previously, system age, companion mass, and orbital geometry are critical parameters when estimating visibility.

A high level of chromospheric activity is seen for $\epsilon$ Eri (e.g., Gray & Baliunas 1995), and is consistent with a relatively young age; $\sim1$ Gyr (Soderblom & Däppen 1989). Saffe et al. (2005) used the calibrations of Donahue (1993) and Rocha-Pinto & Maciel (1998) (which corrected the age with an effect from stellar metallicity) to estimate ages of 0.66 and 0.82 Gyr, respectively. Henry et al. (1996) derived from Ca ii lines a value of 0.8 Gyr. Song et al. (2000) used Li abundances with the star’s position in the H-R diagram and kinematics to derive a value of 0.73 $\pm$ 0.2 Gyr. Di Folco et al. (2004) estimated the age at 0.85 Gyr, a value obtained through the measurement of the radius of $\epsilon$ Eri by long-baseline interferometry. Their modeling is consistent
with a primary mass of \( M = 0.83 \pm 0.05 \, M_\odot \), an estimate that weakly depends on measured metallicity, which ranges over \(-0.13 < [\text{Fe/H}] < -0.06 \) in the literature.

Hubbard et al. (2002) predicted the intrinsic luminosity of extrasolar giant planets as a function of mass and age. From their Figure 11, an age of 800 Myr (Di Folco et al. 2004), and our planetary mass, \( M_b = 1.55 \pm 0.24 \, M_J \), we find for \( \epsilon \, \text{Eri} \), \( L = 4.67 \times 10^{-8} \, L_\odot \). Using the Di Folco et al. (2004) \( T_{\text{eff}} = 5135 \, \text{K} \), their radius, \( R = 0.743 \, R_\odot \), our parallax, \( \pi_{\text{abs}} = 311.37 \, \text{mas} \), and a bolometric correction, \(-0.27 \), from Flower (1996), we find a difference in bolometric magnitude of \( \epsilon \, \text{Eri} \) compared to the Sun of \( \Delta M_{\text{bol}} = +1.17 \). Hence, neglecting reflected light and orbital phase, \( \epsilon \, \text{Eri} \) is 4.67 \( \times 10^{-8} \) times fainter in bolometric luminosity than \( \epsilon \, \text{Eri} \).

**TABLE 12**

\begin{tabular}{|c|c|}
\hline
Parameter & Value \\
\hline
\( a \) & 3.39 \pm 0.36 \, (\text{AU}) \\
\( \Omega \) & 254\degree \\
\( \omega \) & 47\degree \\
Mass function & 5.9e-10 \pm 1.0e-10 \, (M_\odot) \\
\( M \sin i \) & 0.78 M_\odot \pm 0.08 M_\odot \\
\( M_b \) & 0.55 M_\oplus \pm 0.22 M_\oplus \\
\( M_c \) & 1.55 M_\oplus \pm 0.24 M_\oplus \\
\hline
\end{tabular}

\( ^{a} \) Derived from radial velocity alone.

\( ^{b} \) Derived from radial velocity and astrometry, using \( M \sin i / \sin i \).

\( ^{c} \) Derived from radial velocity and astrometry, using \( m_\gamma^2 (m_1 + m_2)^2 = a^3 / P^2 \); includes host-star mass uncertainty.
Sudarsky et al. (2005), Dyudina et al. (2005), and Burrows et al. (2004) discussed exoplanet apparent brightness in reflected host star light as functions of orbit geometry, orbital phase, and cloud cover. Burrows et al. (2004) predicted the full spectrum of \( \epsilon \) Eri b from 0.5 to 6 \( \mu \)m, asserting that the planet is too young for its atmosphere to contain condensed ammonia clouds. However, \( \epsilon \) Eri b should exhibit H\( _2 \)O clouds. They predict a maximum planet/host star flux ratio, \( \log (F_{\text{planet}}/F_{\text{star}}) \sim -7, \) at \( \sim 4.5 \mu \)m with a secondary peak, \( \log (F_{\text{planet}}/F_{\text{star}}) \sim -8, \) at 1 \( \mu \)m. Dyudina et al. (2005) predicted that for \( \omega = 30^\circ, i = 30^\circ, e = 0.5, \) and a Jupiter-like atmosphere, the planet/host star flux ratio will be largest very shortly after periastron, late 2007. However, the separation will remain small (\( \sim 0^\circ 3 \)). The inclination of the \( \epsilon \) Eri system, \( i = 30^\circ, \) is likely to decrease the flux ratio by approximately a factor of 2 (Sudarsky et al. 2005) compared to an \( i = 90^\circ \) edge-on orientation. Given the orientation of the orbit of \( \epsilon \) Eri b (its ascending node \( \Omega' = 254^\circ \)), the disk of \( \epsilon \) Eri b is most fully illuminated at apastron but is 3 times farther away from its primary.

The dusty rings or debris disks surrounding \( \epsilon \) Eri also suggest relative youth for the system. Photometric measurements from the \textit{IRAS} satellite (Aumann 1988) provided the first hint of dust around \( \epsilon \) Eri. Subsequently, Submillimeter Common-User Bolometric Array (SCUBA) measurements were made between 1997 and 2002. These measurements determined that the dust, distributed in a ring, is located 65 AU from the star (Greaves et al. 1998, 2005). The submillimeter bolometer SIMBA provided observational confirmation of this extended dust disk (Schutz et al. 2004). The STIS CCD camera on \textit{HST} took deep optical images around \( \epsilon \) Eri in an effort to find an optical counterpart for the submillimeter observations. These measurements did not provide clear evidence for the detection of that optical counterpart but did place a limit on the optical surface brightness of the dust, that it could not be brighter than approximately 25 STMAG arcsec\(^{-2} \), which places constraints on the nature and amount of the smallest dust grains (Proffit et al. 2004).

Observational and theoretical searches for the signature of planetary/brown dwarf objects in the structure of the dust disk around \( \epsilon \) Eri are underway. Clumps seen in the ring are thought to come from the interaction between the disk and a massive planetary body (Holland et al. 2003). Adaptive optics on the Keck telescope were used to search for extrasolar planets. These studies found no evidence of brown dwarf or planetary companions down to 5\( M_J \) at the angular separations comparable to that of the dust rings (Macintosh et al. 2003). \textit{Spitzer Space Telescope} observations made with the Multiband Imaging Photometer and the Infrared Spectrograph have confirmed the disk and provided evidence for asymmetries in the structure of the disk that may have been caused by the gravitational perturbation of substellar companions (Marengo et al. 2004).

Two recent studies suggested that debris disks and long-period planets coexist, with planetary bodies “sculpting” the disk; \( \epsilon \) Eri is the prototypical system. First, high-resolution modeling of the structure of the disk around \( \epsilon \) Eri predicts an angular motion of the asymmetry of the disk of about 0.6–0.8 yr\(^{-1} \) (Ozernoy et al. 2000). Second, Quillen & Thorndike (2002) carried out numerical simulations of dust particles captured in mean-motion resonances with a hypothetical planet (\( \epsilon = 0.3, M = 10^{-4} M_{\odot}, a = 40 \) AU) at periastron. These produced a dust distribution that agreed with the morphology of the dust ring around \( \epsilon \) Eri presented by Greaves et al. (1998, 2005). An investigation into the dynamics of the dust ring around \( \epsilon \) Eri (Moran et al. 2004) concluded that the eccentricity of the dust released in the inner ring (<20 AU) could reveal patterns in the dust that could confirm the existence of the planet reported by Hatzes et al. (2000).

We determined an inclination of \( i = 30^\circ 1 \pm 3^\circ 2 \) for \( \epsilon \) Eri b. Our measured inclination is consistent with the previously measured dust disk inclination from 450 and 850 \( \mu \)m maps of Greaves et al. (1998, 2005), \( i = 25^\circ \). This suggests that the dust disk and plane of the orbit of \( \epsilon \) Eri b are coincident and that the dust distribution is nearly circular. This provides support for hierarchical accretion models for planet formation (Pollack et al. 1996) in which coplanar dust and a debris disk are expected remnants of planet formation (Tsiganis et al. 2005). Finally, \( \epsilon \) Eri b and the possible tertiary deduced from the linear trend in the radial velocities (\( \sim 6 \)) would most likely eject particles that would spiral inward, and recent SCUBA submillimeter observations have shown that the center of the disk is relatively excavated of dust, with half or less of the signals seen in the ring (Greaves et al. 2005).

8. CONCLUSIONS

Analyzing 3 years of \textit{HST} FGS and over 14 years of Allegheny Observatory MAP astrometry, we find an independently determined parallax and proper motion for \( \epsilon \) Eri that agree within the errors with \textit{Hipparcos}. Astrometric observations with \textit{HST} FGS, combined with long-duration Allegheny MAP astrometry and ground-based radial velocities, have confirmed the existence of the planet orbiting \( \epsilon \) Eri, first suggested by Walker et al. (1995), noted by Cumming et al. (1999), and finally announced by Hatzes et al. (2000).

Combining the astrometry with radial velocities from six different sources, spanning 25 years, and applying the Pourbaix & Jorissen (2000) constraint between astrometry and radial velocities, we obtain for the perturbing object \( \epsilon \) Eri b a period \( P = 6.85 \pm 0.02 \) yr, inclination \( i = 30^\circ 1 \pm 3^\circ 2 \), and perturbation semimajor axis \( a_{\text{d}} = 1.88 \pm 0.19 \) mas. Assuming for \( \epsilon \) Eri a stellar mass \( M_* = 0.83 \pm 0.05 M_{\odot}, \) we obtain a mass for \( \epsilon \) Eri b \( M_b = 1.55 M_J \pm 0.24 M_J \). This companion inclination matches the disk inclination determined by Greaves et al. (2005).

Our astrometry predicts for \( \epsilon \) Eri b periastron passage at \( T_0 = 2007.29, \) with a separation of \( \sim 0^\circ 3 \) in position angle \( -27^\circ (a = 3.39 \) AU). At the next apastron, to occur at 2010.71, the separation should be \( 177^\circ \) in position angle 153\( ^\circ \). The orbital geometry suggests that 2007.97 (late 2007 December) is the most favorable time for direct detection in reflected light. For an \( \epsilon \) Eri age \( \sim 850 \) Myr and our determined mass, \( \epsilon \) Eri b will have an intrinsic luminosity \( L = 1.6 \times 10^{-8} L_{\odot}, \) 4.67 \times 10^{-8} \) times fainter in bolometric luminosity than \( \epsilon \) Eri.

Radial velocities spanning 25 yr indicate a long-term linear trend, an acceleration consistent with a Jupiter-mass object with a period of 50–100 yr. This is a possible detection of a tertiary companion responsible for a major feature of the dust morphology, the central cavity.

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