Optical Spectroscopy of X-Mega targets in the Carina Nebula - VI. FO 15: a new O-Type double-lined eclipsing binary

V.S. Niemela, N.I. Morrell, E. Fernández Lajús, R. Barbá, J.F. Albacete Colombo, M. Orellana

1 Departamento de Física, Universidad de La Serena, Benavente 980, La Serena, Chile
2 Osservatorio Astronomico di Palermo, Piazza del Parlamento 1, Palermo (90141), Italy
3 Instituto Argentino de Radioastronomía, C.C. 5, 1894 Villa Elisa, Argentina

ABSTRACT

We report the discovery of a new O-type double-lined spectroscopic binary with a short orbital period of 1.4 days. We find the primary component of this binary, FO 15, to have an approximate spectral type O5.5Vz, i.e. a Zero-Age-Main-Sequence star. The secondary appears to be of spectral type O9.5V. We have performed a numerical model fit to the public ASAS photometry, which shows that FO 15 is also an eclipsing binary. We find an orbital inclination of \( \sim 80^\circ \). From a simultaneous light-curve and radial velocity solution we find the masses and radii of the two components to be 30 ± 1 and 16 ± 1 solar masses and 7.5 ± 0.5 and 5.3 ± 0.5 solar radii. These radii, and hence also the luminosities, are smaller than those of normal O-type stars, but similar to recently born ZAMS O-type stars. The absolute magnitudes derived from our analysis locate FO 15 at the same distance as \( \eta \) Carinæ. From Chandra and XMM X-ray images we also find that there are two close X-ray sources, one coincident with FO 15 and another one without optical counterpart. This latter seems to be a highly variable source, presumably due to a pre-main-sequence stellar neighbour of FO 15.

Key words: stars: binaries, spectroscopic, eclipsing stars: O-type - stars: fundamental parameters - stars: individual: FO 15 - X-rays: stars

1 INTRODUCTION

In their survey for OB stars in the field of the Carina Nebula (NGC 3372), Forte & Orsatti (1981) discovered an early O type star in the darkest region of the nebula. This star (\( \alpha_{2000} = 10^h45^m36^s; \delta_{2000} = -59^\circ 48' 22''; V = 12.05 \)), number 15 in their list of new OB stars, was assigned a spe-
al. 1989). Because one of the most often proposed mechanisms for producing X-rays from O-type stars are colliding stellar winds in binary systems, we decided to include FO15 in our ongoing optical spectroscopic observations in search for O-type binaries.

In this paper, we will present our spectroscopic observations of FO15 showing this star to be a double-lined binary system with a short orbital period. After our spectroscopic analysis was essentially complete, FO15 also appeared as an eclipsing binary in the All Sky Automated Survey (ASAS) (cf. Pajonk et al., 2003). We have analyzed the ASAS light curve together with our radial velocity study of the binary orbit.

2 OPTICAL SPECTROSCOPY

Twenty five spectral images of FO15 were obtained with the 2.15-m telescope at Complejo Astronómico El Leoncito (CASLEO) in San Juan, Argentina, during several observing runs between February 1996 and March 2003. We used, alternatively, the Cassegrain Boller & Chivens (B&C) spectrograph, with a 600 1 mm$^{-1}$ grating and a PM 516x516 20µm pixel CCD as detector, and the REOSC echelle spectrograph, in its Simple Dispersion mode. For the REOSC spectra a TEK 1024x1024 pixel CCD, with pixel size of 24µm was used as detector. These instrumental configurations provide reciprocal dispersions of ~2.3 and 1.6 Å px$^{-1}$, respectively. The wavelength region observed was roughly $\lambda \lambda$3900 – 5040 Å.

We used a slit width of 2 arcsec for all our CASLEO spectra. Exposure times for the stellar images ranged between 30 minutes and 1 hour, resulting in spectra of signal-to-noise ratio between 50 and 150, depending on seeing and transparency. He-Ar and Cu-Ar comparison arc images were obtained with ESO-VLT UT2 (Kueyen) and the UV-Visual Echelle Spectrograph (UVES) in December 2001. The set-up of the observatory (CASLEO) in San Juan, Argentina, during several observing runs between February 1996 and March 2003, showed that the stellar Hydrogen absorption lines moved from the blueside to the redside of the nebular emission, a signature of a rather high amplitude orbital motion in a binary system. This was confirmed with further observations, which also showed that the neutral Helium lines appeared double at maximum velocities, but ionized Helium lines always appeared single, as shown in Fig. 3 which depicts two spectra obtained at CASLEO during approximate orbital phases of the binary (see below).

The spectrum of FO15 appears somewhat variable, as occasionally faint NIII emission at $\lambda$ 4634-40 appears, as seen in the upper spectrum of Fig. 3. However, the radial velocities of this emission do not clearly correspond to any of the binary components, and it may arise in the zone of interaction of the close components.

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Nebular emission lines are observed in our spectra, as well as nebular He$^+$ $\lambda$ 3888 absorption. The interstellar absorption lines of CaII and NaI appear multiple. These are common features observed towards the giant HII region of Carina (e.g. Walborn & Hesser 1975, Walborn et al. 2002). The main components of CaII in our echelle spectra have a heliocentric radial velocity of $+7 \pm 1$ km s$^{-1}$, the nebular [OIII] $\lambda$ 5007 emission a velocity of $-19 \pm 2$ km s$^{-1}$, and the nebular He$^+$ $\lambda$ 3888 absorption of $-22 \pm 2$ km s$^{-1}$.

We have used these velocities to check the consistency of the stellar radial velocities derived from our lower resolution spectra.
3.1 Spectral types of the binary components

Spectral classification of components in a close binary system is not as straightforward task as classifying spectra of single stars. In very close systems of hot stars, such as FO15, mutual heating effects may introduce a spectral appearance with hotter effective temperature. Furthermore, spectral variations due to the interaction of stellar winds of the components are often observed.

We have chosen the usual approach to classify the binary components of FO15 in the spectrograms observed when the spectral lines have their maximum separation. To determine the spectral types, we measured in our higher resolution spectra the equivalent widths of the He\textsc{i} and He\textsc{ii} lines. We then used the quantitative classification criteria for O-type stars as described by Conti & Alschuler (1971), comparing the equivalent widths of He\textsc{i} λ4471 vs. He\textsc{ii} λ4542. We also compared He\textsc{i} λ4922 vs. He\textsc{ii} λ5411, as suggested by Kerton et al. (1999). According to these criteria, we obtained for the primary component of FO 15 a spectral classification of O5.5\textsuperscript{V}.

We note however, that the spectrum observed near the orbital phase when the primary star is in front of the system (see Fig. 2) and the contribution of the secondary to the spectrum is expected to be minor, corresponds to a spectral type about one subtype later than O5.5, when compared with the digital spectral atlas of O-type stars published by Walborn & Fitzpatrick (1990).

The spectral type of the secondary component is more difficult to ascertain. He\textsc{ii} absorptions corresponding to the secondary component is not observed in our lower resolution spectra, as is evident in Fig. 3. In our high resolution spectra all the He\textsc{i} absorptions appear as double lines, but only the He\textsc{i}λ4686 line corresponding to the secondary component is clearly observed. Both components of this line are shown in Fig. 4. He\textsc{ii}λ5411 absorption of the secondary component may also be present, but it appears blended with the diffuse interstellar bands at λλ 5404 and 5420. The spectral type of
the secondary component probably is O9.5V, but could be slightly later.

We do not observe in our optical spectra of FO15 any mass-loss indicators (signs of strong stellar winds), such as those listed e.g. by Hutchings (1978). The Balmer Hα line is observed in absorption in both binary components, as illustrated in Fig. 2. The radial velocity of this absorption agrees with the values derived from He lines, indicating that the Hα absorption is mostly photospheric, and not formed in the accelerated part of an expanding atmosphere. Thus FO15 may be composed of weak-wind and low mass-loss rate O type dwarfs, as those recently discussed by Martins et al. (2005b).

4 THE RADIAL VELOCITY ORBIT
To determine the radial velocity orbit of the binary, we measured the radial velocities of the He lines in the spectra of FO15 fitting gaussian profiles to the spectral lines within the IRAF routine SPLOT. The results are listed in Table 2. The radial velocities of the primary component are mostly based on the velocities of Hε absorptions, and the velocities of the secondary on those of Hβ. To calculate the orbital parameters, we used a modified version of the program originally written by Bertiau & Grobben (1976), introducing the period determined by ASAS photometry, namely 1.4136 days, as an initial value. We assigned higher weight to the higher resolution observations and to those obtained near quadratures. The orbital parameters are listed in Table 2, along with their formal standard errors as calculated by the above mentioned program.

Our radial velocities define a circular orbit within the errors, the calculated orbital eccentricity being \( e=0.05\pm0.06 \). This is as expected for a massive binary with such a short orbital period, as is the case for FO15.

5 LIGHT CURVE ANALYSIS
Photometric V filter data of FO15 were reported by The All Sky Automated Survey (ASAS) in Pojmanski (2003). This star is catalogued as ASAS 104536-5948.4 in the ASAS Catalog of Variable Stars, being classified as an eclipsing binary with a period of \( P=1.4136 \) days. A visual inspection of the ASAS light curve of FO15 shows periodic light variations with a rather large apparent scatter of data, almost \( \pm0.1 \) mag over all orbital phases. In order to obtain a first estimation of the orbital inclination \( i \) of the binary system, we have attempted to fit a numerical eclipsing binary model to the ASAS obser-
Figure 3. Spectra of FO 15 obtained at CASLEO in 2001 February, during orbital phases 0.78 (upper) and 0.14 (lower) showing the spectral lines of the two components seen in He i $\lambda$ 4471. Note also the faint emission line of Nii.

We generated synthetic light and radial velocity curves adjusting them to the observations. We used the PHOEBE package (Prša & Zwitter 2005) which incorporates numerical innovations and technical aspects to the W–D code. The results for the best fit, optimised by the code, are shown in Figures 6 and 7 and listed in Table 3.

With the inclination of the orbital plane, which we found to be $i = 80 \pm 1^\circ$, the values of the stellar masses for the components of FO 15 $M_1 = 30.4 \pm 1M_\odot$ and $M_2 = 15.8 \pm 1M_\odot$, are in fair agreement with the tabulations by Martins et al. (2005a) based on models of stellar atmospheres.

However, the stellar mean radii that we have obtained, namely $R_1 = 7.5 \pm 0.5R_\odot$ and $R_2 = 5.3 \pm 0.5R_\odot$ for the primary and secondary components, respectively, are about 30% smaller than the tabulated values, hence the bolometric luminosities implied from our light–curve solution are also lower. This is similar to what was observed for another O–type binary system in the Carina nebula, namely Tr16–104 by Rauw et al. (2001), who interpreted the observations as due to fainter absolute magnitudes for stars just entering to the main sequence, i.e. stars of luminosity class Vz. In fact a lower $T_{\text{eff}}$ for the secondary component, would it be e.g. of spectral type B0V, does not modify this result beyond the quoted error bars.
Figure 4. Continuum normalized spectrum of FO 15, obtained with MIKE at the Magellan II telescope in 2002, December, (orbital phase 0.34) showing the He\textsc{ii} λ\text{4686} absorption lines of both binary components.

The spectrum of Tr16-104 also exhibits the spectral signature of ZAMS O-type stars, namely that He\textsc{ii} λ\text{4686} absorption is stronger than other He\textsc{ii} lines, as is illustrated in Fig. 8. The case may apply also to FO 15 but for a more reliable assessment of this problem, an improved and less noisy light curve is needed, and is currently being obtained (Fernández Lajús et al. 2006, in preparation).

6 FO 15 IN THE CARINA NEBULA

Based on their proximity in the sky, Forte & Orsatti (1981) assumed that FO 15 belongs to the open cluster Tr 16, of which η Car is the brightest member. However, the line of sight in this direction of the Galaxy goes almost parallel to the Sagittarius–Carina spiral arm, which is rich in young stellar population. An O5V type star with the colors and apparent magnitude as those observed for FO 15 would have a spectrophotometric distance of ~5 kpc, if normal interstellar extinction is assumed. This would place FO 15 well behind the Carina Nebula and clusters embedded within. On the other hand, it is well known that the total-to-selective extinction ratio (R) in the direction of Carina Nebula is anomalous (e.g. Smith 1987, Tapia et al. 1988). Therefore, we decided to determine the value of R for FO 15 using the published UBV photometry from Forte & Orsatti (1981) and IR magnitudes from the 2MASS All-Sky Catalog of Point Sources (Cutri et al. 2003).

We used the code CHORIZOS developed by Maíz-Apellániz (2004) to derive the value of R for FO 15. CHORIZOS is a code that uses \( \chi^2 \) minimization to find all models of energy distribution compatible with an observed data set in the N-dimensional model parameter space, which in our case are broadband photometry and spectral type. For a complete description of the method, see Maíz-Apellániz (2004). We considered TLUSTY (Lanz & Hubeny, 2002) atmosphere models for the spectral energy distribution (SED) of O-type stars. An effective temperature of \( T_{\text{eff}} = 40000 \) and \( \log g = 4.0 \) were adopted to constrain the models. Using the six color photometry (\( UBVRIJK \)), we derived a colour excess \( E(B-V) = 1.21 \pm 0.02 \) and a ratio of total-to-selective extinction \( R_{5495} = 4.15 \pm 0.09 \), which are the monochromatic equivalents to the usual \( E(B-V) \) and \( R_V \), respectively. The main source of error comes from the adopted values of the magnitudes, which were obtained at different epochs, and therefore they could correspond to different orbital phases and be affected by the photometric variations of the binary system.
Figure 5. Continuum normalized spectrum of FO15, obtained with MIKE at the Magellan I telescope in 2003, May, (orbital phase 0.81) showing the Hα λ 6563 absorption lines of both binary components. Nebular emissions of Hα and [Nii] are also indicated in the spectrum.

Figure 6. ASAS V light curve of FO15. The continuous line represents our best fit W-D model.

With the bolometric magnitudes derived from our light-curve analysis, and assuming that the bolometric corrections corresponding for the spectral types as listed by Martins et al. (2005a) hold for the FO15 binary components, we obtain absolute visual magnitudes of -4.2 and -3.2 for the primary and secondary, respectively. These values are about 1 magnitude fainter than those tabulated by Martins et al. (2005a) for stars of spectral types O5.5V and O9.5V, but are in closer agreement with the absolute magnitudes for ZAMS O type stars as tabulated by Hanson et al. (1997). The values of absolute magnitudes of the binary components that we have obtained coupled with the total-to-selective
extinction ratio $R = 4.15$ derived above, would locate FO 15 at a distance of 2.2 kpc. This is coincident with the distance derived for $\eta$ Car by Davidson et al. (2001) based on spatially resolved Doppler velocities of the bipolar ejecta.

FO 15 is located in the region of the Carina Nebula named South Pillars by Smith et al. (2000) (see Fig. 1) recently imaged by the Spitzer Space Telescope. Newborn stars in dust pillars pointing to $\eta$ Car are observed in the infrared image of Spitzer (Smith et al. 2005). If FO 15 is at the same distance, it can be considered as a ZAMS star embedded in an active star formation region.

7 X–RAY DATA

As mentioned previously, FO 15 was detected as an X-ray source in EINSTEIN observations of the Carina Nebula. Subsequent X-ray data of FO 15 were observed by the ROSAT satellite in the context of the X-Mega international campaign (cf. Corcoran 1996) which also involves spectroscopic observations of hot stars with detectable X-ray emission. The ROSAT-HRI image shows a weak X-ray emission at the position of FO 15, considerably weaker than expected on the basis of the first EINSTEIN observation of this star, thus suggesting a variable X-ray source.

In further X-ray observations by the XMM-Newton satellite, FO 15 appeared as a hard X-ray source (Albacete-Colombo et al. 2003). However, in their analysis of an X-ray
Table 1. Observed heliocentric radial velocities for the primary and secondary components of FO 15. Radial velocities and (O-C) values are in \([\text{km s}^{-1}]\).

| HJD (days) | Phase \(\phi\) | Primary RV | O-C | Secondary RV | O-C |
|------------|----------------|------------|-----|-------------|-----|
| 50125.751(a) | 0.57 | 102 | -7 | -423 | 25 |
| 50127.747(a) | 0.98 | -4 | 14 |
| 50128.758(a) | 0.70 | 222 | 10 |
| 50129.694(a) | 0.36 | -165 | 9 |
| 50471.804(a) | 0.38 | -180 | -28 |
| 50472.773(a) | 0.07 | -148 | -15 |
| 50473.778(a) | 0.78 | 204 | -3 | -431 | 8 |
| 50477.807(a) | 0.63 | 167 | -1 |
| 50478.774(a) | 0.31 | -233 | -15 |
| 50854.825(a) | 0.34 | -211 | -18 |
| 50858.785(a) | 0.14 | -218 | -6 | 367 | 6 |
| 50860.749(a) | 0.53 | 15 | -45 |
| 50861.739(a) | 0.23 | -247 | -1 | 426 | -1 |
| 51355.466(a) | 0.51 | 18 | -11 |
| 51653.594(a) | 0.42 | -93 | 13 |
| 51654.551(a) | 0.10 | -173 | -7 |
| 51718.487(a) | 0.33 | -206 | 2 | 361 | 8 |
| 51959.799(a) | 0.04 | -109 | -15 |
| 51960.842(a) | 0.78 | 199 | -9 | -452 | -11 |
| 51961.765(a) | 0.43 | -76 | 16 |
| 51962.776(a) | 0.14 | -219 | -8 | 369 | 9 |
| 52251.847(b) | 0.64 | 179 | -1 | -382 | 5 |
| 52298.849(a) | 0.89 | 106 | -3 |
| 52302.856(a) | 0.73 | 202 | -14 | -439 | 18 |
| 52329.604(a) | 0.65 | 196 | 10 | -386 | 12 |
| 52332.820(a) | 0.93 | 80 | 12 |
| 52628.844(c) | 0.34 | -192 | 2 | 345 | 18 |
| 52690.606(a) | 0.04 | -113 | -24 |
| 52766.626(c) | 0.81 | 200 | 12 | -399 | 2 |
| 52836.495(d) | 0.24 | -225 | 25 | 420 | -6 |

Notes:
Data origin: (a) CASLEO, (b) ESO-VLT, (c) LCO-Magellan, (d) LCO-du Pont
Phases have been calculated according to the ephemeris
HJD(\(\phi = 0\)) = 2452837.565 + 1.41356E

Table 2. Parameters of Circular Radial Velocity Orbit for FO 15

| Parameter | Unit | Value |
|-----------|------|-------|
| \(P\) \([\text{days}]\) | | 1.41356 ± 0.000003 |
| \(V_o\) \([\text{km s}^{-1}]\) | | -15 ± 2 |
| \(a \sin i\) \([R_O]\) | | 6.42 ± 0.05 |
| \(K\) \([\text{km s}^{-1}]\) | | 231 ± 2 |
| \(M \sin^3 i\) \([M_O]\) | | 29 ± 1 |
| \(T_0\) \([\text{HJD} 2.450.000+]\) | | 3159.5 ± 0.2 |
| \(T_0\) \([\text{HJD} 2.450.000+]\) | | 3150.7 ± 0.2 |

Table 3. Astrophysical data for the binary components of FO 15 derived from the best fitting W-D model. \(R_L\) stand for the effective radius of the Roche lobe

| Parameters | Component | Prim. | Sec. |
|------------|-----------|-------|------|
| \(P\) \([\text{days}]\) | | 1.41356 ± 10^{-5} |
| \(i\) \([\degree]\) | | 80 ± 1 |
| \(a\) \([R_O]\) | | 19 ± 0.3 |
| \(M\) \([M_O]\) | | 30.4 ± 1 |
| \(M_2/M_1\) | | 15.8 ± 1 |
| \(R \text{ mean} (R_O)\) | | 7.5 ± 0.5 |
| \(R_L\) \([R_O]\) | | 8.3 |
| \(T \text{ eff} (^\circ K)\) | | 6.15 |
| \(M_{\text{bol}}\) | | 4000 |
| \(L_2/L_1\) | | 32000 |
| \(L_2/L_1\) | | 7.98 ± 0.02 |
| \(L_2/L_1\) | | 6.27 ± 0.02 |
| \(L_2/L_1\) | | 0.35 ± 0.01 |
| \(\log g\) \([\text{cgs}]\) | | 4.17 ± 0.01 |
| \(\log g\) \([\text{cgs}]\) | | 4.19 ± 0.05 |

* : Fixed

image of \(\eta\) Carinae region obtained by the Chandra satellite, Evans et al. (2003) did not mention FO 15 in their list of sources with OB optical counterparts. In their list of detected sources without optical counterparts, the source number 106 appears close to FO 15 but with a difference of over 10 arcsec in the published positional coordinates. Although FO 15 is observed near the borders of the X-ray images, which all had \(\eta\) Carinae as the aimpoint, a positional difference larger than 10 arcsecs seemed improbable. Therefore, we decided to re-examine the Chandra X-ray image in order to see if there might be some instrumental problem in the non-detection of FO 15 in this image. The result is depicted in Fig. 8 which shows two very close X-ray sources, the southern one is coincident with FO 15 and the northern with source 106 of Evans et al. (2003). This source does not appear in the X-ray image of XMM satellite used by Albacete-Colombo et al. (2003), as seen in Fig. 9. Therefore, it most probably is a variable source due to a pre-main sequence star located in the vicinity of FO 15. Indeed, Evans et al. (2003) already have suggested that the X-ray sources without optical counterparts, such as their source 106 close to FO 15, probably are pre-main sequence stars.

As mentioned above, X-ray flux variability seem to be present in this system. Albacete-Colombo \& Micela (2005) have studied the X-ray emission of FO 15 in the 0.4-10 keV energy range, revealing the existence of long term X-ray variability. Higher and lower un-absorbed X-ray flux limits are between 15.8×10^{-13} to 0.96×10^{-13} erg s^{-1}, implying \(L_X/L_{\text{bol}}\) ranges from 9.0×10^{-7} to 0.54×10^{-7}, respectively. These authors also discuss the origin of the observed hard X-ray photons as Inverse Compton scattering, and confirm the existence of soft (0.2-1.2 keV) short-term variability (~25% of the total flux).
8 SUMMARY OF THE RESULTS

- We have discovered that the O-type star FO 15 immersed in the active star formation site called ‘southern pillars’ in the Carina nebula, is a short period eclipsing binary.
- Both binary components are visible in the spectrum, the secondary component showing considerably weaker lines.
- We classify the primary spectrum as O5.5Vz, i.e. as an early type Zero-Age-Main-Sequence star. The secondary seems to be of spectral type O9.5V.
- Analysis of the ASAS light curve of FO 15 fitting a binary model by the Wilson-Devinney method, yields an orbital inclination of \(\sim 80^\circ\).
- The stellar masses of the components are \(\sim 30 \text{ and } 16 \text{ M}_\odot\).
- Simultaneous light and radial velocity curve analysis yields components with smaller radii and fainter absolute magnitudes when compared with normal galactic O-type stars. These values are in agreement with recently born ZAMS O type stars.
- An individual determination of total-to-selective extinction ratio (R) for FO 15 yields a value of 4.15, which coupled with the values of absolute magnitudes determined from the light curve locate FO 15 at a distance of 2.2kpc, coincident with that of \(\eta\) Car.
- A Chandra X-ray image shows two close sources at the position of FO 15. Presumably the northern source is a pre-main-sequence star with an occasional high X-ray state, as this source apparently is not visible in the X-ray image of the same location observed by the XMM satellite.

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