High-resolution spectroscopic observations of the new CEMP-s star CD-50°776

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ABSTRACT

Carbon enhanced metal poor (CEMP) stars are a particular class of low metallicity halo stars whose chemical analysis may provide important contrains to the chemistry evolution of the Galaxy and to the models of mass transfer and evolution of components in binary systems. Here, we present a detailed analysis of the CEMP star CD-50°776, using high resolution optical spectroscopy. We found that CD-50°776 has a metalicity [Fe/H] = −2.31 and a carbon abundance [C/Fe] = +1.21. Analyzing the s-process elements and the europium abundances, we show that this star is actually a CEMP-s star, based on the criteria set in the literature to classify these chemically peculiar objects. We also show that CD-50°776 is a lead star, since it has a ratio [Pb/Ce] = +0.97. In addition, we show that CD-50°776 develops radial velocity variations that may be attributed to the orbital motion in a binary system. The abundance pattern of CD-50°776 is discussed and compared to other CEMP-s stars already reported in the literature to show that this star is a quite exceptional object among the CEMP stars, particularly due to its low nitrogen abundance. Explaining this pattern may require to improve the nucleosynthesis models, and the evolutionary models of mass transfer and binary interaction.

Key words: nuclear reactions, nucleosynthesis — stars: abundances — stars: individual: CD-50°776 — stars: chemically peculiar — stars: evolution — stars: fundamental parameters

1 INTRODUCTION

During the last decades, considerable theoretical and observational efforts have been made to investigate the formation and evolution of the chemistry of the Galaxy through the study of its halo stars. The chemical composition of the halo stars is important because it can provide information not only about the early stages of the Galaxy formation, but also about some sites where nucleosynthesis of several elements took place, thus providing significant evidence to describe the initial stages of galactic nucleosynthesis. In order to carry on such studies, an adequate sample of halo stars must be selected. After the first surveys of low metallicity stars initiated by Bond et al. (1970, 1980), Bidelman (1981) and Bidelman & MacConnell (1973), where the metallicity limit was around −2.6 (Frebel & Norris, 2013, Beers et al. 2014), the surveys by Beers et al. (1985) and Christlieb et al. (2001) significantly increased the known number of low metallicity stars, including several candidates with metallicities less than −2.0.

Following these surveys, spectroscopic studies revealed that some of the metal-poor stars from Beers et al. (1985) were also carbon-rich objects (Beers et al. 1992). Before 2005, high-resolution spectroscopic analysis of these stars confirmed the carbon-rich nature for some of them. In addition, it was noted that some of these stars were also enriched in either the r- or s- or r/s-processes (McWilliam et al.
2 Rogers et al.

1995; Sneden et al. 1994, 1996, 2003a, 2003b; Barbuy et al. 1997, Norris et al. 1997a, 1997b, Bonifacio et al. 1998, Hill et al. 2000, 2002, Sivarani et al. 2004). In 2005, Rossi et al. (2005) using medium-resolution spectra of the stars in the samples of Beers et al. (1985) and Christlieb et al. (2001), noted the high frequency occurrence of the carbon-rich stars among the metal-poor stars, also known as CEMP (carbon enhanced metal poor) stars. According to Lucatello et al. (2006), 20% of the stars with metalicities down to $-2.0$ are CEMP stars. CEMP stars have been found in all the metallicity range from $-2.0$ to $-4.0$, with increasing frequency towards the lower metallicities (Lucatello et al. 2006). In view of this, several astrophysical sites for the origin of the carbon overabundances have been proposed (see Beers & Christlieb 2005 for a discussion).

Beers & Christlieb (2005) (but see also Masseron et al. 2010) proposed that CEMP stars could be distinguished according to their barium and europium abundances, and also according to their [Ba/Eu] ratio. After their study, the CEMP stars were divided in CEMP-$s$, CEMP-$r$, CEMP-$r/s$ and CEMP-no according to the heavy elements abundance pattern. The majority of CEMP stars are CEMP-$s$ stars (Aoki et al. 2007). The most likely explanation for the observed excess of carbon and s-process elements in CEMP-$s$ stars is the mass-transfer, just like in the CH stars and the barium stars. This conclusion is supported by the radial-velocity variations observed in several CEMP-$s$ stars (Hansen et al. 2016). Therefore, detailed abundance analysis of CEMP-$s$ stars is important to set observational constraints to the physics of mass-transfer (in the case of CEMP-$s$ binaries), and also to the nucleosynthesis models.

In this work we present the spectroscopic analysis of a new CEMP-$s$ star: CD-$50^\circ 776$. CD-$50^\circ 776$ came to our attention during our high-resolution spectroscopy survey started in 1999, during the first agreement between Observatório Nacional and the European Southern Observatory, with the aim to search for halo chemically peculiar stars. Later on, we also searched for metal-poor hypervelocity candidate stars, following our analysis of CD-$62^\circ 1346$, a CH hypervelocity star candidate (Pereira et al. 2012), and the analysis of two metal-poor red-horizontal-branch stars: CD-$41^\circ 115048$ and HD $214362$ (Pereira et al. 2013). To select these peculiar stars, we search over several surveys from the literature. In particular, CD-$50^\circ 776$ was selected from the work of Bidelman & MacConnel (1973), whose stars sample was later investigated by Norris et al. (1985) and Beers et al. (2014, 2017). In particular, Beers et al. (2014), based on a medium-resolution spectrum, determined the metallicity and the [C/Fe] ratio of this star, obtaining values of $-2.23$ and $+1.81$, respectively. Here, we show that CD-$50^\circ 776$ is in fact a CEMP star with an excess of the elements created by the s-process, without europium enrichment. Therefore it can be classified as a CEMP-$s$ star. CD-$50^\circ 776$ is the second brightest CEMP-$s$ star known to date, with $V = 10.05$ (the brightest one is HD $196944$ with $V = 8.4$). The present work is based on the analysis of high-resolution spectra of CD-$50^\circ 776$ to determine its metallicity and abundance pattern.

2 OBSERVATIONS

The high-resolution spectra analyzed in this work were obtained with the Feros (Fiberfed Extended Range Optical Spectrograph) spectrograph (Kaufer et al. 1999), that was initially coupled to the 1.52 m telescope and later to the 2.2 m telescope of ESO, at La Silla (Chile). Two observations were done for CD-$50^\circ 776$. One, on October 26, 1999 and another one on September 25, 2016. The exposures were 3600 and 2400 secs, respectively. Feros consists of a CCD detector of 2048 x 4096 pixels having each pixel a size of 15 µm. Feros has spectral coverage between 3900Å and 9200Å distributed over 39 orders with a resolution of 48000. The spectral reduction was made following a standard procedure, which includes bias subtraction, flat-fielding, spectral order extraction and wavelength calibration. All this procedure has been done using the MIDAS reduction pipeline.

3 ANALYSIS & RESULTS

The atomic absorption lines used for the determination of atmospheric parameters are basically the same as which were used in the study of other chemically peculiar stars (Pereira & Drake 2009). Table 1 shows the Fe$\text{I}$ and Fe$\text{II}$ lines used to determine these parameters. The log $gf$ values for the Fe$\text{I}$ and Fe$\text{II}$ lines were taken from Lambert et al. (1996).

3.1 Determination of the atmospheric parameters

Our analysis was done using the spectral analysis code MOOG (Sneden 1973) and the model atmospheres of Kurucz (1993). The latest version of MOOG includes routines for the calculation of the Rayleigh-scattering contribution to the continuous opacity, as described in Sobeck et al. (2011). The temperature was obtained after searching for a zero slope of the relation between the iron abundances based on Fe$\text{I}$ lines and the excitation potential while the microturbulent velocity was obtained after searching for a zero slope of the relation between the iron abundances based on the same Fe$\text{I}$ lines and the reduced equivalent width ($W_{\lambda}/\lambda$). This procedure also provides the metallicity of the star. The surface gravity of the star was obtained by means of the ionization equilibrium, which means that we should find a solution until the abundance of Fe$\text{I}$ and Fe$\text{II}$ become equal.

The final atmospheric parameters derived for CD-$50^\circ 776$ are given in Table 2. Table 2 also shows the values derived from previous spectroscopic observations of CD-$50^\circ 776$ conducted by Ryan & Deliyannis (1998) and Beers et al. (2014). The three atmospheric parameters given in Beers et al. (2014), labelled as 2a, 2b and 2c, differ according to the techniques used by these authors to obtain them. We note that our atmospheric parameters are in a good agreement either in temperature or surface gravity, depending on the specific technique used by Beers et al. (2014). A model with the highest temperature implies a change of +0.5 dex in the carbon abundance compared to our results. The model with log $g = 3.0$ does not allow a good fit in the region of the C$_2$ molecule, at 5165Å.

The errors reported in our effective temperature ($T_{\text{eff}}$) and microturbulent velocity ($\xi$) were set from the uncertainty in the slope of the Fe$\text{I}$ abundance versus excitation
potential and versus. \(W_\lambda/\lambda\) respectively. For the gravity, the error was estimated using the mean abundances of FeI and FeII differ by 1\(\sigma\) of the standard deviation of the [FeI/H] mean value.

### 3.2 Abundance analysis

The abundance pattern of CD-50\(^{0}\) 776 was determined using either equivalent width measurements of selected atomic lines and using the spectral synthesis technique. We used the solar abundances of Grevesse & Sauval (1998) as a reference. For iron it was used the solar abundance of \(\log \varepsilon(\text{Fe}) = 7.52\). Table 3 shows the atomic lines used to derive the abundances of the elements, with their respective equivalent width measurements. The derived abundances are given in Table 4. For the elements whose abundances were derived using spectral synthesis technique they are labelled as syn.

The abundances of the light elements, carbon and nitrogen, were determined by applying a spectrum synthesis technique in the local thermal dynamic equilibrium (LTE). For carbon, we used the CH lines of the \(A^2\Delta - X^2\Sigma\) system at \(\sim 4365\,\text{Å}\), the \(C_2\) \((0,0)\) band head of the Swan system \(d^3\Pi_g - a^3\Pi_u\), at 5165 Å, and the \(C_2\) \((0,1)\) band head of the Swan system \(d^3\Pi_g - a^3\Pi_u\) at 5635 Å.

For nitrogen we used the \(B^2\Sigma - X^2\Sigma\) violet system band head at 3883 Å with line list provided by VALD. The \((2,0)\) band of the CN red system \(A^2\Pi - X^2\Sigma\) in the 7994–8020 Å often used by us to determine the nitrogen abundance, is not visible in this star. We did not detect the oxygen forbidden line at 6300.0 Å. Therefore we assume that \([\text{O}/\text{Fe}] = +0.50\), which is a typical value for a star of this metallicity (Masseron et al. 2006). We also check our derived nitrogen abundance using a different linelist for the CN band at 3883 Å given by Jonsell et al. (2006) and Sneden et al. (2014), and the results were basically the same as using the linelist given by VALD.

The abundances of barium, europium, cobalt, lead and praseodymium were also determined by means of spectral synthesis technique. The determination of barium abundance was obtained using the BaII lines at \(\lambda\,4554.0\), \(\lambda\,4934.1\), \(\lambda\,5853.7\), and \(\lambda\,6614.1\) Å. Hyperfine and isotope splitting were taken from McWilliam (1998). The europium abundance was found using the line of EuII at \(\lambda\,4129.75\) Å and the hyperfine splitting from Mucciarelli et al. (2008). The cobalt abundance was derived using the CoI line at \(\lambda\,4121.33\) Å, where the hyperfine splitting was taken from McWilliam et al. (1995). The lead abundance was derived from the PbI line at \(\lambda\,4057.81\) Å. The line data, which include isotopic shifts and hyperfine splitting, were taken from van Eck et al. (2003). The abundance of praseodymium was obtained through spectral synthesis technique using the lines at \(5259.73\) Å and \(5322.77\) Å. The hyperfine splitting was taken from Sneden et al. (2009).

Figures 1, 2, 3, 4 and 5 show the observed and synthetic spectra for the spectral regions where the abundances of carbon, the \(^{12}\text{C}/^{13}\text{C}\) isotopic ratio, nitrogen, lead and europium were obtained.

### 3.3 Abundance uncertainties

The uncertainties in the abundances of CD-50\(^{0}\) 776 are given in Table 5. The uncertainties due to the errors of \(T_{\text{eff}}\), log \(g\),
Table 1. Observed Fe\textsc{i} and Fe\textsc{ii} lines.

| Element | \(\lambda\) (Å) | \(\chi\) (eV) | \(\log gf\) | \(W_\lambda\) (mÅ) |
|---------|----------------|-------------|-----------|--------------|
| Fe\textsc{i} | | | | |
| 4187.050 | 2.450 | -0.55 | 88 |
| 4233.610 | 2.480 | -0.60 | 77 |
| 4494.570 | 2.020 | -1.14 | 74 |
| 4531.160 | 1.490 | -2.15 | 73 |
| 4871.330 | 2.860 | -0.36 | 85 |
| 5110.413 | 0.000 | -3.76 | 82 |
| 5171.596 | 1.485 | -1.76 | 87 |
| 5194.942 | 1.557 | -2.09 | 73 |
| 5198.711 | 2.223 | -2.14 | 34 |
| 5202.336 | 2.176 | -1.84 | 57 |
| 5242.491 | 3.634 | -0.97 | 19 |
| 5250.209 | 0.121 | -4.92 | 19 |
| 5281.790 | 3.038 | -0.83 | 49 |
| 5302.307 | 3.283 | -0.74 | 43 |
| 5307.361 | 1.608 | -2.97 | 27 |
| 5339.929 | 3.266 | -0.68 | 48 |
| 5341.024 | 1.608 | -1.95 | 79 |
| 5364.871 | 4.445 | 0.23 | 30 |
| 5367.467 | 4.415 | 0.44 | 37 |
| 5369.962 | 4.371 | 0.54 | 42 |
| 5389.479 | 4.415 | -0.25 | 11 |
| 5393.168 | 3.241 | -0.72 | 44 |
| 5400.502 | 4.371 | -0.10 | 21 |
| 5410.910 | 4.473 | 0.40 | 29 |
| 5445.047 | 4.386 | 0.04 | 28 |
| 5497.516 | 1.011 | -2.84 | 72 |
| 5569.618 | 3.417 | -0.49 | 52 |
| 5572.842 | 3.396 | -0.28 | 60 |
| 5576.089 | 3.430 | -0.85 | 36 |
| 5638.262 | 4.220 | -0.72 | 12 |
| 6005.482 | 2.608 | -1.53 | 46 |
| 6136.615 | 2.453 | -1.40 | 61 |
| 6137.692 | 2.588 | -1.40 | 54 |
| 6191.558 | 2.433 | -1.40 | 57 |
| 6200.313 | 2.605 | -2.44 | 11 |
| 6230.723 | 2.559 | -1.28 | 63 |
| 6252.555 | 2.403 | -1.72 | 57 |
| 6265.130 | 2.180 | -2.55 | 23 |
| 6322.686 | 2.588 | -2.43 | 14 |
| 6333.601 | 2.433 | -1.43 | 57 |
| 6411.649 | 3.653 | -0.66 | 32 |
| 6421.351 | 2.279 | -2.01 | 42 |
| 6430.846 | 2.176 | -2.01 | 49 |
| 6592.914 | 2.723 | -1.47 | 40 |
| 6593.871 | 2.437 | -2.42 | 19 |
| Fe\textsc{ii} | | | | |
| 4515.339 | 2.840 | -2.45 | 37 |
| 4583.837 | 2.810 | -1.80 | 71 |
| 5197.559 | 3.230 | -2.25 | 35 |
| 5234.619 | 3.221 | -2.24 | 41 |
| 5284.098 | 2.891 | -3.01 | 18 |
| 5425.247 | 3.199 | -3.21 | 10 |
| 5534.834 | 3.245 | -2.77 | 16 |
| 6247.545 | 3.891 | -2.34 | 11 |
| 6432.682 | 2.891 | -5.58 | 7 |

\(\xi\), and metallicity were estimated by changing these parameters one at a time by their standard errors given in Table 2. The final uncertainties of the abundances were calculated as the root squared sum of the individual uncertainties due to the errors in each atmospheric parameter and also in the equivalent widths under the assumption that these individual uncertainties are independent.

For the elements analyzed via spectrum synthesis we used the same technique, varying the atmospheric parameters and then computing independently the abundance changes introduced by them. Uncertainties in the carbon
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Figure 3. Observed (dotted red points) and synthetic (solid blue lines) spectra between 3880 Å and 3884 Å. From top to bottom, we show the syntheses for the nitrogen abundances of $\log \epsilon (N) = 5.22$, 5.52 (adopted) and 5.82. The upper line shows the spectrum without contribution of the CN lines.

Figure 4. Observed (dotted red points) and synthetic (solid blue lines) spectra in the region of the Pb line at 4057.8 Å. From top to bottom, we show the syntheses without contribution of the lead and the lead abundances of $\log \epsilon (\text{Pb}) = 1.33$, 1.53 (adopted), and 1.73. Other absorption lines are indicated.

Figure 5. Observed (dotted red points) and synthetic (solid blue lines) spectra for the Eu line at 4129.7 Å. From top to bottom we show the syntheses for the europium abundances of $\log \epsilon (\text{Eu}) = -1.79$, $-1.49$ (adopted) and $-1.19$.

Table 2. Atmospheric parameters of CD-50°776.

| Parameter | Value | Ref. |
|-----------|-------|------|
| $T_{\text{eff}}$ (K) | 4900±60 | 1 |
| | 5305 | 2a |
| | 5000 | 2b |
| | 5176 | 2c |
| | 5000 | 3 |
| $\log g$ (dex) | 2.1±0.2 | 1 |
| | 2.22 | 2a |
| | 3.0 | 2b |
| | 2.22 | 2c |
| [Fe/H] (dex) | $-2.31 \pm 0.08$ | 1 |
| | $-2.39$ | 2a |
| | $-2.23$ | 2b |
| | $-2.52$ | 2c |
| | $-2.23$ | 3 |
| $\xi$ (km s$^{-1}$) | 1.5±0.3 | 1 |

References for Table 2.
1: This work;
2: Beers et al. (2014);
3: Ryan & Deliyannis (1998);

abundances also result in variations of the nitrogen abundances, since the CN molecular lines were used for the nitrogen abundance determination. For carbon and nitrogen, typical uncertainties are 0.10 and 0.20, respectively. In Table 5, we see that the neutral elements are more sensitive to the temperature variations, while singly-ionized elements are more sensitive to the log $g$ variations. For the elements whose abundance is based on stronger lines, such as strontium, the error introduced by the microturbulence is impor-
Table 3. Other lines studied

| \( \lambda (\text{Å}) \) | Species | \( \chi (\text{eV}) \) | \( \log gf \) | Ref. | \( W_{\lambda} (\text{mÅ}) \) |
|-----------------|--------|----------------|-------------|-----|-----------------|
| 5688.22         | NaI    | 2.10           | -0.40       | PS 10 | 10              |
| 4057.51         | MgI    | 4.35           | -0.89       | N96 56 |               |
| 4571.10         |        | 0.00           | -5.61       | N96 62 |               |
| 4702.99         |        | 4.35           | -0.38       | N96 94 |               |
| 5528.42         |        | 4.34           | -0.36       | R99 86 |               |
| 5711.10         |        | 4.34           | -1.75       | R99 22 |               |
| 5581.80         | CaI    | 2.52           | -0.67       | C2003 26 |   |
| 5661.29         |        | 2.52           | -0.52       | C2003 38 |   |
| 5857.46         |        | 2.93           | 0.11        | C2003 40 |   |
| 6122.73         |        | 1.88           | -0.79       | D2002 51 |   |
| 6122.23         |        | 1.89           | -0.32       | D2002 78 |   |
| 6162.18         |        | 1.90           | -0.09       | D2002 90 |   |
| 6166.44         |        | 2.52           | -1.14       | R03 10 |   |
| 6169.04         |        | 2.52           | -0.80       | R03 21 |   |
| 6169.56         |        | 2.53           | -0.48       | D591 30 |   |
| 6439.08         |        | 2.52           | 0.47        | D2002 76 |   |
| 6493.79         |        | 2.52           | -0.11       | D591 49 |   |
| 6499.65         |        | 2.52           | -0.81       | C2003 13 |   |
| 6717.69         |        | 2.71           | -0.52       | C2003 23 |   |
| 4512.74         | TiI    | 0.84           | -0.48       | MFK 26 |   |
| 4518.03         |        | 0.83           | -0.32       | MFK 30 |   |
| 4533.25         |        | 0.85           | +0.48       | MFK 60 |   |
| 4548.77         |        | 0.83           | -0.35       | MFK 23 |   |
| 4555.49         |        | 0.85           | -0.49       | MFK 16 |   |
| 4981.72         |        | 0.84           | 0.50        | MFK 61 |   |
| 4999.51         |        | 0.83           | 0.25        | MFK 58 |   |
| 5016.17         |        | 0.85           | -0.57       | MFK 16 |   |
| 5022.87         |        | 0.83           | -0.43       | MFK 22 |   |
| 5173.75         |        | 0.00           | -1.12       | MFK 30 |   |
| 5210.39         |        | 0.05           | -0.88       | MFK 43 |   |
| 4254.35         | CrI    | 0.00           | -0.09       | S2007 112 | |
| 4496.84         |        | 0.94           | -1.14       | S2007 25 |   |
| 5206.04         |        | 0.94           | 0.02        | S2007 84 |   |
| 5247.57         |        | 0.96           | -1.60       | S2007 15 |   |
| 5286.70         |        | 0.98           | -1.37       | S2007 25 |   |
| 5298.28         |        | 0.98           | -1.14       | S2007 29 |   |
| 5345.81         |        | 1.00           | -0.95       | S2007 41 |   |
| 5348.33         |        | 1.00           | -1.22       | S2007 28 |   |
| 5409.80         |        | 1.03           | -0.67       | S2007 51 |   |
| 4904.41         | NiI    | 3.54           | -0.24       | W2014 19 |   |
| 4648.65         |        | 3.42           | -0.09       | W2014 20 |   |
| 4756.52         |        | 3.48           | -0.27       | W2014 17 |   |
| 5035.36         |        | 3.64           | 0.29        | W2014 25 |   |
| 5476.90         |        | 1.83           | -0.78       | W2014 74 |   |
| 5892.88         |        | 1.99           | -1.92       | W2014 15 |   |
| 6108.11         |        | 1.68           | -2.69       | W2014 10 |   |
| 6482.80         |        | 1.94           | -2.63       | MFK 11 |   |
| 6643.64         |        | 1.68           | -2.03       | W2014 19 |   |
| 6767.77         |        | 1.83           | -2.17       | W2014 18 |   |
| 7788.93         |        | 1.95           | -1.99       | W2014 13 |   |
| 4810.53         | ZnI    | 4.06           | -0.17       | BG80 26 |   |
| 4215.52         | SrII   | 0.00           | -0.17       | N96 142 |   |
| 4883.68         | YII    | 1.08           | 0.07        | H82 44 |   |
| 5087.43         |        | 1.08           | -0.17       | H82 31 |   |
| 5200.41         |        | 0.99           | -0.57       | H82 16 |   |
| 5205.72         |        | 1.03           | -0.34       | S96 21 |   |
4 DISCUSSION

4.1 The luminosity of CD-50°776

Once we estimated the temperature and gravity of CD-50°776, we are able to determine the luminosity considering the relation

$$\log \left( \frac{L_\star}{L_\odot} \right) = 4 \log T_{\text{eff}} - \log g + \frac{M_\star}{M_\odot} + 10.61$$

(1)

where we considered $T_{\text{eff}} = 5777$ K and $\log g = 0.2$. Inserting the values of $T_{\text{eff}} = 4900$ K, $\log g = 2.1$, and assuming a mass $M_\star = 0.8 M_\odot$ for CEMP stars (Aoki et al. 2007), we obtain for the luminosity of CD-50°776 a value of $\log \left( \frac{L_\star}{L_\odot} \right) = 1.95 \pm 0.3$. Spectroscopic luminosities of low-metallicity giants derived from ionization balance may give higher values than those derived from stellar parallaxes or evolutionary models (Mashonkina et al. 2011; Ruchti et al. 2013). According to the recent work of Ruchti et al. (2013), the non-local thermodynamic equilibrium (NLTE) correction to the spectroscopic gravity is about $+1.0$ dex, and for the temperature the correction is around $+400$ K. Introducing these corrections in equation (1), we obtain a luminosity of $\log \left( \frac{L_\star}{L_\odot} \right) = 1.09 \pm 0.3$. In Figure 6 we show the derived temperature and gravity of CD-50°776 in the $\log T_{\text{eff}}$–$\log g$ plane, together with the 12 and 14 Gyr Yale-Yonsei isochrones for a metallicity of [Fe/H] = −2.2 (Kim et al. 2002).

As mentioned in Section 3.1, Beers et al. (2014) also determined the temperature, surface gravity and metallicity of CD-50°776 using three different techniques. However,
can classify CD-50°776. Therefore, based on these two diagrams, we can classify CD-50°776 as a CEMP star. In Figure 7, we reproduce Figure 4 of Aoki et al. (2007), where the authors presented a new constraint for a star to be classified as a CEMP star. In Figure 7a, the position of CD-50°776 occupies in this diagram the same position as other CEMP stars and again CD-50°776 presents variations due to orbital motion. Systematic radial velocity monitoring is necessary to confirm the evolution expected according to the models of Herwig (2004). However, for other CEMP-s stars, the high nitrogen abundance poses challenges to the evolutionary mod-

Table 4. Chemical abundances derived for CD-50°776 in the scale log ε(H) = 12.0, and in the notations [X/H] and [X/Fe].

| Species   | n | log ε | [X/H] | [X/Fe] |
|-----------|---|-------|-------|--------|
| C(C2)     | 3 | 7.42±0.10 | −1.10 | +1.21  |
| N(CN)     | 1 | 5.52  | −2.40 | −0.09  |
| NaI       | 1 | 4.90  | +2.04 | +0.07  |
| MgI       | 5 | 5.74±0.15 | −1.84 | +0.47  |
| CaI       | 13 | 4.54±0.08 | −1.82 | +0.49  |
| TiI       | 11 | 2.91±0.09 | −2.11 | +0.20  |
| CrI       | 9 | 3.17±0.06 | −2.50 | −0.19  |
| CoI       | 11 | 2.52  | −2.40 | −0.09  |
| NiI       | 11 | 3.99±0.14 | −2.26 | +0.05  |
| ZnI       | 1 | 2.52  | −2.08 | +0.23  |
| SrII      | 1 | 0.74  | −2.23 | +0.08  |
| Y II      | 4 | 0.04±0.10 | −2.20 | +0.11  |
| ZrII      | 3 | 0.76±0.08 | −1.84 | +0.47  |
| BaII      | 3 | 0.83±0.10 | −1.30 | +1.01  |
| LaII      | 2 | −0.28 | −1.45 | +0.86  |
| CeII      | 7 | 0.19±0.08 | −1.39 | +0.92  |
| PrII      | 2 | −0.82 | −1.53 | +0.78  |
| NdII      | 10 | 0.04±0.11 | −1.46 | +0.85  |
| SmII      | 5 | −0.61±0.10 | −1.62 | +0.69  |
| EuII      | 1 | −1.49 | −2.00 | +0.31  |
| PbII      | 1 | 1.53  | −0.42 | +1.89  |

$^{12}\text{C}/^{13}\text{C}$ ≥ 64

their results using high-resolution spectroscopy provided a surface gravity +0.9 higher than the value obtained by us.

4.2 CD-50°776 as a new CEMP star

In Figure 7 we reproduce Figure 4 of Aoki et al. (2007), where the authors presented a new constraint for a star to be classified as a CEMP star. In Figure 7a, the position of CD-50°776 is clearly above the lower limit for a star to be considered as a CEMP star. Figure 7b plots the [C/Fe] ratio versus metallicity for the CEMP stars and again CD-50°776 occupies in this same position as other CEMP stars. Therefore, based on these two diagrams, we can classify CD-50°776 as a new CEMP star. In addition, the position of CD-50°776 in figures 2 and 6 of Yoon et al. (2016) also supports our conclusion that CD-50°776 is a CEMP star. We will show in Section 4.4.3 that, based on the abundance analysis, CD-50°776 is actually a new CEMP-s star.

4.3 Radial Velocity

Table 6 shows the all known measurements of the radial velocity of CD-50°776 available in the literature and determined in this work. It is clear that the radial velocity of CD-50°776 presents variations due to orbital motion. Systematic radial velocity monitoring is necessary to confirm the possible binary nature of this new CEMP-s star.

4.4 Abundances

4.4.1 Nitrogen and $^{12}\text{C}/^{13}\text{C}$ isotopic ratio

As shown in Table 4, the nitrogen abundance is low and the $^{12}\text{C}/^{13}\text{C}$ isotopic ratio is high. Combining these results with the high carbon abundance led us to conclude that the CN cycle was not efficient enough in the donor star of the binary system of CD-50°776, and that significant carbon produced by the triple alpha process was transferred in the AGB stage. The sum (C+N) = 7.42 illustrates the fact that carbon is the actual responsible for the total sum of (C+N).

If we assume that the nitrogen observed in the CEMP-s stars has the same origin as carbon, that is, it originates in the companion star during the AGB phase (Masseron et al. 2010), then the low nitrogen abundance observed in CD-50°776 may constrain, in principle, the mass of the donor star. In particular, for CD-50°776, it is likely that the mass of the AGB star should not have been greater than 3.0 M⊙. Models of AGB stars for a metallicity of Z = 0.0001 (Herwig 2004), which is the metallicity of CD-50°776, show that the yields of carbon and nitrogen provide a ratio [C/N] of about 2.3 for a star of 2.0 M⊙ at the end of the AGB phase. Therefore, nitrogen is not enhanced in such models. These models also predict a high $^{12}\text{C}/^{13}\text{C}$ isotopic ratio (figures 7 and 8 of Herwig 2004). For a star of 3.0 M⊙, the ratio of [C/N] is 2.1 according to the yields given in Herwig (2004), allowing to conclude that low metallicity stars with masses between 2.0 and 3.0 M⊙ should not be nitrogen enriched (Johnson et al. 2007). This would explain the low abundance of nitrogen observed in CD-50°776, and implies that this star follows the evolution expected according to the models of Herwig (2004). However, for other CEMP-s stars, the high nitrogen abundance poses challenges to the evolutionary mod-
**Table 5.** Abundance uncertainties for CD-$50^\circ776$. Columns 2 to 6 give the variation of the abundances caused by the variation in $T_{\text{eff}}$, log $g$, $\xi$, [Fe/H], and equivalent widths measurements ($W_{\lambda}$), respectively. The 7th column gives the compounded r.m.s. uncertainty from the 2nd to 6th columns. The last column gives the abundances dispersion observed among the lines for those elements with more than three lines available.

| Species | $\Delta T_{\text{eff}}$ | $\Delta \log g$ | $\Delta \xi$ | $\Delta [\text{Fe/H}]$ | $\Delta W_{\lambda}$ | $(\sum \sigma^2)^{1/2}$ | $\sigma_{\text{obs}}$ |
|---------|-----------------|----------------|-------------|-----------------|------------------|-----------------|----------------|
| C       | +0.12           | +0.03          | 0.00        | 0.00            | 0.12             |                |                |
| N       | +0.16           | -0.10          | 0.00        | 0.00            | 0.19             |                |                |
| Fe I    | +0.08           | 0.00           | -0.07       | +0.01           | +0.08            | 0.11            | 0.08            |
| Fe II   | 0.00            | +0.08          | -0.03       | 0.00            | +0.10            | 0.13            | 0.10            |
| Na I    | +0.03           | 0.00           | -0.01       | 0.00            | +0.13            | 0.13            |                |
| Mg I    | +0.06           | -0.01          | -0.06       | +0.01           | +0.06            | 0.10            | 0.15            |
| Ca I    | +0.05           | -0.01          | -0.05       | +0.01           | +0.07            | 0.10            | 0.08            |
| Ti I    | +0.08           | -0.02          | -0.04       | +0.01           | +0.08            | 0.12            | 0.09            |
| Cr I    | +0.09           | -0.01          | -0.07       | +0.01           | +0.07            | 0.13            | 0.05            |
| Co I    | +0.10           | -0.05          | -0.10       | +0.00           | +0.00            | 0.15            |                |
| Ni I    | +0.07           | 0.00           | -0.01       | 0.00            | +0.10            | 0.12            | 0.21            |
| Zn I    | +0.06           | +0.04          | -0.03       | 0.00            | +0.08            | 0.11            |                |
| Sr II   | +0.06           | +0.01          | -0.23       | 0.00            | +0.04            | 0.25            |                |
| Y II    | +0.02           | +0.06          | -0.04       | -0.01           | +0.07            | 0.10            | 0.10            |
| Zr II   | +0.03           | +0.07          | -0.05       | -0.01           | +0.08            | 0.12            | 0.20            |
| Ba II   | -0.01           | +0.09          | -0.01       | -0.01           | -0.01            | 0.09            |                |
| La II   | -0.03           | +0.06          | -0.06       | -0.01           | +0.12            | 0.15            |                |
| Ce II   | +0.03           | +0.06          | -0.03       | -0.01           | +0.10            | 0.12            | 0.08            |
| Pr II   | +0.10           | +0.10          | -0.05       | -0.01           | -0.01            | 0.15            |                |
| Nd II   | +0.04           | +0.06          | -0.02       | -0.01           | +0.09            | 0.12            | 0.11            |
| Sm II   | +0.03           | +0.07          | -0.01       | -0.01           | +0.14            | 0.16            | 0.10            |
| Eu II   | +0.01           | +0.09          | -0.20       | +0.01           | -0.01            | 0.22            |                |
| Pb II   | 0.10            | -0.03          | +0.05       | 0.00            | -0.01            | 0.12            |                |

**Table 6.** Radial velocity measurements for CD-$50^\circ776$.

| Reference                        | Radial Velocity | Modified Julian Date |
|----------------------------------|-----------------|----------------------|
| This work (September 25, 2016)   | 30.5±0.7        | 57478.17             |
| This work (October 26, 1999)     | 25.2±0.8        | 57657.08             |
| Schuster et al. (2006)           | 26.0±7.0        |                      |
| Beers et al. (2000)              | 18±10           |                      |

Masseron et al. (2010) considered that extra mixing mechanisms should be taken into account in order to explain the high abundance of nitrogen in CEMP-s stars. This is because a high nitrogen abundance is predicted by hot bottom burning, which occurs in stars with masses greater than 4.0 $M_\odot$ (Sackmann & Boothroyd 1992). Notwithstanding, since CEMP-s stars are members of the halo population, it is unlikely that their companions had masses larger than 4.0 $M_\odot$. This led Masseron et al. (2010) to conclude that the nitrogen abundance in CEMP-s stars should not be used to constrain the mass of the donor star.

Figure 8 shows the $[\text{N/Fe}]$ ratio versus metallicity for CD-$50^\circ776$ (red star) compared to CEMP-s giants and dwarfs (squares), CH stars (polygons), one metal-poor barium star (HD 123396, (1)), one CEMP-no star (CS 22877-001, (2)) and one carbon star (HD187216, (3)).

### 4.4.2 Sodium to Nickel

Since CD-$50^\circ776$ is a new CEMP-s star (Section 4.4.3), we also compare its abundances to other CEMP-s stars. Figures 9 and 10 show the abundance ratios $[\text{X/Fe}]$ versus metallicity for Na, $\alpha$-elements and iron-peak elements (Cr, Co, Ni and Zn) of CD-$50^\circ776$ compared to several previous abundance studies of stars of the thin and thick disks and the halo populations. CEMP-s giant stars and dwarfs are represented by filled and open squares, respectively. We also plot in these Figures the abundance ratios of barium stars and of some CH stars (except carbon, cobalt, zinc and barium), based on the recent analysis by de Castro et al. (2016).

Sodium abundance in CEMP-s stars exhibits the same trend as for the other metal-poor field stars. Some CEMP-s stars display higher $[\text{Na/Fe}]$ ratios than the stars with similar metallicity, however this can be caused by NLTE effects, which seem to be stronger in metal-poor stars (see Aoki et al. 2007 for a discussion of sodium abundance in CEMP stars). Our derived value of +0.07 for the $[\text{Na/Fe}]$ ratio indicates that NLTE effects seem to be negligible in this star.

In Figure 9, we verify that the abundances of $\alpha$-elements (Mg, Ca and Ti) are those of other authors in the field stars of the same metallicity as CD-$50^\circ776$. The iron-group element nickel is expected to follow the iron abundance (Fig-
Figure 7. (a) The [C/Fe] ratio versus luminosity for CD-50$^{◦}$776 (red star) in comparison with a sample of CEMP-s stars. The solid line connects the two possible values of luminosity of CD-50$^{◦}$776, derived with and without taking into account the NLTE corrections, respectively. Data for CEMP-s stars are the same as in Figure 6. (b) The [C/Fe] ratio versus metallicity for the same stars as in (a). The position of CD-50$^{◦}$776 in these two diagrams shows that CD-50$^{◦}$776 is CEMP star. Green crosses represent non-carbon-rich metal-poor field stars. Data for these stars were taken from Gratton et al. (2000); Cayrel et al. (2004); Honda et al. (2004) and Aoki et al. (2005).

Figure 8. [N/Fe] ratio versus metallicity for CD-50$^{◦}$776 (red star) and some CEMP-s stars. Black filled squares and open squares represent CEMP-s giants and dwarfs, respectively. Data for CEMP-s stars are the same as in Figure 6. Blue polygons represent CH stars with abundance data taken from Masseron et al. (2010) and Pereira & Drake (2009). Other chemically peculiar stars are also shown: HD 123396, a metal-poor barium star ((1), Allen & Barbuy 2006); CS 22877-001, a CEMP-no star ((2), Masseron et al. 2010) and HD 187216, a carbon star ((3), Komiya et al. 2007).

4.4.3 The heavy-elements: CD-50$^{◦}$776 as a new CEMP-s star

In Figures 11 and 12, we show the [X/Fe] ratios for the elements created by the r- and s-process: Sr, Y, Zr, Ba, La, Ce, Pr, Nd, Sm and Eu, in CD-50$^{◦}$776 compared to other CEMP-s stars, field giants and barium stars, including barium stars and CH stars for several metallicities. Models of galactic chemical evolution do not predict the observed overabundances of the s-process elements observed in these plots (Travaglio et al. 1999, 2004). Since CD-50$^{◦}$776 also follows the criteria given in Masseron et al. (2010) for a star to be considered as a CEMP-s star, that is [Ba/Fe] $> 1.0$ and [Ba/Eu] $> 0.0$ (our results are +1.01 and +1.27, respectively, see Table 4), we can finally classify CD-50$^{◦}$776 as a new CEMP-s star. The mean abundance ratio of the s-process elements ([Sr/Fe], [Y/Fe], [Zr/Fe], [Ba/Fe], [La/Fe], [Ce/Fe], [Nd/Fe] and [Pb/Fe]) for CD-50$^{◦}$776 is high: +0.77. If the radial velocity variation reported in Table 6 can be attributed to orbital motion, then the atmosphere of CD-50$^{◦}$776 could have been contaminated by an extrinsic past event like in the mass-transfer hypothesis, which is the standard scenario to explain the excess of carbon and the overabundances of the s-process elements in these chemically peculiar stars (Hansen et al. 2016).
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5 CONCLUSIONS

Based on high-resolution optical spectroscopic data, we present the first detailed analysis of the chemical abundances of the CEMP star CD-50°776, including the light elements, Na, the α-elements, the iron-peak elements, and the s-process elements. We showed that CD-50°776 is characterized by an enhancement of carbon, s-process elements, and lead. This pattern, together with its low metallicity ([Fe/H] = −2.31), indicates that it is CEMP-s star. CD-50°776 is also a “lead star”, since its lead-to-cerium ratio +0.97 follows the theoretical predictions for a star of this metallicity.

One way to verify that CD-50°776 is indeed a CEMP-s...
star is to use the nucleosynthesis models for AGB stars calculated by Bisterzo et al. (2010). Using the tables given in this paper, we can compare the predicted surface abundance ratios, \([X/Fe]\), with the observed abundances. The nucleosynthesis models forecast the theoretical \([X/Fe]\) ratios for AGB stars with initial masses of 1.3\(M_\odot\), 1.4\(M_\odot\), 1.5\(M_\odot\) and 2.0\(M_\odot\), varying the number of thermal pulses and the quantity of \(^{13}\text{C}\) pocket for a metallicity \([Fe/H] = -2.6\), close to the metallicity of CD-50°776.

Figure 14 illustrates this comparison, and shows that the best nucleosynthesis model that fits the observations is that of a star with an initial AGB mass of 1.3\(M_\odot\) for the ST/2 case. Inspecting another fits for the CEMP-s stars investigated in Bisterzo et al. (2012), we verify that the abundance pattern of CD-50°776 is similar to the pattern of the CEMP-s stars CS 22964-161, CS 22880-074, CS 22942-019, CS 30301-015, HD 196944, and BS 17436-058, where the abundance of lead was also determined. These stars were classified by Bisterzo et al. (2012) as CEMP-s, which means that the ratio \([hs/Fe]\) (defined by Bisterzo et al. (2012) as the mean \([X/Fe]\) ratio given by \([\text{La}/Fe]+[\text{Nd}/Fe]+[\text{Sm}/Fe]/3.]\) is less than 1.5. In fact, CD-50°776 has \([hs/Fe] = 0.8\).

However, CD-50°776 presents another chemical peculiarity rarely observed in the CEMP-s stars, that is, a low abundance of nitrogen. As far as we know, this peculiarity has also been observed in the extragalactic CEMP-s star Scl-1013644 (Salgado et al. 2016). It is worth noting that the nucleosynthesis models of Bisterzo et al. (2010) predict a high abundance of carbon and nitrogen for CD-50°776, which is not supported by our observations.

As mentioned in Bisterzo et al. (2011), the ratios of \([\text{C}/Fe]\), \([\text{N}/Fe]\) and the \(^{12}\text{C}/^{13}\text{C}\) isotopic ratios are overestimated in AGB models where the occurrence of mixing produced by the ‘Cool Bottom Processing’ (CBP) has been accounted to explain the abundances of carbon and nitrogen in CEMP-s stars. However, the efficiency of this process is difficult to estimate due to the influence of other physical phenomena such as rotation, thermohaline mixing, and magnetic fields.

On the other hand, as discussed in Section 4.1.1, the low abundance of nitrogen could be explained assuming an initial mass of 2.0\(M_\odot\) of the donor star without the occurrence of CBP. Thus, it seems that the mixing process and their efficiency in both the AGB star and the star that received the ejected material should be better modeled to fit the observations. Finally, we recall that further spectroscopic observations will be important to obtain radial velocity measurements and to investigate the binary nature of this star.

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Figure 14. Observed (black dots) and predicted (red) [X/Fe] ratios for CD-50776. The predicted [X/Fe] ratios were obtained using the models available in Bisterzo et al. (2010). The best model was obtained for an initial AGB star for 1.3M⊙, case ST/2 after five thermal pulses and no dilution.

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