# Explosive nucleosynthesis of a metal-deficient star as the source of a distinct odd-even effect in the solar twin HIP 11915

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#### ABSTRACT

The abundance patterns observed in the Sun and in metal-poor stars show a clear odd-even effect. An important question is whether the odd-even effect in solar-metallicity stars is similar to the Sun, or if there are variations that can tell us about different chemical enrichment histories. In this work, we report for the first time observational evidence of a differential odd-even effect in the solar twin HIP 11915, relative to the solar odd-even abundance pattern. The spectra of this star were obtained with high resolving power (140 000) and signal-to-noise ratio (~420) using the ESPRESSO spectrograph and the VLT telescope. Thanks to the high spectral quality, we obtained extremely precise stellar parameters ( $\sigma(T_{\text{eff}}) = 2 \text{ K}$ ,  $\sigma([\text{Fe/H}]) = 0.003 \text{ dex}$ , and  $\sigma(\log g) = 0.008 \text{ dex}$ ). We determine the chemical abundance of 20 elements ( $Z \leq 39$ ) with high precision (~0.01 dex), which shows a strong pattern of the odd-even effect even after performing Galactic Chemical Evolution corrections. The odd-even effect is reasonably well-reproduced by a core-collapse supernova of 13 M<sub>o</sub> and metallicity Z = 0.001 diluted into a metal-poor gas of 1 M<sub>o</sub>. Our results indicate that HIP 11915 has an odd-even effect slightly different than the Sun, thus confirming a different supernova enrichment history.

**Key words:** stars: solar-type – stars: abundances – stars: atmospheres – stars: fundamental parameters – techniques: spectroscopic

# **1 INTRODUCTION**

It is very well known that the composition of even-number elements (C, O, Ne, etc) is higher than the odd-number elements (e.g., N, F, Na) of similar atomic mass. Seminal works observed this effect first in chondritic meteorites (Oddo 1914; Harkins 1917). These authors found a sawtoothed pattern when chemical abundances are plotted versus their respective atomic numbers. Since then, this pattern has became known as the odd-even effect or the Oddo-Harking rule. Later, with the advent of astronomical spectroscopy, it was noticed that the solar abundances are not so different from the Earth and meteorites (Payne 1925; Russell 1941). In parallel to these events, new theories based on nuclear shell models began to appear (Mayer 1948, 1949; Haxel et al. 1949). However, it was not until the 1950s that the basis for the development of theories of stellar nucleosynthesis (e.g., Burbidge et al. 1957; Cameron 1959a,b) were established thanks to the cosmic abundance distribution of elements compiled by Suess & Urey (1956). Inspired by these works, more precise abundance compilations were put together, taking into account not only elements from meteorites, but also from the solar photosphere (e.g., Cameron 1973; Anders & Grevesse 1989; Grevesse & Sauval 1998; Lodders 2003; Asplund et al. 2005; Lodders et al. 2009; Asplund et al. 2009). All these results only confirm that the odd-even effect is real in the Sun, thereby suggesting that the proto-cloud of the Sun has this nucleosynthetic signature.

There are two types of supernova explosions, Ia and II. The first is a result from the explosion of a binary system including a white dwarf, while the second is from a massive star with mass above ~10 M<sub>☉</sub> and undergoing core-collapse at the end of their evolution (Nomoto et al. 2013). During the supernova explosion, enormous energies are liberated and newly synthesized elements are ejected to the interstellar medium, enriching the chemical abundances of the Galaxy. These energetic events established the basis for our understanding of Galactic Chemical Evolution (GCE). Stars with masses between 10-13 M<sub>☉</sub> explode as faint supernova (Nomoto et al. 2013), and those with masses between 13-25 M<sub>☉</sub> explode as *normal supernovae* with explosion energy  $E_{51} = E/10^{51}$  ergs = 1 (Blinnikov et al. 2000). The odd-even pattern from early supernovae can be seen in metal-poor stars, as shown by different theoretical

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T <sub>eff</sub> (K)	log g (dex)	[Fe/H] (dex)	$\frac{v_t}{(\mathrm{kms^{-1}})}$	Age (Gyr)	$\begin{array}{c} Mass\\ M_{\odot} \end{array}$	$\log g^{\dagger}$ (dex)	Reference
$5773 \pm 2$	$4.470\pm0.008$	$-0.057 \pm 0.003$	$1.02 \pm 0.01$	$3.87 \pm 0.39^{\star}$	$0.991 \pm 0.003$	$4.483 \pm 0.022$	This work
$5769 \pm 4$	$4.480\pm0.011$	$-0.067 \pm 0.004$	$0.99 \pm 0.01$	$3.40 \pm 0.60^{\bigstar}$	$0.993 \pm 0.007$	$4.482 \pm 0.023$	Spina et al. (2018)
$5760 \pm 4$	$4.460\pm0.010$	$-0.059 \pm 0.004$	$0.97 \pm 0.01$	$4.00\pm0.60^*$	$0.993 \pm 0.005$	$4.480 \pm 0.023$	Ramírez et al. (2014)

Table 1. Comparison of high precision spectroscopic stellar parameters for HIP 11915.

**Notes.** (\*) Isochronal ages estimated using  $\log g$  and parallaxes as priors ( $\log g \& \operatorname{plx}$ ). (\*) Isochronal age determined using only  $\log g$  as input parameter. (†) Trigonometric  $\log g$  obtained using *Gaia* EDR3 parallax and bolometric corrections of Meléndez et al. (2006).

and observational studies (e.g., Umeda & Nomoto 2003; Iwamoto et al. 2005; Tominaga et al. 2007; Heger & Woosley 2010; Nomoto et al. 2013; Siqueira-Mello et al. 2015; Placco et al. 2016; Frebel et al. 2019).

Although the odd-even pattern in the Sun has been known for a long time, to our knowledge no variations have been reported for solar-metallicity stars, relative to the Sun's odd-even pattern. In this work we report for the first time observational evidence of a distinct odd-even effect in a solar-metallicity star, thus providing important clues to a distinct chemical enrichment history to our Sun.

## 2 OBSERVATIONS AND DATA REDUCTIONS

The spectra of HIP 11915 were obtained using the ESPRESSO (Echelle SPectrograph for Rocky Exoplanets and Stable Spectroscopic Observations) spectrograph (Pepe et al. 2014) and the Very Large Telescope (8.2 m telescope) at the Paranal Observatory between 2018 and 2019, under the ESO (European Southern Observatory) program ID 0102.C-0523. The spectra of the Sun (reflected light from the Vesta asteroid) were downloaded from the ESO Science Archive Facility under the program ID 1102.A-0852. The instrument was configured in its High Resolution 1-UT (HR) mode to reach a high resolving power ( $R = \lambda/\Delta\lambda = 140\ 000$ ). The ESPRESSO spectra were reduced by a pipeline using the EsoReflex environment (Freudling et al. 2013). The resulting spectra cover the entire visible wavelength ranging from 3 800 to 7 880 Å.

The reduced ESPRESSO spectra were normalized using our semi-automatic PyRAF<sup>1</sup> scripts that divide each spectrum in several regions to normalize them with order polynomials ranging from 1 to 7 using the task continuum of IRAF and always taking as reference the normalized continuum of the Sun. The script finds a solution when the ratio between the continuum of the Sun and the star is approximately one. Finally, the script combines all the normalized spectra using the scombine task in order to achieve the highest possible signal-to-noise ratio (SNR). The resulting SNR for the Sun and HIP 11915 is ~320 and ~420, respectively.

#### **3** SPECTROSCOPIC ANALYSIS

# 3.1 Fundamental Parameters

The reduced equivalent widths (*EWs*) were measured with our python script (for more details see Yana Galarza et al. 2021, submitted). In summary, the script uses the line list from Meléndez et al. (2014) to plot the spectra of the Sun and HIP 11915 in windows of 6 Å with the line of interest located at the center. Then, the *EW* is measured manually, on a line-by-line basis, through Gaussian fits

<sup>1</sup> PyRAF is a product of the Space Telescope Science Institute, which is operated by AURA for NASA.

to the line profile using the Kapteyn kmpfit Package (Terlouw & Vogelaar 2015). This method is based on the differential technique between the star and the Sun and allow us to achieve a high precision (e.g. Meléndez et al. 2012; Spina et al. 2018; Yana Galarza et al. 2019). The script creates an output file containing information about the local continuum, limits of the Gaussian fits,  $\chi^2$  test, excitation potential (eV), oscillator strength, and laboratory  $\log(gf)$  values, as well as the hyperfine structure information when necessary.

We estimated the spectroscopic stellar parameters (effective temperature  $T_{\text{eff}}$ , surface gravity log g, metallicity [Fe/H], and microturbulence velocity  $v_t$ ) using the automatic qoyllur-quipu python code (hereafter q<sup>2</sup>; Ramírez et al. (2014)). The code determines the abundance of 117 spectral iron lines (Fe I and Fe II taken from Meléndez et al. 2014) using the 2019 version of the local thermodynamic equilibrium (LTE) code MOOG (Sneden 1973) and the Kurucz ODFNEW model atmospheres (Castelli & Kurucz 2003). Then, the stellar parameters are calculated through the spectroscopic equilibrium technique, which consists in the strict fulfillment of four criteria: 1) non-dependence of the differential iron abundance (HIP 1195 - Sun) with the excitation potential, i.e., the slope of them should be zero; 2) non-dependence of the differential iron abundance with the reduced equivalent width (slope consistent with zero); 3) the differential abundance of Fe I and Fe II should be equal; 4) the input metallicity of the model should have the same value as the derived iron abundance. The errors for the stellar parameters are estimated following the prescription given in Epstein et al. (2010) and Bensby et al. (2014)), that is from the propagation of the error associated with the fulfillment of the above conditions. Our results are summarized in Table 1 and compared with those from the literature (Ramírez et al. 2014; Spina et al. 2018). There is an excellent agreement between them, thus validating the results of previous high-precision works that used spectrographs of lower Rthan ESPRESSO (HARPS and MIKE with  $R = 115\ 000$  and 83/65000, respectively).

The isochronal fitting technique has demonstrated to be a powerful tool to determine ages and masses (e.g., Lachaume et al. 1999; Takeda et al. 2007). Ramírez et al. (2013) in their q<sup>2</sup> code replaced the  $M_V$  by precise spectroscopic log g, that improved the results relative to the use of uncertain parallaxes from Hipparcos. Later, Spina et al. (2018) included *Gaia* parallaxes and effects of the  $\alpha$ enhancements into the  $q^2$  calculations (hereafter log g & plx). Both methods achieve a high internal precision with uncertainties ranging from ~1-2 Gyrs. We estimated the age and mass of HIP 11915 using the  $q^2$  code and the Yonsei-Yale isochrone set (Yi et al. 2001; Demarque et al. 2004), following the prescription given by Spina et al. (2018), employing both parallaxes and spectroscopic  $\log g$ . The parallax value adopted in our calculation was taken from Gaia EDR3 (Gaia Collaboration et al. 2020). In Table 1 is shown the good agreement between our age and mass results with those from Spina et al. (2018) and Ramírez et al. (2014). As a consequence of our extremely precise spectroscopic stellar parameters, the internal



Figure 1. Observed (open squares) and GCE-corrected (filled circles) differential abundances relative to the Sun versus condensation temperature, and with their linear fits represented as green solid and red dashed lines, respectively.

**Table 2.** Observed abundances  $\Delta$ [X/H]<sub>Obs</sub> and GCE-corrected abundances  $\Delta$ [X/H]<sub>GCE</sub> of HIP 11915 relative to the Sun and their corresponding errors.

element	Ζ	$\Delta$ [X/H] <sub>Obs</sub>	$\Delta$ [X/H] <sub>GCE</sub>	[X/H] <sub>SN</sub>
С	6	$-0.094 \pm 0.005$	$-0.086 \pm 0.007$	-0.063
0	8	$-0.050 \pm 0.002$	$-0.044 \pm 0.004$	-0.036
Na	11	$-0.081 \pm 0.011$	$-0.075 \pm 0.012$	-0.080
Mg	12	$-0.059 \pm 0.006$	$-0.052 \pm 0.007$	-0.033
Al	13	$-0.099 \pm 0.003$	$-0.089 \pm 0.006$	-0.047

This table is available in its entirety in machine readable format at the CDS.

precision of the age and mass are the lowest reported in the literature. However, special attention should be paid in this point because these reflect only the precision of the differential method employed. As the spectroscopic  $\log g$  is fundamental to determine isochronal ages, we estimated the trigonometric  $\log g$  using parallax from *Gaia* EDR3 and adopting the bolometric corrections of Meléndez et al. (2006). The spectroscopic and trigonometric  $\log g$  are in very good agreement (see Table 1), thereby ruling out any problem in the *EW* measurements, or the spectroscopic method. Similar trigonometric log g values are calculated for Spina et al. (2018) and Ramírez et al. (2014) using their own spectroscopic stellar parameters.

As a sanity test, the age of HIP 11915 was also estimated using other methods. We determined an age of  $3.42 (\pm 0.43)$  Gyr and  $3.32 (\pm 0.41)$  Gyr employing the [Y/Mg]-age correlation independently established by Spina et al. (2018) and Nissen (2016), respectively. In addition, according to the activity-age relation of Lorenzo-Oliveira et al. (2018), the chromospheric age is  $3.6^{+0.5}_{-0.4}$  Gyr. All these independent age results are in good agreement with our isochronal age, thus confirming the high precision achieved in this work.

#### 3.2 Abundance pattern

We measured the extremely high-precision chemical abundance of 19 elements with atomic number lower than 30, plus Y (Z = 39) for age determination. We configured the  $q^2$  code to perform hyperfine corrections for the elements V, Mn, Co, Cu, and Y following the data given in Meléndez et al. (2014); Asplund et al. (2009); McWilliam

(1998); Cohen et al. (2003). The NLTE corrections were only carried out for the O I triplet using the grid of Ramírez et al. (2007). Despite that there are more updated NLTE corrections (e.g. Amarsi et al. 2016, 2019), these are negligible for our purpose since our analysis is strictly differential to the Sun (for more details see Yana Galarza et al. 2016). On the other hand, the interstellar medium is constantly enriched by different sources that produce new elements through stellar nucleosynthesis, and this enrichment mechanism is observed in the chemical abundances of solar twins as a function of time (e.g., Nissen 2015, 2016; Spina et al. 2016b, 2018; Bedell et al. 2018). Therefore, we performed a GCE correction using the [X/Fe]-age correlation of Bedell et al. (2018) by adding GCE trends to the chemical abundance of HIP 11915 following the prescription given in Spina et al. (2016a) and Yana Galarza et al. (2016), so that the abundances of HIP 11915 are corrected to the same age as the Sun.

In Figure 1 we show the classical differential chemical abundance ( $\Delta$ [X/H]) versus condensation temperature (Lodders 2003) plot, where the open squares and filled circles are the observed ( $\Delta$ [X/H]<sub>Obs</sub>) and GCE-corrected abundances ( $\Delta$ [X/H]<sub>GCE</sub>), respectively. We can see that the GCE corrections are very small because of the similarity in age (and [Fe/H]) between HIP 11915 and the Sun. The lines represent linear fits to the data (using the Kapteyn kmpf it Package), whose slopes are both flat within the errors, meaning that both abundance patterns are similar to the Sun, as reported also in the preliminary analysis of Bedell et al. (2015). This is remarkable, since HIP 11915 hosts a Jupiter twin (Bedell et al. 2015), being thus potentially a *solar system twin*. Intriguingly, there is quite a high scatter (~0.020 dex) in the observed abundance, which is significantly larger than the average error bar (0.005 dex), and this still prevails in the GCE-corrected abundances (~0.018 dex).

The upper panel of Figure 2 shows the  $\Delta$ [X/H] versus their atomic numbers. Despite that the estimated abundance is relative to the Sun, our precise abundances allow to clearly see a stronger signature of the odd-even effect, and the pattern still persists in the GCE-corrected abundances (blue filled circles), thus suggesting that this is a chemical signature of a different source. It is important to highlight that we could not determine abundances for N, F, Ne, P, Cl and Ar from our spectra. Only N is marginally available at 7468.31



Figure 2. Upper panel: Comparison of the chemical-abundance pattern before (blue open squares) and after (blue filled circles) performing GCE corrections. Bottom panel: Comparison between the SN model of  $13 M_{\odot}$  (red open circles) and the GCE-corrected differential abundances (blue filled circles). The solid and dashed lines in both panels are only to highlight the odd-even effect in HIP 11915.

Å, however the quality of the spectrum is not adequate for a high precision analysis. A tentative analysis suggests that is more depleted than carbon (N =  $-0.24 \pm 0.05$  dex), therefore also following the predicted odd-even pattern. Atomic diffusion could introduce small variations in the abundance pattern (see Dotter et al. 2017), but the differential effect should be minor for stars of similar ages. Furthermore, the GCE corrections follow the observational trends with age, probably including also the effect of atomic diffusion.

We tried different supernova yields to match our observations. The best model (Tominaga et al. 2007; Nomoto et al. 2013) that reproduces the odd-even pattern of HIP 11915 is a core-collapse SN with a progenitor mass of 13  $M_{\odot}$  and metallicity Z = 0.001 diluted into a protocloud of metal-poor gas (80% of solar, Asplund et al. 2009) of 1  $M_{\odot}$ . We estimated a dilution of 1.5% mass of SN material to match the iron abundance of HIP 11915. The solar metallicity yields adopted for the model are taken from Nomoto et al. (2013) (online table, therein). As can be seen in the bottom

panel of Figure 2 (red open circles), the alpha elements (O, Mg, Ca, Ti), the iron-peaks elements (Sc, V, Cr, Mn, ,Fe) and Na are the best reproduced by the model. More massive SNe model (>13  $M_{\odot}$ ) overproduce the alpha elements.

Despite that some elements such as Al, Si, S and K show an offset, they are qualitatively in agreement with the observations. Our results hint that the observed odd-even effect is a direct nucleosynthetic signature of a particular SN, thereby suggesting that HIP 11915 experienced a distinct chemical enrichment than the Sun. All our differential abundances and those estimated from the SN model ([X/H]<sub>SN</sub>) are summarized in Table 2.

## 4 SUMMARY AND CONCLUSIONS

In this work we determined the stellar parameters of the solar twin HIP 11915 with unprecedented precision (see Table 1) using the ESPRESSO spectrograph at the VLT. The high resolving power (R =140 000), high signal-to-noise ratio (SNR = 420), and the differential technique relative to the Sun allow us to achieve an extremely high internal precision ( $\sigma(T_{\text{eff}}) = 2 \text{ K}, \sigma([\text{Fe}/\text{H}]) = 0.003 \text{ dex}, \text{ and}$  $\sigma(\log g) = 0.008$  dex). A precise isochronal age was estimated using isochrones compared to our stellar parameters (including  $\log g$ ) and the Gaia EDR3 parallax. As a sanity check, we also estimated the age using the [Y/Mg]- and the activity-age correlation, which are in good agreement with our resulting age. We determined the highprecision differential chemical abundances of 19 light elements with atomic number up to 30, and the heavy element Y for the age determination. We also carried out GCE corrections, but the oddeven effect persists in the differential abundance of HIP 11915 (blue filled circles in Figure 2), thus suggesting a stronger odd-even effect than in the Sun. The distinct odd-even pattern, with a peak-to-peak amplitude of only  $\sim 0.02$  dex, is revealed only thanks to the high precision of our work. A mechanisms that explain well the GCEcorrected differential abundances is a core-collapse SN of 13  $M_{\odot}$ and metallicity Z = 0.001 diluted into a 1  $M_{\odot}$  of metal-poor gas cloud (see open red circles in the bottom panel of Figure 2). Albeit a few elements show offsets, overall they follow qualitatively the stronger odd-even pattern.

The main motivation of large spectroscopy surveys (e.g., APOGEE, Gaia and GALAH) is chemical tagging, aiming to identify coeval stellar groups to reconstruct the Milky Way's formation. However, as showed in this work, only an analysis with a spectra of extremely high quality can discern the very subtle abundance pattern due to differences in nucleosynthetic enrichment and thus better identify coeval stars. The comparison between the SN model and the abundance pattern of HIP 11915 provides new insights to understand the fine structure in stellar abundances coming from a particular SNe nucleosynthesis history, as well as to improve SNe vields. In addition, Mackereth & Bovy (2018) estimate that HIP 11915's Galactic orbit has a maximum vertical excursion of 0.2643  $\pm$  0.0027 kpc, an eccentricity of 0.1867  $\pm$  0.0006, and perigalacticon and apogalacticon radii of 5.8036  $\pm$  0.0063 and 8.4695  $\pm$ 0.0025 kpc, respectively. These results indicate that HIP 11915 belongs to the thin disk (considering the thin disk scale height as 0.36 kpc, Sanders & Binney (2015)), but with a significantly higher eccentricity than the Sun (~0.06 - 0.10, Bovy et al. (2012)). This provides evidence that the natal cloud of HIP 11915 may have experienced a somewhat different chemical enrichment history. Despite the somewhat different kinematics, we consider that HIP 11915 is an excellent proxy of the Sun, with similar spectroscopic fundamental parameters, akin age (~4 Gyr), mass (~0.99  $M_{\odot}$ ), and activity index ( $\langle S_{MW} \rangle = 0.187$ , Lorenzo-Oliveira et al. 2018). Considering that a Jupiter twin has been detected in this solar twin (Bedell et al. 2015) and that we find in this work an overall abundance pattern versus dust condensation temperature similar to the Sun, being thus also depleted in rocky-forming elements, we consider HIP 11915 an excellent system for planet searches of Earth analogs.

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#### DATA AVAILABILITY

The datasets were derived from sources in the public domain: http: //archive.eso.org/wdb/wdb/eso/espresso/form(under the ESO program IDs 0102.C-0523 and 1102.A-0852).

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