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Observations of the extreme runaway HD 271791: nucleosynthesis in a core-collapse supernova

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Some young, massive stars can be found in the Galactic halo. As star formation is unlikely to occur in the halo, they must have been formed in the disk and been ejected shortly afterwards. One explanation is a supernova in a tight binary system. The companion is ejected and becomes a runaway star. HD 271791 is the kinematically most extreme runaway star known (Galactic restframe velocity $725 \pm 195\,\mathrm{km\,s^{-1}}$, which is even larger than the Galactic escape velocity). Moreover, an analysis of the optical spectrum showed an enhancement of the α-process elements. This indicates the capture of supernova ejecta, and therefore an origin in a core-collapse supernova. As such high space velocities are not reached by the runaway stars in classical binary supernova ejection scenarios, a very massive but compact primary, probably of Wolf-Rayet type is required. HD 271791 is therefore a perfect candidate for studying nucleosynthesis in a supernova of probably type Ibc. The goal of this project is to determine the abundances of a large number of elements from the α-process, the iron group, and heavier elements by a quantitative analysis of the optical and UV spectral range. Detailed line-formation calculations are employed that account for deviations from local thermodynamic equilibrium (non-LTE). We intend to verify whether core-collapse supernova are a site of r-process element production. Here, we state the current status of the project.

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1. Runaway stars

Young, massive stars are usually found close to the Galactic plane, typically in open clusters and associations. Some of them, however, are observed at high Galactic latitudes far away from star-forming regions. Since no gas clouds are known in the halo that have a sufficiently high density to form massive stars, these stars must have formed in the Galactic disc, and afterwards migrated outwards ('halo run-away OB stars'). They are thought to have been ejected from their place of birth and accelerated to high velocity by dynamical processes either during the initial dynamical relaxation of a star cluster [1], or in binary interactions inside star clusters [2], or by means of a binary supernova (SN) explosion [3].

In the latter scenario the surviving companion is ejected with roughly the orbital velocity and becomes a runaway star. To distinguish the SN scenario from the other scenarios an abundance study may be employed, as the atmosphere of the *close* companion – afterwards the runaway star – is polluted by the SN ejecta. An enrichment of the elements existing in the SN ejecta is expected. Such stars are therefore ideal candidates for studying nucleosynthesis in core-collapse SN. They may in particular facilitate to decide whether core-collapse SN are sites of r-process nucleosynthesis, or not.

HD 271791 is the kinematically most extreme runaway star known (with a Galactic rest-frame velocity $725 \pm 195\,\mathrm{km\,s^{-1}}$, larger than the Galactic escape velocity). Such velocities were believed only to be reached if a star is ejected by interaction with the Galactic super-massive black hole [4]. However, HD 271791 is much younger than the flight-time from the centre of the Galaxy to its current position. Moreover, a reconstruction of the orbit shows that HD 271791 originates in the outskirts of the Galaxy (see Fig. 1). This rules out the supermassive black hole scenario. An abundance study can be used to investigate the viability of the SN scenario.

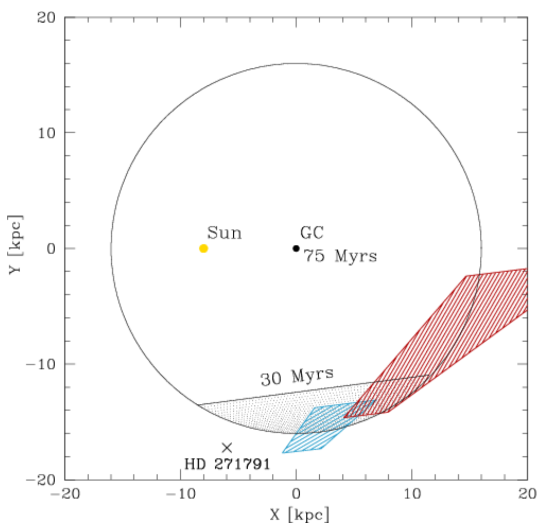

Figure 1: Regions of origin for HD 271791 in the Galactic plane calculated by varying the proper-motion components within their measurement errors. The position of HD 271791 projected to the Galactic plane is marked. The red area is derived from our proper-motion measurement, whereas the blue area follows if proper motions from the UCAC2 catalog are used. From [5].

2. Observations

We intend to perform an abundance study of HD 271791 (B2-3 III, $V = 12.26$) in the optical and the UV spectral range in order to verify the contamination of the stellar atmosphere with SN ejecta. To this aim, we obtained high-S/N optical ESO-VLT UVES spectra in the 3000 to 10 000 Å range at resolving power $R = \lambda/\Delta\lambda = 30\,000$. At UV wavelengths we obtained HST/COS spectra in the 1150 to 1800 Å range at $R = 16\,000$-$21\,000$ and HST/STIS data in the 1600 to 3100 Å region at $R = 30\,000$. These allow us to improve on and vastly extend our initial investigation of the star [6].

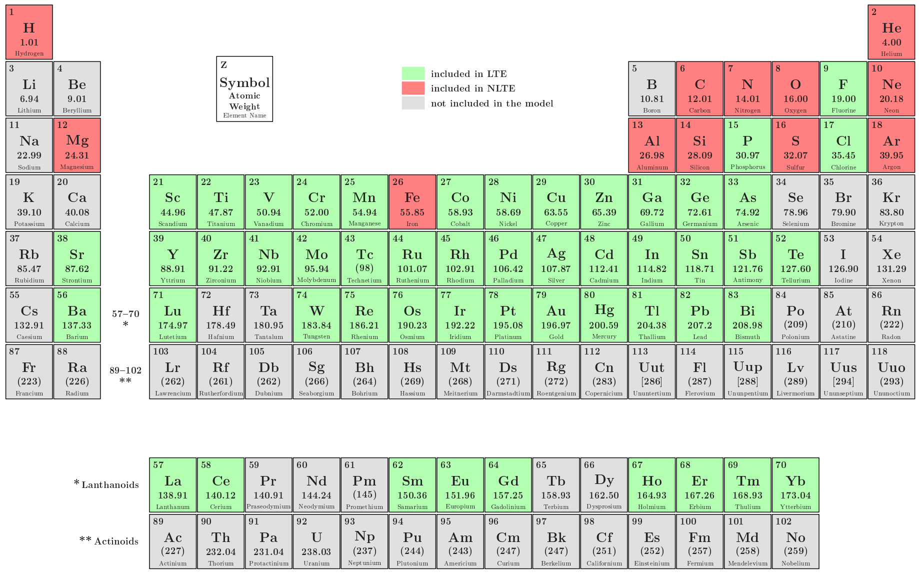

Figure 2: Periodic table showing all elements implemented in our spectrum synthesis. The elements marked in red can be accounted for in non-LTE, the ones marked in green only in LTE.

3. Methods & Analysis Techniques

In a first step, the atmospheric parameters of the star and abundances for a restricted set of elements were determined by non-LTE modelling of the entire optical spectrum [7, 8, 9]. In brief, this is based on a hybrid non-LTE approach, which allows even highly complex model atoms to be employed. Model atmospheres were calculated under the assumption of LTE with the ATLAS12 code. The coupled radiative transfer and statistical equilibrium equations were solved using DETAIL, providing non-LTE level populations. Synthetic spectra were then computed with SURFACE.

The spectrum synthesis for the UV wavelength range had to be implemented in the course of our project. Lists of spectral lines were adopted for all desired elements, using essentially all available atomic data from the literature. Main data sources were NIST[1], the Kurucz database[2], the Iron Project, e.g. [10], and the Morton compilation [11]. Figure 2 shows, the elements currently available for spectrum synthesis. The limiting factor of this project is missing atomic data. For many atoms only data for neutral or single-ionized atoms were available, whereas data for multiple-ionized atoms are required because of the high effective temperature of HD 271791.

As the lines of the runaway star are very broad due to the high rotational velocity, they were not suitable to test the synthetic spectra. Therefore, we used bright B-stars with similar parameters and slow rotation (ι Her, γ Peg, HR 1840) for this purpose. Based on atmospheric parameter and abundances (including iron) determined from the optical spectra – which allows a considerable part of the UV line forest to be treated as background lines – elemental abundances for other iron group and heavier elements were derived by fitting synthetic spectra to observation. The abundance determination was performed strictly differentially in order to minimise systematic errors. Such an approach is particularly suited to the identification of abundance peculiarities.

[1] `http://www.nist.gov/pml/data/asd.cfm`

[2] `http://kurucz.harvard.edu/`

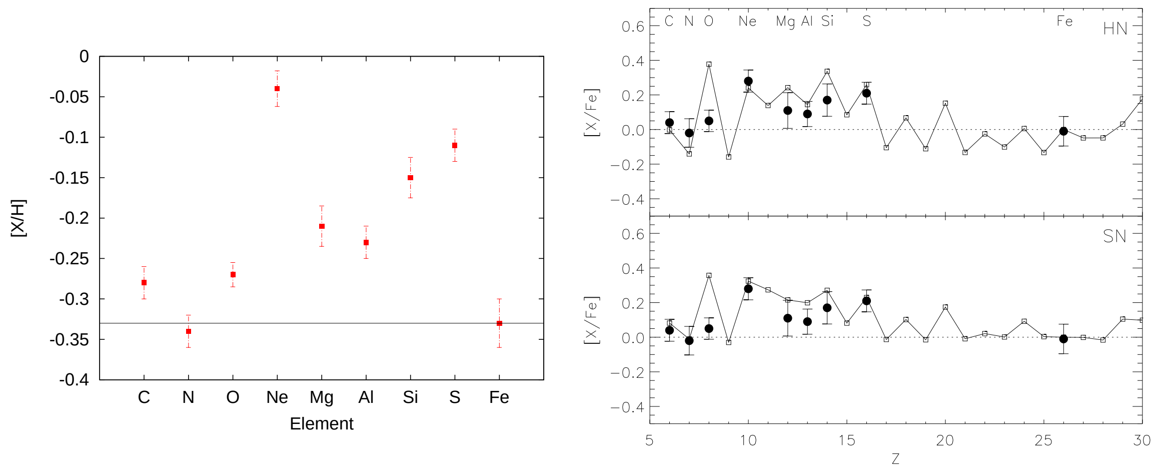

Figure 3: Abundances of HD 271791 as determined from the optical spectrum. The left panel shows the abundances relative to a representative B-star sample (Irrgang et al. in prep.). The baseline metallicity of HD 271791 relative to solar values [12], [Fe/H], is marked by the solid line. The right panel shows the abundances (normalised to iron) compared to hypernova/supernova (HN/SN) yields of Nomoto et al. [13].

4. Results

Optical analysis. Atmospheric parameters of HD 271791 as derived from the analysis of the optical spectrum are summarised in Table 1. A comparison of elemental abundances in the star to those from a representative sample of 63 nearby B-stars by Irrgang et al. (in prep.) are shown in Fig. 3. As it is not expected that the core-collapse SN ejecta that polluted the atmosphere of the runaway contained much iron, we use iron as a baseline. The iron abundance in HD 271791 is $\sim$0.3 dex lower than in the comparison sample. This is not surprising, as the star originates from the metal-poor outskirts of the Galaxy. On the other hand, several of the α-elements, e.g. Ne, Mg, Si and S, are enhanced compared to abundance values expected for the metallicity of HD 271791. The right panel of Fig. 3 shows a comparison of the elemental abundances (normalised to iron) with hypernova/supernova yields of Nomoto et al. [13]. A qualitative agreement between theory and observation is reached for both the hypernova and the supernova yields. Only the oxygen abundance is smaller than would be expected by theory. However, that may be explained because of the use of integrated yields. Chemical homogeneity is not expected within SN ejecta. Therefore, detailed simulations of the SN explosion and of the accretion of the SN ejecta on the runaway are required to improve on the quantitative understanding. In any case, the observed enrichment in the α-elements indicates an ejection of HD 271791 by a SN explosion in a very tight system. To explain the extreme velocity a very massive but compact primary, probably of Wolf-Rayet type is required.

Table 1: Atmospheric parameters of HD 271791 as derived from the optical UVES spectrum

Parameter	Value	Unit	Parameter	Value	Unit
$T_{\rm eff}$	18700 ± 50	K	$v \sin i$	128 ± 1	$\rm km\,s^{-1}$
$\log g$	3.15 ± 0.02	cgs	ζ	22 ± 4	$\rm km\,s^{-1}$
ξ	5.9 ± 0.1	$\rm km\,s^{-1}$	$v_{\rm rad}$	443 ± 1	$\rm km\,s^{-1}$

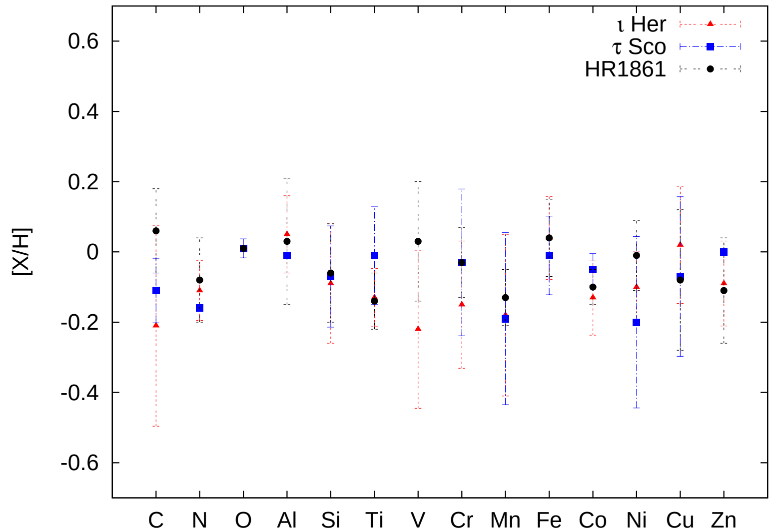

Figure 4: Abundances for three comparison stars of different T_{eff}, determined from the UV spectrum relative to solar values. The error ranges correspond to the standard deviation from the individual line analysis.

UV analysis. Because of the complications caused by the high rotational velocity of HD 271791 on the UV spectral analysis, no results are currently available on this. However, the tests of the models and analysis methodology on the three slowly-rotating comparison stars were highly successful. Abundances of several elements from the UV analysis, derived from single unblended lines, are shown in Fig. 4. They are displayed relative to the abundances from the optical analysis (C, N, O, Al, Si, Fe) or relative to solar values for the remaining elements. The UV analysis reproduces the results from the optical within the errors for all three stars. Moreover, abundances for the other iron group elements turn out to be close to solar, recovering a trend that is found for most of the previously determined B-star elemental abundances. Figure 5 shows a comparison of a synthetic spectrum calculated based on abundances determined from the optical analysis or for solar abundances with an HST/STIS spectrum of ι Her. While there are still some lines missing, the overall match is highly encouraging. We are confident that our spectrum synthesis in the UV has reached a similar degree of maturity as in the optical [8] and provides reliable abundances.

5. Outlook

In the next step we intend to derive abundances of the heavier elements from blended lines. This will lay the grounds for determining abundances for the rapidly rotating HD 271791 and for comparing those with abundances of standard stars. This is in order to constrain iron group and heavier element nucleosynthesis in the particular SN event that ejected HD 271791. In the future we want to construct non-LTE model atoms for the iron group elements to minimise remaining systematic error sources. HST spectroscopy of additional runaway stars would be interesting to study nucleosynthesis in core-collapse SNe more comprehensively.

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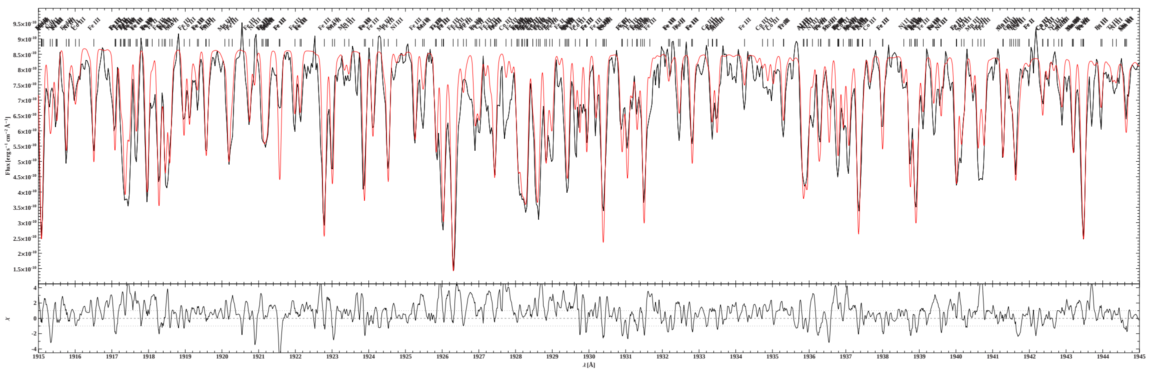

Figure 5: Comparison of the observed UV spectrum of ι Her (HST/STIS) with a synthetic spectrum based on abundances determined from the optical analysis, if available, and solar abundances for the rest of the elements. The lower panel shows the residuals.

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