FIRST, a fibered aperture masking instrument

II. Spectroscopy of the Capella binary system at the diffraction limit

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ABSTRACT

Aims. FIRST is a prototype instrument built to demonstrate the capabilities of the pupil remapping technique, using single-mode fibers and working at visible wavelengths. Our immediate objective is to demonstrate the high angular resolution capability of the instrument and to show that the spectral resolution of the instrument enables characterization of stellar companions.

Methods. The FIRST-18 instrument is an improved version of FIRST-9 that simultaneously recombines two sets of nine fibers instead of one, thus greatly enhancing the \((u,v)\) plane coverage. We report on observations of the binary system Capella at three epochs over a period of 14 months (\(\geq 4\) orbital periods) with FIRST-18 mounted on the 3 m Shane telescope at Lick Observatory. The binary separation during our observations ranges from 0.8 to 1.2 times the diffraction limit of the telescope at the central wavelength of the spectral band.

Results. We successfully resolved the Capella binary system at all epochs, with an astrometric precision as good as 1 mas under the best observing conditions. FIRST also gives access to the spectral flux ratio between the two components directly measured with an unprecedented spectral resolution of \(R \sim 300\) over the 600–850 nm range. In particular, our data allow detection of the well-known overall slope of the flux ratio spectrum, leading to an estimation of the “pivot” wavelength of \(0.64 \pm 0.01\) \(\mu\)m, at which the cooler component becomes the brightest. Spectral features arising from the difference in effective temperature of the two components (specifically the Hα line, TIO, and CN bands) have been used to constrain the stellar parameters. The effective temperatures we derive for both components are slightly lower (\(5–7\%\)) than the well-established properties for this system. This difference mainly comes from deeper molecular features than those predicted by state-of-the-art stellar atmospheric models, suggesting that molecular line lists used in the photospheric models are incomplete and/or oscillator strengths are underestimated, most likely concerning the CN molecule.

Conclusions. These results demonstrate the power of FIRST, which is a fibered pupil remapping-based instrument, in terms of high angular resolution and show that the direct measurement of the spectral flux ratio provides valuable information to characterize little known companions.

Key words. instrumentation: high angular resolution – techniques: interferometric – binaries: close – binaries: visual – stars: fundamental parameters – stars: individual: Capella

1. Introduction

The objective of the FIRST (Fibered Imager for a Single Telescope) prototype development is the detection of faint companions such as exoplanets. Many instruments currently being designed and manufactured are addressing this challenge, which requires high dynamic ranges at high angular resolution. Different solutions are implemented, such as extreme adaptive optics systems, coronagraphic masks, and interferometric techniques (or a combination thereof). FIRST belongs to the last category since its principle relies on aperture masking (Haniff et al. 1987), in which a mask with small holes is put on the pupil of the telescope. In a traditional implementation, these holes are organized in a non-redundant manner to avoid the fringe blurring due to the atmospheric turbulence, which leads to the loss of most of the high spatial frequency information on the object. The image is thus the superimposition of all fringe patterns coded with as many spatial frequencies. Object
FIRST is the implementation of the fibered pupil remapping technique as proposed by Chang & Buscher (1998) and then Perrin et al. (2006) at visible wavelengths. This technique can be seen as a variant of the aperture masking technique that aims at increasing the achievable dynamic range. As stated by Baldwin & Haniff (2002), dynamic range depends directly on the number of subpupils and on the accuracy of the observable measurements (visibilities or closure phases for instance). In the FIRST instrument, single-mode fibers offer a way to improve these two aspects: (i) they allow the whole telescope pupil to be used while their outputs can be non-redundantly recombined, and (ii) they spatially filter the wavefront and thus avoid speckle noise. The spatial phase fluctuations due to the atmospheric turbulence are thus traded against flux fluctuations because of the imperfect coupling efficiency of the fibers. However, these can be more easily handled during data reduction than phase fluctuations. A self-calibration algorithm has indeed been proposed to retrieve the complex visibilities without the need of specific photometric channels (Lacour et al. 2007).

The first light of the instrument was achieved in July 2010 at Lick Observatory with FIRST-9 mounted on the Cassegrain focus of the 3 m Shane telescope (Huby et al. 2012). The instrument has since been significantly improved to increase the number of subpupils and the accuracy on the closure phase measurements, hence the achievable dynamic range. FIRST-9 has thus become FIRST-18, in which 18 subpupils are recombined and has been mechanically enhanced to reach higher stability. Four observing runs have been conducted between October 2011 and December 2012. Several binary systems have been observed, since these simple objects are particularly suited for testing the capabilities of the instrument.

Among these binaries, Capella (α Aurigae, $V = 0.08, R = -0.52$) has been observed at three different epochs with FIRST-18. Capella is a well-known nearby binary system, which has been studied for more than a hundred years, and its historical record is notably linked to the Lick Observatory and the first measurements with interferometers. The first announcement of discovery of this spectroscopic binary dates indeed from Campbell (1899), who used the Mills spectrograph installed on the 36-inch Lick refractor to observe Capella. Simultaneously Newall (1899) made the same discovery using the Cambridge spectroscope. Capella later was the first binary system whose astrometric orbit was interferometrically measured with the 6 m baseline Michelson interferometer on the 100-inch telescope at Mount Wilson (Anderson 1920; Merrill 1922). For decades, this friendly target has been observed with various interferometers and speckle imaging techniques. So far, the most accurate measurements of the astrometric orbit have been performed by Hummel et al. (1994) using the Mark III interferometer at Mount Wilson with baselines from 3 m up to 23.6 m. Concerning the abundant bibliography about Capella, Torres et al. (2009) provide a very complete review of all spectroscopic, as well as the interferometric measurements available at that time, and they used them to derive the parameters of the system: effective temperatures of $4920 \pm 70$ K and $5680 \pm 70$ K, radii of $11.87 \pm 0.56 R_\odot$ and $8.75 \pm 0.32 R_\odot$, luminosities of $79.5 \pm 4.8 L_\odot$ and $72.1 \pm 3.6 L_\odot$, and the parameters of the relative orbit. The latest and most accurate masses have been determined by Weber & Strassmeier (2011) using the spectroscopic orbit combined with the inclination of the orbital plane derived from astrometry measurements: $2.573 \pm 0.009 M_\odot$ and $2.488 \pm 0.008 M_\odot$.

With an angular separation varying from 41 mas to 56 mas, Capella is therefore an ideal target for probing the capabilities of FIRST-18 at the diffraction limit, which ranges from 41 mas at 600 nm to 58 mas at 850 nm for a 3 m telescope. In this paper, we report on the successful detection of Capella as a binary system at the diffraction limit of the telescope using FIRST-18, which is described in Sect. 2, along with the data reduction procedure. The results are presented in Sect. 3. The spectrally-dispersed flux ratio measurement is of particular interest because it is the first time that it is directly measured with $R \simeq 300$ spectral resolution. Higher-resolution spectra of the two components have been estimated by “deblending” the composite spectrum of the binary using spectral templates to disentangle them (Barlow et al. 1993). Flux ratio measurements of the system, on the other hand, have been obtained in discrete broad- and narrow-band filters that are too sparsely distributed to provide fine spectral information (Torres et al. 2009). Thus, the FIRST data offer a unique insight into the Capella system and, by extension, into all systems with separation as small as the diffraction limit of a given telescope. In this work, we model our FIRST flux ratio spectrum to constrain the effective temperatures of the Capella binary, thereby demonstrating the power of FIRST to study previously uncharacterized companions in the future.

2. Observations and data reduction

Observations were conducted with the 3 m Shane telescope at Lick Observatory from 2011 to 2012 (see Table 1). As in previous observations (Huby et al. 2012), the Shane adaptive optics system provided sufficient correction to stabilize the fringes, although it is optimized for the infrared wavelengths.

2.1. FIRST-18

After the first light of the instrument obtained in 2010 (Huby et al. 2012), efforts have been focused on improving the stability, sensitivity, and dynamic range achievable with FIRST. The injection part of the instrument (including the pupil imager, the Iris AO segmented mirror used to steer the beams precisely on the fiber cores that are gathered in the fiber bundle, from Fiberguide Industries) is basically unchanged; however, significant upgrades have been carried out in the recombination part of the instrument, as can be seen in Fig. 1.

Assuming that the noise is uncorrelated between the baselines – a reasonable assumption in the photon-noise-limited regime – the dynamic range increases with the number of visibility and closure phase measurements (Baldwin & Haniff 2002; Lacour et al. 2011; Le Bouquin & Absil 2012). The main development was therefore aimed at increasing the number of subpupils, leading to the FIRST-18 instrument, in reference to the two sets of nine subpupils that are recombined. The non-redundancy of the linear recombination configuration is a technical limit: standard V-groove chips offer 48 spaces where fibers can be positioned. The most compact nine-fiber configuration requires $n_{\text{max}} = 44$ spaces, while the 10-fiber and 11-fiber ones require 55 and 75 spaces, respectively. In addition, the nine-fiber configuration is also a compromise between the available space on the bench (defining the focal length $f'$ of the imaging lens),
the sampling of the highest frequency fringe pattern (for a given focal length of the imaging lens), on the one hand, and to reach a high spectral resolution, on the other. This is achieved thanks to a four-lens (2 spherical and 2 cylindrical lenses) afocal system performing a beam elongation of 20 in the direction of dispersion and a compression of 7 in the orthogonal direction. The two fringe patterns are imaged on the same detector side by side along the wavelength axis. Spectral filters have been inserted in each arm in order to avoid overlapping of the patterns. In the center of the detector, the fringe patterns are cut at 600 nm and 850 nm, thereby defining the spectral range of the instrument.

Improvement of the data quality has also been provided by the use of a more efficient detector, Hamamatsu EMCCD camera with maximal EM gain of 1200, quantum efficiency of 90%, 77% and 54% at 600, 700, and 800 nm, respectively, and 512 x 512 pixels 16 μm wide. The overall mechanical stability has been enhanced, too, allowing objects to be observed up to 40° from zenith without significant loss of flux due to mechanical flexures.

2.2. Acquisition procedure

Capella was observed in October 2011, July 2012, and December 2012 with FIRST-18 mounted on the 3 m Shane telescope at Lick Observatory. The observation log is reported in Table 1. Several bright (0 ≲ R ≲ 3) single stars were observed immediately before/after Capella, so they serve as calibrator for closure phase measurements and baseline calibration (see Sect. 3.2).

The acquisition procedure is similar to the description given in Huby et al. (2012). One data set comprises fringe sequences, fiber calibration files (every fiber diffraction pattern is recorded individually), and background files. However, this procedure has been significantly shortened compared to the previous observations thanks to implementing a dedicated optimization path in the optical set-up. The injection of the flux into the fibers is indeed very sensitive and must be optimized at every target switch, to compensate for residual mechanical flexures occurring in the instrument but also in the AO system. While this optimization was done one fiber at a time in 2010 (by scanning the corresponding micro-segment and measuring the transmitted flux directly on the science camera), it is now done simultaneously for all fibers thanks to a motorized mirror system that allows imaging all the output fibers on a dedicated detector. The 18 corresponding micro-segments can therefore be scanned at the same time. The optimization is now completed in less than two minutes leading to a substantial gain in time and stability.

2.3. Data reduction

The basic principles of the FIRST data analysis are based on the P2VM method (Pixel to Visibility Matrix), which was first developed for the AMBER instrument at the VLTI (Millour et al. 2004) and subsequently adapted to FIRST data, as described in
more detail in Huby et al. (2012). The current data reduction process consists of the following steps:

- background (including dark current) subtraction;
- optical distortion correction;
- spectral calibration based on the fitting of telluric absorption lines and features of the stellar spectrum;
- fitting of the fringe spatial frequencies by adjusting the peak positions in the mean power spectral density;
- calibration of the P2VM matrix from individual fiber profiles and spatial frequencies;
- pseudo-inversion of the P2VM matrix and computation of the best parameter sets in the least-squares sense;
- closure phase computation;
- closure phase calibration by measurements obtained on an unresolved target.

The distortion mentioned in the second step of the reduction results from astigmatism introduced by the prism and has an amplitude of about 10–15 pixels. The shape of this distortion is evaluated by detecting the position of the companion, $\alpha$ and $\delta$, and a flux ratio for each spectral channel, $\rho(\lambda)$. The closure phase model function corresponding to a binary directly reads as (Le Bouquin & Absil 2012)

$$f(\alpha, \delta, \rho) = \arg\left(\frac{(1 + \rho e^{i\alpha})(1 + \rho e^{i\delta})(1 + \rho e^{i\rho})}{(1 + \rho)^3}\right),$$

(1)

with

$$a_{ij}(\alpha, \delta) = 2\pi\left(au_{ij} + \delta v_{ij}\right),$$

(2)

**Table 1. Observation log.**

<table>
<thead>
<tr>
<th>Target</th>
<th>Type</th>
<th>$N_{\text{img}}$</th>
<th>$t_{\text{int}}$ (ms)</th>
<th>$r_0$ at 550 nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Algol</td>
<td>AC</td>
<td>10000</td>
<td>150</td>
<td>~11.5 cm</td>
</tr>
<tr>
<td>Aldebaran</td>
<td>C</td>
<td>10000</td>
<td>50</td>
<td>~10 cm</td>
</tr>
<tr>
<td>Capella</td>
<td></td>
<td>16000</td>
<td>50</td>
<td>~11.5 cm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2011-10-17</td>
</tr>
<tr>
<td>Algol</td>
<td>AC</td>
<td>10000</td>
<td>200</td>
<td>~14 cm</td>
</tr>
<tr>
<td>Aldebaran</td>
<td>C</td>
<td>10000</td>
<td>100</td>
<td>~8 cm</td>
</tr>
<tr>
<td>Capella</td>
<td></td>
<td>12000</td>
<td>100</td>
<td>~13 cm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2012-07-29</td>
</tr>
<tr>
<td>Algol</td>
<td>AC</td>
<td>6000</td>
<td>200</td>
<td>~7 cm</td>
</tr>
<tr>
<td>Capella</td>
<td></td>
<td>5000</td>
<td>200</td>
<td>~8 cm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2012-12-19</td>
</tr>
<tr>
<td>Algol</td>
<td>AC</td>
<td>4000</td>
<td>200</td>
<td>~8 cm</td>
</tr>
<tr>
<td>Capella</td>
<td></td>
<td>5000</td>
<td>200</td>
<td>~6 cm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2012-12-20</td>
</tr>
</tbody>
</table>

**Notes.** The table includes the dates of observation, the type of target (AC stands for astrometric calibrator and C for closure phase calibrator), the number of images acquired with an integration time $t_{\text{int}}$, and an estimate of the $r_0$ parameter (evaluated thanks to the AO system occasionally once or twice during one sequence of observations).

Fig. 3. Mean power spectral density computed from 5000 50 ms-images for Capella on 2011 Oct. 16 using data from a single V-groove. The color-scale has been adjusted by discarding the zero-frequency peak (not visible in the image). The fitted peak positions are superposed as dashed white lines only on the left part of the image for better visibility. The (telluric) absorption line appearing at spectral channel number 147 is exactly vertical, showing that the distortion in the image has been effectively corrected. At least 27 different peaks are clearly visible out of the 36 expected ones.
where $u_{ij}$ and $v_{ij}$ are the projections of the spatial frequency vector $s_{ij}$ corresponding to the subpupils $i$ and $j$ on two orthonormal axes defined by the segmented mirror reference frame (see Sect. 3.2 for details concerning the baseline calibration). This vector expresses as $s_{ij} = B_{ij}/\lambda$ with $B_{ij}$ the baseline vector represented in the telescope pupil.

The $\chi^2$ function is therefore three dimensional. For every spectral channel, the contributions of all $n_{CP}$ closure phases are added quadratically:

$$\chi^2_\lambda(\alpha, \delta, \rho) = \sum_k \frac{\Delta CP^2_k}{\sigma^2_k},$$

with $\sigma^2_k$ the error on closure phase $k$ at wavelength $\lambda$ and

$$\Delta CP^k_\lambda = CP^k_\lambda - f^k_\lambda(\alpha, \delta, \rho) \pmod{2\pi},$$

is the phase difference between the data and the model, defined modulo $2\pi$.

Under the assumption that the noise affecting the data follows a Gaussian distribution, the likelihood function can be derived from the $\chi^2$ function by

$$L_\lambda(\alpha, \delta, \rho) \propto \exp\left(-\frac{\chi^2_\lambda(\alpha, \delta, \rho)}{2}\right).$$

The proportional symbol is a reminder that the likelihood function is normalized afterwards.

The optimal value for a given parameter can then be retrieved after marginalizing the likelihood function, i.e. by integrating over all other parameters. For the $\alpha$ parameter for instance, it is expressed as

$$L_\lambda(\alpha) = \int L_\lambda(\alpha, \delta, \rho) d\delta d\rho.$$  

Similarly, a circular permutation over the set of parameters leads to $L_\lambda(\delta)$ and $L_\lambda(\rho)$. For each spectral channel, the optimal parameter sets $(\tilde{\alpha}_\lambda, \tilde{\delta}_\lambda, \tilde{\rho}(\lambda))$ are then determined by the median value of these probability densities, and the associated error bars are defined as the 68% confidence interval.

3. Results

3.1. The case of Capella

The calibrated closure phases of Capella are shown in Fig. 4. As is readily apparent, large deviations from the null closure phase are detected. Large phase changes of $\sim \pm \pi$ indeed occur when the observed object is centrosymmetric, indicating here that the flux ratio between the two components is close to unity, as is expected for the Capella binary system at visible wavelengths. That the transitions are smooth indicates that the flux ratio is not exactly equal to one. Thus these observations have clearly resolved the binary system.

![Fig. 4. Closure phase measurements obtained on 19 October 2011 (black points with rescaled error bars such that the reduced $\chi^2$ per spectral channel is unity) and best fit model (red points) computed from the best estimates of the binary parameters.](image-url)
Table 2. Companion position measurements for the outer Algol system (C relative to A+B) converted into angular separation and position angle.

<table>
<thead>
<tr>
<th>Date</th>
<th>JD (2 400 000+)</th>
<th>Estimated $\rho$ (mas)</th>
<th>Predicted $\rho$ (mas)</th>
<th>Ratio</th>
<th>Estimated $\theta$ (°)</th>
<th>Predicted $\theta$ (°)</th>
<th>Difference $\theta$ (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011-10-16</td>
<td>55851.9</td>
<td>87.9 ± 9.8</td>
<td>78.0 ± 0.2</td>
<td>0.888 ± 0.099</td>
<td>218.1 ± 7.3</td>
<td>134.4 ± 0.1</td>
<td>-83.7 ± 7.3</td>
</tr>
<tr>
<td>2011-10-19</td>
<td>55854.9</td>
<td>77.6 ± 1.1</td>
<td>77.8 ± 0.2</td>
<td>1.002 ± 0.014</td>
<td>215.5 ± 0.7</td>
<td>134.7 ± 0.1</td>
<td>-80.9 ± 0.7</td>
</tr>
<tr>
<td>2012-07-29</td>
<td>56139.0</td>
<td>84.4 ± 1.4</td>
<td>88.0 ± 0.5</td>
<td>1.043 ± 0.019</td>
<td>13.4 ± 1.4</td>
<td>307.4 ± 0.1</td>
<td>-66.0 ± 1.4</td>
</tr>
<tr>
<td>2012-12-19</td>
<td>56281.7</td>
<td>89.0 ± 5.6</td>
<td>94.0 ± 0.4</td>
<td>1.056 ± 0.067</td>
<td>13.4 ± 4.1</td>
<td>314.5 ± 0.1</td>
<td>-58.9 ± 4.1</td>
</tr>
<tr>
<td>2012-12-20</td>
<td>56282.8</td>
<td>94.6 ± 6.7</td>
<td>93.6 ± 0.4</td>
<td>0.989 ± 0.070</td>
<td>15.5 ± 5.4</td>
<td>314.5 ± 0.1</td>
<td>-60.9 ± 5.4</td>
</tr>
</tbody>
</table>

**Notes.** The ratio between the measured and theoretical angular separations give an estimate of the corrective scaling factor. The differences in position angle indicate the rotation of the segmented mirror reference frame relative to the northeast orientation. Horizontal lines separate the three observing runs considered here. Correction factors are assumed to be constant within a given observing run.

3.2. Orbit

The analysis of our results concerning the companion position requires calibrating the $(u,v)$ plane, that is, a calibration of the baseline lengths and orientations (as explained by Woillez & Lacour 2013, under the imaging baseline section). For the fit, the baselines are conveniently defined by their theoretical lengths and orientation taken in a reference frame linked to the segmented mirror. However, to be scientifically useful, these need to be transformed into the angular separation of the binary and its position angle relative to north. Two aspects have to be considered for the calibration:

- the magnification factor between the telescope pupil and the pupil that is imaged in the FIRST instrument can vary with the alignment;
- the rotation angle between the sky east-west / north-south orientation and the reference frame linked to the segmented mirror orientation.

The rotation of the pupil plane is caused by the periscope sending the beam from the adaptive optics bench towards the hole through the FIRST bench. It uses a mirror combination working at angles different from 45° that therefore induces an unknown rotation of the pupil relative to the subpupils.

The calibration over all baselines can thus be performed by estimating two parameters: a scaling factor and a rotation angle. This is done by measuring the position of another well-known binary star using the same data reduction pipeline as for Capella. Among the binary systems observed at the same epochs as Capella, the triple system of Algol (δ Per) is an ideal calibrator. The inner system (Algol A of type B8V and Algol B of type K2IV) of orbital period 2.87 days and semi-major axis of 2.3 mas is unresolved by a 3 m telescope. On the other hand, the outer system (Algol A+B and Algol C of type F1V) of orbital period ≈680 days, semi-major axis of 93.8 mas, and flux ratio estimated to 10 at visible wavelengths is detected well by FIRST-18. Its orbital period is much longer than the Capella period (104 days), and this makes it a suitable target for the baseline calibration.

The relative positions of Algol A+B and C have therefore been estimated for several dates during the various runs, as shown in Table 2. The results are shown in Table 2. The position parameters have been converted into polar coordinates in order to derive the angle for the rotation to be applied to the field of view. The predicted positions are computed from the orbit resulting from the measurements with the CHARA interferometer fitted by Baron et al. (2012).

The Algol system was observed twice during both the October 2011 and December 2012 observing runs. In both cases,
Table 3. Angular parameter estimates for Capella at different observation dates.

<table>
<thead>
<tr>
<th>Date</th>
<th>JD (2 400 000+)</th>
<th>Angular separation (mas)</th>
<th>Position angle (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Uncorrected</td>
<td>Corrected</td>
</tr>
<tr>
<td>2011-10-16</td>
<td>55852.0</td>
<td>57.1 ± 0.7</td>
<td>57.3 ± 1.1</td>
</tr>
<tr>
<td>2011-10-17</td>
<td>55853.0</td>
<td>56.5 ± 1.2</td>
<td>56.6 ± 1.4</td>
</tr>
<tr>
<td>2011-10-19</td>
<td>55855.0</td>
<td>56.0 ± 0.4</td>
<td>56.1 ± 0.9</td>
</tr>
<tr>
<td>2012-07-29</td>
<td>56139.0</td>
<td>39.2 ± 1.1</td>
<td>40.9 ± 2.2</td>
</tr>
<tr>
<td>2012-12-19</td>
<td>56281.8</td>
<td>45.1 ± 1.0</td>
<td>46.1 ± 2.4</td>
</tr>
<tr>
<td>2012-12-20</td>
<td>56282.8</td>
<td>44.3 ± 1.2</td>
<td>45.4 ± 2.5</td>
</tr>
</tbody>
</table>

Notes. The reference axes are defined by the segmented mirror orientation which is actually rotated compared to the northeast orientation. The uncorrected estimates do not take the rotation of the image plane and the scaling factor into account, while the corrected ones are the final estimates. Horizontal lines separate the three observing runs considered here.

multiple observations of the systems within a given observing run yield consistent calibration factors at the 2σ level or better (see Table 2). This confirms the expectation that the rotation of the pupil in comparison with the FIRST subpupils is stable over the duration of an observing run since the injection part of the set-up was not modified during the course of each run. In October 2011, uncertainties on the calibration factors are much greater on October 16 than on October 19, probably as a consequence of changes in r0 (see Table 1) and short atmospheric coherence time. While the latter could not be measured, the shorter integration times used on October 16, which results from a compromise between sensitivity and fringe visibility, is indicative of a shorter timescale for atmospheric turbulence. We therefore used the estimated position of Algol C regarding Algol A+B on October 19 to correct for the pupil rotation and scaling factor for all three dates of observation in October 2011. For the December 2012 observing run, we used the weighted average of both observations of Algol since they are similar in precision.

The final relative astrometry of the Capella system throughout our observations is shown in Fig. 5. The orbit computed from the model parameters fitted by Torres et al. (2009) is drawn for comparison. Table 3 presents both uncorrected and corrected (field rotation and scaling factor taken into account) estimates, along with their associated uncertainties. Most estimates agree with the predicted positions within the 1–σ range. However, the positions measured in 2011 seem to be affected by a small systematic error of about 2 mas along the north-south direction (see Fig. 5, bottom). It is plausible that this results from the baseline calibration, since all three points have been calibrated by the same astrometric estimate for the Algol system. Ideally, the calibrator should have been observed with sufficient accuracy on the three different dates.

3.3. Spectral model

Along with the astrometry of the binary, our analysis also yields a “spectrum” of the binary flux ratio, ρ(λ). We inspected the quality of the flux ratio spectra from each individual night and for each of the two separate V-grooves. As expected given seeing conditions, the flux ratios measured on December 2012 are of much worse quality than those from October 2011. Similarly, the July 2012 flux ratio spectrum is very noisy, owing to observations taken during early morning twilight. While the astrometric position estimates from these epochs benefit from the average of all spectral channels and are thus reasonably accurate, the flux ratio spectra obtained during the 2012 runs have been discarded for the spectral analysis. We therefore averaged all October 2011 datasets to produce a final flux ratio spectrum for the Capella binary system. The resulting final spectral resolution is about 1.5 pixel as determined from data taken using a monochromatic laser beam. Uncertainties on the flux ratio spectrum were estimated as the standard deviation of the mean over the datasets. These results are available in Table 4.

The flux ratio spectrum obtained with FIRST agrees with historical measurements of the binary taken within our
The columns headed dispersed observations reveal an overall slope that is consistent with data over a broader range and confirm that the cool wavelength range at the \( \leq 2\sigma \) level. Furthermore, our spectrally dispersed observations reveal an overall slope that is consistent with data over a broader range and confirm that the cool component of the system is increasingly brighter at longer visible wavelengths. We find that the flux ratio reversal occurs at a wavelength of 0.64 \( \pm \) 0.01 \( \mu \)m. In addition to its general slope,
the FIRST flux ratio spectrum reveals finer structures, such as a short dip at 0.655 μm and two broad dips around 0.69–0.75 μm and 0.78–0.84 μm. Both can be traced to the differences in effective temperature between the two stars, which leads to photospheric features of different depths: the first is Hα (the slight mismatch in wavelength results from a mild inaccuracy in our wavelength solution) while the last two are molecular bands (most notably TiO and CN) that are characteristic of cool photospheres. These spectral features are a direct confirmation that the infrared-bright component is cooler than the visible-bright one.

To quantify the constraint on stellar properties provided by the FIRST flux ratio spectrum, we use the most recent BT-Settl models1 partially published in a review by (Allard et al. 2012a) and described by Allard et al. (2012b). These model atmospheres are computed with the PHOENIX multipurpose atmosphere code version 15.5 (Allard et al. 2001) solving the radiative transfer in 1D spherical symmetry, with the classical approximations: hydrostatic equilibrium, convection using the mixing length theory, chemical equilibrium, and a sampling treatment of the opacities. The models use a mixing length as derived by the radiation hydrodynamic simulations of Ludwig et al. (2002, 2006) and Freytag et al. (2010, 2012) and a radius as determined by the Baraffe et al. (1998) interior models as a function of the atmospheric parameters (T_eff, log g, [m/H]). The reference solar elemental abundances used in this version of the BT-Settl models are those defined by Asplund et al. (2009). For solar metallicity and higher, no α element enhancement is required.

The PHOENIX library includes stellar spectra with a 100 K and 0.5 sampling in T_eff and log g, respectively. We explored the parameter space as follows: each model consisted of two pairs of stellar parameters (T_eff and log g) for each component. The model flux ratio was computed using the same sampling and resolution as the FIRST data and normalized so as to match the observed median flux ratio. Since the PHOENIX emission spectra are given per unit surface area, this normalization is equivalent to setting the ratio of stellar radii to match the median flux ratio best in our spectral bandpass. In principle, our analysis could consider this ratio as a free parameter in the fit instead. However, since the FIRST flux ratios are in good agreement with previous flux ratio estimates of the binary, we do not expect to gain additional insight into the ratio of stellar radii. We therefore decided to remove one free parameter from our fit by using this a priori normalization to ensure that the model fitting was primarily attempting to reproduce the global slope and finer spectral features, which only depend on the stellar effective temperatures and surface gravities. We believe that our data are more apt to constrain the latter. Nonetheless, we note that our normalization for the best fit models is consistent at the 1σ level with the stellar radii ratio of 0.737 ± 0.044 estimated by Torres et al. (2009).

We have thus created a grid of flux ratio spectra that depends on four parameters, the effective temperature and surface gravity of both components, while approximately maintaining the average stellar luminosity ratio in the FIRST bandpass. By performing a wide grid search around the stellar parameters derived by Torres et al. (2009), the best fitting model has the following parameters: T_eff = 5300 K, T_eff = 4700 K, and log g = log g = 2.0. This combination of stellar parameters yields a reasonably good match to the observed flux ratio spectrum (reduced χ^2 = 2.89, see Fig. 6 and Table 5). We note that there is another peak appearing in the likelihood distribution, which corresponds to a model with T_eff = 5500 K, T_eff = 4800 K and leads to a marginally poorer χ^2, providing a sense for the uncertainties on the derived stellar effective temperatures.

The stellar parameters derived here are significantly different from those estimated by Torres et al. (2009), although the effective temperatures are only 4–7% lower than their nominal values. As shown in Fig. 6, the higher effective temperatures proposed by Torres et al. (2009) also result in detectable molecular features in the flux ratio spectrum, although they are less marked than in our data (especially for the 0.78–0.84 μm feature). This issue can be partially alleviated by using synthetic stellar spectra that correspond to lower surface gravity strengths. However, the overall quality of the fit is much poorer (see Table 5).

One solution for improving the fit consists in assuming a metal-rich composition. Using the series of PHOENIX models computed for [m/H] = +0.5 (where elemental abundances are

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1 http://phoenix.ens-lyon.fr/fallard/
increased uniformly from the set of solar abundances), we find that the FIRST data are best fit with effective temperatures of 5600 and 4900 K and surface gravities of \( \log g_{\text{hot}} = 2.5 \) and \( \log g_{\text{cool}} = 2.5 \). This model is significantly better (reduced \( \chi^2 = 2.31 \), see Fig. 6) than the best fit model at solar metallicity, and it has stellar properties in good agreement with Torres et al. (2009). However, the super-solar metallicity is at odds with all the parameters adopted to mimic those from Torres et al. (2009) are slightly different from those given in their paper because of the discrete sampling of the PHOENIX model grid. The last line of the table gives the ratio of stellar radii derived from the scaling factor used to normalize the spectra as a first step of the modeling.

### Notes
The first two models are at solar metallicity, while the third assumes super-solar metallicity. All three models are shown in Fig. 6. The models used to predict the synthetic spectra are based on in-complete line lists and oscillator strengths from Plez (1998). The CN line list and oscillator strengths were adopted from the SCAN database (Jorgensen & Larsson 1990). The TiO molecule, whose features are frequent in a broad range of cool stars, is much better calibrated, so we conclude that the reason for the underprediction of these features by current atmospheric features most likely stems from the treatment of the CN molecule, either through the incompleteness of its line list or as a result of oscillator strengths that are too low.

### 4. Summary of findings and conclusion
To demonstrate the capabilities of a fibered aperture masking instrument like FIRST to provide valuable spectrally-dispersed information on binary systems whose separation is close to the diffraction limit, the results presented in this paper focused on the binary star Capella. Its separation is indeed comparable to the diffraction limit and its flux ratio close to unity at visible wavelengths. Capella was observed at three different epochs between 2011 and 2012 with FIRST-18 mounted on the 3 m Shane telescope of Lick Observatory (using its adaptive optics system as a fringe tracker). The secondary component was detected at or slightly below the diffraction limit of the telescope at visible wavelengths with an accuracy well below a tenth of the diffraction limit. This first achievement illustrates the high angular resolution capability of the instrument.

Using FIRST, we also directly measured, for the first time, the flux ratio of the binary system at a spectral resolution of \( R \sim 300 \) between 600 and 850 nm. This spectral range gives access to spectral features (H\( \alpha \) line, TiO, and CN bands) that are quite influential when comparing the observed flux ratio spectrum with predictions based on the PHOENIX library of synthetic spectra. The effective temperatures derived from this analysis are slightly offset (by -5% to -7%) from those estimated by Torres et al. (2009) based on the extensive literature on this system. While we cannot exclude a subtle bias affecting our flux ratio measurements arising from the fact that the flux ratio is close to unity, this discrepancy probably indicates that the photospheric models used to predict the synthetic spectra are based on incomplete line lists and/or underestimated oscillator strengths for molecules commonly found in G- and K-type giants (most likely CN). This conclusion illustrates the power of FIRST to provide valuable spectral information to characterize binary systems.

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### Table 5. Stellar parameters of the PHOENIX atmospheric models used in this analysis from Allard et al. (2012b) assuming the set of solar abundances from Asplund et al. (2009).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Nominal</th>
<th>Best fit</th>
<th>Best fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_{\text{hot}} ) (K)</td>
<td>5700</td>
<td>5300</td>
<td>5600</td>
</tr>
<tr>
<td>( T_{\text{cool}} ) (K)</td>
<td>4900</td>
<td>4700</td>
<td>4900</td>
</tr>
<tr>
<td>( \log g_{\text{hot}} )</td>
<td>3.0</td>
<td>2.0</td>
<td>2.5</td>
</tr>
<tr>
<td>( \log g_{\text{cool}} )</td>
<td>2.5</td>
<td>2.0</td>
<td>2.5</td>
</tr>
<tr>
<td>( \chi^2_{\text{hot}} )</td>
<td>4.37</td>
<td>2.89</td>
<td>2.31</td>
</tr>
<tr>
<td>( R_{\text{hot}}/R_{\text{cool}} )</td>
<td>0.703</td>
<td>0.723</td>
<td>0.726</td>
</tr>
</tbody>
</table>

Notes: The first two models are at solar metallicity, while the third assumes super-solar metallicity. All three models are shown in Fig. 6. The parameters adopted to mimic those from Torres et al. (2009) are slightly different from those given in their paper because of the discrete sampling of the PHOENIX model grid. The last line of the table gives the ratio of stellar radii derived from the scaling factor used to normalize the spectra as a first step of the modeling.

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1. Torres et al. (2009).
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