EPSILON AURIGAE: AN IMPROVED SPECTROSCOPIC ORBITAL SOLUTION

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ABSTRACT

A rare eclipse of the mysterious object ϵ Aurigae will occur in 2009–2011. We report an updated single-lined spectroscopic solution for the orbit of the primary star based on 20 years of monitoring at the CfA, combined with historical velocity observations dating back to 1897. There are 518 new CfA observations obtained between 1989 and 2009. Two solutions are presented. One uses the velocities outside the eclipse phases together with mid-times of previous eclipses, from photometry dating back to 1842, which provide the strongest constraint on the ephemeris. This yields a period of 9896.0 ± 1.6 days (27.0938 ± 0.0044 years) with a velocity semi-amplitude of 13.84 ± 0.23 km s−1 and an eccentricity of 0.227 ± 0.011. The middle of the current ongoing eclipse predicted by this combined fit is JD 2,455,413.8 ± 4.8, corresponding to 2010 August 5. If we use only the radial velocities, we find that the predicted middle of the current eclipse is nine months earlier. This would imply that the gravitating companion is not the same as the eclipsing object. Alternatively, the purely spectroscopic solution may be biased by perturbations in the velocities due to the short-period oscillations of the supergiant.

Key words: binaries: eclipsing – stars: individual (epsilon Aurigae) – techniques: radial velocities

Online-only material: machine-readable and VO tables

1. INTRODUCTION

Epsilon Aurigae has been known as a variable system since early in the nineteenth century and as an eclipsing system since the beginning of the twentieth century. It has the longest known period of any eclipsing binary, 27 years. SIMBAD lists over 400 papers on the system, yet the evolutionary state of the system and the properties of neither the primary nor the secondary are clearly understood. Even the star’s spectral classification, generally assumed to be F0 I, is uncertain.

The spectroscopic orbit implies that the companion is nearly the same mass as the F supergiant primary. If the primary is a typical F supergiant with a mass of 16 M⊙ then the companion has a mass of at least 13 M⊙. However, we, like others before us, see no light from the secondary in our spectra. It has also been suggested that the primary is an old post-asymptotic giant branch star with a mass of less than 3 M⊙, implying a secondary mass of ~6 M⊙ (Saito et al. 1987).

The eclipse duration of nearly two years implies a size of the occulting object of many AU. It is generally agreed that the occulting object consists of a complex, donut-shaped, rotating disk and an embedded unseen object (for a review of the properties of the ϵ Aurigae system, see Guinan & DeWarf 2002). Various suggestions have been made on the nature of the secondary body, from a black hole to a protoplanetary system to a pair of stars in a binary system.

The 2009–2011 eclipse has started and a major campaign is underway to observe the system. For more information on the campaign, see http://mysite.du.edu/~rstencil/epsaur.htm and http://www.hposoft.com/Campaign09.html (see also Hopkins & Stencel 2008).

To help in the interpretation of the campaign results, we re-examine the historical radial velocity data and present the results of new radial velocity monitoring of ϵ Aurigae in order to determine an updated spectroscopic orbit. This provides an improved estimate for the time of mid-eclipse of the primary by the gravitating companion responsible for the orbital motion.

2. RADIAL VELOCITY OBSERVATIONS

In order to refine the spectroscopic orbit of the system, we have been monitoring the radial velocity of ϵ Aurigae for nearly 20 years at the Harvard-Smithsonian Center for Astrophysics (CfA) starting in 1989 November. We have used the CfA Digital Speedometers (Latham 1985, 1992) on the 1.5 m Wyeth Reflector at the Oak Ridge Observatory (now closed) in Harvard, Massachusetts and the 1.5 m Tillinghast Reflector at the F. L. Whipple Observatory on Mt. Hopkins, Arizona. These instruments used intensified photon-counting Reticon detectors on nearly identical echelle spectrographs, recording a single echelle order giving a spectral coverage of 45 Å centered at 5187 Å. Radial velocities were derived from the observed spectra using the one-dimensional correlation package r2rvsao (Kurtz & Mink 1998) running inside the IRAF6 environment. For most stars observed with the CfA Digital Speedometers, we use templates drawn from a library of synthetic spectra calculated by Jon Morse using Kurucz models (Latham et al. 2002). For each star, we first run grids of correlations over an appropriate range of values in effective temperature, surface gravity, metallicity, and rotational velocity, and then choose the single template that gives the highest value for the peak of the correlation coefficient, averaged over all the observed spectra. In the case of ϵ Aurigae, when we analyzed the 489
CfA spectra available in 2008 September, we found that the best correlation was obtained for effective temperature $T_{\text{eff}} = 7750$ K, log surface gravity $\log g = 1.5$ (cgs), and line broadening $v_{\text{broad}} = 41$ km s$^{-1}$, assuming solar metallicity. However, this template spectrum is not a particularly good match to the observed spectra, as indicated by the fact that the average peak correlation value was only 0.80 and the average internal error estimate was 3.0 km s$^{-1}$. We experimented with the use of observed spectra as the template, and found that a spectrum obtained on JD 2,447,995 gave a median internal error estimate of 0.75 km s$^{-1}$. Therefore, we used that observation as the template for all the velocity determinations, and adjusted the velocity zero point so that we got the same radial velocity as yielded by the synthetic template, and found that a spectrum obtained on JD 2,447,995 gave the median internal error estimate of 0.75 km s$^{-1}$. Therefore, we used that observation as the template for all the velocity determinations, and adjusted the velocity zero point so that we got the same radial velocity as yielded by the synthetic template for that particular observation. Thus the velocities from the CfA Digital Speedometers which we report for $\epsilon$ Aurigae in this paper should be on (or at least close to) the native CfA system described by Stefanik et al. (1999).

The CfA radial velocities as well as the other historical velocities (see below) are given in Table 1. In this table, we report, as examples, the individual heliocentric radial velocities for a few selected dates; the entire velocity table is available in the online version of the Journal.

Epsilon Aurigae’s radial velocities have been measured several hundred times by others over the years and, we have gathered the previously reported radial velocities in Table 1 along with the CfA velocities. The major sources of the reported radial velocities are: Potsdam, Ludendorff (1924): 186 observations covering 4176 days, these included four velocities from other observatories that were not reported in other publications; Yerkes, Frost et al. (1929): 367, 11856 days, these included 14 velocities in a footnote; and Mt. Wilson, Struve et al. (1958): 123, 10603 days, these included 14 velocities from DAO Victoria. Our listed velocities and errors for Mt. Wilson are the mean velocities of all the spectral lines reported in the paper (Struve et al. 1958) and their standard deviation. A few other velocities reported in Table 1 are from Campbell & Moore (1928), Abt (1970), Parsons (1983), Beavers & Eitter (1986), Cha et al. (1991), Lambert & Sawyer (1986), Saito et al. (1987), Arellano Ferro (1985), and Barsony et al. (1986). We note that many of these velocities are from individual spectral lines obtained during eclipse phases and are attributed to the gas disk.

Combining the CfA and previously published velocities yields a total of 1320 velocities covering over 112 years. In Figure 1, we show all the velocities from Table 1. Also shown are the previous eclipse intervals along with the predicted 2009–2011 eclipse interval. In Figure 1, we see the long period orbital radial velocity variation; the short term, lower amplitude, irregular atmospheric oscillation of the primary, and the complex velocity variation during eclipse phases. Also shown in Figure 1 is the velocity curve calculated using our combined orbital solution (see below).

Combining these data requires consideration of zero-point corrections between the different data sets. However, this is not straightforward because of the atmospheric oscillations and because the various measurements were done at different observatories, by different observers, with different instruments and different techniques and data reduction. Furthermore, the radial velocity determinations for this star have large errors because $\epsilon$ Aurigae is a hot, rapidly rotating star with a line broadening of 40 km s$^{-1}$. Because of these difficulties, no zero-point offsets have been applied when combining the different data sets.

### Table 1

| Julian Date (HJD − 2,400,000) | Radial Velocity (km s$^{-1}$) | Error (km s$^{-1}$) | Reference |
|-------------------------------|-------------------------------|---------------------|------------|
| 13932                         | 9.0                           | ...                | 1, Lick    |
| 14987                         | 4.0                           | ...                | 1, Adams   |
| 14995                         | 4.0                           | ...                | 1, Adams   |
| 14996                         | 4.0                           | ...                | 1, Adams   |
| 15698                         | 5.3                           | ...                | 1          |
| 16072                         | −14.1                         | ...                | 1          |

Note. *References*. (1) Ludendorff 1924; (2) Campbell & Moore 1928; (3) Abt 1970; (4) Frost et al. 1929; (5) Struve et al. 1958; (6) Arellano Ferro 1985; (7) Beavers & Eitter 1986; (8) Parsons 1983; (9) Barsony et al. 1986; (10) Cha et al. 1991; (11) Lambert & Sawyer 1986; (12) CfA.

(This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms in the online journal. A portion is shown here for guidance regarding its form and content.)

Figure 1. History of the radial velocities of $\epsilon$ Aurigae. Dashed lines indicate eclipse “duration.” The shaded area shows the time interval, “duration”± 200 days, with the velocities excluded from the orbital solution shown as open circles. Filled circles are velocities used in the orbital solution and crosses are Hr velocities.

### 3. KEPLERIAN SPECTROSCOPIC ORBIT

The first orbital solution was by Ludendorff (1924). Kuiper et al. (1937) combined Yerkes velocities with Ludendorff’s Potsdam velocities to update the orbital solution. Morris (1962)
added observations from Mt. Wilson and DAO and calculated a new orbital solution. Wright (1970) recalculated the solution using the data reported by Morris. In Table 2, we give the previously computed orbital solutions, where we give the period \( P \) in days, the eccentricity \( e \), the longitude of periastron \( \omega \) in degrees, the heliocentric Julian date of periastron passage \( T \), the center-of-mass velocity \( V \), the observed orbital semi-amplitude \( K \), the projected semi-major axis \( a \), the mass function \( f(M) \), the number of observations \( N \), and the time span in days and in the number of periods covered.

We note that we have not been able to reproduce the values of \( \omega \) reported by these authors. Re-computing the orbital solutions using only the Potsdam, Yerkes, and Mt. Wilson velocities, and various combinations of these data sets, give \( \omega \) values more consistent with the results we report below.

In computing an updated spectroscopic orbit, we have excluded velocities taken during the eclipse phases and 200 days before and after first and last contacts. During these time intervals, the structure of the spectral lines is rather complex, often asymmetric, often multiple, and varies with time with contributions from both the primary and the secondary disk (see, e.g., Struve et al. 1958; Lamberti & Sawyer 1986; Saito et al. 1987). The excluded Julian Date intervals are: 1901–1903 eclipse, JD 2,415,294–16,362; 1928–1930 eclipse, JD 2,425,193–26,261; 1955–1957 eclipse, JD 2,435,091–36,158; 1982–1984 eclipse, JD 2,444,973–46,041, and 2009–2011 eclipse, JD 2,454,880–55,948. We have also excluded the out-of-eclipse \( H \alpha \) velocities because of their complex structure (Cha et al. 1991; Schane 2007). The excluded velocities are shown in Figure 1 as open circles.

This yields a new updated Keplerian spectroscopic orbital solution based on 1014 velocities and with the orbital elements shown in the next-to-last column of Table 2. The rms velocity residual from the orbital fit is 4.6 km s\(^{-1}\), dominated by the radial oscillations of the atmosphere.

The middle of the currently on-going eclipse predicted by our Keplerian orbital solution is JD 2,455,136 ± 59; 2009 October 31. The photometric prediction of mid-eclipse is JD 2,455,413; 2010 August 4 (http://www.hposoft.com/Campaign09.html). Therefore, the spectroscopic mid-eclipse precedes the photometric mid-eclipse prediction by 9 months. Furthermore, the mid-eclipse times of previous eclipses predicted by the orbital solution disagree with the mid-eclipse predictions established by photometry.

This would imply that the gravitating companion responsible for the orbital motion is not the same as the extended structure responsible for the eclipses, and that there is a positional offset between the two, possibly due to a complex disk structure. Alternatively, perturbations in the radial velocities related to the short-period oscillations could be affecting the orbital solution in subtle ways, perhaps biasing the shape parameters \( (e, \omega) \) on which the predicted eclipse times depend rather strongly. We show below that the amplitude of these oscillations is quite significant (roughly half of the orbital amplitude). A combination of both effects is also possible. If the spectroscopic orbit is biased, the observed times of mid-eclipse as established from photometry could be used simultaneously with the radial velocities to constrain the solution. In the next sections, we describe how we determine these times of mid-eclipse, and how we incorporate them into an alternate orbital solution.

### 4. MID-ECLIPSE TIMES

Many estimates have been made of mid-eclipse times using a number of methods. In general, these times are determined from the times of first, second, third, and fourth contacts. These times have generally been established by extrapolating the ingress and egress light curves to the mean out-of-eclipse magnitude, often assuming that the eclipse light curve is symmetrical. Unfortunately, this is not straightforward since there is considerable out-of-eclipse light variation due to the short-period oscillation and, for some of the past eclipses, the contact points were not observationally accessible. Furthermore, the ingress and egress light curves are not symmetrical and not linear between first and second, and third and fourth contacts. Therefore, we have re-determined the mid-eclipse times for all previous eclipses using the following procedure.

We have collected photometry of \( \epsilon \) Aurigae from 1842 to the present. In some cases, the actual data were not published, so we obtained them by digitizing the corresponding figures from the original publications. All measurements are given in Table 3 where columns give JD − 2,400,000, magnitude, flag for linear fit (see below) and bibliographic code. We note that the magnitude scale changed between the 1929 and 1956 eclipse from visually estimated magnitudes to \( V \) magnitudes on the standard Johnson system. The entire photometry table is available in the

| Element | Ludendorff (1924) | Kuiper et al. (1937) | Morris (1962) | Wright (1970) | Keplerian Fit | Combined Fit |
|---------|------------------|---------------------|---------------|---------------|---------------|---------------|
| \( P \) (days) | 9890 | 9890 (assumed) | 9890 (assumed) | 9890 (assumed) | 9890 ± 17 | 9896.0 ± 1.6 |
| \( e \) | 0.35 | 0.33 | 0.172 ± 0.033 | 0.200 ± 0.034 | 0.290 ± 0.016 | 0.227 ± 0.011 |
| \( \omega \) (deg) | 319.7 | 350 | 347.8 ± 15.8 | 346.4 ± 11.0 | 29.8 ± 3.1 | 39.2 ± 3.4 |
| \( T \) (HJD − 2,400,000) | 22512 | 23827 | 23441 ± 402 | 33346 ± 278 | 34425 ± 76 | 34723 ± 80 |
| \( y \) (km s\(^{-1}\)) | −1.8 | −2.5 | −1.29 ± 0.39 | −1.37 ± 0.39 | −2.41 ± 0.15 | −2.26 ± 0.15 |
| \( K \) (km s\(^{-1}\)) | 14.8 | 15.7 | 14.71 ± 0.53 | 15.00 ± 0.58 | 14.43 ± 0.27 | 13.84 ± 0.23 |
| \( a_1 \sin i \) (10\(^6\) km) | 1887 | 2014 | 1970 | 2000 | 1876 ± 50 | 1835 ± 29 |
| \( f(m) \) \( (M_{\odot}) \) | 2.7 | 3.34 | 3.12 | ... | 2.69 ± 0.13 | 2.51 ± 0.12 |
| \( \sigma \) (km s\(^{-1}\)) | ... | ... | ... | ... | 4.59 | 4.63 |
| \( N \) | 197 | ... | ... | ... | 1014 | 1020 |
| Time span (days) | 8583 | ... | ... | ... | 40947 | 40947 |
| Cycles | 0.87 | ... | ... | ... | 4.1 | 4.1 |
| Major source of velocities | Potsdam | Potsdam + Yerkes | Same + DAO + Mt Wilson | Same | Same + CfA | Same + CfA |

**Note:** For the combined fit, we have combined velocity data with the times of mid-eclipses established from photometry, Table 4.
Table 3

| Julian Date (HJD − 2,400,000) | Magnitude | Linear Fit Flag | Reference Codea |
|-------------------------------|-----------|-----------------|-----------------|
| −6050                         | 3.30      | 0               | 2               |
| −5538                         | 3.39      | 0               | 2               |
| −5489                         | 3.15      | 0               | 1               |
| −5430                         | 3.15      | 0               | 1               |
| −5402                         | 3.31      | 0               | 2               |
| −5338                         | 3.31      | 0               | 1               |

Note. aObserver, Reference: (1) Heis, Ludendorff 1903; (2) Argelander, Ludendorff 1903; (3) Schmidt, Ludendorff 1912; (4) Oudemans, Ludendorff 1903; (5) Schonfeld, Ludendorff 1903; (6) Schwab, Ludendorff 1903; (7) Plassmann, Ludendorff 1903; (8) Sawyer, Ludendorff 1903; (9) Porro, Ludendorff 1903; (10) Luizet, Ludendorff 1903; (11) Prittzw, Ludendorff 1903; (12) Kopff, Ludendorff 1903; (13) Gotz, Ludendorff 1903; (14) Nijland, Gussow 1936; (15) Plassmann, Gussow 1936; (16) Enebo, Gussow 1936; (17) Wendell, Gussow 1936; (18) Schiller, Gussow 1936; (19) Lohnert, Gussow 1936; (20) Scharbe, Gussow 1936; (21) Mundler, Gussow 1936; (22) Lau, Gussow 1936; (23) Hornig, Gussow 1936; (24) Menze, Gussow 1936; (25) Guthnick, Gussow 1936; (26) Johansson, Gussow 1936; (27) Guthnick & Pavel, Gussow 1936; (28) Gadamoki, Gussow 1936; (29) Graff, Gussow 1936; (30) Kordylewski, Gussow 1936; (31) Gussow, Gussow 1936; (32) Kukarkin, Gussow 1936; (33) Beyer, Gussow 1936; (34) Danjon, Gussow 1936; (35) Jacchia, Gussow 1936; (36) Pugaczewski, Gussow 1936; (37) Stebbins & Huffer, Gussow 1936; (38) Tschernov, Gussow 1936; (39) Mrzacek, Gussow 1936; (40) Dziewulski, Gussow 1936; (41) Kopal, Gussow 1936; (42) Fredrick 1960; (43) Larson-Leander 1958; (44) Gyldenkerne 1970 plot digitized; (45) Thiessen 1957; (46) Abl 1960; (47) Huruhata & Kitamura 1958; (48) Parthasarathy & Frueh 1986; (49) Japan Amateur Photographic Observers Association 1983; (50) Chochol & Žižkovský 1987; (51) Flin et al. 1985; (52) Sato & Nishimura 1987; (53) Taranova & Shenavrin (2001); (54) Bhatt et al. (1984); (55) Arellano Ferro (1985); (56) Hopkins, Hopkins (2009); (57) Dumont, Hopkins (2009); (58) Ingvarsen, Hopkins (2009); (59) AAVSO; (60) Widorn (1959).

Note. aObserver, Reference: (1) Heis, Ludendorff 1903; (2) Argelander, Ludendorff 1903; (3) Schmidt, Ludendorff 1912; (4) Oudemans, Ludendorff 1903; (5) Schonfeld, Ludendorff 1903; (6) Schwab, Ludendorff 1903; (7) Plassmann, Ludendorff 1903; (8) Sawyer, Ludendorff 1903; (9) Porro, Ludendorff 1903; (10) Luizet, Ludendorff 1903; (11) Prittzw, Ludendorff 1903; (12) Kopff, Ludendorff 1903; (13) Gotz, Ludendorff 1903; (14) Nijland, Gussow 1936; (15) Plassmann, Gussow 1936; (16) Enebo, Gussow 1936; (17) Wendell, Gussow 1936; (18) Schiller, Gussow 1936; (19) Lohnert, Gussow 1936; (20) Scharbe, Gussow 1936; (21) Mundler, Gussow 1936; (22) Lau, Gussow 1936; (23) Hornig, Gussow 1936; (24) Menze, Gussow 1936; (25) Guthnick, Gussow 1936; (26) Johansson, Gussow 1936; (27) Guthnick & Pavel, Gussow 1936; (28) Gadamoki, Gussow 1936; (29) Graff, Gussow 1936; (30) Kordylewski, Gussow 1936; (31) Gussow, Gussow 1936; (32) Kukarkin, Gussow 1936; (33) Beyer, Gussow 1936; (34) Danjon, Gussow 1936; (35) Jacchia, Gussow 1936; (36) Pagaczewski, Gussow 1936; (37) Stebbins & Huffer, Gussow 1936; (38) Tschernov, Gussow 1936; (39) Mrzacek, Gussow 1936; (40) Dziewulski, Gussow 1936; (41) Kopal, Gussow 1936; (42) Fredrick 1960; (43) Larson-Leander 1958; (44) Gyldenkerne 1970 plot digitized; (45) Thiessen 1957; (46) Abl 1960; (47) Huruhata & Kitamura 1958; (48) Parthasarathy & Frueh 1986; (49) Japan Amateur Photographic Observers Association 1983; (50) Chochol & Žižkovský 1987; (51) Flin et al. 1985; (52) Sato & Nishimura 1987; (53) Taranova & Shenavrin (2001); (54) Bhatt et al. (1984); (55) Arellano Ferro (1985); (56) Hopkins, Hopkins (2009); (57) Dumont, Hopkins (2009); (58) Ingvarsen, Hopkins (2009); (59) AAVSO; (60) Widorn (1959).

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Figure 2. History of the photometry of ϵ Aurigae. Note the change in the magnitude scale between the early visual magnitudes and the more recent V magnitudes.

For the 1875, 1902, 1929, 1956, and 1983 eclipses, we use photometry from before and after the eclipses to determine the mean out-of-eclipse magnitude, over as long a time period as possible to average out the short-period light variation of the star. We then fit a straight-line to the “linear” portion of the ingress and egress light curve. The “linear” part of the light curves was established by a careful examination of the photometric data for linearity and, at times, excluding photometric data that was obviously inconsistent with the bulk of the photometric observations, and giving preference to measurements by observers showing the greatest internal consistency. The observations used in the linear fit are flagged with a “1” in Column 3 of Table 3. The time differences established by the intersection of these ingress and egress linear fits and the mean out-of-eclipse magnitude establish a “duration” of each eclipse. We note that the intersection points are not the same as the traditional initial and final contacts nor is our “duration” the same as the traditional eclipse duration, that is, the time from first to fourth contacts. But this procedure has the virtue that it can be determined more easily and objectively, and is much less susceptible to the short-period brightness oscillations in ϵ Aurigae than the traditional method of estimating the contact times. We then estimate the mid-eclipse time as the average of the mid times between the fitted ingress and egress branches at 7 mag levels starting at the mean out-of-eclipse magnitude and separated by 0.1 mag. The results are shown in Table 4 where we give the slopes of the ingress and egress linear fits in magnitudes per day, the “duration,” and our estimate of the mid-eclipse time and an error estimate.

For the 1848 eclipse, the egress was examined as described above. However, there is very little photometry before the eclipse and only one observation during the ingress. We estimated the
Table 4
Mid-eclipse Parameters for \( \epsilon \) Aurigae

| Eclipse | Slope In \( dV \) per day | Slope Out \( dV \) per day | Duration \( \text{days} \) | Mean Magnitude Out-of-eclipse | Mid-eclipse HJD | Std. dev. \( \text{days} \) |
|---------|---------------------------|---------------------------|-----------------|-------------------------------|----------------|-----------------|
| 1848.0  | +0.00363                  | −0.00566                  | 668             | 3.277                         | 2396041.       | 11              |
| 1875.2  | +0.00332                  | −0.00686                  | 649             | 3.352                         | 2405955.       | 15              |
| 1902.2  | +0.00369                  | −0.00355                  | 700             | 3.399                         | 2415827.7      | 2.9             |
| 1929.3  | +0.00387                  | −0.00366                  | 695             | 3.329                         | 2425726.8      | 3.1             |
| 1956.4  | +0.00593                  | −0.00583                  | 645             | 3.003                         | 2435624.6      | 2.7             |
| 1983.5  | +0.00569                  | −0.00927                  | 651             | 3.008                         | 2445507.1      | 7.8             |
| 2009–2011 | +0.00670              | ···                         | ···             | 3.025                         | ···             | ···             |

Figure 3. Eclipse light curves of \( \epsilon \) Aurigae. Open circles are observations used for linear fits, shown as solid lines, to the ingress and egress light variation during the eclipses.
Figure 4. Spectroscopic orbital solution for $\epsilon$ Aurigae. The center-of-mass velocity is indicated by the dashed line. Phase 0.0 corresponds to the time of periastron passage.

Figure 5. Examples of oscillations in the CfA velocity residuals.

“duration” of the 1848 eclipse as the mean of the previous five eclipses, 668 days, and the slope of the ingress as the mean of the 1929, 1902, and 1875 ingress slopes. We then use the procedure described above to estimate the mid-eclipse time.

We show in Figure 3 the eclipse photometry as well as the features described above for all previous eclipses. The observations used for the linear fit are shown as large open circles.

5. COMBINED ORBITAL SOLUTION

The eclipse timings constrain the ephemeris for $\epsilon$ Aurigae (period and epoch) much more precisely than do the radial velocities. In order to make use of this information, for the combined orbital solution, we have incorporated the eclipse times along with the radial velocities into the least-squares fit, with their corresponding observational errors. We did this by predicting the times of eclipse at each iteration based on the current spectroscopic elements, and adding the residuals to those from the velocities in a $\chi^2$ sense. The timing errors for the six historical eclipses were conservatively increased over...
their formal values by adding a fixed amount in quadrature so as to achieve a reduced $\chi^2$ near unity for these measurements. The proper amount (2.65 days) was found by iterations, and the combined uncertainties reported in Table 4 include this adjustment, and are believed to be realistic.

The orbital elements of our combined orbital solution are given in the last column of Table 2. In Figure 4, we plot the individual observed velocities as a function of orbital phase together with the velocity curve calculated from our combined orbital solution. The center-of-mass velocity, $\gamma$, is shown as a horizontal dashed line. In Figure 1, we plot our orbital solution over all the radial velocities as a function of time. According to our combined spectroscopic and photometric orbital solution, the predicted mid time of the eclipse currently underway, is JD 2,455,413.8 ± 4.8, corresponding to 2010 August 5.

6. SHORT-TERM OSCILLATIONS

It is clear from Figure 1 that there are short-term variations in the radial velocity of $\epsilon$ Aurigae both inside and outside of the eclipses. In addition, during the eclipse phases, considerable structure is observed in the spectral lines and multiples of several lines are observed. Presumably, these features are due to structures in the occulting disk. Various authors have speculated about the origin, nature, and regularities of these oscillations, as well as the photometric variations. Arellano Ferro (1985) found no regular oscillation from an examination of the Yerkes (Frost et al. 1929) and Mt. Wilson (Struve et al. 1958) velocities and Arellano Ferro, A. 1985, MNras, 216, 571 as well as the photometric variations. Arellano Ferro, A. 1985, MNRAS, 216, 571

Using CfA velocities outside the eclipse phase, we examined the data to see if they can shed any light on the nature of the short-term oscillations. The CfA velocity residuals from the spectroscopic orbit vary in a range of 5–20 km s$^{-1}$ in no apparent pattern and the power spectrum of the residuals shows no clear periodicities. The CfA velocity residuals, however, often show well defined oscillations that last for only one or two cycles and are reminiscent of radial pulsation (Figure 5). These oscillations differ in period from 75 to 175 days and have peak-to-peak amplitudes of 10–20 km s$^{-1}$. Assuming the radial velocity residuals are coming from the motion of the stellar envelope facing us, this means that if the envelope is moving toward us then after 600 days it is likely, with a correlation of about 0.5, to move again toward us. There are less significant positive features in the autocorrelation at 300 and 450 days.

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Figure 6. Autocorrelation of CfA velocity residuals.