RMC 40 in eruptive phase: CNO and rare-earth elements

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Abstract

Using high-resolution optical and infrared spectra of the LBV star in the Small Magellanic Cloud, RMC 40, obtained during the eruptive phase, we determined chemical abundances of the light (CNO) and rare-earth elements. We found strong decrease in carbon abundance and strong enhancement in nitrogen abundance. The abundances of the s-and r-process elements, such as Ba, La, Ce, Pr, Nd, and Dy, are increased compared to solar-scaled values by +(0.60 - 1.0) dex , pointing to strong pollution of the stellar envelope (pseudo-photosphere) by the products of the CNO cycle and the r- and s-processes.

Observations

The high-resolution spectra of R40 were obtained with FEROS echelle spectrograph at the 2.2m telescope of ESO at la Silla, Chile, during the years 2005 – 2022 The spectral resolution is R = 48000 and the wavelength coverage is from 3800 to 9200 Å.

Atmospheric parameters

The atmospheric parameters of the pseudo-photosphere of R40 in 2014 were determined in Campagnolo et al. (2018) using the LTE model atmospheres of Kurucz (1993) and a current version of the spectral analysis code MOOG (Sneden 1973). Adopting the surface gravity as log g = 0.5, we derived Teff = 6500 ± 200 K, loge(Fe) = 6.86 ([Fe/H] = -0.64), Vmicro = 8.2 km/s. vsin i andVmacro = 23 .0 km/s

Abundance analysis

The abundances of chemical elements were determined by means of synthetic spectra calculations (MOOG). For Ba, and Eu the isotopic shifts and hyperfine splitting were taken into account.

Light elements - CNO

Carbon abundance:

the lines of CI at 7465.45, 7470.09, 7473.31 and 7476 Å

Nitrogen abundance:

NI lines in 7440 – 7480 Å and 8600 – 8730 Å spectral regions (see Figure 1)

Oxygen abundance:

lines at 6155.97, 6156.95, and 6158.17 Å

Results:

loge(C) <= 7.4, [C/Fe] ≤ - 0.5
loge(N) = 8.45 ± 0.2 (2005) and 8.55 ± 0.2 (2014)
loge(O) = 8.0, [O/Fe] = - 0.2
log (C/O) ≤ - 0.6
log (N/O) = + 0.65
log (N/C) ≥ 1.25

The non-LTE corrections (LTE - NLTE)) to the N abundances are negative for the used NI lines (Lyubimkov et al. 2011) and may rich -0.3 dex.

The SMC baseline,CNO composition (Dopita et al. 2019):
log (N/C) = -0.7, log (N/O) = -1.2

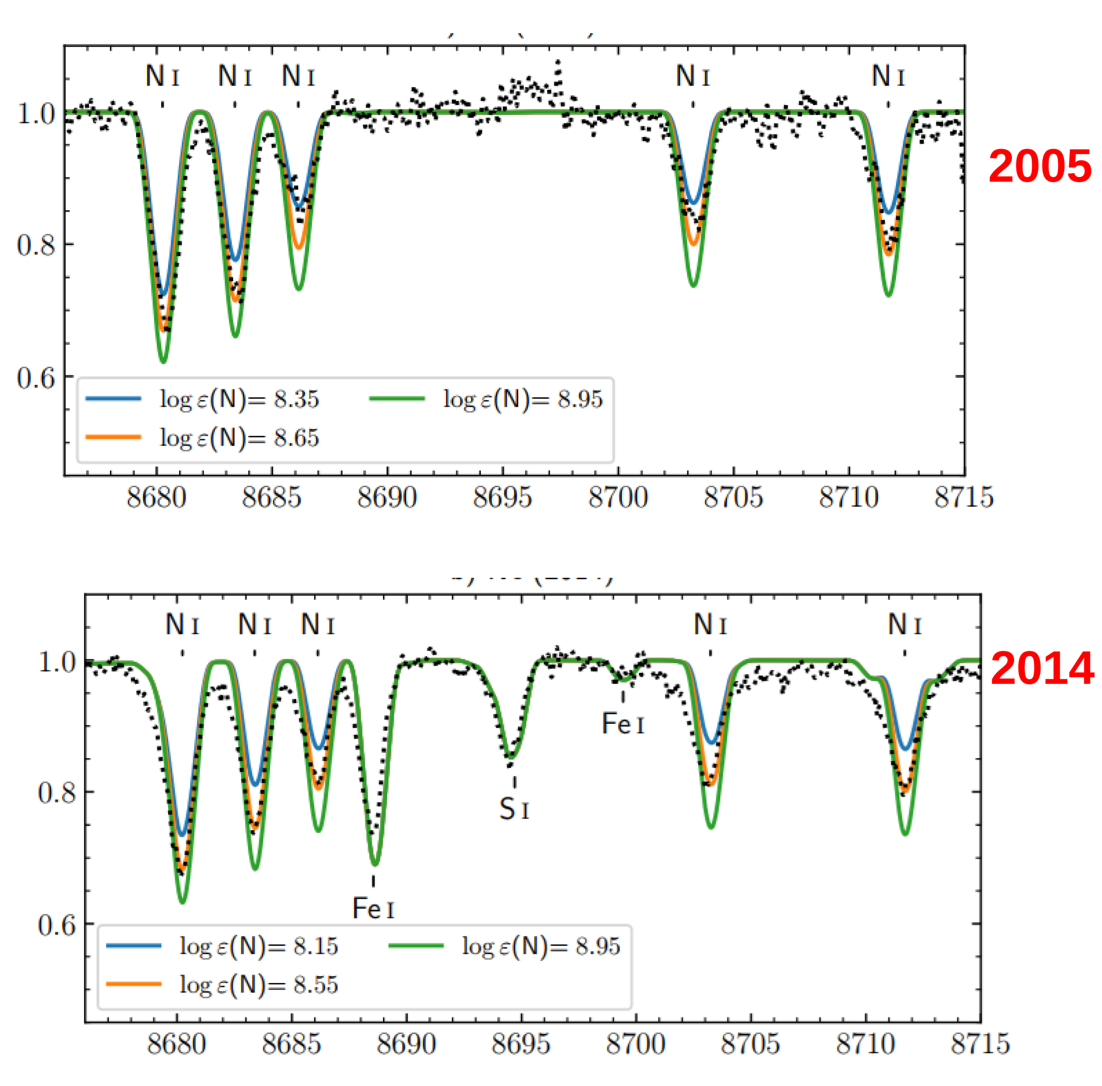

Figure 1. Observed dots) and synthetic (solid lines) spectra of R40 in the region containing the NI lines.

CNO ratios

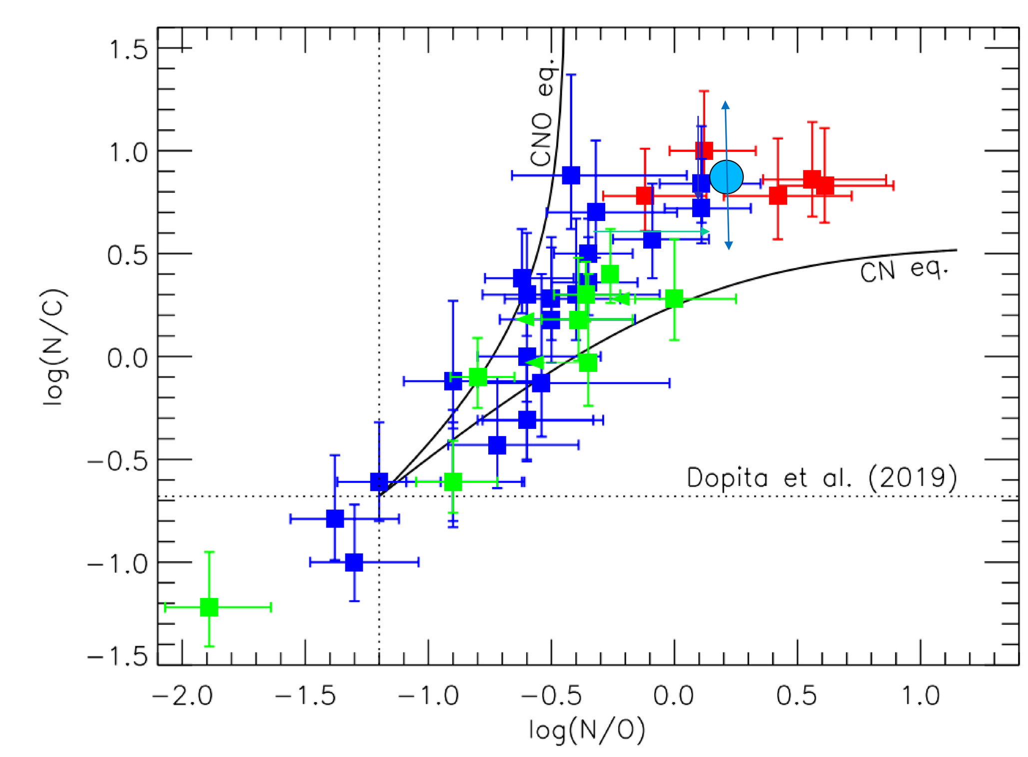

Figure 2. log (N/C) vs. log (N/O) abundances of R40 compared with other massive stars in the SMC (see Figure 8 from Bouret et al., 2021). R40 is presented as a big blue circle. Initial SMC CNO abundances were taken from Dopita et al. (2019): loge(C) = 7.50, loge(N) = 6.82, loge(O) = 8.02. After the NLTE correction of the nitrogen abundance, we obtained the following values: log (N/C) ≥ 0.95, log(N/O) = +0.35
Solid lines indicate the expected trends for the case of the partial CN and complete CNO equilibrium.
Error bars represent estimated uncertainties.

s- and r-processes elements

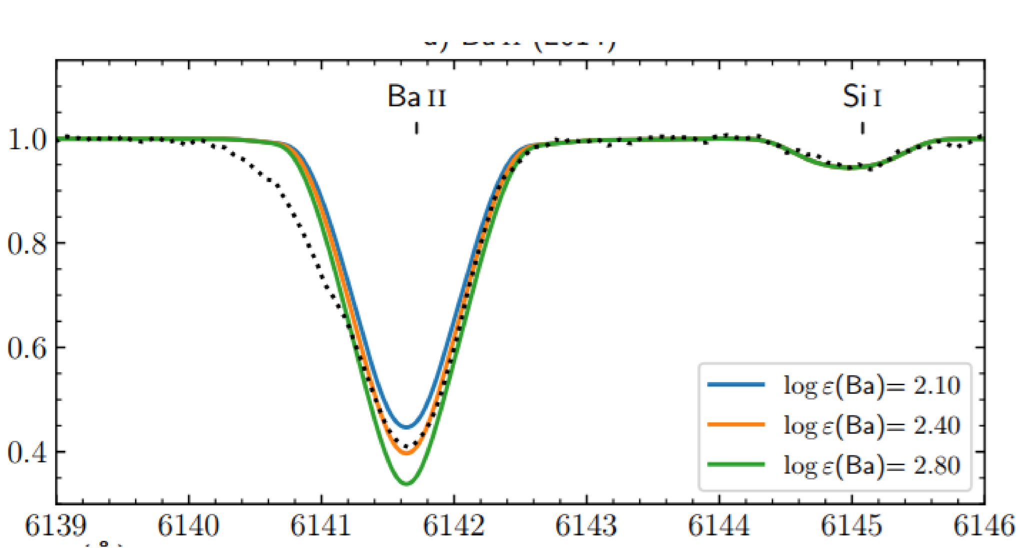

Figure 3. Observed (2014, dotted line) and synthetic (solid lines) spectra of R40 in the region of the BaII line at 6142 Å. Hyperfine and isotopic splitting were taken from McWilliam (1998). The best fitting corresponds to the loge(Ba) = 2.40 ([Ba/Fe] = +0.9)

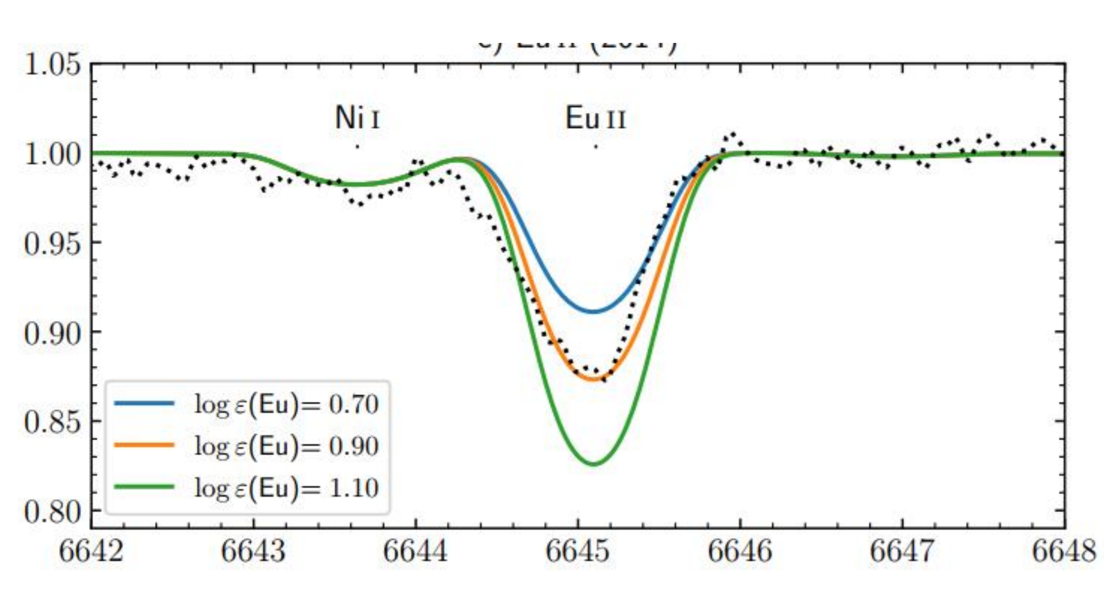

Figure 4. Observed (2014, dotted line) and synthetic (solid lines) spectra of R40 in the region of the EuII line at 6645 Å. Hyperfine splitting was taken from Mucciarelli et al. (2008). The best fitting corresponds to the loge(Eu) = 0.90 ([Eu/Fe] = +1.0).

We determined also the lanthanum abundance:
log e(La) = 1.95 ([La/Fe] = +1.4).

Even considering the uncertainties of our modeling, the enrichment of s- and r-process elements seems to be real

H-band spectrum of R40

By analysing the high-resolution spectrum of R40 obtained by the APOGEE survey (Apache Point Observatory Galactic Evolution Experiment) obtained on October 22, 2018, we found that the CeII lines have double-structure profiles (see Figure 5, abc). Could this be caused by a strong magnetic field in the pseudo-photosphere? Stothers (2004) analyzed the possible magnetic influence on the stability of the outer envelopes of luminous post-main-sequence stars, including the LBV stars, and concluded that these stars would not be expected to be strongly magnetic. However, if the whole radiative interior were permeated with a strong magnetic field, very rapid mass loss at the surface could keep the outer layers strongly magnetic at all times before turbulence could break up the field lines.
It is worth noting that magnetically split absorption CeII lines were detected by Chojnowski et al. (2019) in the APOGEE H-band spectra of Ap/Bp stars, which permitted a significant increase in the number of Ap/Bp stars with magnetic field measurements.
As for the LBV R40 star, the origin of the double-structure CeII profiles remains an open question.

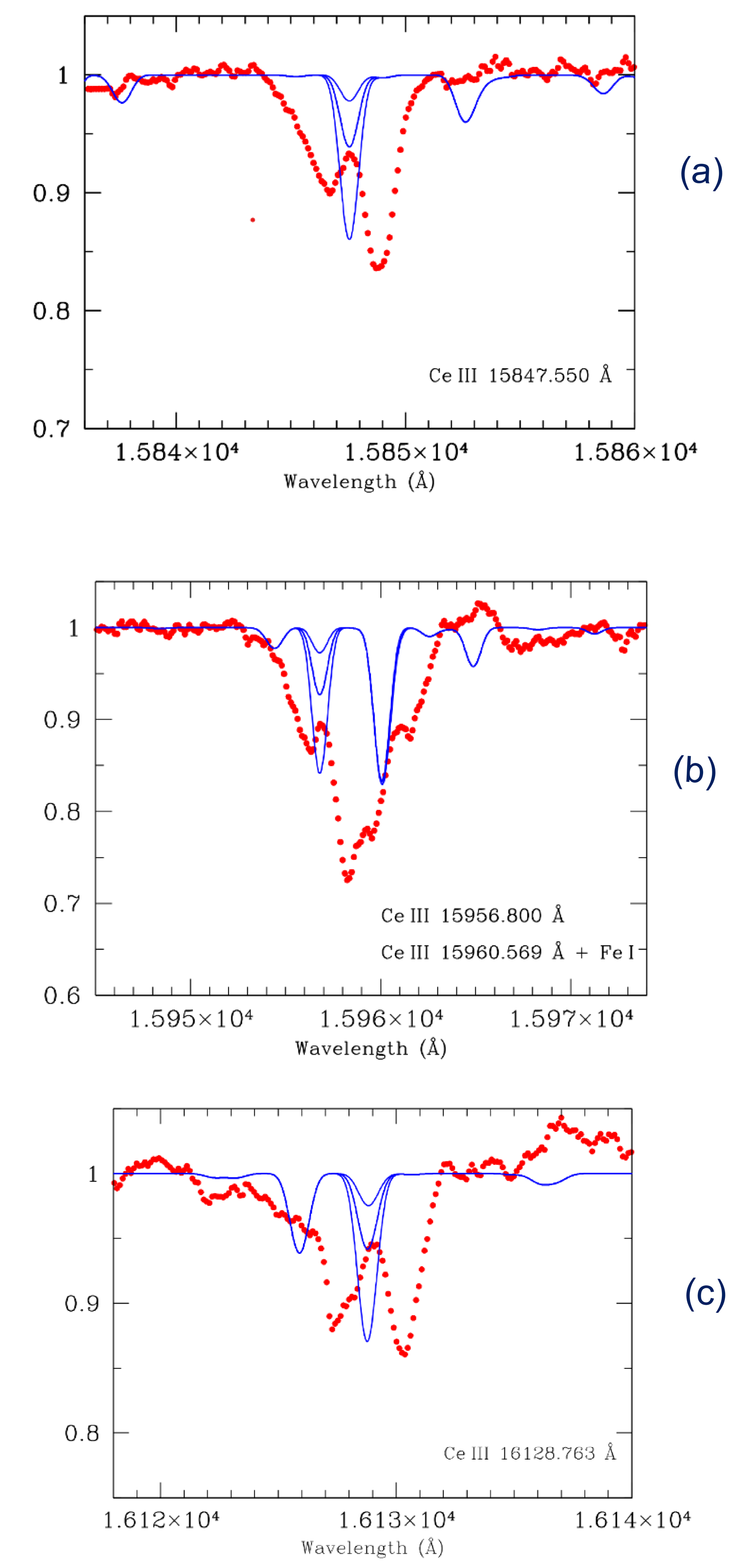

Figure 5 (abc). Observed (dots) and synthetic (blue lines) spectra of R40 in the regions of the CeII lines:
(a) λ15847.550 Å, (b) λ15956.800 Å and λ15960.569 Å, (c) λ16128.763 Å.
Synthetic spectra are shown for cerium abundances logε(Ce) = -0.5, +0.95, +1.45, and 1.95, corresponding to [Ce/Fe] = -1.0, 0.0, 0.5, and +1.0

The usual spectroscopic definitions
$[X/H] = \log \varepsilon(X)_{star} - \log\varepsilon(X)_{sun}$ and $\log \varepsilon(X) = \log \varepsilon(N_X/N_H) + 12.0$ were used.
The adopted solar abundances are from Grevesse & Sauval (1998).

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