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# $\gamma$ Persei: a challenge for stellar evolution models

**D. Pourbaix**[*]

Institut d'Astronomie et d'Astrophysique, Université Libre de Bruxelles, C.P. 226, Boulevard du Triomphe, B-1050 Bruxelles, Belgium

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**Abstract.** From the published visual and spectroscopic observations together with some unpublished radial velocities kindly provided by R.F. Griffin, we determine an orbit which accurately reproduces the time of the primary eclipse observed by Griffin et al. (1994) and also recompute Hipparcos astrometric parameters. The orbital parallax is slightly off with respect to Hipparcos whereas the agreement of the masses with the spectral types is better than with previous estimates. These masses being hypothesis-free, they can be used as milestones for stellar evolution models.

**Key words:** stars: binaries: spectroscopic – stars: evolution – stars: fundamental parameters – stars: individual: $\gamma$ Per

## 1. Introduction

$\gamma$ Per (HD 18925, HIP 14328) is a double-lined spectroscopic, visual and photometric (Griffin 1992) double star with an orbital period of about 15 years. Although a wide range of spectral classifications based on different wavelength intervals has been proposed for this system over the last fifty years (see Ginestet et al. (1997) for a review), one usually adopts G8III+A3V (Bahng 1958). Only the CaII K line can be used to get the radial velocity of the A-star (McLaughlin 1948; Popper & McAlister 1987) whereas a wide range of sharp spectral lines is available for the giant star.

The composite visual magnitude of the system is about 3: Hipparcos (ESA 1997) gives $V = 2.947 \pm 0.0022$ and $B - V = 0.716 \pm 0.002$. During the primary eclipse, the brightness decreases by almost 0.3 mag in $V$ and by 0.55 mag in $B$ (Griffin et al. 1994). Since Griffin argues that the eclipse is total (main sequence A star behind G star), the component individual magnitudes may be derived from the eclipse depth: $V_G = 3.25 \pm 0.01$, $V_A = 4.49 \pm 0.01$, $(B-V)_G = 0.97 \pm 0.05$ and $(B-V)_A = 0.17 \pm 0.05$. These values are in good agreement with the value $V_G = 3.11$ and $(B-V)_G = 0.82 \pm 0.08$ derived by Hünsch & Reimers (1993) from the analysis of IUE spectra.

R.F. Griffin kindly supplied some unpublished radial-velocity data which have been used in Sect. 3 to recompute the orbital parameters from a simultaneous adjustment of the spectroscopic and visual data. An accurate ephemeris for the next eclipse foreseen in 2005 is given in Sect. 4. This new orbit yields an orbital parallax slightly larger than the Hipparcos Catalogue (ESA 1997) parallax. The discrepancy remains after re-evaluating the Hipparcos parallax using a binary fit of the Hipparcos Intermediate Astrometric Data (Sect. 5).

The orbital parameters obtained in Sect. 3 allow an accurate determination of the masses which are in better agreement with the spectral types than previous estimates (McAlister 1982). These data have been confronted to the predictions from stellar evolution models but no satisfactory fit of the two components with the Geneva isochrones could be obtained. Since similar isochrone fittings have been successfully carried out for other systems (e.g. Schröder et al. 1997), $\gamma$ Per seems to be a special case. This puzzling situation is discussed in Sect. 6.

## 2. Previous spectroscopic and interferometric orbits

The first spectroscopic orbit of $\gamma$ Per is due to McLaughlin (1948). Unfortunately, his brief paper does not contain any radial velocity and his orbits for both components have to be taken as they are. From $m_G \sin^3 i = 4.72\mathrm{M}_\odot$, he concludes that the inclination is about 90° in order to obtain a mass close to the then guessed mass of Capella Aa: 4.2M$_\odot$ (Merrill 1922). Assuming the same luminosities for the components as for Capella A and for Sirius A, he derived a parallax of 20 mas. As we are going to see, McLaughlin's masses are plain wrong. However, since the mass of Capella Aa has also been revised (Hummel et al. 1994), the masses of Capella Aa and the G-component of $\gamma$ Per are still very consistent.

Since the angular separation of the two components of $\gamma$ Per never exceeds 0$''$.3, the system is usually resolved with an interferometer only. In 1939, Wilson (1941) observed the system with a Michelson visual interferometer. He did resolve the two components. Owing to an internal problem with the interferometer (noticed by himself only a couple of years later), his measurements are unfortunately almost meaningless. The first reliable visual interferometric observation of $\gamma$ Per is due to Labeyrie et al. (1974).

Using 13 interferometric observations between 1973 and 1981 and adopting $e$, $P$ and $T$ from McLaughlin (1948), McAlister (1982) computed the first visual orbit of $\gamma$ Per. He confirmed the large value of the inclination and the masses (as suspected by McLaughlin). His solution yielded an orbital par-

*Send offprint requests to*: pourbaix@astro.ulb.ac.be

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**Table 1.** Orbital parameters and their standard deviations resulting from the combined adjustment of the visual and spectroscopic data (Popper & McAlister 1987) or a simultaneous fit of the two data sets (this work, solution 1 and 2). Solution 1 is based on published data only whereas solution 2 includes the unpublished radial velocities of the G-star supplied by R.F. Griffin. $\varpi$ stands for the parallax and $\kappa$ for $m_A/(m_G + m_A)$ (the fractional mass)

| | Combined solution | | Solution 1 | | Solution 2 | |
|---|---|---|---|---|---|---|
| Element | Value | Std. dev. | Value | std. dev. | Value | Std. dev. |
| $a$ (mas) | 140. | 4. | 144. | 1.2 | 143.9 | 0.73 |
| $i$ (°) | 90.5 | 1.3 | 90.9 | 0.72 | 90.6 | 0.71 |
| $\omega$ (°) | 353. | 1.5 | 170.0 | 1.3 | 169.6 | 0.71 |
| $\Omega$ (°) | 245.2 | 1.2 | 244.1 | 0.28 | 244.2 | 0.28 |
| $e$ | 0.79 | 0.02 | 0.785 | 0.0089 | 0.786 | 0.0038 |
| $P$ (yr.) | 14.64 | 0.05 | 14.60 | 0.013 | 14.593 | 0.0046 |
| $T$ (Bess. year) | 1947.30 | 0.02 | 1947.28 | 0.025 | 1947.279 | 0.0083 |
| $V_{O,G}$ (km/s) | $-0.7$ | 1.0 | +0.2 | 0.18 | +3.2 | 0.13 |
| $V_{O,A0}$ (km/s) | $+2.0$ | 1.0 | +0.2 | 0.18 | +3.2 | 0.13 |
| $\varpi$ (mas) | 13.5 | 0.07 | 14.6 | 0.25 | 14.7 | 0.19 |
| $\kappa$ | | | 0.384 | 0.0073 | 0.423 | 0.0061 |
| mass G ($M_\odot$) | 3.06 | 0.30 | 2.7 | 0.11 | 2.5 | 0.10 |
| mass A ($M_\odot$) | 2.03 | 0.15 | 1.65 | 0.076 | 1.86 | 0.064 |

allax of only 13.55 mas (almost 30 per cent smaller than the photometric parallax derived by McLaughlin).

Five years later, Popper & McAlister (1987) combined radial velocities and interferometric observations to obtain new orbital parameters. The two data sets are treated separately (i.e. no simultaneous adjustment) but the spectroscopic parameters are used in the visual orbit. The first radial velocity measurement of the G-star is wrongly given as $-19.7$ instead of $+19.7$ km/s.

They propose seven different spectroscopic orbits (actually, almost 14 orbits are considered since the two sets of radial velocities are also treated separately)! Four new visual orbits are also proposed based on different assumptions, different data sets, ... The finally adopted solution is given in Table 1. Although still rather large, the mass of the G-star is now somewhat more plausible with respect to the results of Popper (1980) in his survey on stellar masses.

There is a discrepancy of 180° on $\omega$ between the value of McLaughlin (1948) and those given by McAlister (1982) and Popper & McAlister (1987). In visual orbits, the reference point is the brighter component (the G-star is the primary) and the convention is to give the periastron argument of the fainter component. Hence the $\omega$ provided by Popper & McAlister actually refers to $\omega_A$.

Therefore, all interferometric observations have to be corrected by 180°. We applied that correction to the data plotted in Fig. 1. That conclusion based on the combination of visual and spectroscopic results is confirmed by the unique micrometric observation Couteau (1987) made in 1985.00 (244.4°, $0''.25$).

## 3. Simultaneous visual and spectroscopic orbits

In contrast to Popper & McAlister (1987), we simultaneously fit the visual and spectroscopic data (Pourbaix 1998b). No new radial velocity has been lately published but there are more visual observations than for Popper & McAlister's derivation (the most recent interferometric observation dates back to 1995 (Hartkopf et al. 1997)). The radial velocities we fit are those given by Popper & McAlister. For the visual observations, we use the interferometric data from the third catalog of CHARA (Hartkopf et al. 1997) and the micrometric observation of Couteau (1987). The weights are set according to the procedure described by Pourbaix (1998b).

Our solution is given in Table 1 as solution 1 and plotted in Fig. 1. Although most of the orbital parameters agree quite well with those after Popper & McAlister (1987), we do not confirm their value of the parallax. The consequence is smaller masses which are very consistent with the results obtained for stars of similar spectral types (Popper 1980; McAlister 1982; Bagnuolo & Hartkopf 1989).

## 4. The eclipse: the ultimate check

As predicted by Popper & McAlister (1987), eclipses do occur. Griffin (1991) observed the 1990 one between September 13 (1990.700) and September 21 (1990.722). Such observations provide us with a way to check our orbit as well as to obtain some information about the two components.

The orbit by Popper & McAlister (1987) predicts a minimum separation between the components at about $1990.89 \pm 0.021$ which is off by about two months. With our orbit (solution 1 in Table 1), that minimum occurs at $1990.742 \pm 0.0254$ which is off by only two weeks. Our two-weeks error is consistent with the uncertainties on $P$ and $T$. The fact that eclipses occur is also a point against the orbit of McAlister (1982) since eclipses are unlikely to occur with his solution (according to his own claim).

In his paper describing the eclipse, Griffin (1991) mentioned that $\gamma$ Per had been subject to his spectroscopic investigation for about ten years. He has kindly supplied us with a listing of published radial velocities of the G-star and with his own unpublished radial velocities of the same star (up to November 1997). With this new extended set of observations (covering an interval of 100 years), we determine the orbital parameters given

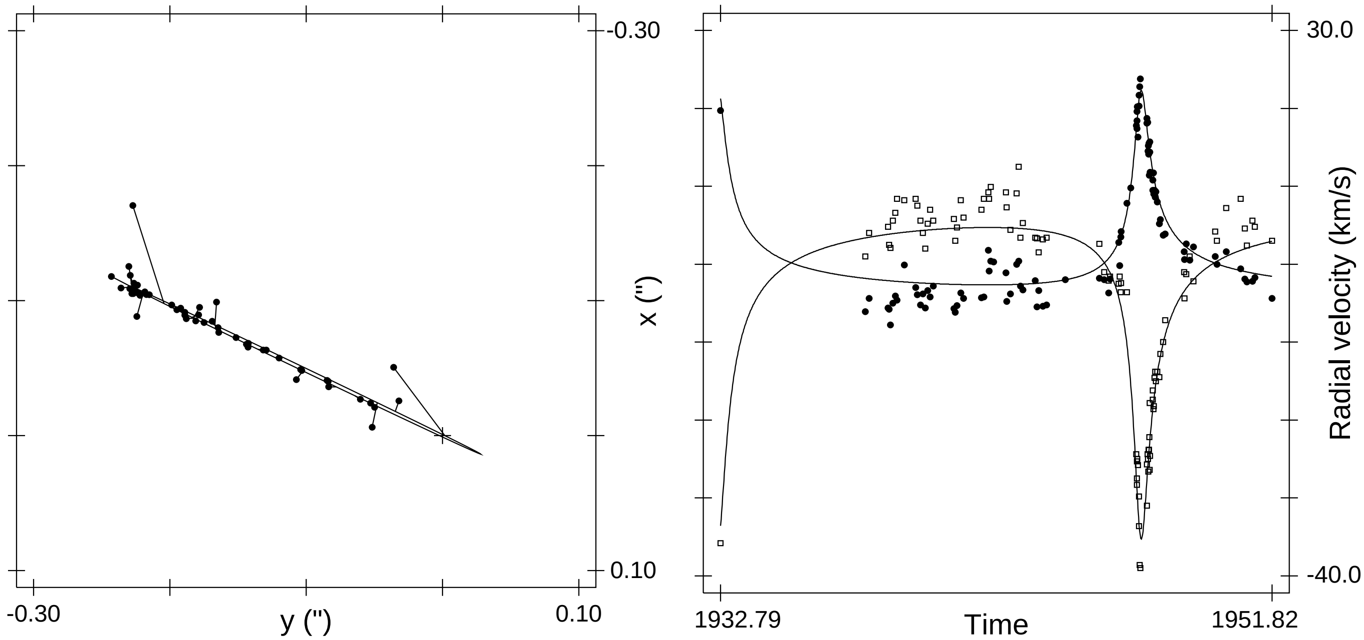



**Fig. 1.** Result of a simultaneous adjustment of the visual and spectroscopic data (this paper). In the radial velocity plot, the filled circles denote G-star data. The left panel corresponds to the relative position of the A star with respect to the G star located at (0,0) (cross).

**Table 2.** Evolution of the 'Hipparcos' parallax and proper motions when our orbital solution (solution 2 in Table 1) is used to reduce the FAST and/or NDAC observations. $\mu_{\alpha*} = \mu_\alpha \cos\delta$

| Solution | $\varpi$ (mas) | $\mu_{\alpha*}$ (mas/yr) | $\mu_\delta$ (mas/yr) |
|---|---|---|---|
| Catalogue | $12.72 \pm 0.71$ | $0.50 \pm 0.74$ | $-4.19 \pm 0.81$ |
| FAST (revised) | $13.5 \pm 0.61$ | $-1. \pm 1.6$ | $-1. \pm 3.4$ |
| NDAC (revised) | $11.6 \pm 0.59$ | $0. \pm 1.8$ | $-5. \pm 2.7$ |
| both (revised) | $12.5 \pm 0.71$ | $0. \pm 2.2$ | $-4. \pm 3.3$ |

in Table 1 as solution 2. That orbit confirms our conclusions about the parallax and masses.

What about $t_e$, the predicted conjunction date? At first sight, one could be puzzled by the fact that Griffin (1991) could estimate $t_e$ from spectroscopic observations only. Indeed, an eclipse depending on the relative position of the two stars with respect to the observer, a visual orbit or, at least, the $\rho$-curve should be necessary. Actually, when $i = 90°$, the two conjunction dates correspond to the two epochs when the radial velocity is halfway between the minimum and maximum radial velocities (the spectroscopic orbit is hence enough). From the data of Popper & McAlister (1987), Griffin was pretty sure that an eclipse would occur and he therefore initiated a worldwide observation campaign (Griffin et al. 1994). Hence, he could satisfactorily determine the date of the eclipse from his spectroscopic orbit *because* he assumed $i = 90°$.

The revised predicted date of minimum separation with the second orbit of Table 1 is $1990.711 \pm 0.0094$. That is probably by accident only but this date corresponds exactly to the middle of the eclipse. Moreover, the confidence interval perfectly overlaps the period between the first and the fourth contact.

One could be puzzled by the fact that $V_0$ and $\kappa$ of solution 2 are very different from solution 1. Griffin's data also contain the corrections to apply to the radial velocities depending on the observatory where they were taken. When a radial velocity of A originated from the same observatory as G, we applied the same correction as for G.

Such corrections are responsible for the change on $V_0$. On the other hand, since all radial velocities are not adjusted in the same way, a modification of $\kappa$ can be expected.

## 5. What about the Hipparcos results?

As indicated in the Hipparcos Catalogue (ESA 1997), the orbit proposed by McAlister (1982) has been used to fit the Hipparcos observations. Only the semi-major axis of the photocentric orbit has been extracted from the astrometric data.

At the $3\sigma$-level one cannot conclude that the Hipparcos parallax $(12.72 \pm 0.71)$ and ours are discrepant. The consistency of the two parallaxes, based on $\sigma_{HIP}$, does no longer hold when our $\sigma$ is used. The fact that a preliminary orbit has been used for the Hipparcos data reduction makes this parallax questionable. To derive our own Hipparcos parallax is worthwhile in order to figure out how sensitive it is to the adopted orbital parameters (e.g. solution 2, Table 1).

We can re-process the Intermediate Astrometric Data using our own orbital solution as an input parameter and see how the parallax changes. We computed three solutions using the data from FAST, NDAC or both consortia (details of the method will appear in a forthcoming paper). The results are given in Table 2. The parallax and proper motions seem to be more sensitive to the fitted data set than to the orbit used in the reduction.

The orbital motion dominates the proper motion. This feature coupled to the duration of the Hipparcos mission with respect to the orbital period explain why the proper motion is poorly constrained.

Very recently, Martin & Mignard (1998) have extensively used Hipparcos observations and results to estimate the masses of the components. Using the orbit of McAlister (1982), they obtained $5.036 \pm 0.951 M_\odot$ for the primary and $2.295 \pm 0.453 M_\odot$ for the secondary. These masses are totally discrepant with what one expects for stars of similar spectral types and illustrate, once again, the risk of using an inaccurate orbit in the computation of the masses.

## 6. $\gamma$ Per and stellar evolution models

During the total eclipse, the system is 0.28 mag fainter in $V$, 0.54 mag in $B$ and 0.88 in $U$ (Griffin et al. 1994). This difference of magnitude with the $V$-filter coupled to the visual magnitude and parallax from Hipparcos yield $-0.92 \pm 0.03$ and $0.33 \pm 0.03$ for the absolute visual magnitudes of the G- and the A-star respectively. The same approach applied to the $B$ filter leads to $(B-V)_G = 0.97 \pm 0.05$ and $(B-V)_A = 0.17 \pm 0.05$. Our value of $(B-V)_G$ is consistent with the +0.82 derived by Hünsch & Reimers (1993) from high resolution IUE spectra as well as the $0.87 \pm 0.08$ obtained by Hummel et al. (1994) for Capella A (also G8III). Hünsch & Reimers (1993) notice that there is no reddening.

Even if there is a $2\sigma$-agreement with the $(B-V)_G$ after Hünsch & Reimers (1993), their results about the absolute visual magnitude of the giant and the distance are discrepant with respect to those derived by Griffin (1991) from the eclipse. Indeed, the formers yield a giant only $0.16$ mag fainter than the overall system whereas Griffin observed $0.3$ mag.

Our absolute magnitudes are more than 1 mag smaller (too bright by 1 mag) than expected for similar spectral types (Lang 1991). McAlister (1982) and then Popper & McAlister (1987) had already noticed that this system seems to be overluminous (with respect to model predictions). Although our estimates are slightly larger than theirs, they almost confirm Popper & McAlister's conclusions. McAlister (1982) partially discarded the discrepancy between the masses and the spectral types by revising the latter one and by proposing G8II – III+B9V instead of G8III+A3V.

Assuming a common origin for the two components, our magnitudes and color indices are used to fit an isochrone. In order to do that, we take advantage of Meynet's code which generates isochrones from the tables of stellar evolution by Schaller et al. (1992). Since each table has a fixed metallicity, our first step consists in guessing the metallicity of the components. McWilliam (1990) quotes $Z = 0.013$ which is not one of the tabulated values. The closest possible values are 0.008 and 0.020. We therefore generate isochrones based on both tables and expect the actual result to be somewhere in between.

With $Z = 0.008$ and $Z = 0.020$, there are three isochrones (number 1, 2 and 3 in Table 3) with convective overshooting which pass through the A-star. Unfortunately, neither its mass nor the absolute visual magnitude of the G-star are correctly estimated. The agreement between the mass of the G-star on the isochrone and our value is better. Can we improve the fit by keeping the metallicity free (regardless of the observed value)? With $Z = 0.004$ and convective overshooting (isochrone 5), one fits the mass and $B-V$ of the giant but the agreement with the other parameters is quite poor. Actually, the best result is obtained with $Z = 0.001$ and convective overshooting (isochrone 4). With that isochrone, five out of the six remaining parameters are fitted within the error bars. The only discrepant parameter is the mass of the giant ($2.0 M_\odot$ instead of $2.5 \pm 0.1 M_\odot$). However, the metallicity is much lower than the one derived by McWilliam (1990). The fact that $\gamma$ Per belongs to the galactic plane and its low space velocity makes a metallicity as low as $Z = 0.001$ very unlikely.

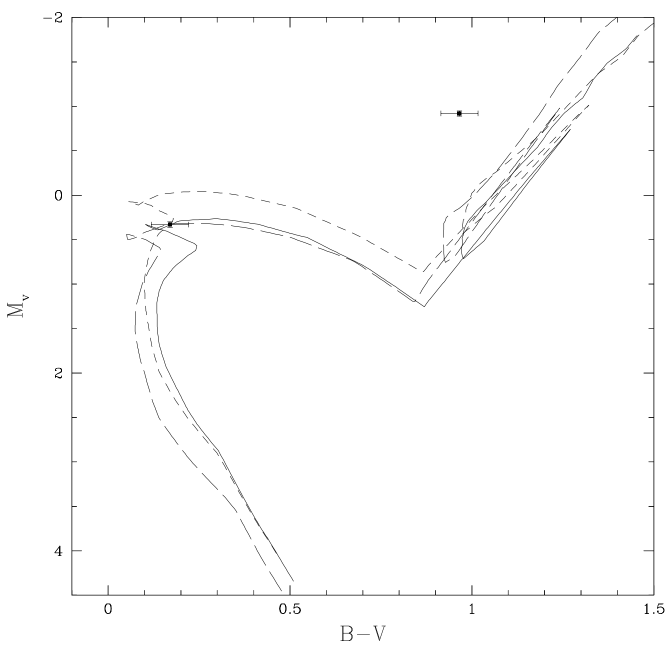
There is no isochrone which satisfactorily fits the seven observables. Such a situation already happened when we processed $\phi$ Cygni (Pourbaix 1998a) and we compared our results with those of Armstrong et al. (1992). We noticed that, with the introduction of new opacity tables, the isochrones predict smaller masses for the same luminosity (at least for G8III – K0III stars). That would explain why our isochrone 4 gives $2.0 M_\odot$ instead of the expected $2.5 M_\odot$. Some new calibrations of these isochrones might be useful. Parsons et al. (1998) has recently mentioned similar problems with the Geneva isochrone fitting (especially in the case of non main-sequence stars).

In order to see whether the problem comes from the stars (especially the giant) or from the isochrones, we adopt the isochrones of Bertelli et al. (1994). Once again, the tabulated value of the metallicity the closest to the observed value is $0.008$. With $\log(\mathrm{age}) = 8.9$ (same as isochrone 2 in Table 3), the agreement with the observed values is much better (as already mentioned by Corbally (1996) after his evaluation of isochrones lately released). However, the primary is likely to be located close to the blue loop region of the isochrone, feature that no isochrone of Bertelli et al. can reproduce very well. The theoretical values are given as isochrone 6 in Table 3 and plotted together with the observations in the right panel of Fig. 2. The mass of the main-sequence star is still a bit high with respect to our derived value. However, since the amplitude of the radial velocity curve of the secondary is still uncertain, that is also true for the mass of that component.

One might question the metallicity after McWilliam (1990) and claim that his result is based on some assumptions (LTE analysis, ...). We therefore tried the isochrones of Bertelli et al. (1994) for $Z = 0.020$. The fit is as poor as with isochrones 2 and 3. One could also try to explain the brightness of the primary with a third component (the primary would be a close binary). However, there is no observational indication that such a scenario is likely. Indeed, the brightness of the primary is constant, its radial velocity residuals seem to be normally distributed and its mass is consistent with the mass of other similar stars (Capella Aa, $\phi$ Cyg). One could also imagine that the system was initially triple and that the inner two components merged together. If that is the case, we cannot satisfactorily fit an

**Table 3.** Observed values and predictions by the different isochrones (Schaller et al. 1992) plotted in Fig. 2. Isochrone 6 is from Bertelli et al. (1994).

| | $\log_{10}$(age (yr.)) | Z | $M_{V_G}$ | $(B-V)_G$ | $M_G$ | $M_{V_A}$ ($M_\odot$) | $(B-V)_A$ | $M_A$ ($M_\odot$) |
|---|---|---|---|---|---|---|---|---|
| Observation | | 0.013 | −0.92 | 0.97 | 2.5 | 0.33 | 0.17 | 1.86 |
| isochrone 1 | 8.9 | 0.008 | 0.12 | 0.97 | 2.32 | 0.33 | 0.17 | 2.15 |
| isochrone 2 | 8.78 | 0.020 | 0.4 | 0.97 | 2.51 | 0.32 | 0.17 | 2.43 |
| isochrone 3 | 8.865 | 0.020 | 0.36 | 0.98 | 2.45 | 0.30 | 0.19 | 2.31 |
| isochrone 4 | 9.0 | 0.001 | −0.91 | 0.98 | 2.0 | 0.30 | 0.17 | 1.90 |
| isochrone 5 | 8.76 | 0.004 | −0.72 | 0.97 | 2.5 | −0.21 | 0.17 | 2.32 |
| isochrone 6 | 8.9 | 0.008 | −0.92 | 1.08 | 2.38 | 0.36 | 0.18 | 2.13 |



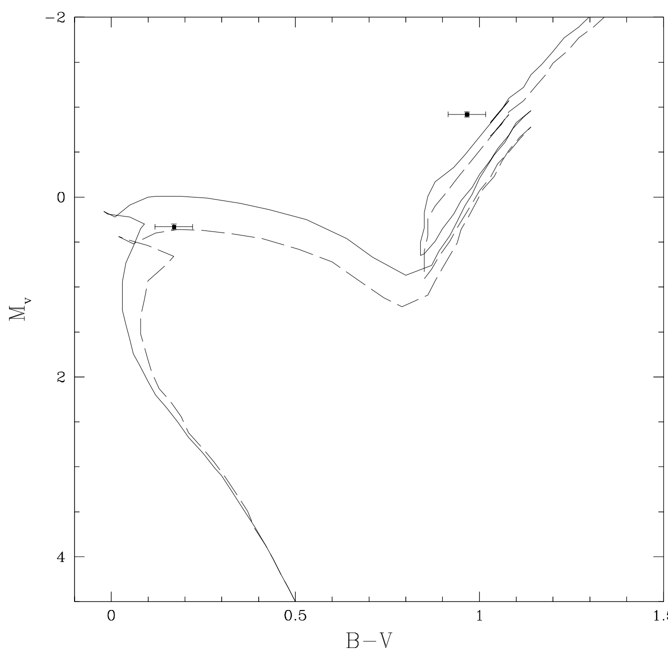




**Fig. 2.** Position of the two components with respect to different isochrones (Schaller et al. 1992). The left panel shows the discrepancy between the best-fitting physically plausible isochrones ($Z = 0.008$, isochrone 1 (long dashed line) and $Z = 0.020$, isochrones 2 & 3 (short dashed and continuous lines)). The right panel shows the isochrones from Bertelli et al. (1994) for $Z = 0.008$ and $\log(\text{age (yr.)}) = 8.76$, isochrone 5 (dashed line) and 8.9, isochrone 6 (solid line)

isochrone anymore. But, once again, there is no observational indication that such a scenario is likely.

## 7. Conclusions

$\gamma$ Per illustrates quite well the interest of the simultaneous adjustment of spectroscopic and visual data. Since our results are based on a hypothesis-free adjustment, they are useful not only for themselves (e.g., individual masses of the components of a peculiar system) but also as checkpoints for models (e.g., the mass from the spectral type). The noticed discrepancy between absolute visual magnitudes and those expected for similar spectral types should be investigated.

The eclipse observed by Griffin (1991) is an excellent check of the reliability of our adjustment. The predicted conjunction date is well within the error bars and within the epochs of first and fourth contact. Now we know that eclipses occur, it will be very important to observe the 2005 one ($2005.30 \pm 0.010$) in order to obtain some accurate spectroscopic and photometric data. The eclipse being total, one can determine the metallicity of the primary and therefore put stronger constraints on the isochrone. Such a clean spectrum will also be very useful in order to obtain precise radial velocities of the secondary (and, *ipso facto*, an accurate value of both masses).

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