The little-studied cluster Berkeley 90

I. LS III +46 11: a very massive O3.5 If* + O3.5 If* binary

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ABSTRACT

Context. It appears that most (if not all) massive stars are born in multiple systems. At the same time, the most massive binaries are hard to find due to their low numbers throughout the Galaxy and the implied large distances and extinctions.

Aims. We want to study: [a] LS III +46 11, identified in this paper as a very massive binary; [b] another nearby massive system, LS III +46 12; and [c] the surrounding stellar cluster, Berkeley 90.

Methods. Most of the data used in this paper are multi-epoch high-S/N optical spectra though we also use Lucky Imaging and archival photometry. The spectra are reduced with devoted pipelines and processed with our own software, such as a spectroscopic-orbit code, CHORIZOS, and MGB.

Results. LS III +46 11 is identified as a new very-early-O-type spectroscopic binary [O3.5 If* + O3.5 If*] and LS III +46 12 as another early O-type system [O4.5 V((f))]. We measure a 97.2-day period for LS III +46 11 and derive minimum masses of 38.80 ± 0.83 M⊙ and 35.60 ± 0.77 M⊙ for its two stars. We measure the extinction to both stars, estimate the distance, search for optical companions, and study the surrounding cluster. In doing so, a variable extinction is found as well as discrepant results for the distance. We discuss possible explanations and suggest that LS III +46 12 may be a hidden binary system, where the companion is currently undetected.

Key words. Binaries: spectroscopic — Dust, extinction — Open clusters and associations: individual: Berkeley 90 — Stars: early-type — Stars: individual: LS III +46 11 — Stars: individual: LS III +46 12

1. Introduction

Multiplicity is an endemic disease among O stars (Mason et al. 1998; Sana et al. 2013a; Sota et al. 2014). Indeed, it is difficult to find an O star that was born in isolation: among the sample of O7-O9.7 V-IV stars south of -20 deg, there is just one clear, currently single object, namely µ Col, which is however a known runaway and thus likely was born in a multiple system or compact cluster. Only a small fraction of the other types of O stars in the sample are apparently single but those cases are more luminous and can easily hide an e.g. main-sequence B-type companion in their glare. Both types of binarity, spectroscopic and visual, are common among O stars and combinations of both types (implying higher-order multiplicities) are also relatively frequent, usually in the form of hierarchical systems, with one pair in a close orbit and additional star(s) at larger separations. The OWN survey (Barba et al. 2010) has detected a peak around 10 days in the spectroscopic period distribution of 240 southern massive stars. Most of those systems will interact during their evolution and many mergers are expected (Sana et al. 2012). Even in those cases where interactions will not take place it is important to

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characterize the binarity of O stars since ignoring it can lead to biases in the measured properties, such as derived masses and predicted colors of small stellar populations or young clusters.

The issue of multiplicity among massive stars also affects the measurement of the stellar upper mass limit, since one has to make sure that a very luminous object is not in reality a combination of two or more objects, an issue that has produced a bias in the measured properties, such as derived masses and evolution.

The Sparce young open cluster Berkeley 90 (Fig. 1) is almost a year-old. Both objects are classified as OB stars, with accurate blue-violet spectral classification known in the Milky Way, HD 93 129 AaAb (Sota et al. 2014), and it is a multiple system located in the center of a dense stellar cluster. We clearly need to find more very massive stars to understand their properties and evolution.

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Table 2. Spectroscopic observation log for LS III +46 11. The date refers to the local evening.

| Date       | HD−2 400 000 Telescope | Wavelength range (Å) |
|------------|-------------------------|----------------------|
| 2009-11-01 | 55 137.317 CAHA-3.5 m | 3950-5050            |
| 2009-11-02 | 55 138.313 CAHA-3.5 m | 3950-5050            |
| 2009-11-03 | 55 139.320 CAHA-3.5 m | 3950-5050            |
| 2009-11-03 | 55 139.503 CAHA-3.5 m | 3950-5050            |
| 2009-12-05 | 55 171.380 OSN-1.5 m  | 5350-6750            |
| 2009-12-07 | 55 172.355 OSN-1.5 m  | 5350-6750            |
| 2009-12-09 | 55 175.317 OSN-1.5 m  | 5350-6750            |
| 2010-05-01 | 55 318.674 OSN-1.5 m  | 5350-6750            |
| 2010-05-17 | 55 363.659 OSN-1.5 m  | 5350-6750            |
| 2010-06-26 | 55 374.669 OSN-1.5 m  | 5350-6750            |
| 2011-06-13 | 55 726.513 WHT        | 3890-5570            |
| 2011-06-15 | 55 728.545 WHT        | 3890-5570            |
| 2011-09-12 | 55 817.381 WHT        | 3890-5570            |
| 2011-10-02 | 55 814.424 WHT        | 3890-5570            |
| 2011-10-03 | 55 813.443 WHT        | 3890-5570            |
| 2011-10-11 | 55 816.460 WHT        | 3890-5570            |
| 2012-09-09 | 55 814.597 WHT        | 3890-5570            |
| 2012-09-10 | 55 813.597 WHT        | 3890-5570            |
| 2012-09-11 | 55 816.460 WHT        | 3890-5570            |
| 2012-09-12 | 55 817.381 WHT        | 3890-5570            |
| 2012-10-03 | 55 814.424 WHT        | 3890-5570            |
| 2012-10-04 | 55 813.443 WHT        | 3890-5570            |
| 2012-10-06 | 55 819.485 NOT        | 3690-5590            |
| 2012-10-12 | 55 817.568 WHT        | 3890-5570            |
| 2013-09-30 | 55 818.791 HET        | 5311-6275 + 6396-7325 |
| 2013-11-15 | 55 881.601 HET        | 5311-6275 + 6396-7325 |
| 2013-11-27 | 55 883.590 HET        | 5311-6275 + 6396-7325 |
| 2014-08-08 | 56 878.584 NOT        | 3690-5590            |
| 2014-08-09 | 56 876.373 CAHA-2.2 m | 3925-9225            |
| 2014-08-10 | 56 875.572 NOT        | 3690-5590            |
| 2014-08-11 | 56 875.266 NOT        | 3690-5590            |
| 2015-03-03 | 57 085.717 CAHA-2.2 m | 3925-9225            |
| 2015-03-04 | 57 110.696 CAHA-2.2 m | 3925-9225            |

Table 3. Spectroscopic observation log for LS III +46 12. The date refers to the local evening.

| Date       | HD−2 400 000 Telescope | Wavelength range (Å) |
|------------|-------------------------|----------------------|
| 2011-06-15 | 55 726.513 WHT        | 3890-5570            |
| 2011-09-09 | 55 814.597 WHT        | 3890-5570            |
| 2011-09-10 | 55 815.443 WHT        | 3890-5570            |
| 2011-09-11 | 55 816.460 WHT        | 3890-5570            |
| 2011-09-12 | 55 817.381 WHT        | 3890-5570            |
| 2012-09-06 | 56 115.596 WHT        | 3910-5590            |
| 2012-09-07 | 56 115.596 WHT        | 3910-5590            |
| 2012-10-02 | 56 089.815 HET        | 5311-6275 + 6396-7325 |
| 2012-10-06 | 56 089.815 HET        | 5311-6275 + 6396-7325 |
| 2013-09-30 | 56 818.791 HET        | 5311-6275 + 6396-7325 |
| 2014-08-06 | 56 876.373 CAHA-2.2 m | 3925-9225            |
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2. Data

2.1. Spectroscopy

The spectroscopic data for LS III +46 11 used in this paper were obtained with six different telescopes and are listed in Table 2. Here we describe the data grouped under the different projects in which they were obtained.

1. GOSSS: the Galactic O-Star Spectroscopic Survey is described in Máiz Apellániz et al. (2011). The GOSSS spectra used here were obtained with the TWIN spectrograph of the 3.5 m telescope at Calar Alto (CAHA) and the ISIS spectrograph of the 4.2 m William Herschel Telescope (WHT) at La Palma. The spectral resolving power was measured in each case and determined to be between 2800 and 3400 (TWIN) and between 3900 and 5400 (ISIS). The typical S/N per resolution element of the data is 300. The spectral range of the WHT data includes both He ii λ4541.59 and He ii λ4511.53 while that of the CAHA-3.5 m data included only the former. GOSSS is also obtaining spectroscopy with the Alibareo spectrograph of the 1.5 m telescope at the Observatorio de Sierra Nevada (OSN) but its aperture is too small to obtain a good S/N in the blue-violet. However, we also obtained some OSN yellow-red spectra at R ~ 2000 in order to study He ii λ4511.53.

2. NoMaDS: the Northern Massive Dim Survey is described in Máiz Apellániz et al. (2012) and Pellerin et al. (2012). NoMaD spectra were obtained with the High Resolution Spectrograph of the 9.1-m Hobby-Eberly Telescope (HET) at McDonald Observatory. Their spectral resolving power is 30000 and all epoches include He ii λ4511.53 though two different setups were used on different occasions: one that goes from the violet to the yellow with a small gap (3811–4709 Å + 4758–
2013. LS III was processed with CHORIZOS, as explained in the next section. (typically 10 000) of very short exposures (typically, 30 ms), and AstraLux Sur (at the 3.6 m NTT telescope at La Silla). in instruments AstraLux Norte (at the 2.2 m CAHA telescope) massive stars we are conducting using the Lucky Imaging imaging data that are part of a visual multiplicity survey of used a Sloan- AstraLux results for individual stars are discussed in Sota et al. itself was presented in Ma´ız Apell´aniz (2010); the reader is referred to that paper for details on the data and processing. Later then combining them with a drizzle-type algorithm. The survey 2.3. Archival photometry We also compiled the IPHAS and 2MASS photometry of the Berkeley 90 and foreground populations. For the case of LS III +46 11, the 2MASS PSC gives \(J\) and \(H\) magnitudes but not a \(K_S\) value, where an X flag appears, indicating that “there is a detection at this location, but no valid brightness estimate can be extracted using any algorithm”. For LS III +46 12, which has similar NIR magnitudes (see Table 3), the 2MASS PSC gives the three magnitudes with good quality flags. We downloaded the 2MASS images to look into this issue. LS III +46 11 and LS III +46 12 have NIR magnitudes that make them slightly saturated (by \(-1 \) magnitude) in the 2MASS images (which have saturation levels of 9.0, 8.5, and 8.0 for \(J\), \(H\), and \(K_S\), respectively). For that reason, their 2MASS PSC magnitudes were obtained by aperture photometry in the 51 ms “Read_1” exposures which, unfortunately, are not publicly available. However, for such a small level of saturation only 1-4 pixels (depending on the star centering) are expected to be saturated so it should be possible to do differential (between the two stars) aperture photometry with an inner and an outer integration radius. We tested this on LS III +46 11 and LS III +46 12 using an inner radius of 1.5 pixels and an outer radius of 4.0 pixels and found \(\Delta J = 0.304\) and \(\Delta H = 0.412\), values that are within one sigma of those in the 2MASS PSC (0.281±0.031 and 0.424±0.025, respectively, see Table 3), lending credibility to the technique. We looked at the LS III +46 11 \(K_S\) radial profile and noticed no peculiarities so we applied the same technique, which yielded \(\Delta K_S = 0.499\). Therefore, we derive a value of \(K_S = 6.971 \pm 0.023\) for LS III +46 11, where we adopted as uncertainty the same value as for LS III +46 12. 3. Results 3.1. Spectral classification of LS III +46 11 and LS III +46 12 The top two plots of Figures 2 and 3 show two GOSSS spectra of LS III +46 11, one near maximum velocity separation and one close to the point where both stars have the same velocity. In the first plot, the spectra of the two components are virtually indistinguishable, with all the relevant stellar lines showing very similar ratios and widths. The only difference can be seen in the different absolute depths, the ones of the primary being \(\sim 10\) more intense than those of the secondary. Therefore, we assign the same spectral type to both components. We classified the spectra using MGB (Maiz Apellaniz et al. 2012) and v2.0 of the GOSSS standard grid (Maiz Apellaniz et al. 2014a). In the middle plot of Figure 2, He i \(\lambda 4471.507\) appears as a very weak line in comparison with He ii \(\lambda 4541.59\) and N iv \(\lambda 4057.75\) is in emission with a similar intensity as N iii \(\lambda 4640.64+4641.85\), indicating a spectral type of O3.5 (Walborn et al. 2002). He ii \(\lambda 4685.71\) has a P-Cygni profile (which appears to be present in both components, see the top plot) yielding a luminosity class of I since II is not defined at O3.5. Therefore, given the required flux (Table 2 in Sota et al. 2014), LS III +46 11 is an O3.5 II* + O3.5 II*. The bottom plot of Figure 2 shows a GOSSS spectrum of LS III +46 12. All the GOSSS spectra are consistent with a constant spectral type i.e. we detect no sign of the target being an SB2. The GOSSS spectra are not calibrated in absolute velocity (the spectra are left in the star reference frame) but a comparison with prominent ISM lines shows no sign of relative velocity shifts, so we do not detect an SB1 character for LS III +46 12, either. N iv \(\lambda 4057.75\) is not seen in emission in the spectrum of LS III +46 12 and He i \(\lambda 4471.507\) is significantly

Note that the absorption component is only slightly blueshifted.
Fig. 2. Sample GOSSS spectra of LS III +46 11 and LS III +46 12 in the classical blue-violet spectral classification range. The top spectrum shows an example of LS III +46 11 near maximum velocity separation, the middle one an example of LS III +46 11 near minimum velocity separation, and the bottom one an example of LS III +46 12. The three cases show WHT data with the original spectral resolving power.

Table 4. LS III +46 11 spectroscopic binary results for $\Delta v \equiv v_2 - v_1$. $K_{12}$ is the radial velocity amplitude of the relative orbit.

| Parameter | Value   |
|-----------|---------|
| $P$       | 97.193 \pm 0.010 days |
| $T_0$     | 56 002.504 \pm 0.088 HJD−2 400 000 |
| $K_{12}$  | 237.3 \pm 1.2 km/s |
| $e$       | 0.5685 \pm 0.0036 |
| $\omega$  | 124.89 \pm 0.62 degrees |
| $a_{12} \sin i$ | 1.7438 \pm 0.0077 AU |
| $(M_1 + M_2) \sin^3 i$ | 74.9 \pm 1.0 M$_\odot$ |
| $n_{\text{spec}}$ | 70 |
| $n_{\text{red}}$ | 65 |
| $\chi^2_{\text{red}}$ | 1.43 |

stronger than in LS III +46 11, yielding a spectral type of O4.5. He II $\lambda 4685.71$ is quite deep, so the luminosity class is V. Since N III $\lambda 4640.64+4641.85$ is clearly in emission, C III $\lambda 4647.419+4650.246+4651.473$ is weak, and there are no signs of line broadening, the final spectral type is O4.5 V((f)).

Note that N IV $\lambda 5200.41+5204.28+5205.15$ is seen in absorption in all cases, as expected for these spectral types (Gamen & Niemelä 2002).

Fig. 3. Same as Fig. 2 for the wavelength range around He II $\lambda 5411.53$, the primary line we use for the stellar velocity measurements.
and plotted in the left panel of Figure 4. In some cases with identification confusion we used a $\Delta v$ of zero with large error bars. The orbit obtained with $\Delta v$ has a good fit ($\chi^2_{red} = 1.43$), a period consistent with the initial estimate, a relatively large eccentricity (as expected), and a very large minimum system mass (uncorrected for inclination) of 74.9 M$_\odot$.

A second analysis was carried out with the separate $v_1$ and $v_2$ measurements. For this second analysis we excluded the CAHA-3.5 m spectra (for which we only had He ii $\lambda4541.591$ and were not calibrated in absolute velocity), the OSN-1.5 m spectra (also uncalibrated in absolute velocity and with identification confusion in all cases, since we always caught LS III +46 11 near $\Delta v = 0$ with that configuration), and the WHT spectra with identification confusion. Results are displayed in Table 5 and plotted in the right panel of Figure 4. The value of $\chi^2_{red}$ is even better than for the first analysis and the results are overall compatible. The uncertainties of $P$, $T_0$, $e$, and $\omega$ are slightly larger due to the exclusion of some epochs. The mass ratio is close to the intensity ratio of the He ii $\lambda4541.53$ or He ii $\lambda4541.591$ lines and in the same sense; the component with the stronger lines is the most massive.

The values of $v_1$ and $v_2$ in Table 5 indicate that the LS III +46 11 center-of-mass radial velocity is in the range between -21 km/s and -17 km/s using the He ii $\lambda4541.53$. Fitting Gaussians to the LS III +46 11 high-resolution spectra with better S/N and lowest velocity separation also yield values in that range. However, doing the same with other lines gives different values: -27.2 $\pm$ 2 km/s for He i $\lambda5875.65$, -23.4 $\pm$ 4 km/s for O iii $\lambda4959.25$, and -11.3 $\pm$ 3 km/s for He ii $\lambda8236.79$. These discrepancies are not uncommon when analyzing early-type O stars due to the intrinsic width of their lines and the effect of winds. We can conclude that the true center-of-mass radial velocity of LS III +46 11 is between -25 km/s and -15 km/s without being able to provide a more precise measurement at this time.

We also analyzed the velocity of LS III +46 12 using the four high-resolution epochs listed in Table 5. We were unable to detect clear radial velocity variations at a level of 10 km/s or higher but with such a small number of epochs it is not possible to ascertain the spectroscopic binary of the system. We measured the radial velocity of the system using the same four spectral lines as for LS III +46 11 and obtained a smaller range between -16 km/s and -10 km/s. The better agreement between lines is possibly caused by the weaker winds in the dwarf compared to the supergiant pair. These results are consistent with LS III +46 12 being a spectroscopic single with the same center-of-mass radial velocity as LS III +46 11 as the stronger winds of the latter likely bias its measured velocity towards more negative (blueshifted) values. Also, the experience with LS III +46 11 and other systems indicates that we should not exclude the possibility of LS III +46 12 being a spectroscopic system within a period of months or longer.

Table 5. LS III +46 11 spectroscopic binary results for $v_1$ and $v_2$. $K_1$ and $K_2$ are the radial velocity amplitudes of each orbit.

| Parameter | Value |
|-----------|-------|
| $P$       | 97.168 $\pm$ 0.025 days |
| $T_0$     | 56 002.80 $\pm$ 0.25 HJD – 2 400 000 |
| $K_1$     | 112.7 $\pm$ 1.2 km/s |
| $K_2$     | 122.9 $\pm$ 1.3 km/s |
| $e$       | 0.5627 $\pm$ 0.0061 |
| $\omega$  | 126.1 $\pm$ 1.2 degrees |
| $v_1$     | -17.68 $\pm$ 0.98 km/s |
| $v_2$     | -20.88 $\pm$ 1.04 km/s |
| $a_1 \sin i$ | 0.8325 $\pm$ 0.0078 AU |
| $a_2 \sin i$ | 0.9073 $\pm$ 0.0081 AU |
| $M_1^i \sin^i i / (M_1 + M_2)^2$ | 8.15 $\pm$ 0.98 M$_\odot$ |
| $M_2^i \sin^i i / (M_1 + M_2)^2$ | 10.55 $\pm$ 0.28 M$_\odot$ |
| $M_1/M_2$ | 0.9175 $\pm$ 0.0095 |
| $M_1 \sin^i i$ | 38.80 $\pm$ 0.83 M$_\odot$ |
| $M_2 \sin^i i$ | 35.60 $\pm$ 0.77 M$_\odot$ |
| $n_{epochs}$ | 44 |
| $n_{tot}$ | 80 |
| $\chi^2_{red}$ | 0.95 |

3.2. The spectroscopic orbit of LS III +46 11

Most spectroscopic orbits for OB stars are studied with He i lines (or even with metallic lines for B stars) because they are intrinsically narrower than He ii lines. However, for a system composed of two O3.5 stars He i lines are not practical because they are too weak and we are forced to resort to the broader He ii line. The strongest He optical absorption lines in an O3.5 II* are He ii $\lambda4541.591$ and He ii $\lambda4541.53$. The large extinction experienced by LS III +46 11 (see below) makes a given S/N easier to attain with the latter than with the former, so we selected He ii $\lambda5411.53$ as our primary line. Note, however, that the CAHA-3.5 m spectra do not include it. In those cases we used He ii $\lambda4541.591$ instead to measure the $\Delta v \equiv v_2 - v_1$, the velocity difference between the primary and the secondary. Also note that the CAHA-3.5 m and OSN-1.5 m spectra were not calibrated in absolute velocity and that the WHT spectra were calibrated using ISM lines (instead of the lamps) present in both the WHT and the high-resolution spectra (which were calibrated using lamps).

All the epochs were fitted simultaneously with an IDL code by leaving the intensity and width of each component fixed (allowing for the different resolutions of each spectrograph) and fitting a four-component Gaussian for He ii $\lambda4541.53$ (the two stellar components plus the two DIBs at 5404.56 Å and 5418.87 Å, with the DIBs fixed at the same velocity for all epochs) and a two-component Gaussian for He ii $\lambda4541.591$. The initial period search was conducted using an IDL implementation of the information entropy algorithm of Cinccota et al. (1995). The orbit fitting itself (including the final period calculation) was done independently by two of us: [a] J.M.A. using a code developed by himself with the help of a previous routine written by R.C.G. and [b] R.H.B. using an improved version of the Bertaux & Grobben (1995) code. Results were compared and found to be compatible, so only the first ones will be reported here.

A first analysis was carried out with $\Delta v \equiv v_2 - v_1$ and all the observations in Table 2. Results are displayed in Table 4 and plotted in the left panel of Figure 4. In some cases with $\Delta v$ close to zero it is not possible to distinguish which component was the one with the larger velocity, since the two components are blended into a single Gaussian and, given the similar fluxes,
Fig. 4. Phased radial velocity curves for $\Delta v$ (left) and $v_1 + v_2$ (right). The color code identifies the telescope. Note that the left plot includes all data points while the right plot excludes the two telescopes without accurate absolute velocity calibration (CAHA-3.5 m and OSN-1.5 m).

Fig. 5. Best SED CHORIZOS fits for LS III +46 11 (left, luminosity class of 1.0 used) and LS III +46 12 (right, luminosity class of 5.0 used). Blue data points are used for the input photometry (vertical error bars indicate photometric uncertainties, horizontal ones approximate filter extent) and green stars for the synthetic photometry.

quantity is defined in an analogous way to the spectroscopic equivalent but instead of being discrete it is a continuous variable that varies from 0.0 (highest luminosity for that $T_{\text{eff}}$) to 5.5 (lowest luminosity for that $T_{\text{eff}}$). Note that the range is selected in order to make objects with spectroscopic luminosity class V (dwarfs) have LC≈5 and objects with spectral luminosity class I have LC≈1. For O stars the spectral energy distributions (SEDs) are TLUSTY (Lanz & Hubeny 2003).

- The extinction laws were those of Maíz Apellániz et al. (2014b), which are a single-family parameter with the type of extinction defined by $R_{5495}$. The amount of extinction is parameterized by $E(4405 - 5495)$. See Maíz Apellániz (2013a) for their relationship with $R_V$ and $E(B-V)$ and why
those quantities are not good choices to characterize extinction.
- The $T_{\text{eff}}$-spectral type conversion used is an adapted version of [Martins et al. (2005)] that includes the spectral subtypes used by [Sota et al. (2011, 2014)].
- $T_{\text{eff}}$ and LC were fixed while $R_{5495}$, $E(4405-5495)$, and $log d$ were left as free parameters. The values of the $T_{\text{eff}}$ were estimated from the used $T_{\text{eff}}$-spectral type conversion (see previous point). For LC we explored a range of possible values by doing CHORIZOS runs with 0.0, 0.5, 1.0, 1.5, and 2.0 for LS III +46 11 and runs with 4.0, 4.5, 5.0, and 5.5 for LS III +46 12.

The CHORIZOS results are shown in Table 6 and the best SEDs are plotted in Figure 5 along with the input and synthetic photometry.

- As expected, the different runs for a given star with different values of LC give nearly identical results for $\chi^2_{\text{red}}$, $R_{5495}$, and $E(4405-5495)$ and only differ in $log d$. This happens because the optical+NIR colors of O stars are nearly independent of luminosity for a fixed $T_{\text{eff}}$. Therefore, here we will concentrate on the results for LC=1.0 (LS III +46 11) and LC=5.0 (LS III +46 12) and consider the others runs only when discussing the distance.
- The values of $\chi^2_{\text{red}}$ indicate that the fit is good, even for two cases such as these where the extinction is considerable. We also ran alternative CHORIZOS executions using the Cardelli et al. (1989) and Fitzpatrick (1999) extinction laws. For Cardelli et al. (1989) the $\chi^2_{\text{red}}$ were similar, as expected for stars with moderate extinction with broad-band photometry and $R_{5495}$ values close to the canonical 3.1. For Fitzpatrick (1999) the $\chi^2_{\text{red}}$ were significantly worse (by a factor of $\approx 2$). Therefore, these results are another sign of the validity of the [Maiz Apellániz et al. (2014)] extinction laws for Galactic targets.
- The two stars show values of $R_{5495}$ which are compatible between them and only slightly larger than the canonical value of 3.1. Therefore, the same type of dust appears to lie between each star and us and the grain size is typical for the Milky Way.
- The LS III +46 11 extinction is significantly higher than that of LS III +46 12, which explains the similar magnitudes of the two objects despite LS III +46 11 being expected to be intrinsically more luminous and located at the same distance. This result also implies that there is significant differential extinction within the Berkeley 90 field. The value of $E(4405-5495)$ for LS III +46 12 is close to the $E(B-V) = 1.15$ result for Berkeley 90 of Tadross (2008).

- The values for $log d$ listed are the uncorrected CHORIZOS output and are equivalent to spectroscopic parallaxes. They do not take into account the fact that LS III +46 11 is an SB2 system with two components with similar luminosities while LS III +46 12 is apparently single. Therefore, the $log d$ values for LS III +46 11 have to be increased by $\approx \log \sqrt{2} = 0.151$. This implies that the derived distances for LS III +46 11 and LS III +46 12 are incompatible. Another way to look at the discrepancy is that if we use the extinction-corrected apparent Johnson V magnitude ($V_{\text{app}}$) for LS III +46 11 and apply $a = 2.5\log 2 = 0.753$ correction, we end up with two stars with $V_{\text{app}}$ values between 6.1 and 6.2, not brighter but actually slightly fainter than LS III +46 12. In other words, if the three stars are at the same distance, we would require the two objects with spectroscopic class I to be fainter than the object with spectroscopic class V. We analyze the distance issue later on.

### Table 6. Results of the CHORIZOS fits for LS III +46 11 and LS III +46 12.

| Quantity | LS III +46 11 | LS III +46 12 |
|----------|---------------|---------------|
| $T_{\text{eff}}$(K) | 41 300 | 41 900 |
| luminosity class | 1.0 | 5.0 |
| $\chi^2_{\text{red}}$ | 1.36 | 1.42 |
| $R_{5495}$ | $3.303 \pm 0.058$ | $3.377 \pm 0.040$ |
| $E(4405-5495)$ (mag) | $1.653 \pm 0.020$ | $1.255 \pm 0.011$ |
| $A_V$ (mag) | $5.475 \pm 0.037$ | $4.272 \pm 0.021$ |
| $V_{\text{app}}$ (mag) | $5.414 \pm 0.021$ | $5.995 \pm 0.017$ |
| $log d$ (pc, min) | 3.308 | 3.103 |
| $log d$ (pc, used) | 3.407 | 3.172 |
| $log d$ (pc, max) | 3.525 | 3.276 |

$\chi^2_{\text{red}}$ is the difference between the brightest star in the AstraLux Norte images (either LS III +46 11 or LS III +46 12) and the rest of the detected point sources. Note that the AstraLux Norte images are not absolutely calibrated, so only differential photometry is provided; hence, all the data refer to stellar pairs. Nevertheless, the photometry in the i and z bands for the two bright stars can be derived from the best SED in the previous subsection: LS III +46 11 A has zero-point-corrected AB $i$ and z magnitudes of 9.549 and 9.017, respectively, and LS III +46 12 A has zero-point-corrected AB $i$ and z magnitudes of 9.371 and 9.043, respectively. Table 6 gives the 2MASS $JHK_S$ magnitudes for the stars in the AstraLux images. All are detected except for LS III +46 11 F, the dimmest star in the AstraLux image. Note that the 2MASS magnitudes are not complete, as usual for moderately crowded fields such as this one.

The most relevant result is that LS III +46 11 has no visual companions within 11′′ and that LS III +46 12 has just one dim companion 6′′ away. From the photometric point of view, this means that the analysis in the previous subsection does not appear to include additional stars, so one can refer to the photometry of LS III +46 11 and LS III +46 12 as indistinguishable (as we have done in the previous paragraph) and the same can be said about LS III +46 12 and LS III +46 12 A. From the physical point of view, this means that (barring any undetected components) LS III +46 11 is a double system but likely not a higher-order one, since F or C (the closest companions) are likely to be unbound, especially considering that their environment is the center of a cluster. On the other hand, LS III +46 12 B is ~10 0000 AU in the plane of the sky away from A and could possibly be bound [Maiz Apellániz (2010)]. There is also another component visible in the 2MASS images (but not listed in Tables 7) because it fell just outside the 25′′×25′′ AstraLux field.

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1. The largest difference takes place in the $K_s$ band due to the wind contribution but that effect is not taken into account in the TLUSTY SEDs and is only expected to be of the order of 0.01 magnitudes for the cases of interest here.

2. LS III +46 11 A includes two spectroscopic components but their separation, as previously derived, is of the order of 1 mas, two orders of magnitude below what can be resolved with AstraLux Norte. See Fig. 2 in [Maiz Apellániz (2010)] for the values of separations and magnitude differences that AstraLux Norte can resolve.
in Fig. 6.

cross-matched our selection with the IPHAS catalogue. As the bright nebulosity, we have only accepted sources with a 2MASS counterpart within a 0\arcsec. Furthermore, we have set an upper limit on the separation for the targets detected in the AstraLux images. ABC flags are used for normal detections (with increasingly larger uncertainties), U flags for upper limits on magnitudes, and T for measurements done in this work.

Table 7. AstraLux results for LS III +46 11 and LS III +46 12.

| Star      | 2MASS ID | J (mag) | H (mag) | Ks (mag) | Flag |
|-----------|----------|---------|---------|----------|------|
| LS III +46 11 A | J20351264+4651212 | 7.65±0.023 | 7.19±0.018 | 6.97±0.023 | AA  |
| LS III +46 11 B | J20351402+4650549 | 12.326 | 12.050±0.054 | 11.821±0.053 | UAA |
| LS III +46 11 C | J20351389+4651065 | 13.402±0.049 | 12.847±0.066 | 12.585±0.070 | AAE |
| LS III +46 11 D | J20351436+4650562 | 12.614 | 12.638±0.033 | 12.235±0.030 | UAA |
| LS III +46 11 E | J20351405+4651025 | 14.295±0.062 | 13.373±0.049 | 12.990±0.050 | AAE |
| LS III +46 11 F | undetected | | | | |
| LS III +46 12 A | J20351857+4650028 | 7.93±0.021 | 7.618±0.017 | 7.470±0.023 | AAA |
| LS III +46 12 B | J20351823+4650072 | 10.333 | 10.158 | 12.551±0.205 | UUC |
| LS III +46 12 C | J20351786+4650112 | 14.450±0.124 | 13.466±0.134 | 13.242±0.050 | BBA |

Table 8. 2MASS photometry for the stars detected in the AstraLux images. ABC flags are used for normal detections (with increasingly larger uncertainties), U flags for upper limits on magnitudes, and T for measurements done in this work.

Norte field of view) 7′′ to the E of LS III +46 12 A, thus increasing the probability of the existence of a bound companion.

3.5. Berkeley 90 photometry

The area of Berkeley 90 is immersed in bright nebulosity (Sh 2-115, Sharpless 1959), indicating the existence of sources with large ionizing fluxes, but the cluster has surprisingly received very little attention. We have used photometric data from 2MASS (Skrutskie et al. 2006) and IPHAS (Barentsen et al. 2014) to study its properties. We have selected 2MASS sources within 3′ of the nominal center of the cluster, as given in SIMBAD. We have rejected stars with bad quality flags, and cross-matched our selection with the IPHAS catalogue. As the IPHAS catalogue contains many spurious sources in areas of bright nebulosity, we have only accepted sources with a 2MASS counterpart within a 0′.6 radius. The QH parameter, defined as $Q_{BH} = (J - H) - 1.8 \times (H - K_s)$, is very effective at separating early and late-type stars (e.g., Comerón & Pasquali 2003, Negueruela & Schurach 2007), with early-type stars showing values ≈ 0.0. We select objects with $Q_{BH} < 0.08$ as candidate early-type stars (see Negueruela & Schurach 2007), though emission-line stars also display negative values due to their $K_s$ excesses. The candidates are clearly concentrated towards the cluster center, confirming that they mainly represent the cluster population. The $K_s/(J - K_s)$ diagram for the resulting selection is displayed in Fig. 6.

Possible cluster members show a broad distribution in $(J - K_s)$. Three objects with $(J - K_s) < 0.4$ are located away from the cluster and may be foreground stars. Interestingly, LS III +46 12 has the second lowest $(J - K_s)$ of all possible members, with 0.46 ± 0.03, while the location of LS III +46 11 in Fig. 6 shows that it is more reddened (as we already knew from the CHORIZOS analysis). We assume that the bulk of cluster members is given by the vertical strip extending between $(J - K_s) = 0.45$ and $(J - K_s) = 0.9$. This is confirmed by their concentration in the IPHAS $(r' - i')/(r' - H\alpha)$ diagram (Fig. 7), where all except three are distributed in a narrow strip with $0.7 \leq (r' - i') \leq 1.05$ that follows the reddening vector, and the vast majority have $0.8 \leq (r' - i') \leq 1.0$. The main concentration of cluster members, lying between LS III +46 11 and LS III +46 12, shows only a small spread in color, while the stars lying immediately adjacent to LS III +46 11 both to the North and West display higher values. The average $(J - K_s)$ for all stars with values between 0.45 and 0.9 is 0.67, with a standard deviation $\sigma = 0.12$, showing that the objects are evenly distributed between these values and therefore defining a typical reddening for the cluster is meaningless.
In spite of the presence of three early O-type stars (two in LS III +46 11 and at least one in LS III +46 12), Berkeley 90 seems to contain very few OB stars. Only one photometric member is sufficiently bright in $K_S$ to be a late-O star, 2MASS J20350798+4649321 (Fig. 1), and this object has a position in the PHAS diagrams consistent with being an emission-line star (it is the object marked with both a blue circle and a red-star symbol in Figs. 5 and 7). The bulk of the population starts almost 3 magnitudes below LS III +46 12, at $K_S \approx 10.5$, an intrinsic magnitude roughly corresponding to a B1 V spectral type.

### 4. Discussion

O stars earlier than type O4 are very scarce in the Galaxy. Prior to this work, there were only two examples known in the northern hemisphere, Cyg OB2-7 and Cyg OB2-22 A (Walborn et al. 2002, Sota et al. 2011). Given that we know so few very massive stars, it is crucial to keep searching for them to increase our statistics if we want to establish what is the stellar upper mass limit and its dependence on metallicity and environmental conditions.

We have shown that LS III +46 11 as a very massive eccentric binary composed of two near-twin stars. A few years ago this may have been seen as a fluke but several similar systems have been discovered recently.

- **HD 93 129** AaAb (Nelan et al. 2004, 2010; Maiz Apellaniz et al. 2005, 2008; Sota et al. 2014) may be even more massive, given that the primary is of spectral type O2 if*, but the secondary is one magnitude fainter and the orbit is yet undetermined and appears to be decades long.
- Cyg OB2-9 (Nazé et al. 2012) O5-5.5 I + O3-4 III has a very similar mass ratio and a somewhat larger eccentricity, its $(M_1 + M_2)\sin^3 i$ is only slightly lower, its period is an order of magnitude larger, and the spectral types are slightly later.
- R139 (Taylor et al. 2011) O6.5 Iaf + O6 Iaf is also similar to LS III +46 11 in terms of period, eccentricity, and mass ratio but the two stars are mid-O supergiants and their lower mass limits are significantly higher, between 60 and 80 $M_\odot$. Those masses indicate that not all objects above 60 $M_\odot$ are WNe stars (of course, as long as we do not know the inclinations in this and other cases, we will not know what the true masses are).
- Two additional examples of very massive stars in elliptical orbits whose large eccentricity made the discovery of their binarity difficult are WR 22 = HD 92740 (Moffat & Seggewiss 1978; Conti et al. 1979; Schweickhardt et al. 1999, WN7 + O8-9.5 III), and HD 93 162 (Gamen et al. 2008; Sota et al. 2014, O2.5 If*/WN6 + OB).
- There are also very massive twin systems in shorter, near-circular orbits such as NGC 3603-A1 (Moffat et al. 2004; Schnurr et al. 2008, WN6ha + WN6ha), WR 20a (Rauw et al. 2004; Bonanos et al. 2004; Crowther & Walborn 2011, O3 If*/WN6 + O3 If*/WN6), and Pismis 24-1 (Maiz Apellaniz et al. 2007, O3.5 If* + O4 III(f) + ...). The latter also includes a third very massive component in a long orbit.
- All of those systems are located in regions with large numbers of O stars (Carina Nebula; Cygnus OB2; 30 Doradus; NGC 3603; Westerlund 2; and, to a lesser extent, Pismis 24).
LS III +46 11 is the oddity in that respect, being located in a significantly less massive cluster or association. In that respect, a more similar case may be HD 150136, which is apparently less evolved but is a triple system [O3-3.5 V((f*)) + O5.5-6 V((f*)) + O6.5-7 V((f*))] with a most massive star of 53±10 M⊙ in a relatively small cluster, NGC 6193, with another nearby star, HD 150135 [O6.5 V((i)x)], yielding a similar makeup to that of Berkeley 90 (Niemelä & Gamen 2005; Mahy et al. 2012; Sana et al. 2013b; Sánchez-Bermúdez et al. 2013; Sota et al. 2014).

All of the cases mentioned above refer to distant very massive stars (Cyg OB2-9 and HD 150136 are the closest ones but they are beyond 1 kpc) but what should be even more surprising is that some of the brightest and closest O stars in the sky have been recently discovered to have eccentric companions. That is, is that some of the brightest and closest O stars in the sky have not these systems been discovered before? There are two reasons: eccentric systems require extensive spectroscopic monitoring since their velocity differences may be too small to be detected during a large fraction of their orbits (as it happened with LS III +46 11) and in some cases interferometry is the only way to detect their multiplicity because of their large semi-major axes. It has not been until the last decade that large-scale spectroscopic monitoring of many O stars has started and that interferometric technology has allowed similar surveys using those techniques. However, many systems still remain outside the reach of such surveys so discoveries should continue in the following years.

Our data cannot provide conclusive results on the masses of LS III +46 11 and LS III +46 12. Without eclipses, we cannot accurately measure the inclination of the LS III +46 11 orbit and our keplerian masses of 38.80±0.83 M⊙ and 35.60±0.77 M⊙ have the sin^3 i factor included in them, making them just lower limits. Note that the star is not present in the public release of the Northern Sky Variability Survey (Woźniak et al. 2004) and that the time coverage in the SuperWASP (Pollacco et al. 2006) public archive is very limited, so a thorough search for eclipses is not possible at this time. In any case, eclipses are unlikely, since the large separations in the orbit would require an inclination very close to 90 degrees in order for them to take place. The inclination could be constrained in the future with broadband polarimetry or through the phase-dependent behaviour of excess emission from colliding winds.

For evolutionary masses, we have a different problem: our results for the spectral types and distances are inconsistent. There are three possible explanations:

1. A straightforward interpretation of the CHORIZOS results place LS III +46 11 at a log d between 3.45 and 3.67 (in parsecs, after correcting for the existence of two stars) and LS III +46 12 at a log d between 3.10 and 3.28. Therefore, one possibility would be that both objects are physically unrelated and just the result of a chance alignment. In this case, the luminosity classification criteria for early-type O stars would retain their physical meaning and there would be no need to invoke the existence of undetected multiple systems. Nevertheless, we judge this possibility to be highly unlikely, given the small number of early-type O stars that exist and the existence of the underlying cluster Berkeley 90. In any case, this hypothesis will be tested soon once the Gaia parallaxes become available.

2. An alternative would place both LS III +46 11 and LS III +46 12 at a log d of 3.4, consistent with the 2MASS photometry of Berkeley 90, but would require that the current luminosity classification criteria for O stars based on the depth of He II λ4868.71 does not really reflect a function or luminosity but instead is just a measurement of wind strength. We consider this option unlikely, as there are both theoretical reasons why (for the same T_e and metallicity) wind strength should strongly correlate with luminosity and observational data that corroborate that association (e.g., Walborn et al. 2014). This hypothesis could be tested by obtaining a good-S/N high-resolution spectrum of LS III +46 12 and modelling it with e.g. FASTWIND or CMFGEN. Those codes derive gravity from a fit to the Balmer line profiles which is independent of He II λ4868.71.

3. A third option is that LS III +46 12 is another near-twin binary system composed of two very-early-type O dwarfs. In this scenario, log d would be in the 3.40-3.45 range, marginally consistent with the spectroscopic parallaxes for LS III +46 11 and Berkeley 90. This solution may be ad hoc but we believe it to be the most likely one. Indeed, there is a precedent with an object that is a near-spectroscopic twin of LS III +46 12, HD 93 250 (O4 III(f)c), Sota et al. 2014). Its spectroscopic parallax was incompatible with the well known value of the Carina Nebula until it was discovered to be a binary through interferometry (Sana et al. 2011). Note that there is a large range of separations for which we would not detect significant velocity variations if the system were a spectroscopic binary, that the inclination could be small, that our spectroscopic campaign has not been as thorough for LS III +46 12 as it has been for LS III +46 11, and that X-ray excesses due to wind-wind collisions are expected to be weaker for dwarfs than for supergiants.

Related to the issue of the masses is the age of Berkeley 90. Until one of the above explanations is confirmed, we cannot provide a final answer. We should note, however, that if the third option is the correct one, it is possible to derive a consistent age of 1.5-2.0 Ma for LS III +46 11, LS III +46 12, and Berkeley 90 using the low-rotation Geneva evolutionary tracks of Lejeune & Schaerer (2001). Under those assumptions, the masses of the two stars in LS III +46 11 would be in the 60-70 M⊙ range and those in LS III +46 12 would be 35-45 M⊙.

The results in this paper reveal that Berkeley 90 can be an important cluster to resolve the issue of how the stellar Initial Mass Function (IMF) is sampled. There are two alternative theories, one that states that the IMF is built in a sorted way, with many low-mass stars being formed before any high-mass star can appear, and another one that states that the IMF is built in a stochastic way, with some rare cases where it is possible to form high-mass stars with a relatively small number of low-mass ones (see Bressert et al. 2012 and references therein). If the third option on the LS III +46 11 and LS III +46 12 masses above is correct, we would have a cluster with four stars above 35 M⊙, one of them with ~70 M⊙, and none or just one (2MASS J20350798+4649321) between 20 and 35 M⊙ (see Fig. 6 and the associated discussion in the text). Using the total stellar mass above 20 M⊙ and assuming a Kroupa IMF (Kroupa 2001) between 0.1 M⊙ and 100 M⊙, we derive that the mass...
of Berkeley 90 is $\approx 2000 \, M_\odot$, which is consistent with the appearance of the cluster in relationship with other similar objects. However, such a large maximum stellar mass in such a small cluster could be incompatible with the sorted sampling scenario (Weidner & Kroupa 2006) but can be accomodated within the stochastic scenario: a $2000 \, M_\odot$ with the conditions above should have, on average, 2.3 stars in the 20-35 $M_\odot$ range and 1.6 stars in the 35-100 $M_\odot$ range. We observe 1 and 4, respectively i.e. off from the expected values but within the range of possibilities expected for a single case within the number of similar clusters in the solar neighborhood. We need better data (constraining the nature of LS III +46 12 with interferometry, studying a deep CMD of Berkeley 90 to accurately measure the cluster mass, and resolving the distance issues with Gaia) to provide a final answer but Berkeley 90 appears to be a good candidate for a small cluster with a star too massive for the sorted sampling scenario.

5. Conclusions

- Berkeley 90 is a young stellar cluster dominated by two early O-type systems. LS III +46 11 is an SB2 composed of two very similar O3.5 II* stars. LS III +46 12 is spectroscopically single and has a spectral type O4 V (f(v)).
- LS III +46 11 has an eccentric orbit (e = 0.56 and 0.57) with a 97.2-day period and minimum masses of $38.80 \pm 0.83 \, M_\odot$ and $35.60 \pm 0.77 \, M_\odot$. Since we do not know the inclination we cannot calculate accurate keplerian masses.
- LS III +46 11 has a significantly higher extinction than LS III +46 12. The optical+NIR extinction law is close to the average one in the Galaxy.
- There are no apparent bright visual companions to either system.
- The evolutionary masses of LS III +46 11 and LS III +46 12 are incompatible with the two systems being located at the same distance and having the same age. We consider different solutions to the problem and consider that the most likely one is the existence of an undetected companion for LS III +46 12, for which there is plenty of room in terms of period, inclination, and eccentricity not yet explored.
- Berkeley 90 is a cluster with considerable differential extinction and its stellar mass is possibly too low to harbor both LS III +46 11 and LS III +46 12 under the sorted sampling scenario for the IMF.

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