Astron. Astrophys. 320, 791–798 (1997)

ASTRONOMY
AND
ASTROPHYSICS

A spectroscopic study of the binary star γ Gem

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Received 27 December 1995 / Accepted 2 August 1996

Abstract. Analysis of an extensive collection of 730 spectroscopic observations of the bright A0IV star γ Gem lead to the following conclusions:

(1) A new orbital solution is presented. Some hints of a small gradual increase of the systemic velocity were found but cannot be taken as real until confirmed by continuing observations. There is still no compelling evidence of the apsidal motion, however.

(2) A new, more accurate value of the projected rotational velocity of the primary, (10.2 ± 0.2) km s^{-1}, was derived from the 2 Å mm^{-1} spectrograms. Together with available estimates of the radius of the primary it sets up an upper limit of about one month on its rotational period. Period analyses of the O-C velocity deviations from the orbital solution revealed no significant *periodic* RV variations on time scales from $0\overset{\mathrm{d}}{.}01$ to $30\overset{\mathrm{d}}{.}0$ which we could assign to the rotation of the star or pulations as they are to expect in case that γ Gem is a member of the so-called Maia sequence.

(3) We confirm the existence of a strong global magnetic field in the atmosphere of γ Gem if we use an empirical correlation between the magnetic field strength and the relative differences of the equivalent widths of a pair of spectral lines belonging to the same multiplet but with different magnetic sensivity.

Key words: stars: standard – binaries: spectroscopic – binaries: visual – stars: individual: γ Gem

1. Introduction

The γ Gem (HR 2421, HD 47105, GC 8633) has often been used as a spectrophotometric, MKK and rotational-velocity standard star (cf., e.g., Guthrie 1984; Nishimura and Sadakane 1994). It is, however, a radial-velocity (RV hereafter) variable. The first RV measurements were published by Vogel (1892) but the RV variability was first reported by Campbell & Curtis (1905). Slipher (1905) obtained new RVs, compiled the existing ones and suggested the star could be a spectroscopic binary with a highly eccentric orbit and a period of about 3.5 years. A period of 2175 d (5.96 years) was derived by Harper (1912) who obtained additional spectra and attempted to derive the first orbital elements. In reaction to it, Ludendorff (1912) reported Potsdam RVs which clearly invalidated Harper's period as well. Colacevich (1935) also refuted Harper's period on the basis of further Lick RVs. He was probably the first who raised the question of possible rapid RV variations of γ Gem, occurring within a few days. Curiously, the correct period of 12.5 years was finally derived by Wagman et al. (1963) from a long series of parallax measurements. Guided by this finding, Beardsley (1967) derived the first realistic spectroscopic orbital elements of γ Gem:

P = 4710 d (12.9 y), e = 0.80 and ω = 325°.

Beardsley suspected cycle-to-cycle variations in the length of the orbital period but this suspicion was later withdrawn by Kamper & Beardsley (1987) who obtained and compiled 447 RVs secured within an interval of about 38000 days. Combining spectroscopic and astrometric observations, they derived the following accurate elements:

P = 4613.6 d (12.632 y), e = 0.8959 and $\omega = 312\overset{\circ}{.}5$.

They, too, noted larger than expected scatter in RVs from some data sets and undertook a period analysis of the RV residuals from the orbit but with a completely negative result. Fekel & Tomkin (1993) obtained a number of electronic spectra of γ Gem in an effort to discover some lines of the secondary. They reported a probable detection of a very weak Mg I 8806 Å line from the secondary and derived an improved set of the orbital elements.

Recently, Lehmann et al. (1995) made an extensive search for possible rapid spectral and light variations of the so-called Maia variables (B7 to A2 stars which lie between the β Cep and δ Sct stars in the HR diagram), including also γ Gem after a collection of possible Maia candidates by McNamara (1987). They briefly reported that the spectroscopic survey, based on high-dispersion photographic spectrograms from the Tautenburg 2.0-m reflector, was completely negative for γ Gem. To set up even more stringent limits on the measuring accuracy, one of us (PH)

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Table 1. Journal of spectroscopic observations

Source	Epoch covered (JD-2400000)	No. of spectra	Spg. No.	Disp. (Å mm^{-1})	RV Cor. to IAU	Rem.
Vogel (1892)	10986.4-11771.3	4	1	13	No	
Campbell & Moore (1928)	14919.0-17698.7	11	2	12.5-10.9	No	
this paper	15427.2-19819.3	74	3	17	Yes	A
Frost et al. (1929)	15704.8-16821.9	5	4	10	No	
Slipher (1905)	16038.0-16949.0	6	5	30.5	No	
Kamper (1995)	16915.7-16949.6	4	6			
	17646.6-17690.5	9	7	40	Yes	
Harper (1912)	17857.9-19441.8	16	8	10	No	
Lunt (1918)	20524.4-20927.3	3	9		No	
Harper (1935)	24979.7-25693.7	2	10	15?	No	
Kamper (1995)	25613.8-38866.8	16	11	4?	Yes	
	25889.5-26410.5	5	12			
	27140.8-32223.9	80	13	11?	Yes	B
	28218.5-37699.8	51	10	15?	No	
	30036.5-30318.5	2	14			
	30774.5-30792.6	6	15			
Kamper & Beardsley (1987)	35577.5-46065.1	121	16	8-40	Yes	C
Palmer et al. (1968)	37623.7-37640.6	5	17	100	Yes	
	37640.6	1	14			
Kamper & Beardsley (1987)	37679.7-40977.7	95	7	40?	Yes	
Abt et al. (1980)	39807.0-41016.8	3	18	13.3	No	
Kamper (1995)	41642.2-43959.7	5	18	16.9	No	
this paper	43498.5-49412.4	144	19	4.0-15.8	Yes	D
Fekel & Tomkin (1993)	43921.6-48729.6	17	20	4.0	Yes	E
	45814.7-49104.7	25	21	7.0	Yes	
this paper	49702.4-49840.3	18	22	17.1	Yes	
	49608.7	2	23	2.0	Yes	

Telescopes and spectrographs used (see column "Spg. No."): 1... Potsdam 0.30-m double refractor, prism spg. D; 2... Lick 0.91-m refractor, orig. and new Mills prism spg.; 3... Potsdam 0.325-m refractor, prism spg. IV; 4... Yerkes 1.02-m refractor, 3-prism spg.; 5... Lowell 0.62-m Clark refractor, 3-prism Brashear spg; 6... ? (code "l" from Kamper 1995); 7... Allegheny, the Keeler Memorial 0.79-m reflector, 1-prism Mellon spg.; 8... Ottawa, 3-prism spg.; 9... Cape Town 0.6-m (24-inch) refractor, 4-prism spg.; 10... Dominion Astrophys. Obs. 1.83-m reflector, Cass. prism spg.; 11... Mt Wilson 2.54-m reflector, coudé grating spg.; 12... ? (code "S" from Kamper 1995); 13... Lick 0.91-m refractor, more recent measures by E. Scott; cf. Kamper 1995; 14... ? (codes "d and X" from Kamper 1995); 15... ? (code "p" from Kamper 1995); 16... David Dunlap 1.88-m reflector, prism and grating spgs.; 17... Herstmonceux Yapp 0.91-m reflector, Hilger 1-prism spg.; 18... Kitt Peak 2.1-m reflector, coudé grating spg.; 19... Tautenburg 2.0-m reflector, coudé grating spg.; 20... McDonald 2.7-m and 2.1-m reflectors, coudé grating spg. + Reticon; 21... Kitt Peak 1-m coudé feed reflector, coudé grating spg. + Texas Inst. CCD; 22... Ondřejov 2.0-m reflector, coudé grating spg. + Reticon 1872; 23... Calar Alto 2.2-m reflector, f/12 coudé camera.

observed γ Gem during two nights with a Reticon detector in the coudé focus of the Ondřejov 2.0-m reflector. Since many of the Tautenburg spectra were obtained during the last periastron passage, and since the unpublished Potsdam, Tautenburg and Ondřejov RVs represent a significant contribution to the existing body of RV data for this interesting binary, we felt that a new study of its orbital and possibly non-orbital variations is warranted. This became even more topical after two recent reports: Sato et al. (1993) observed the secondary directly during the occultation of γ Gem by the asteroid 381 Myrrha in Jan. 1991 and reported that its position disagreed with the position predicted by the astrometric orbit of Kamper & Beardsley (1987) while Takada-Hidai & Jugaku (1993) reported the possible presence of a strong global magnetic field of γ Gem.

The rest of this study is devoted to analyses of our new spectrograms, and to combined analyses of our and published radial velocities of γ Gem.

2. Observations and reductions

The following sets of spectrograms at our disposal were investigated:

i. 74 prismatic photographic spectrograms obtained by Ludendorff with spectrograph IV of the 0.325-m Potsdam refractor between Feb. 1901 and Feb. 1912. A few of these spectra were originally investigated by Ludendorff (1912).

ii. 144 photographic coudé spectrograms (dispersions 3.9, 7.9 and 15.8 Å mm^{-1}) from the Tautenburg 2.0-m reflector obtained between Dec. 1977 and Feb. 1994;

iii. 18 Reticon spectra (dispersion 17 Å mm^{-1}) obtained at the coudé focus of the Ondřejov 2.0-m telescope on Dec. 16, 1994 and May 2, 1995.

iv. 2 CCD spectrograms (dispersion 2 Å mm^{-1}) obtained with the f/12 camera at the coudé focus of the Calar Alto 2.2-m telescope on Sept. 13, 1994.

Additionally, we also carefully compiled numerous published RVs from the astronomical literature. Journal of all RVs at our disposal can be found in Table 1. All times of mid-exposures of the older spectrograms given in the form of either a G.M.T. or U.T. date or local sidereal time were converted to heliocentric Julian dates (HJDs hereafter) by a computer program. Details of the reduction of our data as well as some remarks on the archival data sets can be found in the Appendix.

For the purpose of the new orbital solution, all RVs were weighted according to the following formula:

$w = 15 \times Q / D$,

where D is the dispersion of the spectrogram and Q is set to 1 for the photographic, and to 2 for electronic spectra. A justification for this weighting scheme can be found in Horn et al. (1996). Although it is clear that it may not reflect the true errors of the measurements (which, however, are not easy to be derived properly for many of the published data), we find it useful and acceptable. In practice, most of the weights assigned were between 0.37 and 1.90, with a few having more extreme range from 0.15 to 15.

Our new velocity measurements and all compiled RVs are presented in detail in Table 2.[1]

3. Identifying timescales of spectral variations

3.1. Orbital variations and a new orbital solution

The complete set of RV observations of γ Gem at our disposal consists of 730 RVs spanning an interval of 38854 d, i.e. more than eight orbital periods. This certainly justifies calculation of a new set of the orbital elements, especially since many of our new data were obtained during the 1991 periastron passage.

All RVs are plotted vs. Julian date in Fig. 1. One can see that certain data sets show an excessive scatter. Upon closer investigation, we found that this comes mainly from Allegheny, unpublished DAO, and Herstmonceux data sets and also from some small data sets from the compilation of Kamper & Beardsley (1987). This scatter is not systematic, often the largest differences are found from a pair of spectrograms obtained on the same night. It must be, for the most part, probably attributed to occasional large observational or measuring errors.

We first tested the constancy of the period and other orbital elements, calculating separate orbital solutions for the data obtained prior to, and after HJD 2432000 and also for an intermediate subset covering the epoch from HJD 2425000 to HJD 2440000. All orbital solutions to be discussed here were calculated with the Fortran77 program FOTEL developed by Hadrava (1990). We used the latest version of the program - see Hadrava (1995). The advantage of the program is that it allows calculation of individual γ-velocities for individual spectrographs as a part of the solution, and also calculation of apsidal motion and secular changes of the elements if desired. The errors of the elements are derived from the cross-correlation matrix.

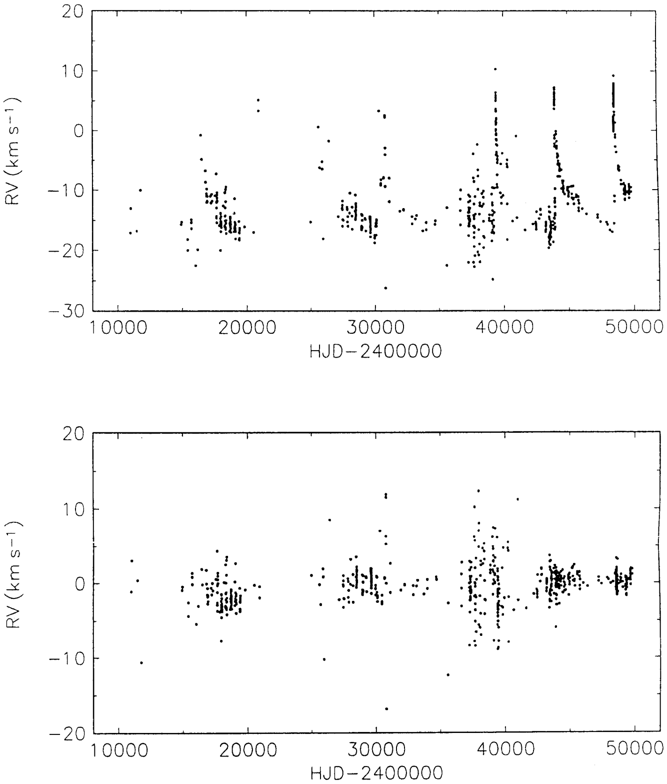

Fig. 1. Time plots of all RVs of γ Gem and O-C deviations from the orbital solution 1 in which one joint systemic velocity was adopted

The oldest data subset turned out to be prone to numerical instabilities during the solution and tends to provide longer values of the orbital period (typically about 4635 d) but with a large associated error. Solutions for the other two data subsets led to identical periods near 4615 d within the limits of errors of their detemination which was also true for the first subset if we kept the orbital eccentricity fixed at a value of 0.89. Formally, the data indicate a very slow apsidal motion. The following values of the epochs of periastron passage and longitude of periastron were found from the solutions for the three subsets:

HJD 2416315.9 ±4.4	319.7 ±2.9
HJD 2430150.1 ±3.2	313.1 ±1.4
HJD 2443995.5 ±1.5	312.3 ±1.5.

When the program was allowed to iterate also the periastron change, it converged to a value of -4.7° per century but the associated error was twice as large as the value itself. When we tried the same solution omitting the data with larger scatter (see above), the apsidal motion turned out to be completely insignificant. In all subsequent analyses, we therefore assumed that both the orbital period and longitude of periastron have

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[1] Table 2 is only available in electronic form: see the Editorial in A&AS 103, No.1 (1994)

Table 3. Orbital solutions for the primary component of γ Gem

	solution 1	solution 2	solution 3
P (d)	4614.89±0.64	4615.37±0.75	4614.51±0.47
$T_{\rm per.pas.}$	43996.6± 1.2	43996.2±1.0	43996.71±0.80
$T_{\rm max.RV}$	44013.6	44012.2	44013.67
e	0.8930±.0042	0.8969±.0030	0.8940±.0028
ω	313°.5±1°.5	313°.3±1°.1	312°.9±1°.0
K_1	12.19±0.22	11.74±0.16	11.89±0.15
$\gamma_{\rm joint}$	-12.47±0.10	–	–
γ_1	–	-14.5±2.3	–
γ_2	–	-12.96±0.20	-13.05±0.20
γ_3	–	-15.06±0.13	-15.03±0.13
γ_4	–	-11.78±0.36	-11.78±0.34
γ_5	–	-14.31±0.99	-14.48±0.90
γ_6	–	-14.45±0.24	–
γ_7	–	-12.56±0.42	-12.89±0.79
γ_8	–	-13.14±0.62	–
γ_9	–	-13.54±0.73	-12.45±0.79
γ_{10}	–	-13.01±0.34	–
γ_{11}	–	-12.13±0.39	-12.12±0.39
γ_{12}	–	-11.8±2.7	–
γ_{13}	–	-12.62±0.16	-12.54±0.16
γ_{14}	–	-07.6±1.7	–
γ_{15}	–	-09.3±4.0	–
γ_{16}	–	-12.51±0.15	-12.50±0.15
γ_{17}	–	-11.6±2.9	–
γ_{18}	–	-14.23±0.72	-14.22±0.74
γ_{19}	–	-11.53±0.14	-11.68±0.14
γ_{20}	–	-11.52±0.31	-11.69±0.29
γ_{21}	–	-11.98±0.15	-12.09±0.13
γ_{22}	–	-11.28±0.14	-11.34±0.14
γ_{23}	–	-11.97±0.07	-12.03±0.07
No. RVs	730	730	539
rms	1.82	1.60	1.16

Notes: All epochs are in HJD-2400000, the rms errors are the root-mean-square errors of 1 observation of unit weight. The semi-amplitude of the RV curve K_1, all systemic velocities and the rms of the solutions are in km s^{-1}.

remained constant (within the accuracy of their determination) over the period covered by the RV observations.

To proceed further, we first calculated an orbital solution based on all RVs assuming one joint systemic velocity for all data. This solution 1 is given in Table 3 and the O-C deviations are shown in the lower panel of Fig. 1 vs. time. For comparison, we also calculated another solution for all RVs, allowing for individual γ-velocities to be calculated for each spectrograph. This is tabulated as solution 2. It is seen that with the exception of a few RVs from instruments 14 and 15, all other data sets give quite similar systemic velocities. One can suspect, however, a gradual increase of the γ-velocity with time.

To check if there is indeed some mild secular trend in the velocities observed, we calculated another orbital solution, this time using only those RVs which we believe are on the IAU velocity system. The O-C deviations from this solution, averaged over 2000 d, are shown in Fig. 2. It is seen that some systematic secular variation can be suspected. It is true, however, that for the most part it rests on the old Potsdam RVs which we re-measured. All other normal points can be considered zero within the limits of their errors. Given the results for the standard-velocity stars from Potsdam (see Appendix for the details), we have no reasons to question the accuracy of Potsdam RVs. Yet, it is clear that only continuing observations may provide firm proof of the suspected secular change.

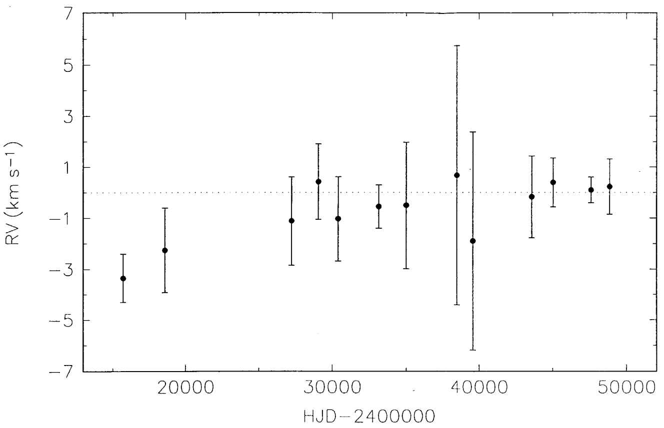

Fig. 2. A time plot of O-C velocity residuals (averaged over 2000-d) from a solution for only those RVs which are supposed to be on the IAU velocity system (one joint systemic velocity was assumed). A slight secular increase of the RV of γ Gem is suspected

Solution 3 in Table 3 is based on a subset of data from which the above-mentioned data sets with larger scatter were omitted. It comprises 539 RVs. This is the solution with the smallest errors of most of the elements, and we consider the value of the orbital period from this solution as the most accurate one and adopt it hereafter.

To obtain the best possible estimate of the basic physical elements of the binary and its components, we calculated two other solutions (solutions 4 and 5 of Table 4), based only on 206 RVs from instruments 19 to 23 (see Table 1) and with the period of solution 3 fixed. To these, we also added the two RVs for the secondary published by Fekel & Tomkin (1993). These secondary RVs were assigned weights 0.01 so as not to affect the solution but to provide an estimate of the mass ratio. One can see from the comparison of both solutions how closely the individual systemic velocities of these more recent data sets agree. For all practical purposes, the elements from both solutions are identical. Formally, we shall adopt the results from solution 4 as the final ones. The corresponding RV curve and a phase plot of O-C deviations from the orbital solution are shown in Fig. 3.

3.2. *Search for variability on other time scales*

To check for variability on a time scale of hours to weeks we investigated the O-C values obtained from solution 4. For the period search we used two nearly equivalent techniques, the usual half-amplitude periodogram, which gives the contributions of different frequencies in km s^{-1}, as well as a least squares fit of

Table 4. Orbital solutions used to estimate the masses and other basic physical elements of the binary. The period of solution 3 $4614^{\rm d}.51\pm0^{\rm d}.47$ was adopted and kept fixed. Our new solutions are compared to previous results of Fekel & Tomkin (1993) and Kamper & Beardsley (1987)

	solution 4	solution 5	FT1993	KB1987
P	$4614^{\rm d}.51$ fixed	$4614^{\rm d}.51$ fixed	$4614^{\rm d}.0\pm0^{\rm d}.7$	4613.6±1.2
$T_{\rm periast.pas.}$	43996.95±0.77	43996.97±0.78	39382.7±1.6	34766.6±2.7
$T_{\rm max.RV}$	44014.20	44014.01		
$T_{\rm inf.conj.}$	44219.55	44216.81		
e	0.8941±0.0035	0.8938±0.0040	0.893±0.002	0.8959±0.0030
ω	$312^\circ.2\pm1^\circ.4$	$312^\circ.5\pm1^\circ.5$	$312^\circ.6\pm0^\circ.9$	$312^\circ.5\pm1^\circ.4$
K_1	11.90±0.17	11.82±0.20	12.1±0.1	
K_2	32.11±0.64	32.12±0.77		
$\gamma_{\rm joint}$	-11.74±0.13	–	-12.23±0.08	-12.65±0.09
γ_{19}	–	-11.63±0.15		
γ_{20}	–	-11.61±0.29		
γ_{21}	–	-12.01±0.15		
γ_{22}	–	-11.35±0.15		
γ_{23}	–	-12.04±0.09		
No. of RVs	208	208	240	447
rms	0.92	0.90	0.5	
$f_1(m)$ ($M_\odot$)	0.0725	0.0713	0.077	
$M_1 \sin^3 i$ ($M_\odot$)	2.67±0.30	2.68±0.33	2.64±0.44	
$M_2 \sin^3 i$ ($M_\odot$)	0.99±0.10	0.98±0.11	1.01±0.14	
$A \sin i$ ($R_\odot$)	1798±68	1797±77	1791	

Notes: All epochs are in HJD-2400000, the rms errors are the root-mean-square errors of 1 observation of unit weight. The semi-amplitude of the RV curve K_1, all systemic velocities and the rms of the solutions are all in km $\rm s^{-1}$.

Table 5. Mean central intensities of Hα and Si II lines as observed during two nights with Reticon in Ondřejov. The errors quoted are the rms errors of one observation

HJD	λ 6347	λ 6371	λ 6562
2449702	0.807 ± 0.003	0.844 ± 0.002	0.280 ± 0.002
2449840	0.792 ± 0.001	0.838 ± 0.001	0.274 ± 0.003

sine waves. Details of these techniques and of the determination of the significance of a detected period have been described in Lehmann et al. (1995). The calculations were carried out for the complete set of RV residuals and also for several data subsets, denoted with A...E in Table 1, and combinations of them. No significant period was found in any of the subsets in the time interval from $0^{\rm d}.01$ to $30^{\rm d}.0$ by either period-search technique; in all cases the amplitudes in the periodograms were smaller than 1 km $\rm s^{-1}$.

In contrast to this, the Reticon spectra seem to show a slight systematic differences between the mean central intensities of the 2 Si II and Hα lines from the two nights of observations - cf. Table 5. Reality of this effect need to be checked by future observations.

4. Basic physical elements of the binary

Solution 4 and the orbital inclination of $(101\pm6)^\circ$, which follows from the astrometric solution by Kamper & Beardsley (1987), imply the components masses of

M_1 = 2.82 ± 0.43 $M_\odot$ and M_2 = 1.04 ± 0.16 $M_\odot$,

in an excellent agreement with Fekel & Tomkin (1993). The radius of the primary can be estimated from the accurate parallax derived by Kamper & Beardsley (1987), $\pi = 0''.032\pm0''.002$, and from the angular diameter of the star published by Code et al. (1976), $\theta = 0''.00139\pm0''.00009$. One gets

R_1 = (4.67 ± 0.60) $R_\odot$.

Yet another check on the mutual consistency of the observed basic physical elements of the system is to use the gravity acceleration derived by Napiwotzki et al. (1993) from the fit of Balmer line profiles,

log g = 3.49 ± 0.10 (CGS),

and the mass derived here to an independent estimate of the stellar radius. It leads to

R_1 = (5.00 ± 0.96) $R_\odot$.

To estimate the rotational period of γ Gem a new, more accurate value of the projected rotational velocity of the primary was derived from the 2 Å $\rm mm^{-1}$ Calar Alto CCD spectrograms. Two methods were used:

1. Multi-gaussian fit in the original pixel data (to avoid profile smoothing by the rebinning to the wavelength scale) and transformation of the results via the dispersion curve. This gives

<FWHM> = 0.35 Å.

If we simply assume that the square of the observed FWHM is the sum of squares of the original FWHM and the FWHM of the instrumental profile represented by the projected width of the slit, we obtain FWHM = 0.32 Å, i.e.

$v \sin i < 10.2$ km $\rm s^{-1}$

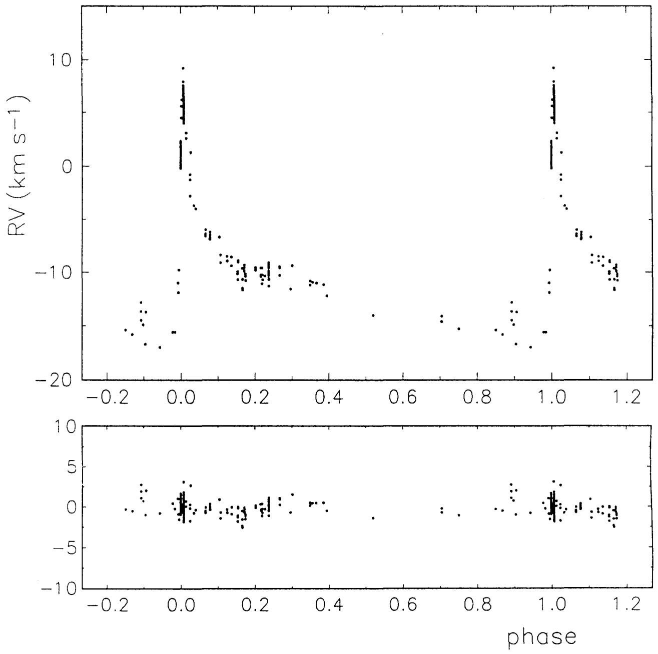

Fig. 3. The radial-velocity curve of the primary of γ Gem corresponding to orbital solution 4 and the phase plot of O-C deviations from the curve

Table 6. The values of the projected rotational velocity of the primary component of γ Gem derived by Carroll's method from the Calar Alto CCD spectrograms

line (Å)	v sin i (km s^{-1})
Ba II 6141.718	10.0
Fe II 6149.238	10.4
Ca I 6162.172	10.6

where the inequality takes into account that the lines have also their intrinsic widths.

2. v sin i was derived from the power spectrum of the Fourier-transformed line profiles following the method of Carroll (1933). Unfortunately, only 3 lines could be measured by this method because of the line blending in the wings. Even for these 3 lines there are no extended wings which implies that only the first zero point in the power spectra was detectable. However, a comparison with the result obtained by the first method justifies our a priori assumption that the first zero point is determined by the rotation of the star. The results are summarized in Table 6.

Giving the same weight to both methods and adopting 10.1 km s^{-1} as representative result for the first method, we conlude that the projected rotational velocity of γ Gem is

$$v \sin i = (10.2 \pm 0.2)\ \mathrm{km\ s^{-1}}.$$

This value is about three times smaller than those listed frequently in the literature (Slettebak (1954), 48 km s^{-1}; Dworetsky (1974), $\leq$40 km s^{-1}; Uesugi & Fukuda (1981), 30 km s^{-1}; note, however, that Slettebak et al. (1975) also arrived at a value of less than 10 km s^{-1}).

Using the larger value of the stellar radius of the primary with its error and assumimg the value of v sin i derived here, one obtains an upper limit of about 30 d for the rotational period of the primary. If γ Gem has indeed a strong global magnetic field (cf. Sect. 5 below), the assumption of complanarity of the orbital and rotational axes seems plausible even for long periods - see Stawikowski (1996). For the orbital inclination of 101.°3, the rotational period of the primary would then be between 19 and 29 d. Even though no hints at periodic RV variation with amplitude larger than 1 km s^{-1} have been found, the detection of any periodicity in this range could strengthen the evidence for a global magnetic field in the atmosphere of the primary.

Summarizing, one can say that the two estimates of the stellar radius agree within the limits of their errors. Less satisfactory is, however, that these errors are still much larger than similar errors for well-observed eclipsing binaries. An important source of error in the particular case of γ Gem is the uncertainty associated with the value of K_2 which rests solely on the tentative detection of the secondary on two occasions. (We were not able to find a trace of the secondary even in our 2 Å mm^{-1} spectrograms.) Attempts at detecting the lines of the secondary should, therefore, belong to the priorities of the future research devoted to γ Gem.

In passing, we want to make a comment on the reported disagreement of the observed position of the secondary during the occultation of γ Gem by the asteroid 381 Myrrha on January 13, 1991 (JD 2448270). Sato et al. (1993) observed the secondary at a position angle of 129°±59° and separation of (64±8) mas. Dr. David Holmgren kindly calculated for us the position of the secondary predicted by our solution 4 and by astrometric solution of Kamper & Beardsley (1987). He obtained P.A. of 79.°4 and separation of 52.5 mas. It thus appears that there is no serious discrepancy between the observed and predicted position of the secondary.

5. Magnetic field of γ Gem

According to Mathys (1990), the magnetic line splitting of the two neighbouring iron lines Fe II 6148/6149 Å occurs under the regime of the partial Paschen-Back effect. This leads to a different magnetic intensification of the equivalent widths W_1 and W_2 of those two iron lines in the presence of a magnetic field. Using empirical data, Mathys & Lanz (1992) derived the following formula

$$< H > = (1.59 \pm 0.24) + (13.3 \pm 1.3) \times V,$$

where

$$V = 2\,(W_1 - W_2)\,/\,(W_1 + W_2),$$

the intensity of the magnetic field is expressed in kG. Note that the relation holds strictly only for 3 kG< H <5 kG. The error of the determination can be estimated from

$$dH = 0.24 + 1.3\,V + 13.3\,dV.$$

Using the determination of W_1 and W_2 from the multigaussian fit for the Calar Alto spectrograms (see above), one has

$W_1 = (46.8 \pm 1.1)$ mÅ, $W_2 = (43.8 \pm 1.7)$ mÅ,
$V = 0.066 \pm 0.064$, therefore $H = (2.5 \pm 1.2)$ kG.
This can be compared to the results obtained earlier by Takada-Hidai & Jugaku (1993):
$H = 0 - 2$ kG using Mathys & Lanz's relation, and
$H = (2.78 \pm 0.07)$ kG if a relation by Takeda (1991) is used.
From a polarization measurement, Landstreet (1982) obtained
$H = (-0.17 \pm 0.12)$ kG.

In conclusion, our present data do not allow us to resolve the existing controversy and the existence of a strong organized magnetic field in the atmosphere of γ Gem must still be considered uncertain.

Acknowledgements. PH gratefully acknowledges the support for the accomodation and living expenses from the Astrophysical Institute in Potsdam for his one-month visit there during which this study was finished. We are deeply obliged to Dr. Karl Kamper from the David Dunlap Observatory who was kind enough to provide us with a table of all RVs which he and the late Dr. Beardsley were using in their own study. Useful comments were also contributed by him and by Drs. David Holmgren and Detlef Schönberner. We also thank Dr. David Holmgren for calculating the predicted position of the secondary based on the most recent astrometric and spectroscopic solutions. Drs. C. Tom Bolton, David McDavid and Jocelyn Tomkin helped us to find certain pieces of information on some of the data sets. We also profitted from the use of the computerized bibliography provided by the Centre for Astronomical Data in Strasbourg. Finally, we thank the referee, Dr. F.C. Fekel for his useful suggestions and a careful proofreading of the manuscript.

Appendix A: details on individual sets of RV observations

Potsdam The very first RVs of γ Gem come from 4 early Potsdam spectrograms and were published by Vogel (1892). Each spectrogram was measured at least twice, by Vogel and by Scheiner. Regrettably, we were unable to locate these spectrograms and have to use the original measurements. We were able, however, to find the original observing diaries and assign correct HJDs to all four spectrograms. The original measurements were tabulated in geographical miles (1 geogr. mile = 7.420439 km). It seems that their conversion to km s^{-1} tabulated by Slipher (1905) was not entirely correct and should not be used. Vogel (1892) investigated possible systematic differences between his and Scheiner's RV measurements but did not find any. Therefore, we simply adopted a mean RV of 2–3 independent measurements available for each spectrogram in the original study.

All Ludendorff's Potsdam spectrograms were re-measured by GS with the oscilloscopic Abbé comparator of the Potsdam Observatory. This allowed measurements of about 15 spectral lines on most of the spectrograms, therefore detemination of rather reliable mean plate RVs. Two IAU RV standards, observed during the same period with the same instrument and spectrograph were also measured. For 9 spectra of β Gem we obtained

RV = (3.6±0.6) km s^{-1} compared to RV$_{\rm IAU}$ = 3.3 km s^{-1}

while for 2 spectra of α Ari we got

RV = (-13.9±1.3) km s^{-1} compared to RV$_{\rm IAU}$ = -14.3 km s^{-1}.

We therefore added a correction of -0.3 km s^{-1} to all measured RVs of γ Gem from Ludendorff's spectra and consider them as being on the IAU RV scale for the purpose of this study.

Lick The early Lick observations were published by Campbell & Curtis (1905). There is obviously a one-year error in the date of exposure of the last spectrogram: Feb. 13, 1904 is given instead of the correct one Feb. 13, 1905. This misprint was corrected already in tabulation by Slipher (1905). We adopted all early Lick RVs from the final tabulation by Campbell & Moore (1928) where also accurate times of mid-exposures are given. Additional Lick data come from Kamper (1995) and are corrected to the IAU scale.

Yerkes The five published RVs were adopted.

Lowell The six published RVs were adopted. We were not able to find the exact times of mid-exposures of these spectra.

Allegheny The JDs of the nine early RVs were adopted from Beardsley (1969) but their RV values were adopted from Kamper (1995), similarly to 94 more recent RVs, all calibrated to the IAU system through the observations of standard stars.

Ottawa The sixteen published RVs were adopted.

Cape Town The three published RVs were adopted. Two of them were obtained near a periastron passage.

Dominion Astrophysical Observatory Two published spectra from the 1.83-m reflector were adopted. Additionally 51 RVs come from Kamper (1995).

Herstmonceux The five published RVs were adopted, though mainly for completeness and with a low weight since they come from a prism spectrograph giving linear dispersions of 173 Å mm^{-1} at Hβ, 120 Å mm^{-1} at Hγ and 70 Å mm^{-1} at the limit of the Balmer series. (We note, however, that Koubský et al. 1989 were able to find an orbital motion of V923 Aql with a full amplitude of only about 10 km s^{-1} from the Herstmonceux RVs published in the same paper.)

David Dunlap Altogether, 121 RVs were adopted from the plates obtained with both prismatic and grating spectrographs attached to the 1.88-m reflector – see Kamper & Beardsley (1987). All these data were carefully corrected to the standard velocity system by their authors.

Mt. Wilson The 16 unpublished RVs come from Kamper (1995).

Kitt Peak National Observatory RVs from 3 photographic spectra were published by Abt et al. (1980) while 5 more were provided by Kamper (1995). From the description in Abt et al. (1980) and from a remark by Kamper & Beardsley (1987) is seems safer not to assume that these RVs are necessarily on the IAU RV system. Furthermore 25 RVs from electronic spectra, calibrated through observations of IAU RV standards, were adopted from Fekel & Tomkin (1993).

McDonald 17 calibrated electronic spectra were published by Fekel & Tomkin (1993).

Tautenburg Altogether, 144 coudé photographic spectra were obtained with the coudé spectrograph of the 2.0-m telescope. They cover the range from 3800 to 4600 Å and have dispersions of 16, 8 or 4 Å mm^{-1}. For the 16 Å mm^{-1} spectra, 19 spectral lines could usually be measured for the mean RV, compared to about 55 lines measurable in the higher-dispersion spectrograms. Many 16 Å mm^{-1} spectrograms were obtained during the 1991 periastron passage. Several whole-night series were also secured in an effort to check on possible rapid RV changes. All spectrograms were measured for RV by GS with the computer-controlled Abbe comparator of the Potsdam Observatory which allows settings to be made using a direct and reverse image of the line profile.

Ondřejov The Ondřejov Reticon spectra were secured in the red spectral region (6300–6700 Å) and have a linear dispersion of 17 Å mm^{-1}and resolution 20 000. They consist of one whole-night series of 16 spectrograms, secured on Dec. 16, 1994, and two additional spectrograms obtained on May 2, 1995. They have S/N ratios better than 1000. Their complete reduction was carried out by PH with the reduction software SPEFO written by the late Dr. Jiří Horn. The wavelength calibration of the spectra was defined by a polynomial fit to the thorium-argon comparison spectra. A polynomial of 3$^{\text{rd}}$ degree was invariably used. The spectra were rectified interactively on the computer screen but the program ensured that the fiducial points defining the continuum were always placed at the same wavelengths. Radial velocities were measured through the comparison of the direct and reverse images of the line profiles on the computer screen.

To keep the RV zero point of the spectrograph under control, we measured a selection of good atmospheric lines in all spectra and applied necessary corrections. Tests of this procedure on several IAU RV standards showed that the spectrograms thus reduced are on the IAU RV scale (see Horn et al. (1996) for more details). Table 2 contains the corrected velocities.

Calar Alto Two 2 Å mm^{-1} CCD spectra (spectral resolution of 50 mÅ per 1 pixel) were obtained by HL on September 13, 1994. They cover the wavelength range from 6120 to 6180 Å. Their S/N (estimated from the photon statistics of the spectra and flat-field calibrations) is 300 for the first, and 430 for the second exposure. The projected width of the entrance slit on CCD is 2.7 pixels = 0.135 Å. The spectra were reduced with the help of MIDAS software by HL. RVs could be derived from 9 good spectral lines and were measured independently by HL and PH. HL used a multi-gaussian fit (Newton-Raphson iteration) of 9 lines to be measured plus 5 weak lines for a better fit of the continuum. The method yields the amplitude, position and FWHM of each line and the corresponding error of each value. PH derived the RVs from a comparison of the direct and reversed images of the rectified line profiles using the SPEFO software, as for the Ondřejov Reticon spectra. The second method gave slighly smaller rms errors of the mean but the mean RV itself was identical to that obtained by the first method.

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