Robotic observations of the most eccentric spectroscopic binary in the sky∗,∗∗

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ABSTRACT

Context. The visual A component of the Gliese 586AB system is a double-lined spectroscopic binary consisting of two cool stars with the unusual orbit which is the highest eccentricity known among visual binaries. Such an extreme eccentricity system may be important for our understanding of low-mass binary formation.

Aims. Precise stellar masses, ages, orbital elements, and rotational periods are a prerequisite for comparing stellar observations to angular-momentum evolution models.

Methods. We present a total of 598 high-resolution échelle spectra from our robotic facility STELLA from 2006–2012 which we used to compute orbital elements of unprecedented accuracy. New Johnson VI photometry for the two visual components is also presented.

Results. Our double-lined orbital solution for the A system has average velocity residuals for a measure of unit weight of 41 m s⁻¹ for the G9V primary and 258 m s⁻¹ for the M0V secondary, better by a factor ≈10 than the discovery orbit. The orbit constrains the eccentricity to 0.97608 ± 0.00004 and the orbital period to 889.8915 ± 0.0003 d. The masses of the two components are 0.87 ± 0.05 M☉ and 0.88 ± 0.03 M☉, if the inclination is 55 ± 1.5° as determined from adaptive-optics images, that is good to only 6% due to the error of the inclination uncertainty. The minimum masses reached a precision of 0.3%. The flux ratio Aa:Ab in the optical is between 30:1 in Johnson-B and 11:1 in I. Radial velocities of the visual B-component (K0-1V) appear constant to within 130 m s⁻¹ over six years. Sinusoidal modulations of Tₜₐₐ of Aa with an amplitude of ≈55 K are seen with the orbital period. Component Aa appears warmest at periastron and coolest at apastron, indicating atmospheric changes induced by the high orbital eccentricity. No light variations larger than approximately 4 mmag are detected for A, while a photometric period of 8.5 ± 0.2 d with an amplitude of 7 mmag is discovered for the active star B, which we interpret to be its rotation period. We estimate an orbital period of ≈50,000 yr for the AB system. The most likely age of the AB system is ≈2 Gyr, while the activity of the B component, if it were a single star, would imply 0.5 Gyr. Both Aa and Ab are matched with single-star evolutionary tracks of their respective mass.

Key words. Stars: radial velocities – starspots – stars: individual: Gliese 586AB – stars: late-type – stars: activity of

1. Introduction

Two investigations independently discovered Gliese 586A (=HD 137763, HIP 75718, G9V + M0V, P ≈ 890 d) to be a spectroscopic binary with an extreme eccentricity as determined from adaptive-optics images, that is good to only 6% due to the error of the inclination uncertainty. The minimum masses reached a precision of 0.3%. The flux ratio Aa:Ab in the optical is between 30:1 in Johnson-B and 11:1 in I. Radial velocities of the visual B-component (K0-1V) appear constant to within 130 m s⁻¹ over six years. Sinusoidal modulations of Tₜₐₐ of Aa with an amplitude of ≈55 K are seen with the orbital period. Component Aa appears warmest at periastron and coolest at apastron, indicating atmospheric changes induced by the high orbital eccentricity. No light variations larger than approximately 4 mmag are detected for A, while a photometric period of 8.5 ± 0.2 d with an amplitude of 7 mmag is discovered for the active star B, which we interpret to be its rotation period. We estimate an orbital period of ≈50,000 yr for the AB system. The most likely age of the AB system is ≈2 Gyr, while the activity of the B component, if it were a single star, would imply 0.5 Gyr. Both Aa and Ab are matched with single-star evolutionary tracks of their respective mass.

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* Based on data obtained with the STELLA robotic telescope in Tenerife, an AIP facility jointly operated by AIP and IAC, as well as on data products from observations made with ESO Telescopes at the La Silla Paranal Observatory under programme IDs 75.C-0733(A) and 60.A-9800(J).
** Table 1 is only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/cgi-bin/qcat?j/A+A/
remain well detached, but pass each other at a distance of only
≈10 R\odot (Duquennoy et al. 1992). If the same orbital properties
also existed during the pre-main-sequence phase of the two com-
ponents, the two stars must have been directly or nearly in con-
tact during periastron passage, or even were too large to fit into
the above separation. Alternatively, the orbit was not as eccentric
in the past as it is today.

A typical cool star in a synchronized binary system with an
orbital period and axial rotation of ≈3.5 d would be expected to
show strong chromospheric emission that would be interpreted
as magnetic activity. This is because its convective turn-over
time would be expected to be longer than or of same order as the
rotational period, making internal dynamo action and a surface
magnetic field most likely. However, only very weak Ca ii H& K
emission lines, if at all, were seen in a single high-resolution,
high signal-to-noise spectrum taken at orbital phase 0.844 in
1992 (Strassmeier 1992) and no magnetic-field measure exists
to date.

In 2006, we placed Gl586A on the observing schedule of
our then newly inaugurated robotic spectroscopic telescope
STELLA in Tenerife as part of its science-demonstration test.
This paper analyzes data from a total of six consecutive years
with a cadence of roughly one spectrum per week. At an eccen-
tricity of 0.976 and a period of 890 d, the periastron passage of
Gl586A lasts a mere 24 hours. While bad weather prevented us
from seeing the full 2007 event, the Sun was in the line of sight
in 2010. The recent passage in February 2012 was only visible for
at most five hours per clear night, but in all allowed for a
decent periastron coverage. We include also radial velocities for
Gl586B, the visual companion, and discuss its variability. Time-
series photometry for the two visual components is presented for
the first time. The instrument and data are described in Sect. 2.

The new SB2 orbit for component A is presented in Sect. 3 along
with new velocities for the visual B component. We discuss the
orbital elements in relation with the absolute dimensions, ages,
and stellar activity of the A and B components in Sect. 4 Sect. 5
summarizes our conclusions.

2. Observations

2.1. STELLA/SES spectroscopy in 2006–2012

High-resolution time-series spectroscopy was obtained with the
STELLA Échelle Spectrograph (SES) at the robotic 1.2-m
STELLA-I telescope in Tenerife, Spain (Strassmeier et al. 2010,
Granzer et al. 2010, Weber et al. 2012). A total of 598 échelle
spectra of Gliese 586A were acquired over the course of almost
six years (2006–2012) with a check-star program. A total of 39 spectra of Gl586B
of similar quality as for the A component were acquired for this
paper. Gl586B was observed between March 30, 2007 and until
May 17, 2012 but with a much lower cadence. The SES is a fiber-
fed white-pupil échelle spectrograph with a fixed wavelength
format of 388–882 nm. Despite increasing inter-order gaps in the
red, it continuously records the range 390–720 nm. Its two-pixel
resolution is R = 55,000. The CCD was an e2v 42-40/848×2048
13.5 μm-pixel device. Figure 1 shows spectra of the A stars for the
time around periastron and of B for an arbitrary time. Shown
is the wavelength range around Hα so that one can recognize the
Ab component by eye. Our échelle spectra have a useful wave-
length coverage of nearly 490 nm (of which 3 nm are shown in
Fig. 1).

Integrations on Gl586A were set to 2400 s and achieved signal-to-noise (S/N) ratios of up to 350:1 per resolution ele-
ment, depending on weather conditions. During periastron pas-
gage the exposure time was shortened to 600 s and had on aver-
age S/N ratios of up to ≈100:1. Our data are automatically
reduced and extracted using the IRAF-based STELLA data-
reduction pipeline (see Weber et al. 2008). The two-dimensional
data were corrected for bad pixels and cosmic rays. Bias lev-
els were removed by subtracting the average overscan from each
image followed by the subtraction of the mean of the (already
overscan-subtracted) master bias frame. The target spectra were
flattened by dividing them by the master flat, which had been
normalized to unity. The robot’s time series also includes nightly
and daily Th-Ar comparison-lamp exposures for wavelength cal-
bilation and spectrograph focus monitoring. Continuous mon-
toring of the environmental parameters inside and outside of
the spectrograph room, most notably temperature and baromet-
ric pressure, allows one to apply proper corrections. For details of
the échelle data reduction with particular emphasis on the
on the temperature and pressure dependencies of the SES, we refer to
Weber et al. (2005).

Twenty-two radial velocity standard stars were observed with the same set-up and were analyzed in Strassmeier et al.
(2012). The STELLA system appears to have a zero-point offset with respect to CORAVEL of +0.503 km s\(^{-1}\) (Udry et al. 1998).
The best external rms radial-velocity precision over the six years
of observation was around 30 m s\(^{-1}\) for late-type stars with nar-
row spectral lines. All velocities in this paper are on the STELLA
zero-point scale if not mentioned otherwise. The individual ve-
locities are listed in Table 1 available only in electronic form via
CDS Strasbourg.

Table 1. Barycentric radial velocities of Gl586A and B.

| Instrument | HJD | \(v_{\text{Ab}}\) | \(\sigma_{v_{\text{Ab}}}\) | \(v_{\text{Ab}}\) | \(\sigma_{v_{\text{Ab}}}\) |
|------------|-----|-------------|-----------------|-------------|-----------------|
| A          |     |             |                 |             |                 |
| SES        | 2453913.41442 | 5.226 | 0.008 | 10.628 | 0.031 |
| SES        | 2453914.40831 | 5.208 | 0.007 | 10.626 | 0.029 |
| SES        | 2453915.40807 | 5.191 | 0.008 | 10.719 | 0.031 |
| B          |     |             |                 |             |                 |
| SES        | 2454189.64040 | 7.898 | 0.003 |             |                 |
| SES        | 2454189.67627 | 7.921 | 0.004 |             |                 |
| SES        | 2454507.72402 | 8.158 | 0.002 |             |                 |

2.2. Amadeus APT photometry

Johnson-Cousins \(V(J)_C\) photometry of Gl586A and Gl586B was
accomplished with the Amadeus automatic photoelectric tele-
scope (APT) at Fairborn Observatory in southern Arizona from April 6
through May 30, 2012. A total of 1384 measures were made dif-
ferentially with respect to HD 137666 (\(V = 7^m 636, B = V = 1^m 006, V - I = 1^m 152\)) as the comparison star and HD 138425 (\(V = 6^m 637, B = V = 0^m 88, V - I = 0^m 986\)) as the check star. Each data point
consists of four measurements of the comparison star separated by
three measurements of the variable (Gl586A and Gl586B, re-
spectively). At the beginning and end of each block, a check-star
measure and a sky-background measure were obtained. A 30′′
diaphragm was used. Using the standard deviation of the indi-
vidual target and comparison measures, all data points with an
rms of \(\geq 0^m 005\) were rejected, yielding 678 measures for Gl586A
and 706 measures for Gl586B. The standard error of a nightly
mean from the overall seasonal mean was \(0^m 004\) in \(V\) and \(0^m 006\)

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in $I_C$. For more details we refer to Strassmeier et al. (1997) and Granzer et al. (2001). From concurrent observations of Johnson standards in $V(R)C$, we deduce average values for Gl586A of $V=6^m952\pm0.004$ and $(V-I)_C=0^m991\pm0.01$ and for Gl586B of $V=7^m620\pm0.009$ and $(V-I)_C=0^m989\pm0.01$.

3. New spectroscopic orbital elements

3.1. High-precision radial velocities

The STELLA velocities in this paper were determined from a simultaneous cross-correlation of 62 échelle orders with a synthetic spectrum. From a pre-computed grid of synthetic spectra from ATLAS-9 atmospheres (Kurucz 1993), we selected two spectra that matched the respective target spectral classification. For component Aa, we chose a $T_{\text{eff}}=5500\,\text{K}$ model, and for Ab a $T_{\text{eff}}=4250\,\text{K}$ model, both with $\log g=4.5$ and solar metallicities. We combined the two template spectra to one artificial spectrum using $v\sin i$ of 2 km s$^{-1}$ and a macroturbulence of 3 km s$^{-1}$ for both components. We then adjusted the (wavelength-dependent) intensity ratio using the flux-calibrated spectra from Pickels (1998) multiplied by 16.5. We then applied a series of radial-velocity differences between the two components and computed a two-dimensional cross-correlation function for each of these shifts. The highest correlation value in the resulting two-dimensional image corresponds to the measured velocity of component Aa in one dimension, and the velocity difference of the two components in the other dimension. To estimate the uncertainties of this method, we performed a series of 1000 Monte-Carlo variations of these two-dimensional images using only 63% of the original number of échelle orders, and found $\sigma$ to be 1/1,349 of the interquartile range of the resulting distribution.

During the initial year of STELLA operation (2006/7), the external rms values were significantly higher (120 m s$^{-1}$) than thereafter (30 m s$^{-1}$) and also induced a radial velocity zero-point offset of about 300 m s$^{-1}$. In December 2011, we upgraded the spectrograph’s cross disperser but had to use the same optical camera and CCD until June 2012. During this epoch the CCD recorded only 45 échelle orders instead of the full 82. The wavelength range was accordingly more narrow, 470–760 nm. During these periods, our radial-velocity standard stars exhibit systematic velocity offsets on the order of several 100 m s$^{-1}$. These offsets were applied to the data as well as a barycentric correction.

The last step included corrections for systematic residual line blending (Fig. 2). We applied a correction similar to that described in Torres et al. (2009) and Weber & Strassmeier (2011) and then removed the predicted systematic error from the data. Briefly, we used synthetic template spectra of the two binary components with an infinite S/N ratio and rotationally broadened and shifted them to the expected velocities from an initial SB2 orbit. These spectra have exactly the same (pixel and phase) sampling as the observations. They were then flux adjusted and combined into a single spectrum to mimic an observation of the combined A spectrum. We then processed it with the same velocity-extraction pipeline as the real observations and used the differences of the real to the theoretically expected velocities for the corrections. These differences for the primary and secondary are compared in the two panels in Fig. 2. For Gliese 586A, the residual blending is particularly severe for the secondary velocities because of the high intensity ratio between components Aa and Ab. It amounts to up to 2 km s$^{-1}$.
3.2 Double-lined orbit for Gliese 586A

We solved for the usual elements of a double-lined spectroscopic binary using the general least-squares fitting algorithm MPFIT (Markwardt 2009). To calculate the eccentric anomaly, we followed the prescription of Danby & Burkardt (1983).

The initial step is an SB1 solution for component Aa to constrain the orbital period and verify the high eccentricity. Not all of the literature CORAVEL data were used, but only the data around the periastron passage in 1990 (Table 1 in Duquennoy et al. 1992). These were shifted by $-0.503 \text{ km s}^{-1}$ to match the STELLA zero point ($v_{\text{STELLA}} - v_{\text{CORAVEL}} = +0.503 \text{ km s}^{-1}$; Strassmeier et al. 2012). We also made use of the 17 archival spectra from ELODIE, which we re-analyzed to derive the primary and secondary radial velocities as described above, and
two from SOPHIE (see Mouttaka et al. 2011 for ELODIE & SOPHIE archives). The ELODIE data were concentrated around May 2002. Two recent SB1 radial velocities of star Aa from the RAVE survey (Matijevic et al. 2011) achieved an rms of around 1–2 km s\(^{-1}\) and could not be used for our high-precision orbit determination. Note that we also chose not to add the data of Tokovinin (1991) because we did not know its zero-point offset with respect to STELLA or CORA VEL, nor did the authors cover any of the periastron passages. The combined SB1 solution from STELLA, CORA VEL, ELODIE, and SOPHIE (total of 695 velocities) converged at an orbital period of 889.81948\(^d\) with an error of only 0.00028\(^d\) and an rms residual of an observation of unit weight of 168 m s\(^{-1}\). Note that we always give orbital periods as observed and not corrected for the rest frame of the system. The SB1 solution from STELLA data alone was very close to the original Duquennoy et al. orbit, but achieved a significantly better rms of the residuals of 108 m s\(^{-1}\). Its eccentricity, 0.97556\(\pm0.00014\), was within one \(\sigma\) of the Duquennoy et al. solution, but the longitude of the periastron, \(\omega\), appeared to be offset by 1.5\(\pm5\)\(^\circ\) and the semi-amplitude \(K_1\) was larger by 0.51 km s\(^{-1}\). The mass functions also agreed to within its errors, 0.0521\(\pm0.0002\) compared with 0.0523\(\pm0.00056\) from STELLA alone.

For the SB2 solution, we use only the STELLA data. First, we corrected the radial velocities of both components for the difference in gravitational redshift according to Lindgren & Dravins (2003). For component Aa this amounts to 520 m s\(^{-1}\) and for component Ab to 448 m s\(^{-1}\). A nominal primary mass and radius were adopted from Gray (2005b), while the secondary mass was iteratively fit to our observed mass ratio in Table 2. Thus, the net differential velocity offset is 72 m s\(^{-1}\), and this was applied to the data.

We kept the orbital period fixed at the value from the combined-data SB1 solution and then solved for the remaining elements simultaneously. The final SB2 solution is shown in Fig. 3 and listed in Table 2. Assuming that the fit is of good quality, we derived the element uncertainties by scaling the formal one-sigma errors from the covariance matrix using the measured \(\chi^2\) values. For comparison, we also give expected error estimates from a Monte-Carlo reconfiguration of the data.

### 3.3. Giese 586B

Our STELLA observations of the visual B component are listed in Table A. As for all previously published data sets, its velocity appears quite stable for the time span of the observation, in our case nearly six years (2007–12). The data show an rms dispersion of \(\approx130\) m s\(^{-1}\), which is approximately four times our long-term external precision of a single measurement. The average velocity is 8.143\(\pm0.013\) km s\(^{-1}\) (7.640 km s\(^{-1}\) in the CORA VEL system).

The basis for the assumption that the Giese AB components are indeed gravitationally bound and not just a common propagation pair is the small velocity difference of 638\(\pm13\) m s\(^{-1}\) between B and the center of mass of A. Duquennoy et al. (1992) provided the first velocities of the B component in March 1978 and the last in May 1990, a time span of 12.2 yr with an average velocity of 7.23\(\pm0.07\) km s\(^{-1}\) (in their own zero-point system). However, their \(\chi^2\) test suggested a fairly high probability of 0.915 that it is not constant. Tokovinin (1991) just mentioned that the velocity of Giese 586B was constant at 7.6 km s\(^{-1}\) (in the Sterbenz zero-point system) except for two isolated measures with 13.4 and 10.6 km s\(^{-1}\). No data were given, but the time must have been between 1986–1991. From this, Tokovinin (1991) assumed that Giese 586B could itself be a spectroscopic binary with a high eccentricity. Earlier, Beavers \\& Eiter (1986) listed four Fick measurements from June–July 1982 that had a mean velocity of 7.7 km s\(^{-1}\) with one deviant velocity of 10.5 km s\(^{-1}\). They also determined a zero-point shift of \(-0.51\) km s\(^{-1}\) with respect to CORA VEL. Nidever et al. (2002) listed a mean velocity of 7.752 km s\(^{-1}\) (in their zero-point system) with an absolute standard deviation of less than 100 m s\(^{-1}\) for a time span of 1479 d from 1997 to 2001. These authors also determined the relative zero point of their iodine-cell measures to CORA VEL to be 53\(\pm7\) m s\(^{-1}\) which brings their data to within 60 m s\(^{-1}\) of the STELLA data (Table 2). Nordström et al. (2004) gave a mean velocity of 7.2\(\pm0.3\) km s\(^{-1}\) from 18 CORA VEL runs.

### Table 2. Spectroscopic orbital elements for Gl586A.

| Parameter          | This paper | Monte-Carlo | Duquennoy et al. (1992) |
|--------------------|------------|-------------|-------------------------|
| \(P\) (days)       | 889.81948±0.00028\(^d\) | assumed | 889.62±0.12 |
| \(T_{\text{peri}}\) (HJD) | 2,454,196.2885±0.00033 | 0.0019 | 2,447,967.5420±0.0031 |
| \(\gamma\) (km s\(^{-1}\)) | 7.5047±0.0015 | 0.0039 | 7.323±0.04\(^d\) |
| \(e\)              | 0.976081±0.000012 | 0.00004 | 0.9752±0.0003 |
| \(K_\text{Aa}\) (km s\(^{-1}\)) | 37.84±0.0058 | 0.028 | 37.14±0.12 |
| \(K_\text{Ab}\) (km s\(^{-1}\)) | 56.597±0.031 | 0.034 | 55.50±0.43 |
| \(\omega\) (deg)   | 255.690±0.0098 | 0.032 | 253.9±0.3 |
| \(a_\text{Aa} \sin i\) (10\(^6\) km) | 100.67±0.029 | 0.11 | 100.95±0.34 |
| \(a_\text{Ab} \sin i\) (10\(^6\) km) | 150.56±0.090 | 0.15 | 150.87±1.20 |
| \(M_\text{Aa} \sin i\) (\(M_\odot\)) | 0.4782±0.00068 | 0.0013 | 0.480±0.030 |
| \(M_\text{Ab} \sin i\) (\(M_\odot\)) | 0.3197±0.00033 | 0.00089 | 0.322±0.018 |
| mass ratio, \(q = M_\text{Ab}/M_\text{Aa}\) | 0.6696±0.0007 | ... | 0.670±0.009 |
| \(N_{\text{Aa}}, N_{\text{Ab}}\) | 598, 598 | ... | 97, 10 |
| rms\(\text{Aa}\) (m s\(^{-1}\)) | 41 | ... | 300 |
| rms\(\text{Ab}\) (m s\(^{-1}\)) | 258 | ... | 2020 |

Notes: ¹from the combined-data SB1 solution as described in the text.
²converted to the STELLA zero point for easier comparison.

\(N\) is the number of radial-velocity measurements used in the orbit computation.
Haute-Provence observations spanning 6014 d, but did not list the times. No individual observations were given, but the authors remarked a fairly low probability of 0.285 that these velocities were indeed all constant.

Table 3 summarizes the mean radial velocities from the literature. The current STELLA data alone do not show significant agreement with the data from Nidever et al. (2002) from 1997 to 2001. Even though all the mean velocities could indicate a long-term increase of ≈0.5 km s\(^{-1}\) from 1978 to 2012, the uncertainties of zero-point determinations are such that we believe this to be not conclusive.

### Table 3. Long-term trend of average Gliese 586B velocities, in km s\(^{-1}\).

| Year    | Average \(v_r\) \(\text{km s}^{-1}\) | \(N\) | rms | zero point | Reference |
|---------|-----------------------------------|------|-----|------------|-----------|
| 1978-79 | 7.701                             | 9    | 0.26 | +0.503     | Duquennoy et al. |
| 1981-82 | 7.238                             | 2    | 0.22 | +0.503     | Duquennoy et al. |
| 1982    | 7.707                             | 4    | ... | +0.007     | Beavers & Eitter |
| 1985-87 | 7.643                             | 2    | 0.06 | +0.503     | Duquennoy et al. |
| 1989-90 | 7.940                             | 4    | 0.18 | +0.503     | Duquennoy et al. |
| 16yr    | 7.703                             | 18   | 0.3  | +0.503     | Nordstrom et al. |
| 1997-01 | 8.202                             | 12   | 0.10 | +0.450     | Nidever et al. |
| 2007-12 | 8.143                             | 39   | 0.13 | 0          | STELLA, this paper |

Notes: *In the STELLA zero-point system. \(N\) is the number of spectra.

### 3.4. Gliese 586C

Gl586C is listed in the Washington Double Star catalog (Mason et al. 2001) as a possible visual component to the AB pair. However, it is still not clear whether the bona-fide C component Gl586C = BD-8°3984 is physically associated with the AB pair (see Makarov et al. 2008). Although its trigonometric parallax of 47.6 mas (Dahn et al. 1982) places it close to the same distance as the AB pair, it is 20′ away in the sky. The proper motions are slightly uncertain, 63±30 in right ascension and 347±30 mas yr\(^{-1}\) in declination, but formally agree with the A and B components. The available magnitudes in \(V, J, H, K\) suggest a mid-M dwarf (\(V\) magnitude of 15.0\(^{\circ}\), \(B\) magnitude of 17.5\(^{\circ}\)).

Duquennoy et al. (1993) cited a single radial velocity of 40.0 km s\(^{-1}\) taken in July 1991, from which they concluded that Gl586C is most likely not physically connected to Gliese 586AB. However, this needs to be verified. Our own attempt to obtain a spectrum with SINFON at the NOT in December 2011 failed due to mediocre weather and too high an air mass.

### 3.5. Gliese 586A orbital inclination

Orbit determinations from radial velocity curves leave the inclination of the orbital plane with respect to the line of sight as an unknown. However, separating the AB component in adaptive-optics images, we were able to indirectly infer the orbital inclination \(i\). A series of observations with NAOS+CONICA (NaCo) at the UT-4 VLT is available in the ESO archive (program by Beuzit et al.; see paper by Montagner et al. 2006), as well as another recent series using the same instrument during technical time. Both sets of images show the two A components to be clearly separated by 7.82 ± 0.02 pixel (103.8±0.3 mas) at a position angle of 328.8±0.2° in May 2005, and 9.40 ± 0.04 pixel (124.7±0.5 mas) at a position angle of 336.0±0.2° in March 2013. The picture in Fig. 4 was taken on May 2, 2005 (2,453,492.3208) with a filter centered at 1.64 μm and an exposure time of 14 s.

Using the Hipparcos parallax of Gl586A of 48.58±1.33 mas, the apparent projected A separation is converted into a projected true separation of \(D\). Inserting \(D\) into \(D^2 = r^2(1 - \sin^2 i \sin^2 (\omega + \nu))\) after rewriting the equation such that the right-hand side contains only known values,

\[
\sin^2 i = \left[\sin^2 (\omega + \nu) + \left(\frac{D}{a \sin \nu}\right)^2\right]^{-1},
\]

we find an inclination of \(i=54.3°±3.0°\) for the first, and \(i=53.7°±2.7°\) for the second set of images, respectively (\(r\) being the radius vector between the two stars, \(a\) the orbital semi-major axis, \(\omega\) the argument of periastron, and \(\nu\) the true anomaly). The errors were determined by considering that the orbital parameters are correlated amongst each other. The error propagation included the covariance according to

\[
\sigma^2 = \sum_{m,n} \left(\frac{\partial i}{\partial x_m}\right) \left(\frac{\partial i}{\partial x_n}\right) \text{cov}(x_m, x_n).
\]

Note that this equation reduces to the well-known Gaussian error propagation for uncorrelated values for vanishing non-diagonal elements in the covariance matrix.

Jancart et al. (2005) detected the motion of the photocenter of A as seen by Hipparcos. Relating this to the expected center of mass from the spectroscopic orbit by Duquennoy et al., the authors were able to determine the orbital inclination to 60.3°±1.8°. However, as stated by Jancart et al. (2005), their orbital solution failed at least one consistency test and thus was flagged as uncertain. Therefore, Gl586A did not appear in their main table (appeared only in their Table 4). Because both values, ours from the AO image and Jancart et al.’s from Hipparcos, differ by less than 2σ, we are confident of their reality.

Searching the CFHT archive, we found another set of twelve adaptive-optics images. Our analysis of these images led to positions that were more than one order of magnitude less precise...
than the NaCo images above, and a formal visual orbit fit to these data (keeping the four known parameters from the spectroscopic orbit fixed) did not improve the error bars on the orbital inclination. To estimate the uncertainties introduced by the less precise CFHT values, we calculated the visual orbit with a series of 1000 Monte-Carlo variations of the position measurements, each using only 63% of the twelve CFHT data points, but adding the two high-quality NaCo data points throughout. Estimating \( \sigma \) to be 1/1.349 of the interquartile range of the resulting distribution, we derive \( a=104.2\pm2.8\text{ mas}, \ i=55.0\pm1.5^\circ, \) and \( \Omega=272.7\pm0.9^\circ \) as final values for the additional parameters of the visual orbit. We can now determine the distance to be 19.69\pm0.65\ pc, in good agreement with, but slightly less precise than, the \textit{Hipparcos} value of 20.58\pm0.56\ pc.

4. Discussion

4.1. Orbit

The two previous orbit determinations, Duquennoy et al. \cite{1992} from CORAVEL observations and Tokovinin \cite{1991} from Sternberg observations, had rms residuals for the primary of 0.30 and 0.40 km s\(^{-1}\), respectively, but 2.02 km s\(^{-1}\) for the secondary (only Duquennoy et al. \cite{1992}, Tokovinin \cite{1991} did not see traces of the secondary and presented an SB1 solution.

The precision of an individual STELLA measurement is superior to any of the two previous data sets, owing mostly to spectrograph stability and higher spectral resolution. Considering the expected systematic errors due to the velocity measuring technique, and a relative gravitational redshift between the components, our rms residual from the orbital solution is just 41 m s\(^{-1}\) for the primary and 258 m s\(^{-1}\) for the secondary. If we exclude the data points during periastron \( \pm 0.05\) s, which have higher than normal rms due to the rapid velocity change, then the rms is 13 m s\(^{-1}\) for the primary and 103 m s\(^{-1}\) for the secondary. Formally, this is better by approximately a factor 23 and 20 for the primary and the secondary, respectively, than the CORAVEL orbit. Sampling done by a robot is expectedly unprecedented and a total of 598 velocities for both components were available. However, because our total time coverage is shorter than what was available for the initial CORAVEL orbit, 12 yr versus 6 yr, we chose to include the CORAVEL data from around periastron passage in 1990 and a few ELODIE and SOPHIE measures from 2002 for the period determination. This gave us a baseline of 18 yr or approximately 7.4 orbital revolutions.

The semi-amplitude of component Aa from our orbit is larger by 704 m s\(^{-1}\) \((6\ \sigma)\) than the Duquennoy et al. \cite{1992} value, but more precise by a factor of 10, while for component Ab it is larger by 1097 m s\(^{-1}\) \((2.5\ \sigma)\) and more precise by a similar factor. The same can be said for the eccentricity, which is confined to within 3.8\times10^{-5} at \( e = 0.97608 \) and more precise by a factor 10 than the initial CORAVEL orbit. Because of these very low rms numbers and the fact that an inspection of the radial-velocity curves in Fig. 3 shows residual systematic errors only at the level of around the accuracy of a single measurement, we conclude that our orbit is also more accurate by similar factors.

The STELLA \( \gamma \) velocity of the A pair from 2006–2012 is higher by 182 m s\(^{-1}\) than the Duquennoy et al. value of 6.82\pm0.04 km s\(^{-1}\) from 1978–1990 \( (\text{i.e. } 7.323\text{ km s}^{-1}\text{ in the STELLA system}) \). The mean velocity of the B component is also higher, on average by \( \approx 500\text{ m s}^{-1}\), instead of being decreased by a similar amount, as would be expected for a physical pair. If both velocity offsets are real, this would be puzzling unless B itself is an undetected long-period spectroscopic binary with a full radial-velocity amplitude of smaller or around the rms of our data or that of Nidever et al. \cite{2002} \((\approx 100\text{ m s}^{-1}\)\), Alternatively, the A and B stars are gravitationally unbound and are just a co-moving pair of similar stars.

Fig. 5. Atmospheric parameters of Gl586Aa from the PARES analysis. Note a \( \approx 55\text{ K} \) amplitude of the effective temperature with the period of the orbit in the top panel.

In pursuing the question whether the A–B system is truly bound or just a co-moving pair, we converted the projected A-B separation into 1066\pm35\ au, which equals a minimum separation between A and B, and compared it to the observed radial velocities. The independently measured \textit{Hipparcos} distances for the A and B stars are consistent with each other within their errors (Table 4). We can safely assume that they are equally far away, and together with the observed radial velocity difference of B with respect to the center-of-mass velocity of A, that is 638\pm13 m s\(^{-1}\), would formally allow for a bound orbit. For \( e = 0 \) and the mass estimates given in Table 4 the unprojected orbital velocity of the B component with respect to A would indeed equal 640 m s\(^{-1}\), which is very close to the observed relative radial velocity of 638 m s\(^{-1}\). The expected period for such a circular orbit would still be \( \approx 50,000\text{ yr}\), beyond hope of being observable within the few years of coverage. We can independently estimate the tangential velocity of the AB system from the differences of their proper motions to be between 0.49 \pm 0.3 km s\(^{-1}\) and \( -1.75 \pm 1.2\text{ km s}^{-1}\). The total velocity turns out to be almost exactly the escape velocity of the AB system. Although the errors are too large to give conclusively constrained velocities, one can calculate the maximum separation between A and B for a just marginally bound system. This, in turn, can be converted into a minimum orbital A-B inclination of 78°. If \( i = 90^\circ \), the eccentricity of the A-B orbit would be required to be as high as \( e = 0.98 \), similar to that of the A system.

The bona-fide C component, if at all part of the Gl586 system, has a minimum separation to A of 25,500 \( \text{au}\). For a circular orbit this transforms to an exorbitant long orbital period of \( \gtrsim 27\text{ Myr}\).

4.2. Physical properties

We applied our tool PARES (“PARameters from SES”; Allende-Prieto \cite{2004}) to all individual STELLA spectra. PARES is implemented as a suite of Fortran programs within the STELLA data analysis pipeline and is based on the synthetic-spectrum-fitting procedure described in Allende-Prieto \cite{2004}.
Table 4. Summary of astrophysical properties of Gliese 586AB.

| Parameter          | Aa     | Ab     | B      |
|--------------------|--------|--------|--------|
| V, mag             | 7.01   | 10.15  | 7.62   |
| Spectral class     | G9V    | M0V    | K0-1V  |
| Parallax, mas/yr   | 48.58±1.33 | 48.58 | 48.80±0.89 |
| P.m.δ, mas/yr      | −374±1 | ...    | −356±1 |
| Teff, K            | 5330±70 (4000) | 5110±50 |
| log g, cm s⁻²       | 4.48±0.03 | ...    | 4.34±0.03 |
| [Fe/H], solar      | +0.15±0.01 | ...    | +0.24±0.02 |
| sin i, km s⁻¹       | 1.2±0.5 | 3±1    | 1.5±0.5 |
| Inclination, °      | 55±1.5 | ...    | 12-27  |
| Rotation period, d  | n.d.   | ...    | 8.5±0.2 |
| Radius, Rₚ         | 0.92±0.04 | 0.59±0.03 | 0.78±0.04 |
| Luminosity, Lₚ     | 0.61±0.04 | 0.080±0.006 | 0.37±0.02 |
| Mass, Mₚ           | 0.87±0.05 | 0.58±0.03 | 0.85±0.05 |
| log Li abundance    | n.d.   | n.d.   | n.d.   |
| Age, Gyr           | ≥2     | ...    | (0.5)  |

n.d.: not detected.

Synthetic spectra are computed and pre-tabulated for relative logarithmic metallicities of −2.5 to +1.0, logarithmic gravities between 0 to 5.0, and temperatures between 3000 K to 7000 K for a wavelength range of 380–920 nm. All calculations were based on MARCS model atmospheres (Gustafsson et al. 2008) with the VALD3 line list (Kupka et al. 2011) with updates on some specific log f values and were fixed with a microturbulence of 1.1 km s⁻¹ for Gl586 A and B. Macroturbulence was set to 3 km s⁻¹. This grid was then used to fit 50 selected echelle orders of each STELLA/SES spectrum. The four parameters Tₚ eff, log g, [Fe/H], and v sin i were solved for simultaneously in all orders. Internal errors of the fits were estimated using the original noise in the spectra. We verified this approach by applying it to the ELODIE library (Prugniel & Soubiran 2001), and used linear regressions to the offsets with respect to the literature values to correct our PARES results.

PARSES treats the Gl586A spectrum as a single-star spectrum and per default does not extract the secondary. Values would be formally “combined values”, but nevertheless are quite precise for the primary due to the faintness of the secondary and the fact that for most of the spectra the two components are unblended. Our next step in the analysis was the removal of the secondary spectrum from all (598) Gl586A spectra before the PARES analysis. This was done by using the same synthetic spectrum for Ab as for the systematic-error correction of the radial velocities in Sect. 4 and with the same wavelength-dependent scaling as given in Fig. 6.

The PARES results for Aa are shown in Fig. 5 as a function of time. Systematic changes are obvious and a Lomb-Scargle periodogram of the Tₚ eff results reveals a clear period of 885±35 d with a full amplitude of ≈55 K and an rms of below 10 K (correlation coefficient of 0.89), which is equal to the orbital period within its errors. The highest temperature occurs repeatedly at periastron and the lowest temperature at apastron. The same is noted for the log g and [Fe/H] time series, but with significantly smaller relative amplitudes; 0.05±0.03(rms) in log g and 0.03±0.02(rms) in [Fe/H]. Table 4 lists the long-term average values with their grand rms errors.

We used the NAOS-CONICA images to perform psf-modeling and aperture photometry of the residuals for both components for two sets of six and ten exposures at 1.26 μm and 1.64 μm, respectively. The averaged magnitude differences Gliese 586 Aa-minus-Ab are Iₚ 890±0.013 at 1.26 μm and Iₚ 480±0.015 mag at 1.64 μm. For comparison, the flux ratio primary to secondary at optical wavelengths from the dip of the radial-velocity cross-correlation function is 13.5±0.5 in the R band and 18±1 in the V band, that is, a magnitude difference of approximately 2m8 in R and 3m15 in V.

If we adopt the orbital inclination of 55±1.5°, the individual masses for Aa and Ab are 0.87±0.05 Mₜ and 0.58±0.03 Mₜ, respectively. These are masses with an accuracy of only 6%, but are by far dominated by the error of the inclination. Note that the minimum masses are good to ≈0.3%. The primary mass fits an ≈G7-8 dwarf star with a nominal radius of 0.9 Rₜ, but even better a K0V from its effective temperature of 5250 K according to the table in Gray (2005a). The MILES atmospheric parameter library (Cenarro et al. 2007) suggests a G8-9V classification, but with a slightly smaller log g of +4.32. We adopted G9V for the remainder of the paper and note that this value is not based on a direct spectral classification. The secondary mass suggests an ≈K7-M0 star with a predicted radius of 0.57 Rₜ according to the models of a 4 Gyr, [Fe/H]=0 isochrone from Baraffe et al. (1998) as given in Fernandez et al. (2009). With a mass-radius relation of R ≈ M⁸/₉ would we expect radii of 0.92 Rₜ and 0.67 Rₜ for the two components, respectively. A more direct determination of the radii comes from the combined magnitudes of the two Gl586A stars and the known distance. Together with their flux ratio of 18±1 at V-band wavelengths, the combined apparent magnitudes translate into absolute magnitudes of Mₐ = 5.044±0.006 for Aa and 8.58±0.007 for Ab. For normal main-sequence stars this implies G7-8V and M0V according to the tables in Gray (2005a). Similarly, Gl586B has Mₐ = 6.06±0.005 and thus approximately fits a canonical K0-1V star. With the bolometric corrections from Flower (1996) based on the Tₚ eff from our spectrum synthesis and a solar bolometric magnitude of 4.72, the three stars’ bolometric magnitudes correspond to luminosities of 0.610±0.041 Lₜ, 0.080±0.006 Lₜ, and 0.37±0.02 Lₜ (Aa, Ab, B). These luminosities suggest radii of 0.92±0.04 Rₜ, 0.59±0.03 Rₜ, and 0.78±0.035 Rₜ for Aa, Ab, and B, respectively, again with the effective temperatures...
from Table 4. Errors are simply propagated from $L$ and $T_{eff}$. The M0 secondary is indeed slightly larger than predicted from the Baraffe et al. tracks for solar metallicity, in agreement with recent radii measurements of eclipsing late-K and M dwarfs (see López-Morales 2007, Fernandez et al. 2009).

Koen et al. (2010) listed spectral types of G9V for component A (i.e., Aa and Ab combined) and K2V for component B from their UBVIJK photometry, both in overall agreement with our spectroscopic values. The Aa and the B star differ in their effective temperatures by only 200 K and agree in their (logarithmic) metallicities and their gravities to within 2 $\sigma$ of the measurement error, but their luminosities differ significantly.

4.3. Stellar rotation and magnetic activity

The projected rotational line broadening is determined to be $v \sin i = 1.2 \pm 0.5$ km s$^{-1}$ for Aa, $3 \pm 1$ km s$^{-1}$ for Ab, and $1.5 \pm 0.5$ km s$^{-1}$ for B with adopted macroturbulences of 2 km s$^{-1}$ for all three stars following the recipe in Fekel (1997). Microturbulent broadening was assumed to be 1.0 km s$^{-1}$. The PARES spectrum fit yielded average $v \sin i$’s of $2.0 \pm 0.4$ km s$^{-1}$ for Aa and $2.4 \pm 0.4$ km s$^{-1}$ for B, in reasonable agreement with Fekel’s recipe. The high orbital eccentricity suggests a rather speedy pseudo-synchronous rotation period for Aa of $\approx3.4$ d according to the tidal-friction theory of Hut (1981), which would be just 2.6% of the orbital angular velocity. This clearly disagrees with the measured $v \sin i$, which suggests a rotation period closer to $\approx30$ d if $i = 55^\circ$. Most likely, the Aa star is a strongly asynchronous rotator. Note that Wright et al. (2004) had determined expected periods from the strength of the Ca ii S-index for Aa and B based on the rotation-activity relation from Noyes et al. (1984) of 39 d and 9 d, respectively. While they had observed the B component 15 times, the A component(s) had only a single H&K measurement (A on JD2,450,277; B between 2,450,277–835).

We analyzed our APT photometry with the Lomb-Scargle periodogram (Lomb 1976; Scargle 1982) and also the minimum string-length algorithm following Dworetsky (1983). The $V$-band rms scatter of our data sets were 4 mmag for the combined A light curve, but 9 mmag for the B component, while it was in the $I$-band 10 mmag for A and 7 mmag for B. The larger-than-normal $V$-band rms scatter of Gl586B indicates that it is photospherically mildly active, in agreement with the Ca ii H&K observations of Duncan et al. (1991) and Wright et al. (2004), and our own spectra. The 4-mmag rms scatter for A agrees with the expected observational error if the star is constant. Its Lomb-Scargle periodogram shows a period of $\approx1.2$ d (in addition to the dominating 1 d aliasing from the window function). Its full amplitude of $\approx0.003$ is below the intrinsic scatter of the data and this period is consequently judged spurious. No other variability could be detected.

The Gl586B-minus-comparison data after JD 2,456,032 show a periodicity of 8.71 d with a full amplitude of $0.0056$. Given the external uncertainty of $0.0049$ from the check-minus-comparison light curve, this period does not appear to be significant. However, the differential data with respect to the check star show a similar period of 8.33 d with an amplitude of $0.0085$ at an intrinsic scatter of $0.007$. The respective two light curves are shown in Fig. 7. Expected (minimum) period errors are determined from refitting of synthetic photometry (see also Strassmeier et al. 2012). This method estimates confidence intervals by synthesizing a large number of data subsets out from the original data by adding Gaussian random values to the measurements proportional to the actual rms of the data. By generating $10^5$ synthetic data sets and calculating a Lomb-Scargle periodogram on all of them, we adapted the standard deviation of its periods as the expected error. Errors retrieved in this way were 0.09 d for the variable-minus-comparison data and 0.1 d for the variable-minus-check data. However, these errors are lower limits because the method does not take into account systematic noise. We conclude that the two periods are not significantly different and thus adopted their arithmetic average as the best value from the current data, that is $P_{rot}$(Gl586B) = $8.5\pm0.2$ d. Note that this period agrees well with the expected period of 9 d from the rotation-activity relation.

The range of inclinations of the rotation axis of B would be just 12–27$^\circ$ from the measured $v \sin i$ range and the 0.78-R$_\odot$ radius from the Boltzmann-relation and above $P_{rot}$ (with the error of $v \sin i$ dominating over the error of $R/P_{rot}$ by a factor 10). All inclination values within this range are equally likely, but do not overlap with the 55$\pm1.5^\circ$ inclination of the A orbital plane. Because Gl586B shows moderately strong H&K emission, it is actually unusual that the photometric light amplitude is so small, $\approx7$ mmag, and barely detectable from the ground. The low inclination of the rotation axis would be a natural explanation for this.

4.4. Ages

Figure 8 compares the position of the three Gliese-586 stars with theoretical evolutionary tracks and isochrones in the $L$ – $T_{eff}$ plane. Tracks and isochrones are taken from Spada et al. (2013) and were computed for [Fe/H] = ±0.15 with an updated version of the Yale Rotating stellar Evolution Code (YREC; Demarque et al. 2003) in its non-rotating configuration. These models also include moments of inertia of the radiative and convective zones and convective turnover timescales, in view of their application to studies of the rotational and magnetic evolution of low-mass stars. The most important difference to the previous YREC version is the treatment of the equation of state and the use of outer boundary conditions based on updated non-gray atmospheric models.

The locations of Aa and B in the H-R diagram match their corresponding main-sequence YREC tracks within their errors.
The same holds true for both the Basti (Pietrinferni et al. 2004) and the Parsec tracks (Bressan et al. 2013). The B-component is an effectively single star without a mass determination. It is approximately matched with a track of mass 0.85 ± 0.05 M\odot for the metallicity of 0.15.

No lithium absorption line at 670.78 nm is detected for Gl586A or for B down to our detection limit of 2–3 mÅ. This effectively rules out a pre-main-sequence nature of the two stars and points to an older age than the 0.6 Gyr of the Hyades (Sestito & Randich 2005). The three $^{12}$C/$^{13}$C lines around 800.35 nm are clearly detectable with a combined equivalent width of 61 mÅ for Aa and 77 mÅ for Ab. However, the equivalent width of the $^{13}$C line at 800.46 nm is not detected in either of the two stars, and we may again state just a lower limit of $\approx$2–3 mÅ. Thus, the $^{12}$C/$^{13}$C ratio must be lower than $\approx$24 for Aa and lower than $\approx$30 for B, which is significantly lower than the presumed initial solar ratio of about 90 (see Lambert & Ries 1981) and indicative of evolved main-sequence stars. If we assume that all three Gliese-586 stars fit in with other local dwarfs within 15 pc of the Sun, defined by the S$^4$N survey (Allende Prieto et al. 2004), we might expect an age younger than that of the Sun, though. The age concentration of the S$^4$N survey peaks sharply at $\approx$1 Gyr with the Sun being among the oldest stars in our galactic neighborhood. However, the formal range of ages is 0.16–10 Gyr for the whole sample. In any case, the two moderately high $^{12}$C/$^{13}$C ratios together with the statistical results from S$^4$N suggest a “few Gyr” age for Gl586Aa and B.

An independent cross-check is provided by the gyrochronological approach of Barnes (2009). Although it is not applicable to tidally interacting binaries, it is interesting to state what the effective temperatures and rotation periods would predict. Because Gl586Aa has no detected rotation period, we rely on its indirectly determined value based on the measured equatorial rotational velocity and the stellar radius (based on the orbital inclination and additionally assuming that the spin axis is perpendicular to the orbital plane). With the values in Table 4, the most likely rotation period for Aa is 30 d, while we measured a period of 8.5 d for B. Then, the Barnes (2009) relation would suggest gyroages of approximately 5 Gyr for Aa but 0.5 Gyr for B, which would agree with the observed magnetic activity levels of both stars, but would obviously disagree with the common assumption that the AB components are coeval. Ages of 2 Gyr for Aa and 0.5 Gyr are obtained when the red-dwarf calibration of Engle & Guinan (2011) is applied. Most likely, this just demonstrates that gyrochronology is not applicable to binaries. Even for a single star with planets, gyroages are probably biased due to expected star-planet interactions, as demonstrated recently for HD 189733 (Santapaga et al. 2011).

5. Conclusions

We confirmed the extreme eccentricity of Gliese 586A and presented a new and much more precise and accurate spectroscopic orbit. Currently there exists no formation scenario for a binary system with an orbital period as short as 889.8195 ± 0.0003 d and an eccentricity as high as 0.97608 ± 0.00004 in a triple system. An evolutionary scenario based on a theory for the coupling of the envelope shear with a constant turbulent viscosity (Zahn 1989) would require an initial semi-major axis of about 1 pc and an even higher eccentricity. Such a large separation between the components would make the survival of the system very unlikely. Goldman & Mazeh (1994) favored a quadratic reduction of the convective-envelope viscosity over time that solves this problem and results in initial conditions very similar to the present one. Of course, it does not explain how such a system is formed in the first place and whether, for instance, a capture mechanism is a viable option or can be excluded. A crucial piece in this puzzle is the existence of the close-by and very similar Gliese 586B star at the same distance and location and with a similar proper motion. Our new data for Gliese 586A and B agrees with the assumption that B is gravitationally bound to the A stars, but does not conclusively exclude the common proper-motion scenario. The fact that the $\gamma$-velocity of the A system and the velocity of the visual B star are both increasing over time would agree if B itself were a long-period very eccentric spectroscopic binary just like A. We now have evidence that the inclination of the rotation axis of B is very low, $i \approx 12^\circ \ldots 27^\circ$. If perpendicular to the orbital plane of a hypothetical (unseen) secondary star, radial-velocity variations would be very difficult to measure and thus not contradict the current measurements of B.

Observations of the faint, bona-fide C component are still needed to confirm its membership in the system.

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Fig. 8. Comparison of the Gliese 586 stars (dots marked Aa, Ab, and B) with theoretical evolutionary tracks and isochrones for a metallicity of 0.15 matching Gl586Aa. The full lines are taken from the grid of Spada et al. (2013) computed with YREC. Shown are pre-main-sequence and post-main-sequence tracks for the masses labeled and two isochrones of age 0.1 and 10 Gyr. For comparison, the dotted and dash-dotted lines are the $0.9$-$M\odot$ main-sequence tracks from Basti (Pietrinferni et al. 2004) and Parsec (Bressan et al. 2013), respectively.
