9-1993

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Recommended Citation

Fekel, F.C.; Tomkin, J. "The Spectroscopic Orbit of Gamma Geminorum and a Search for its Secondary" Astronomical Journal v.106, p.1156 (1993)

THE ASTRONOMICAL JOURNAL VOLUME 106, NUMBER 3 SEPTEMBER 1993

THE SPECTROSCOPIC ORBIT OF GAMMA GEMINORUM AND A SEARCH FOR ITS SECONDARY

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Received 1993 March 22; revised 1993 May 21

ABSTRACT

New spectroscopic observations of γ Geminorum, a bright, "normal" A1 IV star have resulted in an improved spectroscopic orbit. The orbital period is 12.632 ± 0.002 yr, the eccentricity is 0.893 ± 0.002, and the orbital parallax is $0.0291'' \pm 0.0024''$ or a distance of 34 pc. We determine a $v \sin i$ of 8 ± 1 km s^{-1} for the A star, which confirms that it is a slow rotator. Near-infrared spectroscopic observations at 8806 Å, obtained through the brief nodal passage, have resulted in the probable detection of the secondary. The masses are 2.8 and 1.07 $\mathscr{M}_\odot$ and the ΔV of the components is 6.0 mag. This ΔV supports the value of 5.6 mag obtained by Sato *et al.* [AJ, 105,1553 (1993)] from observations of the asteroid occultation of γ Gem in 1991. The magnitude difference and mass of the secondary are consistent with a G dwarf spectral type. The detection of such a faint secondary does not compromise the use in most contexts of γ Gem as a standard star.

1. INTRODUCTION

Gamma Geminorum = HR 2421 [$\alpha = 6^h37^m42.7^s$, $\delta = 16°23'57''(2000)$] is a bright, $V = 1.93$, narrow lined early-type star, A1 IV (Gray & Garrison 1987; Cowley *et al.* 1969), that has long been known as a spectroscopic binary. Campbell & Curtis (1905) first announced its velocity variability. They noted that the "star's spectrum is of the Sirian type and the lines are capable of accurate measurement." Beardsley (1967) reviewed the early efforts to determine the correct orbital period, which were unsuccessful for a number of decades because of the long period and very high eccentricity of the system. An approximate period that was determined astrometrically (Wagman *et al.* 1963) enabled Beardsley (1967) to compute a preliminary spectroscopic orbit. Shortly afterward, an improved astrometric orbit was determined by Kamper (1972). Finally, the extensive amount of astrometric and spectroscopic data, accumulated over a number of decades, resulted in the combined astrometric–spectroscopic orbit of Kamper & Beardsley (1987).

Since γ Gem is slowly rotating, several abundance analyses have been made (Conti & Strom 1968; Sadakane & Nishimura 1979; Cowley & Aikman 1980; Adelman & Philip 1992) to look for abundance peculiarities and to examine its suitability as a standard for relative abundance studies. These analyses have shown that contrary to many other slowly rotating early-A stars that have Ap or Am abundance characteristics, γ Gem is indeed a "normal" A star. Roby & Lambert (1990) used γ Gem as one of their standard stars in an analysis of carbon, nitrogen, and oxygen abundances in chemically peculiar B and A stars. They noted that the above studies and others (e.g., Holweger *et al.* 1986) have shown that most, if not all, of the stars considered to have normal (i.e., solarlike) composition simply have a very mild degree of various chemical peculiarities.

Gamma Gem has been used as a standard in a number of other contexts. Oke (1964) examined its suitability as a spectrophotometric standard and it has been used extensively as such. The star is well represented in four papers presented at IAU Symposium 111 on the calibration of fundamental stellar quantities, which was held in Italy in 1984. It also has been used as a rotational–velocity standard (Slettebak *et al.* 1975) and as a MK standard (e.g., Morgan *et al.* 1943).

Our interest in γ Gem was sparked by the preliminary analysis of Kamper & Beardsley (1979) and was intensified by their more extensive recent discussion and analysis (Kamper & Beardsley 1987). As a result, in addition to our long term monitoring effort, begun in 1979, we obtained a number of observations during the most recent periastron and nodal passage of 1991 November through 1992 January. Included in this effort was a search at near-infrared wavelengths for the secondary component.

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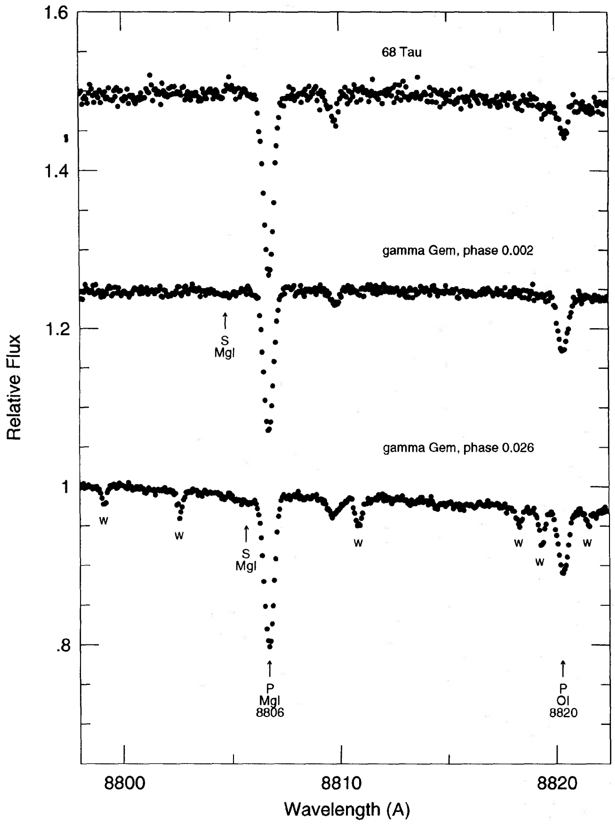

FIG. 1. McDonald observations of 68 Tau and γ Gem at 8800 Å made when the velocity separation between γ Gem's primary and secondary lines was large. In the upper γ Gem spectrum (phase 0.002; HJD 2448619.772) the very weak line 2 Å to the blue of the primary's 8806 Å Mg I line is its likely counterpart in the secondary. Its location and the fact that unlike the other lines, it has no counterpart in 68 Tau both suggest its identification as the secondary Mg I line. In the lower γ Gem spectrum (phase 0.026; HJD 2448729.642) the separation between the primary and secondary Mg I lines has decreased, consistent with the observation's phase being further away from the ascending node (phase 0.0037). Division by a broad-lined hot star spectrum has removed the water lines, except for the bottom spectrum, which was divided by a flat-field lamp. The water lines in this spectrum are labeled "w"; the wing of the Paschen line at 8862 Å depresses its red side.

2. OBSERVATIONS AND REDUCTIONS

From 1979 February through 1993 April, we obtained 31 high-dispersion spectroscopic observations at the McDonald Observatory or at the Kitt Peak National Observatory (KPNO). This interval is slightly longer than γ Gem's orbital period of 12.6 yr and includes two periastron passages, one at the beginning and one at the end of the interval, so our observations provide the basis for an independent redetermination of γ Gem's spectroscopic orbital elements including the period. The first nine observations, obtained from 1979 through 1981, we made at the McDonald Observatory with the 2.7 m telescope, coudé spectrograph, and a Reticon detector or the 2.1 m telescope, coudé spectrograph, and a Reticon detector. From 1983 through 1993, 22 observations were obtained at the KPNO with the coudé feed telescope, coudé spectrograph, and a Texas Instruments charge-coupled device (CCD). The above observations usually were centered in the blue at 4500 Å or in the red at 6430 Å. However, several observations also were centered at 6375 Å and one early observation was centered at 8800 Å to search for the secondary. The spectrograms typically cover a wavelength range of about 80 Å and have a resolution of about 0.2 Å. Most of the spectra have signal-to-noise ratios of 150 or better.

The radial velocities were determined relative to those of stars of known velocity. Details of the velocity-reduction procedure have been given by Fekel *et al.* (1978). At blue wavelengths 5 or 6 lines or Ti II or Fe II were used to determine each velocity. In the red region near 6430 Å 2 Fe II lines were used while at 6375 Å 2 Si II lines were used. At present there are no early-type radial-velocity standard stars and the International Astronomical Union (IAU) radial-velocity system of the late-type stars is also undergoing revision (Latham & Stefanik 1992). Our radial velocities were determined relative to one of the following stars: β Gem, β Vir, 68 Tau, or θ Leo. The first two are IAU late-type radial-velocity standard stars (Pearce 1957) whose velocities of 3.2 and 4.4 km s^{-1}, respectively, are assumed from the work of Scarfe *et al.* (1990). The stars 68 Tau and θ Leo are A stars that have recently been suggested as possible early-type velocity standards (Fekel 1985; Latham & Stefanik 1992). Cole *et al.* (1992) have determined a velocity of 39.0 km s^{-1} for 68 Tau while Fekel (Latham & Stefanik 1992) has determined a velocity of 7.7 km s^{-1} for θ Leo.

From 1991 December to 1992 February, Helmut Abt obtained three observations at the KPNO with the coudé feed telescope, coudé spectrograph, and CCD detectors. The central wavelength of each of these observations is close to 4500 Å. Radial velocities were determined by Daryl Willmarth with a cross-correlation reduction program, FXCOR, that is part of the IRAF software package, which is distributed by the National Optical Astronomy Observatories. The star 68 Tau was used as the cross-correlation standard.

The last set of observations of γ Gem was made at McDonald Observatory during the 1991–2 periastron and nodal passage. The primary purpose of these observations was to search for evidence of the spectrum of the faint secondary when it was separated from the spectrum of the much brighter primary by the rapid motion near periastron passage. To improve the prospects of secondary detection, the observations were made in the near infrared (8806 Å) where the cool secondary is relatively brighter than it is at visual wavelengths. Tomkin & Popper (1986) successfully used similar observations of α CrB, which also has an early-A-type primary, to detect lines of its G star secondary. As a bonus, the observations provided critical additional velocities for the primary during periastron passage.

The observations were made with the 2.7 m telescope and coudé spectrograph. The detector was a Texas Instruments CCD with 15 μm square pixels arranged in an 800 $\times$800 pixel format. We used two-pixel on-chip coaddition in the direction perpendicular to the dispersion and no coaddition in the direction of the dispersion.

TABLE 1. Velocity observations of γ Gem.

HJD − 2400000	Phase	Velocity (km s^{-1})	(O−C) (km s^{-1})	Central Wavelength (Å)	Observatory
43921.623	0.984	−15.6	0.3	6430	McDonald
43973.736	0.995	−9.8	−1.4	6455	McDonald
44001.614	0.001	5.6	0.2	6375	McDonald
44007.607	0.002	6.2	−0.6	6375	McDonald
44179.036	0.040	−4.0	−0.1	4500	McDonald
44356.596	0.078	−6.9	0.1	8800	McDonald
44357.675	0.078	−6.5	0.5	4500	McDonald
44474.967	0.104	−6.7	1.3	4500	McDonald
44625.702	0.136	−9.4	−0.4	4500	McDonald
45814.658	0.394	−12.2	0.1	4500	KPNO
46393.070	0.519	−14.0	−0.8	6430	KPNO
47248.681	0.705	−14.1	0.4	6430	KPNO
47248.706	0.705	−14.6	−0.1	4500	KPNO
47458.884	0.750	−15.3	−0.4	4500	KPNO
47917.787	0.850	−15.4	0.4	4500	KPNO
48003.629	0.868	−15.8	0.2	4500	KPNO
48167.888	0.904	−16.7	−0.3	4500	KPNO
48348.722	0.943	−17.0	−0.1	6430	KPNO
48509.015	0.978	−15.6	1.0	6430	KPNO
48573.874	0.992	−11.0	1.2	4500	KPNO
48578.822	0.993	−11.9	−0.8	6430	KPNO
48604.860	0.999	0.3	0.0	6430	KPNO
48605.780	0.999	0.2	−0.6	6430	KPNO
48606.761	0.999	1.9	0.6	6430	KPNO
48607.793	0.999	1.7	−0.2	4500	KPNO
48613.842	0.001	4.5	−0.1	4455	KPNO
48619.758	0.002	6.2	−0.3	8806	McDonald
48619.772	0.002	6.2	−0.3	8806	McDonald
48639.692	0.006	6.6	0.3	4515	KPNO
48641.787	0.007	5.7	−0.4	8806	McDonald
48641.797	0.007	5.9	−0.2	8806	McDonald
48673.559	0.014	2.6	0.3	8806	McDonald
48673.561	0.014	2.6	0.3	8806	McDonald
48674.669	0.014	3.1	0.8	4545	KPNO
48729.642[a]	0.026	1.3	2.9	8806	McDonald
48729.647[a]	0.026	1.3	2.9	8806	McDonald
48770.621	0.035	−3.7	−0.4	6430	KPNO
48915.020	0.066	−6.4	−0.1	6430	KPNO
48915.022	0.066	−6.6	−0.3	6430	KPNO
48916.904	0.066	−6.0	0.3	4500	KPNO
49102.666	0.107	−9.1	−0.9	6430	KPNO
49104.658	0.107	−8.4	−0.2	6430	KPNO

[a]Given zero weight

The observations were centered at 8806 Å and covered 49 Å. The resolution was 0.25 Å (four pixels) and the signal-to-noise ratio was typically 400. This wavelength region was chosen because it is relatively free of telluric lines, it suffers minimal interference from Paschen lines, which are strong in the A1 IV primary, and it includes some Mg I and Fe I lines that are strong in cool main-sequence stars and so afford the most promising means of detecting a cool secondary.

The stars 68 Tau (A1 IV) and 10 Tau (F8 V), the latter an IAU standard with an assumed velocity of 27.9 km s^{-1} (Scarfe *et al.* 1990), were observed for use as radial-velocity standards for the primary and secondary of γ Gem, respectively. A rapidly rotating hot star was also observed at a similar airmass to that of γ Gem. This spectrum was used to divide out the weak telluric water vapor lines that inhabit this part of the spectrum. Although our observations were made in winter when water-vapor lines are weak, their line strengths are not negligible.

We did the data reduction with the IRAF package of programs installed on a microVAX workstation in the Astronomy Department at the University of Texas. The main steps in the data reduction procedure were subtraction of the bias from the star spectrum, division of the star spectrum by the lamp observation, and the collapse of the flat-fielded star spectrum to produce a one-dimensional spectrum.

The primary boasts a clean sharp 8806 Å Mg I line with a depth of 17% (Fig. 1) which we used to measure primary velocities for the McDonald observations. The IRAF cross-correlation routine RVDIRECT was used to measure the pixel shift between this line and the same line in the radial velocity standard (68 Tau). After conversion of this shift into a velocity difference, allowance for the heliocentric corrections, and adoption of the heliocentric velocity for 68 Tau, we then obtained the heliocentric velocity for

TABLE 2. Orbital elements.

	Our data			Combined solution		
P	4612.3	±	1.2 days	4614.0	±	0.7 days
T	2439386.4	±	2.5 days	2439382.7	±	1.6 days
γ	-12.2	±	0.1 km s^{-1}	-12.23	±	0.08 km s^{-1}
e	0.893	±	0.002	0.893	±	.002
K	12.1	±	0.1 km s^{-1}	12.1	±	0.1 km s^{-1}
ω	313°0	±	1°2	312°6	±	0°9
$a_1 \sin i$	3.45	±	0.06 x 10^8 km	3.45	±	0.04 x 10^8 km
$a_2 \sin i$	9.02	±	0.84 x 10^8 km			
f(m)	0.077	±	0.004 $M_\odot$	0.077	±	0.003 $M_\odot$
$M_1 \sin^3 i$	2.64	±	0.44 $M_\odot$			
$M_2 \sin^3 i$	1.01	±	0.14 $M_\odot$			

Standard error of an observation of unit weight is 0.5 km s^{-1}

the primary. These primary velocities and their heliocentric Julian dates are tabulated in Table 1.

3. ORBIT

Because of its extremely high orbital eccentricity and orbital orientation, observations of γ Gem near periastron passage are critical to the determination of an accurate orbit. Kamper & Beardsley (1987) noted that nodal and periastron passage occur during a brief two month period. Despite the numerous radial-velocity data sets listed by Kamper & Beardsley (1987), only at the David Dunlap Observatory (DDO) and Lick Observatory have a significant number of velocities been obtained that are distributed through the 2 month node-to-node passage near periastron and are of sufficient accuracy to be of possible additional value in our determination of the orbital elements.

We used the differential-corrections computer program of Barker *et al.* (1967) to obtain separate orbital-element solutions of our data as well as those of the DDO and Lick Observatory. A combined solution was made with these three data sets appropriately weighted. A weight of 1.0 was assigned to each of our velocities, except for the last two McDonald velocities, which were given zero weight because of their large residuals. Each velocity of the other two data sets was given a weight of 0.15. No additional velocity correction was made to the Lick velocities but +0.5 km s^{-1} was added to the previously corrected velocities of the DDO (Kamper & Beardsley 1987). A combined solution with 40 McDonald and KPNO velocities, 79 Lick velocities, and 119 DDO velocities resulted in elements that are nearly identical to those obtained with our data alone (Table 2) although modest improvements in the errors of the elements are seen. Likewise, there is good agreement between the elements of the *combined astrometric–spectroscopic* solution found by Kamper & Beardsley (1987), although they did not list the semiamplitude of their solution, and those from a solution of our data alone. Table 1 lists only our velocities as well as their residuals in the combined orbital solution. Our radial velocities, excluding the two given zero weight, and the computed radial-velocity curve for the combined solution are plotted in Fig. 2.

4. SPECTRUM OF THE SECONDARY

Our near-infrared McDonald spectrograms include a number of atomic lines that must be strong in the putative cool dwarf secondary. Of these the 8806 Å Mg I line would be the strongest and the 8790, 8793, and 8824 Å Fe I lines might also be detectable.

Our spectra reveal a weak feature that may well be the secondary's 8806 Å Mg I line. In the observations of 1991 December 29 (HJD 2448619.8) and 1992 January 20 (HJD 2448641.8) it is 2 Å to the blue of the same line in the primary, in the observations of 1992 February 21 (HJD 2448673.6) its presence is uncertain, and in the observations of 1992 April 17 (HJD 2448729.6) it may be present as a weak asymmetry in the blue wing of the same line in the primary. The sense and magnitude of the feature's separation from the primary's 8806 Å Mg I line both suggest that it is probably the secondary's Mg I line. Also,

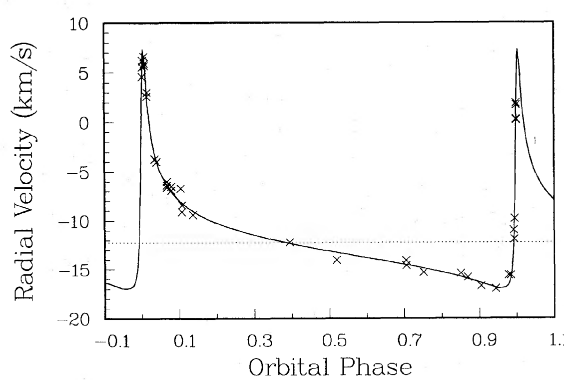

FIG. 2. McDonald Observatory and KPNO radial velocities of γ Gem's primary compared with the computed radial velocity curve. The center-of-mass velocity is plotted as a dotted line.

TABLE 3. Secondary velocities.

Date	HJD − 2400000	Separation (Å)	(km s^{-1})	V(pri) (km s^{-1})	V(sec) (km s^{-1})	Mass Ratio
29 Dec 91	48619.772	2.0	68	6.2	-61.8	2.71
20 Jan 92	48641.787	1.9	65	5.7	-59.3	2.65

the date (1992 January 6) of the ascending node, which is the time of maximum separation of the primary and secondary spectra, means that the velocity separation on 1992 April 17 must have been less than it was for the observations of 1991 December 29 and 1992 January 20. For the 1992 April 17 observations, therefore, the presence of the feature as a weak asymmetry in the wing of the primary 8806 Å Mg I line, rather than a separate feature, is consistent with identification as the secondary's 8806 Å Mg I line (see Fig. 1). But because there is no sign of other secondary lines at similar separations from their primary counterparts and because the feature is extremely weak, we do not claim a definite detection of the secondary.

We have, however, measured the separations between the likely 8806 Å Mg I line of the secondary and its primary counterpart in the observations of 1991 December 29 and 1992 January 20 and used them to make a provisional estimate of the mass ratio. The separation gives the velocity difference between the primary and secondary, which combined with knowledge of the primary's velocity and the systemic velocity from the solution of our data (Table 2), then provides the ratio of the semiamplitudes and, hence, the mass ratio. Our results are given in Table 3. Our provisional estimate of the ratio of the secondary's semiamplitude to the primary's is, thus, 2.7 ± 0.4, where the error estimate is set by the estimated ±0.2 Å accuracy of the wavelength separation. Our provisional mass ratio is, therefore, $M_{\rm sec}/M_{\rm pri}=0.37\pm0.05$.

A second estimate of the mass ratio comes from a double-lined orbital solution in which the two secondary velocities were given a weight of 0.01. This results in a mass ratio of 0.38.

The provisional detection of the secondary also enables us to estimate the magnitude difference between the primary and secondary. The depth of the suspected secondary 8806 Å Mg I feature, which is $0.5\%\pm0.2\%$, combined with the depth of the same line in 10 Tau, which is 53%, leads to an estimated magnitude difference of 5.1 ± 0.5. This calculation makes the approximation that the Mg I line has the same depth in 10 Tau as in γ Gem's (undiluted) secondary. Although 10 Tau (F8V) is of earlier spectral type than γ Gem's secondary, which much be G type or later, the Mg I line's saturation means it cannot be much deeper in γ Gem's secondary than it is in 10 Tau so the approximation is probably adequate for the present purposes. This magnitude difference is at 8800 Å, which happens to be the effective wavelength of the I filter, so it is also the magnitude difference in I. With the aid of the $V-I$ for main-sequence stars tabulated by Johnson (1966) we then translate this into a magnitude difference of 6.0 ±0.5 in V. (The estimated $V-I$ for the secondary required a minor iteration between the assumed spectral type for the secondary and the spectral type we eventually estimated.) Because of such a magnitude difference, it is not surprising that γ Gem is noted in the null results speckle-interferometry papers of McAlister (1978) and Hartkopf & McAlister (1984), who observed it at visual wavelengths. Observations in the infrared, however, with direct-imaging techniques such as those of McCarthy *et al.* (1993) should be able to directly resolve the secondary.

Support for our magnitude difference and spectral type come from an unexpected source. Sato *et al.* (1993) have just reported the results of an occultation of γ Gem by the asteroid 381 Myrrha on 1991 January 13. This unusual event was seen by a well-organized network of observers in Japan and China. During the occultation of the A-type star the secondary was directly observed both photographically and visually. Sato *et al.* (1993) commented that the color of the companion is yellowish as would be expected for a G-type star and estimated the magnitude of the companion to be about 7.5 compared with our value of 7.9.

5. DISCUSSION

The above magnitude difference combined with an absolute magnitude for γ Gem, $M_V=-0.5$, which we estimate from its apparent brightness ($V=1.93$) and parallax ($\pi=0.0326''\pm0.0025''$; Kamper & Beardsley 1987), leads to an absolute magnitude for the secondary, $M_V=5.5\pm0.5$. Our orbital parallax, determined below, increases the brightness of the components by 0.25 mag. Allen's (1973) calibration between absolute magnitude and spectral type then puts the secondary's spectral type at approximately late G.

The minimum masses from the double lined solution are $2.64\pm0.44\ \mathscr{M}_\odot$ and $1.01\pm0.14\ \mathscr{M}_\odot$. These values, combined with an inclination of 101.3° from the astrometric solution of Kamper & Beardsley (1987), result in masses of 2.8 $\mathscr{M}_\odot$ and 1.07 $\mathscr{M}_\odot$ for the A star and G star, respectively. Although the mass of the secondary would suggest a late-F or G0 dwarf (Allen 1973) rather than a late-G star, as suggested by the magnitude difference, the uncertainties in both the magnitude difference determination and the mass determination are large enough to admit such a range in spectral types. Preliminary results for a number of eclipsing G dwarf binaries (Popper 1993) support this conclusion.

Our redetermination of $a_1 \sin i$ allows new determinations of the semimajor axis of the primary's orbit (a_1) and γ Gem's orbital parallax. With the aid of the $a_1 \sin i = 3.45 \pm 0.04 \times 10^8$ km from our combined solution and the orbital inclination of $i = 101.3° \pm 6.1°$ provided by the astrometric orbit (Kamper & Beardsley 1987), we find $a_1 = 3.52 \pm 0.09 \times 10^8$ km or 2.35 ± 0.06 *AU*, where the estimated error is dominated by the error in the inclination. This confirms Kamper & Beardsley's value of 2.280 ± 0.065 *AU*. The combination of the linear and angular sizes of the primary's orbit then tells us γ Gem's orbital parallax; $\pi = \alpha / a_1$, where α—the angular semimajor axis of the primary's true orbit—is one of the fruits of the astrometry and is $0.0685'' \pm 0.0056''$ (Kamper & Beardsley 1987). Our new determination of the orbital parallax is $\pi = 0.0291'' \pm 0.0024''$ or a distance of 34 pc. The estimated error is set entirely by the difficulty of measuring the astrometric orbit and the consequent poor definition of α. This result supports Kamper & Beardsley's measurement of both the orbital ($\pi = 0.0300'' = 0.0026''$) and trigonometric ($\pi = 0.0326'' \pm 0.0025''$) parallax.

We also note that the large magnitude difference, $\Delta V = 6.0$ mag, between γ Gem's components means that Kamper & Beardsley's (1987) assumption of an "effectively dark companion" is valid so the elements of their astrometric orbit are secure in that sense. The astrometric orbit's fuzziness, however, is what blurs our view; a major improvement in it would immediately lead to a corresponding improvement in our measurement of the distance to γ Gem.

A $v \sin i$ value of 8 ± 1 km s^{-1} was computed from measurement of the full width at half maximum of a number of metal lines in the 4500 Å region and an empirical relationship between linewidth and $v \sin i$ (Fekel *et al.* 1986). Cowley *et al.* (1982) have estimated a value of 7 km s^{-1} from high resolution plates while Slettebak *et al.* (1975) find less than 10 km s^{-1}, both in excellent agreement with our value. Ramella *et al.*'s (1989) value of 19.0 ± 4 km s^{-1} from a measurement of the Fe II line at 4233.167 Å appears to be too large. The value of 30 km s^{-1} listed by Uesugi & Fukuda (1982) in their revised catalog of rotational velocities and the value of 32 km s^{-1} listed by Hoffleit (1982) in the fourth edition of *The Bright Star Catalogue* obviously were estimated from resolution limited plates and are superceded by the above results. If the rotational axis of the A star has an inclination that is similar to the orbital axis, γ Gem is indeed slowly rotating.

We thank David Lambert and Verne Smith for obtaining some of the McDonald observations. We greatly appreciate the additional observations obtained by Helmut Abt and measured by Daryl Willmarth. We also thank Karl Kamper for providing the Lick and DDO velocities. J. T. acknowledges the support of NSF Grant No. AST-9115090.

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