Surface abundances of ON stars

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Received / Accepted

ABSTRACT

Context. Massive stars burn hydrogen through the CNO cycle during most of their evolution. When mixing is efficient, or when mass transfer in binary systems happens, chemically processed material is observed at the surface of O and B stars.

Aims. ON stars show stronger lines of nitrogen than morphologically normal counterparts. Whether this corresponds to the presence of material processed through the CNO cycle or not is not known. Our goal is to answer this question.

Methods. We perform a spectroscopic analysis of a sample of ON stars with atmosphere models. We determine the fundamental parameters as well as the He, C, N, and O surface abundances. We also measure the projected rotational velocities. We compare the properties of the ON stars to those of normal O stars.

Results. We show that ON stars are usually helium-rich. Their CNO surface abundances are fully consistent with predictions of nucleosynthesis. ON stars are more chemically evolved and rotate - on average - faster than normal O stars. Evolutionary models including rotation cannot account for the extreme enrichment observed among ON main sequence stars. Some ON stars are members of binary systems, but others are single stars as indicated by stable radial velocities. Hence, mass transfer is not a simple explanation for the observed chemical properties.

Conclusions. We conclude that ON stars show extreme chemical enrichment at their surface, consistent with nucleosynthesis through the CNO cycle. Its origin is not clear at present.

Key words. Stars: early-type – Stars: atmospheres – Stars: fundamental parameters – Stars: abundances – Stars: binaries: general

1. Introduction

Massive stars are born as O and B dwarfs on the main sequence. They subsequently evolve into supergiants of various type (blue, yellow, red) as their effective temperature decreases and their radius increases. Some stars may evolve back and forth between these types of supergiants due to as-yet poorly-known physical mechanisms (e.g. Georgy et al. 2014). Above about 25 M\textsubscript{\odot} (at solar metallicity) these stars develop strong winds after the supergiant phase, becoming nitrogen- or carbon-rich Wolf-Rayet stars (WN, WC; e.g., Crowther 2007). The different types of Wolf-Rayet star reflect the different compositions of their surface material: WN stars show nitrogen enrichments and carbon depletions, while WC stars are hydrogen-free and have a high fraction of carbon in their atmospheres.

These chemical properties are direct consequences of a different evolutionary states. Massive stars burn hydrogen to helium through the partial or complete CNO cycling (depending on the temperature). In equilibrium, most of the nuclei in the CNO cycle are in the form of nitrogen; consequently, nucleosynthesis in massive stars produces an excess of nitrogen and a depletion of carbon and oxygen. If mixing processes are efficient, part of this processed material can be brought to the surface, and thus be detected spectroscopically. WN stars show the typical chemical
patterns of CNO burning; in subsequent evolutionary phases, helium burns to carbon, accounting for the chemical appearance of WC stars.

The CNO cycle proceeds in the cores of massive stars as long as hydrogen is available (i.e. during the main sequence). Hence we expect massive stars to become increasingly nitrogen rich, and carbon/oxygen poor, as they evolve off the zero-age main sequence.

Rotation is a powerful way of triggering mixing mechanisms in massive stars (Maeder & Meynet 2000; Langer 2012), and evolutionary calculations of rotating stars show that the surface composition of OB stars can be modified by CNO-processed material, even during early evolutionary phases (Brott et al. 2011; Ekström et al. 2012; Chielli & Limongi 2013). The degree of enrichment depends on several parameters: rotation speed, metallicity, initial mass, magnetic field.

Observationally, the predictions of stellar-evolution models incorporating rotation have been partly confirmed (Hunter et al. 2008, 2009), showed that the majority of the B stars they studied in the Galaxy, LMC and SMC exhibit nitrogen enrichments as predicted by rotating models, although a non-negligible fraction (20 to 40%) were found to be more enriched than expected for their rotation speed. Przybilla et al. (2010) and Maeder et al. (2014) demonstrated that B stars showed surface CNO patterns consistent with the expectations of nucleosynthesis. Martins et al. (2015) reached similar conclusions for a large sample of Galactic single O stars (see also Bouret et al. 2012, 2013).

Surface abundances can also be modified by mass transfer in binary systems. If the binary separation is small, the more massive component fills its Roche lobe first, because of its faster evolution, and may dump processed material onto the surface of the secondary (Langer et al. 2008). The primary may subsequently explode as supernova, which will either disrupt the system, leaving the chemically-contaminated secondary as a single star, or produce a binary system with a high-mass star and a compact object. During the mass-transfer process, the primary may also transfer angular momentum to the secondary, which is thereby spun up (Wellstein et al. 2001; Petrovic et al. 2005). The faster rotation can trigger additional mixing of CNO material produced in the secondary’s core, contributing further to the modification of surface abundances. Even in the absence of mass transfer, the rotation of binary components may be affected by tidal interactions, with consequences for mixing.

Surface abundances are therefore a key to understanding the evolution of single and binary massive stars. Walborn (1976, 1977, 1978) reported the existence of O and B stars with peculiar CNO spectra: the OBN and OBC stars (see also Walborn et al. 2004). In the former, lines of nitrogen (especially $\lambda$4630–4640) are much stronger than in normal OB stars, while in the latter, they are weaker. At the same time, C lines at $\lambda$4650 is weak in OBN stars. Most ON stars have a spectral type of O8.5 and O9.7 – where C and N lines are easily observed – but some are also found at spectral type O2, based on the morphology of Nv and Oiv lines (Walborn et al. 2004). Lesteven (1973) studied the ON star HD 201345 and concluded that its spectroscopic appearance was due to the presence of CNO processed material on its surface. Schönberner et al. (1988) studied three ON stars together with two normal O stars, and concluded that the ON stars were helium-rich and showed clear signs of CNO processing at their surfaces. Similar conclusions were reached by Villamariz et al. (2002) for the ON star HD 191423. Smith & Howarth (1994) determined the helium abundance of one OC, one normal O and one ON star. They found an increasing ratio He/H along the OC/O/ON sequence, confirming the suggestion of Walborn (1976) that the OBN and OBC stars represent different degrees of chemical evolution of OB stars. Howarth & Smith (2001) studied the distribution of rotational velocities of ON stars and concluded that, on average, they rotate faster than normal stars, supporting the hypothesis that rotational mixing could account for their anomalous surface abundances (see also Schönberner et al. 1988; Bolton & Rogers 1978) investigated the binary frequency of OBN/ OBC stars (see also Bovajian et al. 2005). They found that most OBN stars show radial-velocity variations (with some binary systems clearly identified), while OBC stars seem to be constant.

While these earlier investigations have provided evidence of CNO processing, to date quantitative spectroscopic analyses have focussed on helium (Schönberner et al. 1988; Smith & Howarth 1994; Villamariz et al. 2002), employing relatively simple model atmospheres; determinations of CNO abundances have relied on equivalent-width measurements and curve-of-growth analyses (Schönberner et al. 1988; Villamariz et al. 2002). Consequently, the status of OBN/OBC stars remains unclear, and the origins of the chemical-abundance peculiarities observed at their surfaces are not fully understood – e.g., what are the relative roles of rotation and binarity? In order to make progress in the understanding of OBN stars, we have conducted the first quantitative analysis of the helium and CNO abundances of a significant sample of ON stars, using modern non-LTE/line-blanketed atmosphere models. Section 2 of the paper presents the sample and the observational material; analysis methods are described in Section 3 and the results in Section 4. These results are discussed in Section 5 with our conclusions given in Section 6.
3. Modelling and spectroscopic analysis

We have used the atmosphere code CMFGEN to analyze the surface properties of the ON stars. A full description of CMFGEN can be found in Hillier & Miller (1998). In a nutshell, CMFGEN solves the radiative transfer and statistical equilibrium equations in the comoving frame, leading to non-LTE models. The temperature structure is set from the radiative-equilibrium constraint. Spherical geometry is adopted to take into account extension due to the strong winds of O stars. The density structure is computed from mass conservation and the velocity structure is constructed from a pseudo-photospheric structure connected to a \( \beta \)-velocity law. The photospheric structure is obtained from a few iterations of the hydrodynamical solution in which the radiative force computed from the level populations and atomic data is included. The final synthetic spectrum is obtained from a formal solution of the radiative transfer equation.

The synthetic spectra are subsequently compared to observations to determine the stellar parameters. In practice, we proceeded as follows:

- **Rotation and macroturbulence:** we used the Fourier-transform method (Gray 1973) to determine \( V \sin \) the projected equatorial rotational velocity. We relied on \( \text{O} \equiv \lambda 5592 \) when possible; otherwise, we used \( \text{He} \equiv \lambda 4920 \). We subsequently estimated the expected \( T_{\text{eff}} \) and log \( g \) from the target’s spectral type, using the calibration of Martins et al. (2005), and selected a corresponding synthetic spectrum from our database of models. We convolved this spectrum with a rotational profile (adopting \( V \sin \) from the previous step), and performed an additional convolution by a radial–tangential profile (parameterized by a velocity \( v_{\text{mac}} \)) to take macroturbulence into account (Simón-Díaz & Herrero 2014). We varied \( v_{\text{mac}} \) until a good match was obtained to the observed spectrum (especially around 4100 Å, 4700 Å and 4900 Å). Uncertainties in \( V \sin \) and \( v_{\text{mac}} \) are of the order \( \sim 10 \) and 20 km s\(^{-1}\) respectively.

- **Effective temperature:** we relied on the traditional ionization-balance method to constrain \( T_{\text{eff}} \). We used the helium lines \( \text{He} \equiv \lambda 4026, \text{He} \equiv \lambda 4440, \text{He} \equiv \lambda 5016, \text{He} \equiv \lambda 5412 \). We found that when \( \text{He} \equiv \lambda 4542 \) was perfectly matched, \( \text{He} \equiv \lambda 4200 \) was usually slightly too strong and \( \text{He} \equiv \lambda 5412 \) slightly too weak. This is partly attributed to the échelle nature of most of our spectra and thus to uncertain normalization. As a consequence, effective temperatures are determined within about \( \pm 1500 \) K.

- **Surface gravity:** the wings of Balmer lines were used to determine log \( g \), with a typical uncertainty of \( \pm 0.15 \) dex.

Since our principal focus is on surface parameters, we did not try to reproduce the details of emission lines likely to be formed in the wind (particularly \( \text{H} \equiv \lambda 6566, \text{He} \equiv \lambda 6678 \)), instead, we simply adopted combinations of terminal velocity and mass-loss rate that give a reasonable fit to these features in each star, with the wind-acceleration parameter \( \beta \) fixed at 1.0. luminosities were adopted from the calibration given by Martins et al. (2005). Instrumental broadening was negligible given the high resolution of the observed spectra and the generally large rotational broadening, and our final synthetic spectra were simply convolved by rotational and radial–tangential profiles (see above).

For the determination of surface abundances, we proceeded as in Martins et al. (2015). For a given \( T_{\text{eff}} \) and log \( g \) we ran models with different \( \text{He}, \text{C}, \text{N}, \) and \( \text{O} \) abundances. We identified the cleanest lines of each element in the observed spectrum, and performed a \( \chi^2 \) analysis combining all selected features. The computed \( \chi^2 \) values were renormalized to a minimum value of 1.0, with the best-fit abundance taken to correspond to this minimum, and 1–\( \sigma \) uncertainties defined by \( \chi^2=2 \).\(^2\)

For helium, we utilized from seven to ten lines selected from \( \text{He} \equiv \lambda 4026, \text{He} \equiv \lambda 4440, \text{He} \equiv \lambda 4920, \text{He} \equiv \lambda 5016, \text{He} \equiv \lambda 5412, \) and \( \text{He} \equiv \lambda 6680 \). Figure II shows an example of \( \text{He}/\text{H} \) determination, illustrated by HD 48279. An abundance greater than 0.1 (by number) is clearly favoured, simply by inspection. The quantitative analysis restablishes that \( \text{He}/\text{H}=0.16\pm0.05 \) best reproduces the set of helium lines.
Our primary carbon-abundance diagnostic was C $\text{ii}\ \lambda 4070$. For a few stars, C $\text{ii}\ \lambda 4465$ could also be used. We did not use C $\text{iii}\ \lambda 4650$ because of its sensitivity to winds, to metallicity and to uncertainties in the atomic data (Martins & Hillier 2012). In most cases, we could obtain only an upper limit on C/H because C $\text{ii}\ \lambda 4070$ is the only useful carbon line that could be detected, and is rather weak. Difficulties in normalizing the spectra resulting from the presence of nearby H$\alpha$ further undermine any attempt to put a better constraint on C/H. Figure 2 shows an example of C/H determination, for HD 117490. In this case a conservative upper limit on C/H of $3 \times 10^{-5}$ is adopted.

The principal nitrogen-abundance indicator was the N $\text{ii}\ \lambda 4510–4535$ complex of lines. Occasionally, other indicators were added: N $\text{i}\ \lambda 3995$, N $\text{i}\ \lambda 4004$, N $\text{i}\ \lambda 4044$, N $\text{ii}\ \lambda 4447$, N $\text{ii}\ \lambda 4467$, N $\text{i}\ \lambda 5001$, N $\text{i}\ \lambda 5005$, N $\text{i}\ \lambda 5501$, N $\text{ii}\ \lambda 5576$ and N $\text{i}\ \lambda 5680$. Finally, O $\text{ii}\ \lambda 45592$ was adopted as the main oxygen-abundance indicator. In some stars, we could also make use of O $\text{i}\ \lambda 3993$, O $\text{ii}\ \lambda 3963$, O $\text{ii}\ \lambda 4277–78$, O $\text{ii}\ \lambda 4318$, O $\text{ii}\ \lambda 4355$, O $\text{ii}\ \lambda 4416–18$, O $\text{ii}\ \lambda 4603$, and O $\text{ii}\ \lambda 4611$. Compared to normal O stars, fewer useful lines are generally available to determine surface abundances because the ON stars typically have relatively large $V\ \text{sin}\ i$ values (Howarth & Smith [2001]); hence weak metallic lines are too broad to be readily detected. Lines from two ionization states are usually taken into account in the abundance determination, so that the error bars include uncertainties related to flawed N and O ionization balances. At the same time, by performing the abundance determination on an ensemble of lines we minimize uncertainties related to the formation/physics of individual lines (see Fig. 1 in Martins et al. [2015]).

4. Results

The results of the spectroscopic analysis are summarized in Table 2 and the best-fit models compared to the observed spectra in Figs. B.1–B.12. We emphasize that the numerical results listed in Table 2 should be viewed as ‘surface average’ values; many of the sample stars have large rotational velocities, which can affect their shapes, and create surface gradients in the physical parameters (e.g. Howarth & Smith [2001]; Puls et al. [2013]). For HD 191423, the fastest rotator of the sample, rotational broadening is so large that normalization of the echelle spectra was extremely difficult, and carbon and oxygen abundances could not be determined.

Table 2 shows that most ON stars are helium-rich. Smith & Howarth [1994] performed a helium-abundance determination for HD 123008 and obtained He/H = $0.20 \pm 0.05$, in agreement with the best-fit models (Santolaya-Rey et al. 1997; Puls et al. 2005). This completely independent approach allows the determination of $T_{\text{eff}}$, log $g$, $v\ \text{sin}\ i$, $v_{\text{mac}}$, and He/H. The results turned out to be in excellent agreement with the CMFGEN analyses, within the respective error bars, lending strong support to our quantitative results.

We adopted a photospheric microturbulent velocity of $10 \text{ km s}^{-1}$ in our synthetic spectra. A larger value would tend to reduce the derived abundances, especially for helium. McErlean et al. [1998]; Villamariz & Herrero [2000]; Howarth & Smith [2001]. Using HD 191423 as a test case, we find that increasing the microturbulence to $20 \text{ km s}^{-1}$ leads to a reduction of $0.05$ in the inferred He/H ratio.

As a check on our results, we performed a separate analysis of our sample using the TACOB-GAIA package (Simón-Díaz et al. 2011; Sabín-Sanjulián et al. 2014), which uses a $\chi^2$-fitting algorithm coupled to a large, pre-computed grid of FASTWIND models (Santolaya-Rey et al. 1997; Puls et al. 2005). This completely independent approach allows the determination of $T_{\text{eff}}$, log $g$, $v\ \text{sin}\ i$, $v_{\text{mac}}$, and He/H. The results turned out to be in excellent agreement with the CMFGEN analyses, within the respective error bars, lending strong support to our quantitative results.

Except for HD 123008 for which we found that $20 \text{ km s}^{-1}$ gave a better fit of the helium lines.
Table 2. Parameters of the sample stars.

| Star        | Spectral Type | Teff  [kK] | log g | loge | V sin i [km s⁻¹] | vₘₐₖ [km s⁻¹] | He/H | C/H [10⁻³] | N/H [10⁻⁴] | O/H [10⁻⁴] |
|-------------|---------------|------------|-------|------|-----------------|----------------|------|-----------|-----------|-----------|
| HD 12323    | ON9.2 V       | 33.5       | 4.00  | 4.01 | 130             | -              | 0.16±0.03 | <0.3      | 3.5±1.8    | 2.5±1.9    |
| HD 13268    | ON9.5 III n   | 32         | 3.50  | 3.63 | 310             | -              | 0.20±0.10 | <0.5      | 5.0±2.0    | 3.1±1.4    |
| HD 14633    | ON8.5 V       | 34         | 3.80  | 3.81 | 100             | 120            | 0.13±0.04 | <0.3      | 5.2±1.5    | 1.7±0.8    |
| HD 48279    | ON8.5 V       | 34.5       | 3.80  | 3.82 | 137             | 50             | 0.16±0.05 | 0.65±0.20 | 4.6±2.0    | 4.3±2.3    |
| HD 91651    | ON9.5 III n   | 31         | 3.50  | 3.62 | 310             | -              | 0.14±0.08 | <0.5      | 5.4±1.6    | 2.3±1.4    |
| HD 102415   | ON9 III n     | 31         | 3.50  | 3.70 | 376             | -              | 0.21±0.10 | <0.6      | 7.6±2.6    | <3.0       |
| HD 117490   | ON9.5 III n   | 30.5       | 3.50  | 3.66 | 375             | -              | 0.16±0.09 | <0.3      | 7.6±2.6    | 2.5±2.6    |
| HD 123008   | ON9.2 Iab     | 30         | 3.10  | 3.10 | 37              | 100            | 0.21±0.11 | 0.22±0.21 | 13.5±6.7   | 4.8±1.1    |
| HD 150574   | ON9 III(n)    | 31         | 3.40  | 3.49 | 240             | -              | 0.23±0.06 | <0.5      | >10.0      | 6.0±2.3    |
| HD 191423   | ON9 II-III m  | 31.5       | 3.50  | 3.72 | 445             | -              | 0.25±0.08 | <0.5      | 7.3±7.6    | 3.1±0.8    |
| HD 191781   | ON9.7 Iab     | 28         | 3.10  | 3.12 | 107             | 70             | 0.25±0.2 | <0.1      | 6.5±3.4    | 3.1±0.8    |
| HD 201345   | ON9.2 IV      | 34         | 4.00  | 4.01 | 95              | 60             | 0.1      | <0.4      | 4.0±2.3    | 3.6±2.2    |

Notes. Uncertainties on Teff, log g, V sin i and vₘₐₖ are ~1.5kK, 0.15 dex, 10 and 20 km s⁻¹ respectively. loge is the surface gravity corrected for centrifugal acceleration. Abundances are number ratios.

Fig. 3. log g - log(Teff) diagram for the sample stars. Triangles (pentagons, squares, circles) are for luminosity class V (IV, III, I) stars. Typical uncertainties are shown in the upper-left corner. Evolutionary tracks including rotation, from [Ekström et al. 2012], are overplotted, labelled by ZAMS masses.

Fig. 4. N/H as a function of He/H for the ON stars. The abundance ratios are by number. Symbols have the same meaning as in Fig. 3. The evolutionary tracks including rotation of [Ekström et al. 2012] are overplotted. The bold part corresponds to the main sequence (central hydrogen mass fraction > 0).

good agreement with our estimate, [Howarth & Smith 2001] determined He/H in HD 191423 using simple non-LTE models without line-blanketing but a better treatment of 2D effects than our approach. They obtained He/H= 0.23 ± 0.04 in very good agreement with our value. The relatively large helium enrichment of most ON stars indicates a peculiar chemical history compared to normal OB stars, which do not show systematically values of He/H larger than 0.1 (e.g. Mokiem et al. 2007).

Figure 3 shows the surface gravity as a function of effective temperature in our sample. ‘Geneva’ evolutionary tracks, from [Ekström et al. 2012], are overplotted. We see that the ON stars follow a relatively clear sequence: dwarfs have higher log g values than giants, while supergiants have the lowest log g, a trend similar to that found for normal O stars by [Martins et al. 2015]. Stars classified as ON have a rather narrow range of initial masses: 20–25 M⊙ for the dwarfs/giants, and a little over 25 M⊙ for the supergiants, according to the Geneva tracks.

Figure 4 illustrates the N/H ratio (by number) as a function of He/H. The evolutionary models predict a correlation between N/H and He/H that simply results from nucleosynthesis through the CNO cycle: the higher the helium content, the higher the nitrogen abundance. Figure 4 shows a possible trend of this kind among the ON stars, but the rather large error bars on the abundance determinations don’t allow for a clear-cut conclusion ob-
dance as a function of surface gravity for the ON stars

The distribution of observed N/C ratios for ON stars is compared to results for morphologically normal stars with spectral types O8.5–9.7 (small symbols), taken from Martins et al. (2015).

Fig. 5. The N/C abundance ratio as a function of surface gravity for the ON stars (large symbols), compared to results for morphologically normal stars with spectral types O8.5–9.7 (small symbols), taken from Martins et al. (2015).

Most stars appear more enriched than expected from their position in the log g - log(T_eff) diagram.

Figure 5 shows the ratio of nitrogen to carbon surface abundance as a function of surface gravity for the ON stars and for a reference sample of morphologically normal O stars taken from Martins et al. (2015). For the reference sample, only stars with spectral types between O8.5 and O9.7 are considered, corresponding to the spectral-type range of the ON sample. The dwarf, giant, and supergiant stars are well separated in this plane, among both ON and reference groups, largely reflecting the surface-gravity differences between luminosity classes, as is also seen in Fig. 3. The most striking feature of Fig. 5 is the higher log(N/C) ratios found for ON stars, for a given luminosity class. The difference amounts to 0.5-1.0 dex or more, since most of the log(N/C) values for ON stars are actually lower limits (due to the upper limits on C/H; Table 2). Another possible trend is that of higher log(N/C) among ON stars as one moves from dwarfs to giants and supergiants. This trend was clearly established for morphologically normal stars by Martins et al. (2015), and appears to hold also for ON stars. This suggests that the physics of chemical mixing follows the same patterns in normal and ON stars, pointing to a common origin for surface chemical enrichment. However, we caution that the trend for ON stars is less clear due to both the small number of objects, and the fact that for most stars we have only lower limits on log(N/C).

Fig. 5 shows the log(N/C) versus log(N/O) diagram. The upper-left panel reveals that the ON stars are systematically more enriched than the comparison O stars taken from Martins et al. (2015). They extend the relation between log(N/C) and log(N/O) observed for normal stars to higher abundance ratios, and are also located between the limits corresponding to partial CN burning and complete CNO burning. Consequently, the abundance patterns of ON stars are consistent with the predictions of nucleosynthesis through the CNO cycle.

Other panels of Fig. 6 compare results for ON and normal O stars at different luminosity classes. In each case, the ON stars are clearly separated from the comparison stars, indicating that their surface abundances result from a much stronger mixing than that experienced by normal stars. Martins et al. (2015) showed that, on average, supergiants are more enriched than giants and dwarfs. We saw in Fig. 5 that this trend may exist among ON stars, too. Fig. 6 tends to confirm that there is a sequence of higher enrichment when moving from dwarfs to giants and supergiants, although there is one outlier (HD 14633, a dwarf that appears to be as chemically mixed as the giants).

Figures 5 and 6 show gaps between the distributions of the ON stars and those of the comparison stars, and the reader may wonder whether these are real features. In this context, then, supposing that chemical mixing may be due to rotation (and Howarth & Smith (2003) have shown that ON stars rotate on average faster than normal O stars), it is informative to consider the distributions of projected rotational velocities in the two samples. This comparison is performed in Fig. 7, clearly, on average the stars in the comparison sample are rotating much more slowly than those of the ON stars. The median V_sini value for the ON and comparison-O samples are 208.0 and 52.5 km s^{-1}, and a KS test indicates a probability of less than 1% that the two populations are drawn from the same parent distribution.

Fig. 5 further includes the V_sini distribution of the IACOB sample studied by Simón-Díaz & Herrero (2014). They provided projected rotational velocities for 199 Galactic O stars, which can be viewed as a reference distribution for O stars in general; the ON stars have higher V_sini values, and our comparison O stars lower ones, than the Simón-Díaz & Herrero reference sample. Potentially, therefore, the very different ranges of V_sini covered by our two samples (ON and comparison) can explain the gap seen in Fig. 6 if rotation leads to a continuous increase of mixing as V_sini increases, and if our two samples are well separated in terms of projected rotational velocity, then a separation into two groups in the log(N/C)–log(N/O) and log(N/C)–log g diagrams is expected.

5. Discussion

5.1. Spectral classification and ON stars

The spectroscopic classification qualifier ‘N’ was developed in the context of late-O/early-B stars, as is illustrated by our sample, which is limited to spectral types between O8.5 and O9.7. Walborn et al. (2004) discovered a related morphological dichotomy in terms of CNO features at the earliest spectral type, O2, where some stars show relatively strong O iv lines and weak N iv lines. The opposite behaviour is found in a second group, for which the spectral classification ON2 was therefore created, by analogy to the behaviour in late-O stars.

It is important to note that different lines are used when classifying ON2 and late-type ON stars: lines from more highly ionized elements are observed in the former group (O iv, N iv) than in the latter (C iii, N iii). This, rather than some fundamental difference in surface chemistry, largely accounts for why the ‘N’ qualifier is not assigned to O stars at intermediate spectral types – when moving from O2 to later spectral types, the diagnostic O iv and N iv lines disappear because of ionization effects. On the other side of the classification scheme, the C iii and N iii lines around 4630–4650 Å, which define the late-type ON category, progressively go into emission at spectral types earlier than
Fig. 6. Distributions of log (N/C) versus log(N/O) for the ON stars (large symbols) and for a comparison set of normal O stars with spectral types O8.5-O9.7 (small symbols) taken from Martins et al. (2015). The upper-left panel shows the full sample. The upper-right (lower-left, lower-right) shows the dwarf–subgiant (giant, supergiant) sample. Solid lines in the upper-left panel show the relations expected for partial CN or complete CNO burning in equilibrium.

In principle, the strength of these emission features could be used in a similar manner to their absorption counterparts in late-type stars, but the strength of the emission in these lines is complicated by wind effects (Rivero González et al. 2011; Martins & Hillier 2012). Interestingly, Walborn et al. (2010) recently defined the Ofc class, corresponding to stars showing N\textsc{iii} λ4630-4640 in emission and C\textsc{iii} 4650 of comparable strength. The difference between Ofc and Of stars may be the equivalent of the ON phenomenon at O2 and late-O spectral types (Of stars having comparatively weaker C lines than Ofc stars).

5.2. Rotation and the ON phenomenon

Fast rotation could explain the strong chemical enrichments that we have found in ON stars, which rotate on average faster than normal O stars (Howarth & Smith 2001, and section 4). Theoretical predictions indicate that faster rotation leads to stronger mixing (Maeder & Meynet 2000; Langer 2012; Brott et al. 2011; Ekström et al. 2012; Chieffi & Limongi 2013; Georgy et al. 2013a), and thus to the appearance of more-strongly processed material at the surface of OB stars. Walborn et al. (2004) performed surface-abundance determinations

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\[5\] We recall that such fast rotation could result from formation processes, or may arise through tidal interactions in binary systems (which would not necessarily have experienced mass transfer; Langer et al. 2008).
tions for O2 and ON2 stars and concluded that the latter were more chemically processed than the former. From their positions in the Hertzsprung–Russell diagram, they argued that ON2 stars may be the product of homogeneous evolution, which is usually understood as a consequence of fast rotation (Maeder 1987; Langer 1992).

Figure 7 confronts our abundance determinations with several stellar-evolution models, computed for 25 $M_\odot$ stars at solar metallicity, from Ekström et al. (2012), Chieffi & Limongi (2013), and a dedicated model computed with the STAREVOL code (Siess 2006; Decressin et al. 2009) for which we implemented the same physical ingredients as in Ekström et al. (2012): core overshooting, mass-loss prescriptions, angular-momentum-transport equation, and turbulent-transport prescriptions. All the models start on the zero-age main sequence with an equatorial surface velocity of 300 km s$^{-1}$ (equivalent to $V \approx 0.4V_c$, where $V_c$ the critical surface velocity).

All the inferred abundances lie close to the theoretical tracks, which confirms that they broadly follow the predictions of nucleosynthesis and chemical mixing. However, the abundances predicted at the end of the main sequence (i.e., when the hydrogen mass fraction in the core reaches zero) vary significantly between codes, due to the sensitivity of the mixing efficiency on both the adopted prescriptions for the shear turbulence (vertical shear from Maeder (1997) in Ekström et al. (2012), and from Talon & Zahn (1997) in Chieffi & Limongi (2013)), and on the numerical treatment itself. Nevertheless, we see that the ON stars are all located beyond the end of the main sequence in the log(N/C)–log(N/O) plane. While this may be possible for supergiants, the giants and dwarfs are certainly expected still to be core hydrogen burning (see Fig. 8). The surface abundances of ON stars are thus more enriched than predicted by any of the available models, assuming a standard rotation rate on the main sequence.

Scrutiny of 15-$M_\odot$ models from Georgy et al. (2013b) suggests that surface enrichment of CNO-cycle products can be increased significantly (by up to a factor of 3 compared to normally rotating stars) through adopting initial rotation rates close to the break-up velocity. It is therefore tempting to speculate that the nitrogen abundances of ON stars can be attributed to enhanced efficiency of rotational mixing in extremely fast-rotating stars. To test this hypothesis, new 25-$M_\odot$ models were computed using the Geneva code, with ratios of initial to critical equatorial velocities, $V/V_c$, of 0.6 and 0.8 (see Fig. 9). Results are presented in Fig. 9. The left-hand panel shows that increasing the initial rotational velocity leads to a more ‘upward’ evolution (i.e., the effective temperature decreases less at higher velocity). All non-supergiant ON stars are located between the zero-age main sequence and the terminal main sequence, whatever the initial rotation speed. The middle panel of Fig. 9 shows the corresponding surface abundances; as expected, faster rotation leads to stronger enrichment. At the end of the main sequence, the $V/V_c = 0.8$ model barely reaches the region occupied by the ON stars. However, this happens when log $g < 3.5$; for the range of surface gravities of non-supergiant ON stars (3.5–4.0) the surface enrichment is weaker. Consequently, evolutionary models with high rotation velocities do not appear to explain the extreme enrichment of ON stars, at least with the current formalism used to treat rotation.

The right-hand panel of Fig. 9 shows the effect of adding magnetism to the $V/V_c = 0.6$ model. This model includes the effects of the internal magnetic fields on the mixing of chemicals and angular momentum, according to the Tayler-Spruit dynamo theory (Spruit 2002, Maeder & Meynet 2004). In this framework, internal magnetic fields produces a strong coupling between the core and the surface, and considerably increases the internal mixing (e.g. Maeder & Meynet 2005). Significant enrichment, consistent with that of ON stars, can be produced while log $g > 3.5$. However, inspection of the left-hand panel of Fig. 9 reveals that this model produces a blueward evolution and never reaches the position of the ON stars.

Models aside, if rotational mixing is the principal cause of the ON phenomenon, one may wonder why not all fast-rotating O stars are classified as ON. For example, ζ Oph has a projected rotational velocity of about 400 km s$^{-1}$ (e.g., Marcolino et al. 2009), but its spectral type is simply O9.2 Vn (Sota et al. 2014), where the ‘nn’ qualifier reflects the strong rotational broadening; that is, ζ Oph is not classified as an ON star (see also Howarth & Smith 2001). Villamariz & Herrero (2005) performed a quantitative analysis of its stellar parameters and surface abundances (using equivalent widths measurements and the curve-of-growth method). Marcolino et al. (2009), using more recent atmosphere models than Villamariz & Herrero, refined the $T_{\text{eff}}$ and log $g$ determination. ζ Oph, together with the fast rotators of the sample of Martins et al. (2015) (i.e., stars with $V \sin i > 250$ km s$^{-1}$) are shown in Fig. 10. The left-hand panel of Fig. 10 demonstrates that the ON stars are more chemically processed than the non-ON fast rotators. The only non-ON fast rotator with a strong enrichment is HD 192281 (O4.5 Vn(f)), the most massive dwarf of the sample; its enrichment is probably due to its higher mass (see discussion in Martins et al. 2015).

Since chemical enrichment depends not only on rotation but also on metallicity, mass and age, one may wonder if the non-ON fast rotators are less evolved or less massive than the ON stars (supposing their metallicities to be similar since all stars are located in the Galaxy). The right-hand panel of Fig. 10 shows

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6 The STAREVOL calculations were stopped just after the end of the main sequence.
that ON and non-ON stars are distributed in the same area of the log $g$–$T_{\text{eff}}$ diagram. Thus, they have similar mass and age ranges. In conclusion, if ON stars appear to rotate on average faster than normal stars, not all fast rotators necessarily display the ON phenomenon. Another mechanism may be required, in addition to rotation, to produce ON stars.

5.3. Binarity and the ON phenomenon

Bolton & Rogers (1978) reported that most of the ON stars known at the time of their study were radial velocity (RV) variables, but OC stars were all RV constant. Walborn et al. (2011) discussed radial-velocity variability and the presence of companions in the most recent ON sample. Of the two O supergiants in our study, HD 123008 is reported to be constant in radial velocity, while HD191781 may be variable. The variability status of the giants is quite uncertain, with some claims of RV variations but based on limited numbers of measurements. The nature of the tentative variability observed in the giant sample is also unclear: binarity or wind/photospheric variability? Of the five dwarfs/subgiants, HD 48279 is constant in radial velocity (Mahy et al. 2009), HD 12323 is a single-lined
spectroscopic binary (SB1; Bolton & Rogers 1978), HD 14633 an SB1 with a low mass component and a high eccentricity (Boyajian et al. 2005), HD 102415 is reported as “likely variable” by Walborn et al. (2011) and HD 201345 has an unclear status.

Figure 11 provides more information on the line-profile and radial-velocity variations of ten of the ON stars studied in the present paper. The data used to build Fig. 11 are described in Table A.1. We chose He i λ5876 for study, as nearby telluric lines can be checked for wavelength-calibration issues. We confirm that HD 12323 and HD 14633 are SB1, with clear RV variations. HD 48279 is very stable in our data, nor do HD 191423 or HD 201345 show signs of variability. All other stars examined (HD 13268, HD 91651, HD 102415, HD 117490, HD 123008) show some degree of RV variability, the origins of which are unclear (RV modulations, pulsations, wind variability).

The exact position in respect of binarity among ON star is thus not completely clear. Variations in radial velocities are observed in a large fraction of the sample, but these are unambiguously attributable to binarity only in the few cases for which an orbital solution can be performed (HD 12323, HD 14633) or when an SB2 spectrum is observed (HD 89137). For the majority of the sample stars, radial velocity-variations do not have an unambiguous origin (they may be due to binarity or wind/photospheric variability), while a few stars’ spectra are consistent with constant radial velocities.

This raises the question of the role of binarity in the strong chemical mixing that we have shown to be a clear-cut characteristic of ON stars. More specifically, one may wonder if mass
transfer is responsible for this strong enrichment. In the classical mass-transfer scenario, material processed through nucleosynthesis in the core of a companion is dumped onto what we observe today as an ON star. Stars with an SB1 spectrum may be consistent with this scenario; the secondary may be a low-mass star, possibly a compact object resulting from the evolution and supernova explosion of an initially more massive star than the present-day primary. This initially more massive star could have contaminated the companion that we observe today as chemically enriched before exploding as a supernova. The system would have had to stay bound during the supernova phase to account for the SB1 RV curve. A mass-transfer scenario may also be applicable to RV-constant ON stars. These stars could have been initially part of binary systems in which mass transfer occurred before disruption in the supernova phase.

Bolton & Rogers (1978) argued that no sign of current episodes of mass transfer was observed among ON stars, especially dwarfs. Plaskett’s star is a famous binary system which is very probably in a post Roche-lobe overflow phase (Linder et al. 2008) and which shows strong line emission and variability. This is not observed currently among the ON stars we studied in the present paper, indicating that active mass transfer is probably not important among them. HD 48279, which has very similar parameters to the SB1 system HD 14633, does not show RV variations. Both stars are located very close to each other in the log g–T eff diagram (Fig. 3), hence their surface chemical enrichment cannot be clearly attributed to mass transfer, given that one is in a binary system and the other apparently is not. Although we cannot exclude the possibility that HD 48279 is the result of the merger of two stars, which could explain, at least qualitatively, the strong mixing of CNO material.

However, mass transfer is very probably taking place in the binary BD+36 4063 (not included in our sample). Williams et al. (2009) showed that this system contains a ON9.7b star with periodic radial-velocity variations. The secondary component is not observed, although for its estimated mass it should be seen in high-resolution spectra. Williams et al. argue that the ON star is currently transferring mass to the companion, surrounding it by a thick disk, preventing the secondary from being detected spectroscopically. In this system, therefore, the ON star is currently the mass donor.

A parallel situation is encountered in the massive SB2 system LZ Cep. Unlike BD+36 4063, the companion in LZ Cep is clearly detected, excluding the presence of a thick circumstellar disk arising from ongoing mass transfer. Mahy et al. (2011) obtained multi-epoch spectroscopy of the system and disentangled the spectra of both components, to which they assigned spectral types of O9 III + ON9.7 V (primary, secondary). Their quantitative analysis of the individual components’ spectra showed the secondary to be significantly nitrogen rich and carbon/oxygen poor: log(N/C) (respectively log(N/O)) reaches 1.6 (1.3). The secondary component therefore shows the typical abundance patterns of ON stars, as established in the present study. Mahy et al. (2011) interpreted the surface abundances of the secondary as the result of a previous episode of mass transfer in which the secondary was initially the most massive star. The ON star in LZ Cep evolved faster and transferred mass to what was original the secondary (now seen as the primary). In this scenario, the abundance pattern of the ON secondary star is due to the removal of external layers during the mass-transfer phase, thereby exposing internal layers of the star. These internal layers are more chemically mixed and thus show CNO processed material; that is, for LZ Cep (and possibly BD+36 4063) the ON star would have been created because of mass removal and not mass accretion.

Thus, the role of binarity (and mass transfer) in the appearance of the ON phenomenon is not obvious. It is even less clear if we consider once again the fast rotator ζ Oph, which is a runaway (Blauw 1961; Tetzlaff et al. 2011). Runaways may be produced by dynamical interactions in young, dense clusters or by supernova ejection from a binary system. Dynamical interaction in clusters usually involves at least one binary system (Hut & Bahcall 1983; Hoffel 1983; Hoogerwerf et al. 2001). Consequently, there is a high probability that ζ Oph was part of a binary system at an earlier stage in its evolution; in particular, Hoogerwerf et al. (2000) (see also van Rensbergen et al. 1996) argue that ζ Oph resulted from a supernova kick. Whatever the evolutionary and dynamical history of this star, it did not reach the level of enrichment seen in ON stars. Consequently, the combination of binarity and fast rotation (possibly acquired through tidal spin-up) does not appear to lead inevitably to the ON phenomenon.

6. Conclusions and final remarks

We have performed a spectroscopic analysis of a sample of ON stars using atmosphere models computed with the code CMFGEN. We have determined the fundamental parameters and the He, C, N, and O surface abundances, along with projected rotational velocities. The results can be summarized as follows:

- These late-type ON stars have initial masses in the range 20 to 25 M☉, with the two supergiants of the sample being slightly more massive.
- The projected rotational velocities of ON stars are on average higher than those of comparison samples of normal O stars (Martins et al, 2015; Simón-Díaz & Herrero, 2014).
- ON stars are chemically enriched; almost all have a helium to hydrogen number ratio larger than 0.1. All stars are nitrogen rich, carbon poor, and, to a lesser extent, oxygen poor. The surface CNO abundances are consistent with nucleosynthesis predictions.
- ON stars are more chemically mixed than morphologically normal stars of similar spectral types and luminosity classes in the sample of Martins et al. (2015).
- Some ON stars are members of binary systems; some show radial-velocity variations of unclear origin; some are constant in radial velocity.
- Evolutionary models including rotation are not able to reproduce the high degree of chemical mixing observed on the main sequence among ON stars.

From these results, we conclude that ON stars are O stars showing CNO-processed material at their surface; the N/C and N/O ratios we establish are the highest observed so far in O stars. The processed material is the product of nucleosynthesis, but the mechanisms by which it is brought to the surface remains unclear (rotational mixing and binary mass transfer being the prime suspects). ON stars rotate on average faster than normal stars, but there exist fast rotators with similar masses and ages that are not ON stars. There are also binary and (presumably) single stars among the ON category, as well as non-ON fast rotators that are (probably) former members of binary systems.

Acknowledgments

We thank John Hillier for making CMFGEN available to the community. FM and AP thank the Agence Nationale de la
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Appendix A: Additional observational information

Table A.1 provides information on the spectra used to investigate spectral variability and binarity in the ON stars sample. The spectra are shown in Fig. 11.

Fig. B.1. Best fit (red) of the observed spectrum (black) of HD 12323.

Fig. B.2. Best fit (red) of the observed spectrum (black) of HD 13268.

Appendix B: Best fits to the observed spectra
Table A.1. Spectroscopic data used to study variability.

| Star   | date of observation | Instrument            | Status  |
|--------|---------------------|-----------------------|---------|
| HD 12323 | 08 sep 2011       | N-NOT/FIES           | SB1     |
|        | 12 sep 2011        | N-NOT/FIES           |         |
|        | 29 oct 2012        | M-MERCATOR/HERMES    |         |
|        | 29 oct 2012        | M-MERCATOR/HERMES    |         |
|        | 25 dec 2012        | N-NOT/FIES           |         |
| HD 13268 | 12 jan 2011       | N-NOT/FIES           | variable|
|        | 26 oct 2012        | M-MERCATOR/HERMES    |         |
|        | 28 jan 2013        | N-NOT/FIES           |         |
|        | 29 jan 2013        | N-NOT/FIES           |         |
| HD 14633 | 13 jan 2009       | N-NOT/FIES           | SB1     |
|        | 10 sep 2011        | N-NOT/FIES           |         |
|        | 26 oct 2012        | M-MERCATOR/HERMES    |         |
|        | 23 dec 2012        | N-NOT/FIES           |         |
| HD 48279 | 14 jan 2011       | N-NOT/FIES           | constant|
|        | 24 dec 2012        | N-NOT/FIES           |         |
|        | 25 dec 2012        | N-NOT/FIES           |         |
| HD 91651 | 04 apr 2009       | ESO2.2/FEROS         | variable|
|        | 11 feb 2011        | ESO2.2/FEROS         |         |
|        | 20 mar 2011        | ESO2.2/FEROS         |         |
|        | 14 may 2011        | ESO2.2/FEROS         |         |
|        | 15 may 2011        | ESO2.2/FEROS         |         |
|        | 16 may 2011        | ESO2.2/FEROS         |         |
| HD 102415 | 12 may 2008      | ESO2.2/FEROS         | variable|
|        | 16 may 2011        | ESO2.2/FEROS         |         |
|        | 17 may 2011        | ESO2.2/FEROS         |         |
| HD 117490 | 12 may 2008      | ESO2.2/FEROS         | variable|
|        | 13 may 2011        | ESO2.2/FEROS         |         |
|        | 20 mar 2011        | ESO2.2/FEROS         |         |
|        | 21 mar 2011        | ESO2.2/FEROS         |         |
|        | 14 may 2011        | ESO2.2/FEROS         |         |
|        | 15 may 2011        | ESO2.2/FEROS         |         |
| HD 123008 | 13 may 2008      | ESO2.2/FEROS         | variable|
|        | 16 may 2011        | ESO2.2/FEROS         |         |
| HD 191423 | 29 aug 2011      | N-NOT/FIES           | constant|
|        | 11 sep 2011        | N-NOT/FIES           |         |
| HD 201345 | 09 sep 2010      | N-NOT/FIES           | constant|
|        | 17 jun 2011        | M-MERCATOR/HERMES    |         |
|        | 10 sep 2011        | N-NOT/FIES           |         |
|        | 25 dec 2012        | N-NOT/FIES           |         |
Fig. 11. Variability of ON stars. For each object, a selection of spectra centered on He I λ5876 is shown. The spectra are described in Table A.1.
Fig. B.3. Best fit (red) of the observed spectrum (black) of HD 14633.

Fig. B.4. Best fit (red) of the observed spectrum (black) of HD 48279.

Fig. B.5. Best fit (red) of the observed spectrum (black) of HD 91651.

Fig. B.6. Best fit (red) of the observed spectrum (black) of HD 102415.
Fig. B.7. Best fit (red) of the observed spectrum (black) of HD 117490.

Fig. B.8. Best fit (red) of the observed spectrum (black) of HD 123008.

Fig. B.9. Best fit (red) of the observed spectrum (black) of HD 150574.

Fig. B.10. Best fit (red) of the observed spectrum (black) of HD 191423.
Fig. B.11. Best fit (red) of the observed spectrum (black) of HD 191781.

Fig. B.12. Best fit (red) of the observed spectrum (black) of HD 201345.