Spatial intensity interferometry on three bright stars

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ABSTRACT

The present Letter reports on the first spatial intensity interferometry measurements on stars since the observations at Narrabri Observatory by Hanbury Brown et al. in the 1970’s. Taking advantage of the progresses in recent years on photon-counting detectors and fast electronics, we were able to measure the zero-time delay intensity correlation \( g^{(2)}(\tau = 0, r) \) between the light collected by two 1-m optical telescopes separated by 15 m. Using two marginally resolved stars (\( \alpha \) Lyr and \( \beta \) Ori) with R magnitudes of 0.01 and 0.13 respectively, we demonstrate that 4-hour correlation exposures provide reliable visibilities, whilst a significant loss of contrast is found on \( \alpha \) Aur, in agreement with its binary-star nature.

Key words: techniques: interferometric

1 INTRODUCTION

Surpassing the angular resolution of the present ground-based largest optical telescopes, i.e. 8 to 10 m, in spite of the atmospheric turbulence, remains a challenge of modern observational astrophysics. Future 30-40 m extremely large telescopes, even equipped with laser-guided adaptive optics, will still be limited typically to 10 mas resolution in the visible. Aperture synthesis techniques are nowadays currently used to observe mas structures on the surface or around stars in the visible (Mourard et al. 2015; Garcia et al. 2016; Gomes et al. 2017). These interferometers are very sensitive but require a real-time control of the optical path difference (OPD) between the telescopes below the optical wavelength, a daunting task if the baseline is to be further extended to the km range and with increasing difficulty at short wavelengths and for faint stars.

An alternative solution is “intensity interferometry”, a technique based on the measurement of the intensity correlation function between light collected by several telescopes from a same source. This technique was successfully employed by Hanbury Brown and Twiss (HBT) in the 60’s and 70’s (Hanbury Brown & Twiss 1956; Hanbury Brown et al. 1974), but latter abandoned due to its intrinsic lack of sensitivity in terms of limiting magnitude. However, intensity interferometry presents the important advantage to be easier to implement, since the acceptable fluctuations of the OPD are not determined by the optical wavelength but by the temporal resolution of the detection chain: a typical resolution of 100 ps corresponds to a maximal OPD variation of 3 cm. As a consequence, intensity interferometers are essentially insensitive to atmospheric turbulence for detectors with temporal resolutions above a few ps (Hanbury Brown & Twiss 1958b; Tan et al. 2016). This fact, as well as the progress achieved in the last decades in the quantum efficiency of detectors and down-stream digital electronics, have sparked a renewed interest in intensity interferometry involving several research groups worldwide (Horch et al. 2013; Dravins 2016; Zampieri et al. 2016; Tan et al. 2016; Pilyavsky et al. 2017; Wang et al. 2018; Matthews et al. 2018; Rivet et al. 2018).

Recently, we reported the first measurement of the temporal intensity autocorrelation function from an unresolved star since the seminal work of HBT (Guerin et al. 2017). The present Letter presents the first re-implementation of a two-telescope intensity interferometer, accessing the spatial intensity correlation function from two 1-m optical telescopes separated by an East-West baseline of 15 m. The first measurements were done on two marginally resolved stars, \( \beta \) Ori (Rigel) and \( \alpha \) Lyr (Vega), to check the reliability of our setup. We also present our results on \( \alpha \) Aur (Capella), for which a loss of visibility is clearly observed, consistent with the binary nature of this object.
2 SETUP

2.1 Principle

To measure spatial intensity correlations, one needs to correlate intensities collected by two telescopes distant by \( r \). The quantity of interest is the time correlation function given by

\[
g^{(2)}(\tau, r) = \frac{\langle I(t)I(t + \tau) \rangle}{\langle I(t) \rangle \langle I(t + \tau) \rangle},
\]

where the brackets denote the average over times \( t \).

In ref. (Guerin et al. 2017), we used a single telescope and thus measured the temporal autocorrelation function \( g^{(2)}(\tau, r = 0) \). The shape of this function allows to identify the nature of the light source. For instance, a coherent field such as emitted by a laser yields \( g^{(2)}(\tau) = 1 \) for any \( \tau \). Thermal (chaotic) light with a coherence time \( \tau_c \) (inversely proportional to the spectral bandwidth \( \Delta \nu \)), such as detected from a star, yields a correlation function peaking at 2 for \( \tau = 0 \) and decaying to 1 for \( \tau \gg \tau_c \). The contrast of the correlation function (also called the “bunching peak”) is given by \( C = g^{(2)}(\tau = 0) - 1 \). For thermal and spatially unresolved light, \( C = 1 \). In situations where the coherence time can be resolved, the temporal correlation function can inform on the processes taking place in the light source, such as the temperature of a cold-atom sample (Nakayama et al. 2010; Eloy et al. 2018) or multiple scattering processes in a hot vapor (Dussaux et al. 2016).

When the source has a broad spectrum, however, the temporal resolution of the detection chain \( \tau_{det} \) is usually lower than \( \tau_c \) (i.e. \( \tau_c \ll \tau_{det} \)), in which case the correlation function is convoluted with the temporal response of the detection, yielding a bunching peak with a width set by \( \tau_{det} \). This leads to a reduced contrast \( C \approx \tau_c/\tau_{det} \), which has to be calibrated, either in the lab or on sky, with an unresolved (natural or artificial) star.

2.2 Instrumental setup

To achieve the measurements presented in this Letter, we used the two 1-m telescopes of the C2PU facility at the plateau de Calern site of Observatoire de la Côte d’Azur as illustrated in Fig. 1. These two telescopes are separated by a fixed, nearly East-West baseline of 15 m and their absolute positions are known through GPS differential measurements with 2σ uncertainties of \( \pm 1 \) cm in the horizontal plane and \( \pm 2 \) cm along the vertical direction. Coupling assemblies (CAs) collect, filter and inject the light from the telescopes into optical fibers, and allow monitoring the star’s position on auxiliary cameras. The CA was presented in (Guerin et al. 2017). In summary, it is composed of two cascaded focal reducers to decrease the focal spot size at the position of the fiber tip, plus a polarizer and two frequency filters of 10 nm and \( \Delta \lambda = 1 \) nm bandwidths respectively. The role of the spectral filters is to increase the width of the intensity correlation function \( \tau_c \approx \lambda_0^2/(2c\Delta \lambda) \approx 1 \) ps, where \( c \) is the speed of light and \( \lambda_0 = 780 \) nm is the central wavelength of the filters. The light collected by each telescope is then injected in a 20 m-long multimode optical fiber (MMF) connected to an avalanche photodiode (APD). The effective temporal resolution of the APDs is of the order of 500 ps (FWHM). Finally, the outputs of the APDs are sent to a time-to-digital converter (TDC) through 50Ω coaxial cables. To avoid the cross-talk of the TDC around zero delay between channels, we introduce a large electronic delay of about 200 ns by using different lengths for the two coaxial cables (2 m and 45 m respectively).

The experiment described in this Letter was performed using the “Time Tagger Ultra” TDC from Swabian Instruments. Compared to the TDC used in (Guerin et al. 2017), it presents several improvements. First, the true temporal correlation function is computed and recorded in real time, as well as the total photon flux. Second, the correlation artifact described in (Guerin et al. 2017) is absent, eliminating the need to subtract the correlation background from a “white” source. The timing resolution of this TDC is 29 ps (FWHM) and is not a limitation for this experiment since it is much better than the resolution of the APDs.

2.3 Visibility measurement

The squared visibility \( V^2 \) is given by the height of the temporal correlation function extracted using a Gaussian fit. However, during the tests performed in the laboratory using an unresolved artificial star (Guerin et al. 2017), we found small day to day fluctuations of the bunching peak. This hints to an additional, fluctuating source of convolution for the correlation peak, inducing a fluctuation of the detection resolution \( \tau_{det} \) and thus of the contrast \( C \). The origin of this fluctuation is at present not completely understood, but this problem can be overcome by measuring the area of the bunching peak instead of its height. This area \( A \) expressed in ps, does not depend anymore on \( \tau_{det} \) and gives access to the correlation time \( \tau_c \) with \( A \approx \tau_c \), with a multiplicative factor which depends on the precise spectral shape of the filter. Laboratory measurements of \( g^{(2)}(\tau, 0) \) on an artificial star gives \( A_0 = 1.37 \pm 0.05 \) ps, which serves as zero baseline calibration for following on-sky observations.

Figure 1. Experimental setup. The star light collected by two similar 1-m telescopes (T) separated by a 15-m baseline is coupled by the coupling assemblies (CA), into two multimode optical fibers (MMF) and detected by two avalanche photodiodes (APDs), connected via coaxial cables to a time-to-digital converter (TDC). A CCD camera is also connected to each CA in order to track the desired star.
Table 1. Main characteristics of the three stars used for this experiment.

| Name   | α2000 | δ2000 | R mag | I mag | Spectral type | Comment              |
|--------|-------|-------|-------|-------|---------------|----------------------|
| β Ori  | 05h 14m 32.27s | 08° 12’ 05.9”  | +0.13 | +0.15 | B8Iae | Blue supergiant |
| α Lyr  | 18h 36m 56.34s | +38° 47’ 01.3” | +0.07 | +0.10 | A0Vsa |                      |
| α Aur  | 05h 16m 41.36s | +45° 39’ 52.8” | -0.52 | -0.96 | G8III + G0III | Spectroscopic binary |

2.4 Data acquisition and analysis

As can be seen from Fig. 1, the position of the star in the sky determines the on-sky projected baseline (which varies between 9.6 and 15 m in our observations), and the optical path difference (OPD) between the two telescopes. This later quantity is important since it introduces an optical time delay \( t_d = \text{OPD}/c \). During the full observation period this delay can vary up to 38 ns, corresponding to an OPD variation of 11.5 m.

During the observation nights, we measured the correlation signal in real time and recorded it every 10 seconds. The knowledge of the absolute recording time and the star position allows us to compute both the projected baseline and the OPD for each recording period. The averaging over a given number of recordings is then performed by first time-shifting every recording by the corresponding optical delay \( t_d \), and then adding up all the shifted recordings. The electronic delay is also subtracted.

3 RESULTS AND DISCUSSION

3.1 Observation conditions

During the four nights from 10/10/2017 to 10/14/2017, we observed three bright stars: β Ori, α Lyr, and α Aur. Their main parameters are summarized in Table 1. The observational conditions are detailed in Table 2.

The stars β Ori and α Lyr have angular diameters of respectively \( \theta = (2.526 \pm 0.006) \) mas and \( \theta = (3.198 \pm 0.016) \) mas (uniform disk diameters, Baines et al. (2018)), which correspond to baselines of 77.7 m and 61.4 m to be fully resolved at \( \lambda_0 = 780 \) nm (first minimum of the spatial correlation function given by Eq. (2)). Since our maximal baseline is 15 m, the expected loss of squared visibility is at most 13% for β Ori and 20% for α Lyr. Thus, these stars were used as “calibration” sources to check the consistency of our observations and the reliability of our detection method. On the contrary, α Aur is a binary system whose individual components have roughly twice the apparent diameter of α Lyr or β Ori. In addition, the binary nature of the star system leads to oscillations of the visibility during the observation time, as will be further discussed in section 3.3.

3.2 Results on marginally resolved stars

We first present in Figs. 2a and 2b the correlation curves obtained for β Ori and α Lyr. As these stars are not resolved and the projected baseline variation is rather small, we show the data averaged over the full observation duration (4.3 h for β Ori and 11.1 h over three successive nights for α Lyr). The bunching peak is clearly seen for both stars.

We observe that the bunching peak from β Ori has a higher contrast than that from α Lyr, whilst its width is smaller. By comparing the three curves obtained for each night of observation on α Lyr, we also found some fluctuations of the height and width of the correlation peaks. As discussed in section 2.3, this phenomenon was also observed in the laboratory and we concluded that the measurement of the bunching peak area is more reliable than its amplitude at zero delay. As illustrated in Fig. 3. The measured area for the two stars and for different nights of observation are well consistent with each other.

We can now compare in Fig. 4 our data to the expected visibility curves of β Ori and α Lyr calculated using Eq. (2) and their known angular diameters (Baines et al. 2018). On this plot, the black square at zero baseline corresponds to the calibration of \( g^{(2)}(r,0) \) performed in the laboratory, \( A_0 = 1.37 \pm 0.05 \) ps (section 2.3). This value is used to normalize the computed squared visibility. The triangle and circle correspond to the fully averaged data for β Ori and α Lyr respectively. The horizontal error bars correspond to the variation of the projected baseline during the total observation time. The vertical error bars reflect the 1σ uncertainty on the area extracted from the fits. The signal-to-noise ratio (SNR) is 10 for α Lyr and 6 for β Ori (due to shorter integration time), and is well consistent by the shot-noise limit given by \( \text{SNR} = C \sqrt{N_c} \), where \( N_c = F^2 T \tau \) is the total number of coincidences accumulated during the integration time \( T \) in a time window \( \tau \), with \( F \) the detected photon flux per detector. The solid lines surrounding the shaded areas correspond to the theoretical uniform disk visibility curves for the two stars, given by

\[
V^2(r) = \left[ \frac{2J_1(\pi r/\lambda_0)}{\pi r/\lambda_0} \right]^2.
\]

For each pair, the upper and lower lines are normalized with the upper and lower bounds of the calibrated \( A_0 \). We see a good agreement between the measurements and the expected curves, without any free parameter, showing that we
can either use the laboratory measurement or the measurements on unresolved stars for the normalisation.

3.3 Results on α Aur

As to the observations on α Aur, the data was recorded during two nights (total duration of 12.5 h), with a high photon count rate of 4.9 Mcounts/s per detector. Fig. 2c shows the correlation peak corresponding to an averaging over the full dataset. As can be seen, the contrast of the bunching peak is strongly reduced but still measurable. The area of the bunching peak is now (0.25 ± 0.05) ps, about 4 times lower than for α Lyr and β Ori. This observation is an unambiguous signature that α Aur as a whole is resolved.

However, the detailed analysis is complicated by the fact that α Aur is a binary source. The visibility now depends not only on the projected baseline but also on the angular baseline between the binary components and the angle they make with the on-sky projection of the baseline (Hanbury Brown et al. 1967):

$$ V^2(r) = \frac{1}{(I_a + I_b)^2} \left[ I_a^2 V_a^2(r) + I_b^2 V_b^2(r) + 2I_aI_b V_a(r)V_b(r) \cos \left( \frac{2 \pi \vartheta \cos \psi}{\lambda_b} \right) \right]. \quad (3) $$

with $I_a$ and $I_b$ the intensities of the A and B components at 780 nm, $V_a(r)$ and $V_b(r)$ their respective visibility curves, $r$ the on-sky projection of the baseline, $\vartheta \simeq 55$ mas the angular separation between the two components and $\psi$ the angle between the on-sky projected baseline and the vector sepa-

Figure 2. Temporal correlation functions for two marginally resolved stars and one binary star (solid line: data, dashed line: Gaussian fit). a) β Ori. The integration time is 4.3 h. The average count rate per detector is 1.8 Mcounts/s. The projected baseline varied between 10.7 and 15 m. b) α Lyr. The total integration time is 11.1 h over three nights. The average count rate per detector is 2.3 Mcounts/s. The projected baseline varied between 9.6 and 14.3 m. c) α Aur. The total integration time is 12.5 h over two nights. The average count rate per detector is 4.9 Mcounts/s. The projected baseline varied between 11.5 and 15 m.

Figure 3. Area of the photon bunching peak in ps for β Ori and α Lyr for the different nights of observation. For each night the observation time is around 4 h. The error bars correspond to the 1σ uncertainty. All the values are consistent with each other within the error bars.

Figure 4. Area of the photon bunching peak for α Lyr (red circle) and β Ori (blue triangle) with their respective error bars ($A = 1.07 \pm 0.11$ ps and $A = 1.11 \pm 0.20$ ps respectively). The black square at zero baseline corresponds to a calibration of $g^{(2)}(r,0)$ performed in the laboratory using an artificial star ($A_0 = 1.37 \pm 0.05$ ps). The red and blue pairs of curves and shaded areas in between indicate the expected visibility curves for α Lyr and β Ori respectively.

Figure 5. Expected normalized squared visibility of α Aur during the two nights of observations. The continuous curves are computed by Eq. (3) convoluted by the pupil shape of each telescope, and black dots correspond to instants where data have been recorded. The horizontal dashed line show the averaged computed visibility for the observation. The measured visibility is represented in green as a 68% confidence interval.
ration of the two components. The visibility is expected to oscillate as a function of time, mainly because of the daily rotation of the on-sky projected baseline w.r.t. the A – B direction of the binary star. Since a Aur’s individual components have nearly identical luminosities \( I_1 = (84.5 \pm 8.6) \times L_{\odot} \) and \( I_2 = (76.3 \pm 6.3) \times L_{\odot} \) at 780 \pm 0.5 nm; estimation through a black body model with physical parameters from Torres et al. (2015), the contrast of the visibility oscillations is large, as shown in Fig. 5 for the two observation nights. Note that Eq. (3) is only valid when each telescope is too small to resolve the binary star, which is presently not completely the case. In particular, this induces a reduction of the correlation at zero baseline (Hanbury Brown & Twiss 1958a). This effect is taken into account for the calculations considering the size of the telescope as well as its central obstruction (approximated to 30 cm in diameter).

The SNR ratio of the data is too low to extract in a reliable way the evolution of the visibility as a function of time. Nevertheless we can compare the expected and measured visibilities averaged over the whole observing period. We get \( \langle V^2_{\mathrm{meas}} \rangle = 0.18 \pm 0.03 \) for the measured averaged normalized squared visibility, in fair agreement with the computed one \( \langle V^2 \rangle = 0.14 \).

4 CONCLUSION

We have reported in this Letter the first measurements of intensity correlations from two 1-m telescopes in the visible domain, since the Narrabri Observatory measurements achieved by Hanbury-Brown et al. 50 years ago. We show that in spite of the modest collecting surface of our telescopes and of our limited observation time (typically a few hours per target star), we measured the contrast of the bunching peak, alternatively the squared visibility, with a SNR ratio on the order of 10 on two early type stars: \( \alpha \) Lyr and \( \beta \) Ori of spectral types A and B respectively. With the bright binary G type star \( \alpha \) Aur, we have been able to measure a squared visibility as low as 14%, corresponding to the partial resolution of the individual components of the binary combined with min-max modulation of the visibility.

The present demonstration of intensity interferometry with rather modest telescopes opens a new window on very high angular resolution in visible wavelengths. It also confirms that intensity interferometry can be extended nowadays to red and IR wavelengths, probably to the H spectral band. Moreover, today’s time-transfer technologies enable the synchronization of separate telescopes as distant as several kilometers across. As demonstrated in this work, the focal instrument of individual telescopes can be directly replicated on as many telescopes as available and thanks to the improving time resolution of detectors and backbone digital correlators there is no limitation to extend baselines to several kilometers if not tens of kilometers. Alas, the longer the baselines, the lower the visibilities (or correlation contrast). Therefore the question of improving the SNR ratio becomes central. As suggested originally by Hanbury Brown himself (Hanbury Brown 1968), one can use many simultaneous spectral channels with a net gain of square root of their number. Recording several hundreds of spectral channels and the two polarization channels could gain 3 to 4 magnitudes. Then much larger telescopes in the 4–10 m class will bring 3–5 more magnitudes to cover a broad spectrum of stars. Finally the intrinsic advantage of intensity interferometry over amplitude interferometry is that its signal can be integrated night-to-night for a very long time without the limitation due to fringe-tracking.

Following this approach we currently extend our experiments to 3 telescopes interferometry with dual focal detectors working in two simultaneous polarizations and/or two spectral channels to compare correlation measurements between emission line and continuum wavelengths and to perform polarization-resolved interferometry.

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