The Astrophysical Journal, 684: L103–L106, 2008 September 10

HD 271791: AN EXTREME SUPERNOVA RUNAWAY B STAR ESCAPING FROM THE GALAXY[1]

Norbert Przybilla,[2] M. Fernanda Nieva,[2,3] Ulrich Heber,[2] and Keith Butler[4]
Received 2008 July 3; accepted 2008 August 4; published 2008 August 13

ABSTRACT

Hypervelocity stars (HVSs) were first predicted by theory to be the result of the tidal disruption of a binary system by a supermassive black hole (SMBH) that accelerates one component to beyond the Galactic escape velocity (the Hills mechanism). Because the Galactic center hosts such a SMBH it is the suggested place of origin for HVSs. However, the SMBH paradigm has been challenged recently by the young HVS HD 271791 because its kinematics point to a birthplace in the metal-poor rim of the Galactic disk. Here we report the atmosphere of HD 271791 to indeed show a subsolar iron abundance along with an enhancement of the α-elements, indicating capture of nucleosynthesis products from a supernova or a more energetic hypernova. This implies that HD 271791 is the surviving secondary of a massive binary system disrupted in a supernova explosion. No such runaway star has ever been found to exceed the Galactic escape velocity; hence HD 271791 is the first hyperrunaway star. Such a runaway scenario is an alternative to the Hills mechanism for the acceleration of some HVSs with moderate velocities. The observed chemical composition of HD 271791 puts invaluable observational constraints on nucleosynthesis in a supernova from the core collapse of a very massive star ($M_{\rm ZAMS} \gtrsim 55\ M_{\odot}$), which may be observed as a gamma-ray burst of the long-duration/soft-spectrum type.

Subject headings: Galaxy: halo — stars: abundances — stars: individual (HD 271791) — supernovae: general

1. INTRODUCTION

Studies of stellar dynamical processes in the vicinity of a supermassive black hole (SMBH) predicted the existence of so-called hypervelocity stars (HVSs), objects moving faster than the Galactic escape velocity (Hills 1988; Yu & Tremaine 2003). Besides being indicators of the properties of the SMBH in the Galactic center (GC) and the surrounding stellar population, HVSs are also regarded as valuable probes for the shape of the Galactic dark matter halo because of the unique kinematic properties of stars expelled from the GC (Gnedin et al. 2005; Yu & Madau 2007).

The first HVSs have only recently been discovered serendipitously (Brown et al. 2005; Edelmann et al. 2005; Hirsch et al. 2005; Heber et al. 2008, hereafter Paper I). A total of 11 faint blue stars at high Galactic latitude have been identified as HVSs so far after a systematic search (see Brown et al. 2007). All except two were found to be compatible with a scenario of ejection by the SMBH in the GC. One exception is the early B-type star HE 0437−5439 which probably originates in the Large Magellanic Cloud (LMC; Przybilla et al. 2008), possibly expelled dynamically by interaction of massive binaries in a dense star cluster (Leonard 1991) or by an intermediate-mass black hole (Gualandris & Portegies Zwart 2007), as no SMBH is known to exist in the LMC.

A measurement of the proper motion of the bright ($V = 12.26$ mag) early B-type giant HD 271791 allowed the Galactic rest-frame velocity to be determined to lie within the range 530–920 km s^{-1}, exceeding the local Galactic escape velocity and thus qualifying the star as a HVS, and the place of birth to be constrained to the outer rim of the Galactic disk at a galactocentric distance of $\gtrsim$15 kpc (Paper I). This left the question of the ejection mechanism to be answered as models invoking the SMBH in the GC are ruled out.

[1] Based on observations obtained at the European Southern Observatory, proposal 073.D-0495(A).

[2] Dr. Karl Remeis Observatory, University of Erlangen–Nuremberg, Sternwartstrasse 7, D-96049 Bamberg, Germany; przybilla@sternwarte.uni-erlangen.de.

[3] Max Planck Institute for Astrophysics, Karl-Schwarzschild-Strasse 1, D-85741 Garching, Germany.

[4] University Observatory, Scheinerstrasse 1, D-86179 Munich, Germany.

2. ANALYSIS

HD 271791 was observed in early 2005 at the European Southern Observatory on La Silla, Chile, using the FEROS spectrograph on the 2.2 m telescope (Paper I). Four individual spectra with resolving power $\lambda/\Delta\lambda = 48{,}000$ were co-added and smoothed over 5 pixels for the present work, resulting in a S/N of ~120 to ~160 in the blue visual range.

The quantitative analysis of the spectrum of HD 271791 was carried out following the hybrid NLTE approach discussed by Nieva & Przybilla (2007, 2008) and Przybilla et al. (2006). In brief, line-blanketed LTE model atmospheres were computed with ATLAS9 and ATLAS12 (Kurucz 1993, 1996), the latter in order to account for the chemical peculiarity of the star. NLTE line formation calculations were performed using updated versions of DETAIL and SURFACE (Giddings 1981; Butler & Giddings 1985). State-of-the-art model atoms were adopted (see Table 1), which allow absolute elemental abundances to be obtained with high accuracy.

Multiple independent spectroscopic indicators are considered simultaneously for the determination of the atmospheric parameters, effective temperature $T_{\rm eff}$, and (logarithmic) surface gravity log g: all Stark-broadened Balmer lines and simultaneously four metal ionization equilibria, of Si ii/iii, O i/ii, S ii/iii, and Fe ii/iii. The resulting redundancy helps to avoid systematic errors. The microturbulent velocity ξ was determined in the standard way by demanding abundances to be independent of line equivalent widths. Elemental abundances and the (projected) rotational velocity $v \sin i$ were determined from fits to individual line profiles. Fundamental stellar parameters such as mass M, radius R, and luminosity L, as well as the evolutionary age $\tau_{\rm evol}$ were constrained by comparison with stellar evolution tracks, in analogy to Paper I.

The results are summarized in Table 1 and a comparison of the final model spectrum with many strategic regions of the observed spectrum is made in Figure 1. An excellent match between the observed and synthetic spectrum is obtained from the large scale to minute details. Our stellar parameters for HD 271791 are consistent with earlier work (Paper I; Kilkenny & Stone 1988), but more precise. This applies in particular to

TABLE 1
STELLAR PARAMETERS AND ELEMENTAL ABUNDANCES OF HD 271791

Parameter	Value	Unit	Parameter	Value	Unit
$T_{\rm eff}$	18,000 ± 500	K	$M/M_\odot$	11 ± 1	
log g	3.10 ± 0.10	cgs	$R/R_\odot$	15.5 ± 0.3	
ξ	4 ± 1	km s^{-1}	log $L/L_\odot$	4.35 ± 0.05	
v sin i	124 ± 2	km s^{-1}	$\tau_{\rm evol}$	25 ± 5	Myr
Ion	$\varepsilon^{\rm NLTE}$	$N_{\rm lines}$	Ion	$\varepsilon^{\rm NLTE}$	$N_{\rm lines}$
He I[a]	10.99 ± 0.05	15	Al III[h]	6.33 ± 0.08	3
C II[b]	8.32 ± 0.12	4	Si II[i]	7.72 ± 0.06	3
N II[c]	7.60 ± 0.09	9	Si III[i]	7.71 ± 0.10	5
O I[d]	8.85 ± 0.07	2	S II[j]	7.02 ± 0.10	6
O II[e]	8.81 ± 0.07	14	S III[j]	7.08 ± 0.11	2
Ne I[f]	8.01 ± 0.08	2	Fe II[k]	7.30 ± 0.10	1
Mg II[g]	7.28 ± 0.12	1	Fe III[l]	7.22 ± 0.08	6

NOTES.—ε(X) = log (X/H) + 12. Statistical 1 σ uncertainties determined from the line-to-line scatter ($N_{\rm lines}$ = number of lines) are given. Uncertainties for for Mg II and Fe II are estimates. NLTE model atoms (for H, see Przybilla & Butler 2004): (a) Przybilla 2005; (b) Nieva & Przybilla 2006, 2008; (c) Przybilla & Butler 2001; (d) Przybilla et al. 2000; (e) Becker & Butler 1988, updated; (f) Morel & Butler 2008; (g) Przybilla et al. 2001; (h) Dufton et al. 1986; (i) Becker & Butler 1990, extended and updated; (j) Vrancken et al. 1996, updated; (k) Becker 1998; (l) Morel et al. 2006.

elemental abundances which have uncertainties of only about 20% (statistical 1 σ standard deviation).

The uncertainties in the atmospheric parameters were constrained from the quality of the simultaneous fits to all diagnostic indicators. Statistical uncertainties for metal abundances were determined from the individual line abundances. Systematic errors in the abundances due to uncertainties in atmospheric parameters, atomic data, and the quality of the spectrum are about 0.1 dex (Nieva & Przybilla 2008; Przybilla et al. 2006), i.e., as large as the statistical errors.

Elemental abundances of HD 271791 (averaged over all lines of an element) are displayed in Figure 2, relative to the solar standard. All abundances are within a factor of 2 relative to solar, confirming the findings from Paper I. However, the higher

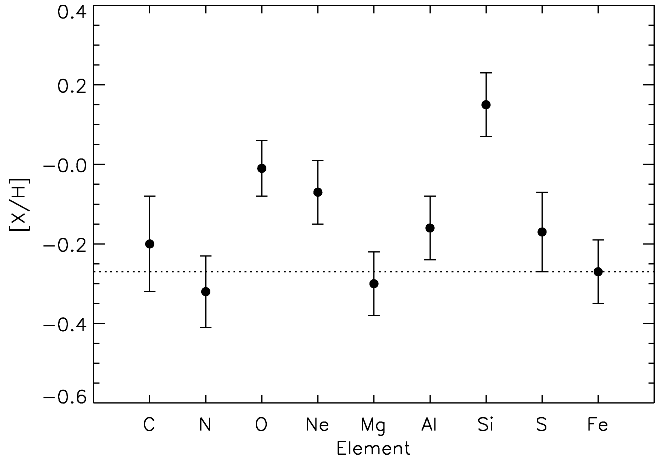

FIG. 2.—Metal abundance pattern of HD 271791, relative to solar values (Grevesse & Sauval 1998). Error bars account for statistical 1σ uncertainties. The baseline metallicity of HD 271791, [Fe/H], is marked by the dotted line.

accuracy of the present work allows an underlying pattern in the elemental abundances to be uncovered, which is atypical for a young Population I star. The Fe abundance is subsolar by 0.27 dex, indicating that the star was formed in a metal-poor environment. This is consistent with the outer metal-poor rim of the Galactic disk suggested by the star's kinematic properties (Paper I). The α-process elements O, Ne, S, and in particular Si are enhanced, with the exception of Mg, which along with C and N is compatible with the iron underabundance by about a factor of 2 relative to solar. This is the first detection of α-enhancement in a massive star outside the GC.

Enhancement of the α-elements is a characteristic of material ejected in the supernova (SN) explosion of a massive star. In situ formation of these elements in HD 271791 via hydrostatic nuclear burning and subsequent mixing into the stellar atmosphere can be excluded. Typically, only low-mass stars of the old Population II and the GC population show a chemical com-

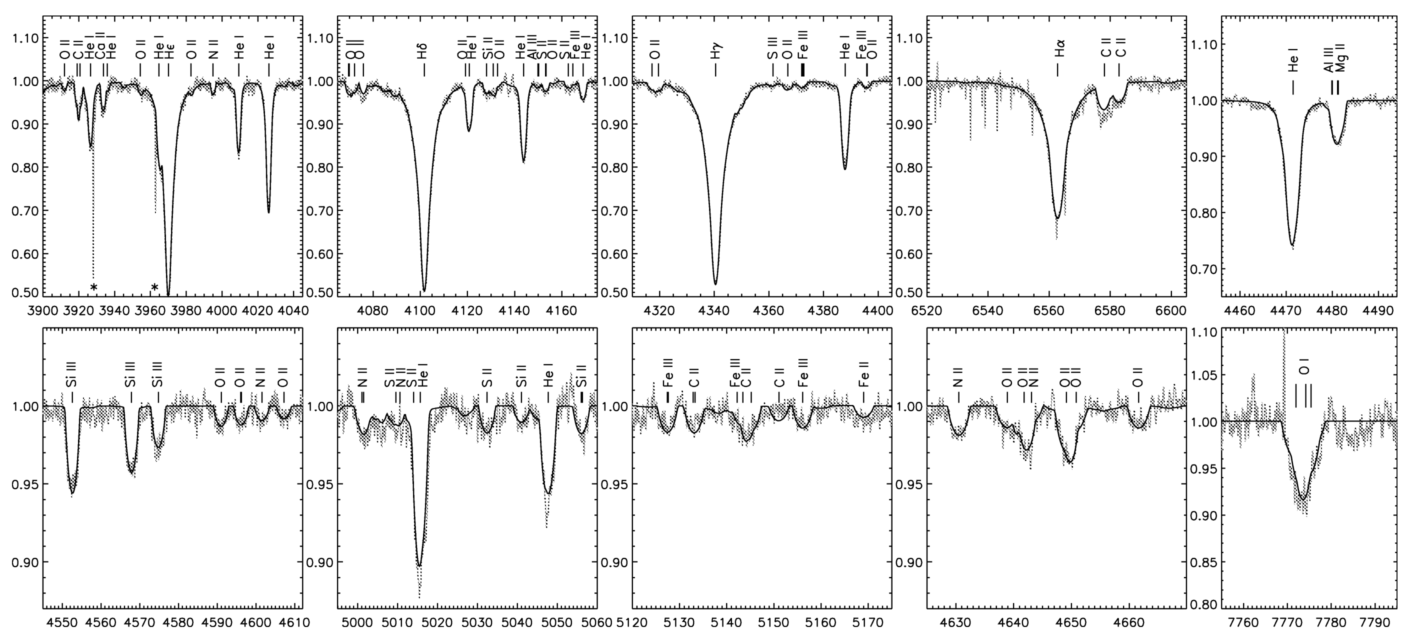

FIG. 1.—Comparison of spectrum synthesis for HD 271791 (*black line*) with observation (*gray line*). The top panels illustrate the excellent fit of Balmer and He I lines. The ionization equilibria of Si II/III, O I/II, S II/III, and Fe II/III are perfectly matched (*bottom panels*; plus S III λ4361 above). A selection of lines from most ions detected can be found in the panels. Note that all atmospheric features of the observed spectrum are simultaneously reproduced by the final model spectrum (for abundances as in Table 1). Abscissa is wavelength (in Å); ordinate is normalized flux. Interstellar Ca II lines are marked by an asterisk.

position with α-enhancement in the Galaxy at present. Membership of the massive B star HD 271791 in either population is ruled out. Note that HD 271791 cannot be of GC origin (where [Fe/H] $\approx$ 0 and [α/Fe] $\approx$ 0.3; e.g., Cunha et al. 2007) by reason of its chemical signature in addition to its kinematics.

However, contamination of the surface layers of a star in a binary system is possible when the companion explodes in a SN, as reported, e.g., for the secondary of the low-mass X-ray binary Nova Scorpii 1994 (Israelian et al. 1999). A scenario is therefore developed in which the violent disruption of a massive binary by a SN-like event accounts for both, the α-enhancement of the atmosphere of the surviving secondary (HD 271791) and its acceleration to hypervelocity.

3. BINARY SCENARIO FOR ACCRETION OF SN EJECTA AND ACCELERATION

Any plausible progenitor system has to include a very massive primary, as the travel time of HD 271791 from the Galactic disk to its present location in the halo requires the SN-like event to happen early in the star's lifetime. Stars above 40 $M_\odot$ die within less than 6 Myr (Meynet & Maeder 2005), which is sufficiently short for this scenario.

Mass accretion from a SN shell by the secondary depends strongly on geometric factors because of the high velocity of the ejecta compared to the escape velocity from the surface of the secondary (several 10^3 vs. $\sim 10^3$ km s^{-1}). Interaction of the SN shell with the secondary is therefore possible for a fraction of mass equal to the solid angle subtended from the primary at most (Fryxell & Arnett 1981, hereafter FA81), unless there is significant fall-back of material onto the remnant. A close binary system is therefore favored, similar to the scenario developed for Nova Sco 1994 (Podsiadlowski et al. 2002; see in particular their Fig. 2). In the present case, both components must be massive and the explosion of the primary has to be strongly asymmetric to disrupt the system and to release the secondary at its orbital velocity.

The absence of N enrichment indicates that HD 271791 did not accrete significant amounts of (CN-processed) mass from the primary; i.e., the system avoided Roche lobe overflow (Vanbeveren et al. 1998). This implies that the system has undergone a common-envelope phase, with spiral-in of the secondary because of viscous forces. Systems with mass ratios (secondary/primary mass) $q \leq 0.2$ qualify for a wide range of initial periods (Vanbeveren et al. 1998), resulting in a minimum mass of $\sim$55 $M_\odot$ for the primary on the zero-age main sequence.

The spiral-in process can expel the H-rich envelope of the primary (stopping the merger) when sufficient orbital energy is deposited, at the expense of a very large reduction of the orbital separation (Vanbeveren et al. 1998). Accordingly, a binary composed of a Wolf-Rayet (WR) + an early B-type main-sequence star is a conceivable progenitor system for the SN-like event involving HD 271791. The radius of an 11 $M_\odot$ star is $\sim$4 $R_\odot$ on the main sequence, and $\sim$2–3 $R_\odot$ for a WR star with mass $\leq$20 $M_\odot$ of WC subclass at the baseline metallicity of HD 271791 (Crowther et al. 2002). As a consequence, the separation a between the binary components before the SN-like event could be as small as 13–15 $R_\odot$ for a detached system, resulting in an orbital period of $\sim$1 day and an orbital velocity of the secondary of $\sim$400 km s^{-1}.

At this point a first phase of accretion onto HD 271791 is likely to occur. The WR star has a dense and strong wind that will directly impact on the surface of the secondary, as a metal-poor B1 V star has no significant wind of its own (a situation similar to but more extreme than that observed for the massive binary CPD $-$41 7742; Sana et al. 2005). Using conservative assumptions on WR mass-loss rates and lifetime, we estimate that about 0.04 $M_\odot$ of material, rich in C and to a lesser degree abundant in O and Ne, could be deposited.

The final collapse of the WC star into a black hole (Heger et al. 2003) results in an ordinary Type Ic SN or a more energetic hypernova (HN). The kick experienced by the (proto-) black hole disrupts the binary and releases the companion at its orbital velocity, in analogy to the classical scenario of runaway stars (Blaauw 1961).

This gives rise to the second—and main—mass accretion event onto HD 271791. The interaction of the expanding SN shell with the secondary is a complex hydrodynamical process involving ablation of mass from the outer layers of the secondary and accretion from the shell, which is not completely understood (FA81). Also interaction with fall-back material from the explosion can be significant (Podsiadlowski et al. 2002). We therefore made conservative assumptions to estimate the effects of accretion of SN-processed material on the chemical composition of the secondary. Nucleosynthesis yields of Nomoto et al. (2006) were used. We chose the highest mass models available, for a star of initially 40 $M_\odot$ and metallicity $Z = 0.004$, that comes closest to the adopted pristine value. The total kinetic energy of the explosion predicted by the models is 3×10^{52} erg for the HN and 10^{51} erg for the SN, respectively. A total of $M_{\rm acc} = M_{\rm ejecta} R_2^2/4a^2$ may be accreted by the secondary with radius R_2. However, due to the large momentum of the impacting material the efficiency of accretion is small, i.e., $\sim$10% (FA81). About 0.02 $M_\odot$ of heavy elements can therefore be accreted in the event that expels $M_{\rm ejecta} \approx 10$ $M_\odot$ of metals in total (for $a = 13$–15 $R_\odot$). At the same time $\sim$1% (0.1 $M_\odot$) of the secondary mass is ablated from the surface layers (FA81), including a considerable part of the material accreted previously from the WR wind.

The accreted material has been mixed with unpolluted matter from the secondary's deeper layers and possibly with CN-processed material from its core over the past $\sim$20 Myr. Chemical mixing in the radiative envelopes of rotating stars is slow, approximated well by diffusion (Maeder & Meynet 2000). The metal-rich material will therefore be only partially mixed, leading to a dilution of the original HN/SN abundance pattern.

In order to model the observed abundance pattern, several parameters have to be adjusted: (1) the initial chemical composition, (2) the fraction of the SN-shell that is accreted, and (3) the equivalent envelope mass affected by complete mixing (in reality the heavy-element abundances will be stratified). The scenario has to reproduce the observed Fe abundance as a boundary condition as the abundance patterns are normalized with respect to iron. The model abundance patterns do not account for the surviving fraction of the C-rich and N-free WC wind and rotational mixing with slightly C-depleted and N-enriched material from the core as quantitative estimates are difficult to make. However, both processes tend to cancel each other, so that the net effect is expected to be small.

Results are shown in Figure 3, for the mixing of 0.12%/0.08% of the HN/SN ejecta with 1 $M_\odot$ envelope material of HD 271791 of pristine composition [X/H] $= -0.4/-0.24$ dex. Note that mixing of a higher fraction of envelope mass can compensate for an increase of the accreted mass and vice versa. Overall, reasonable agreement between the model predictions and observation is obtained, except that too large a Mg and too low a Si abundance is predicted. However, this is likely an artifact of the use of integrated yields. More realistic is a latitudinal dependency of the ejecta composition in the likely case of an aspherical explosion (Maeda

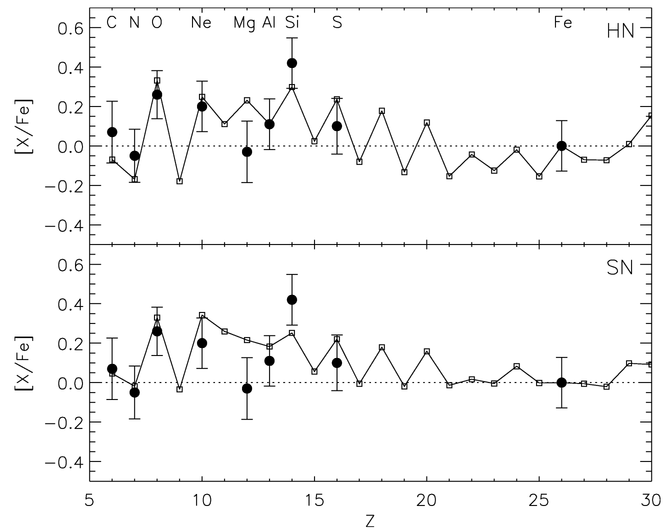

FIG. 3.—Elemental abundance pattern of HD 271791 (*filled circles*; relative to solar as a function of atomic number Z, normalized to Fe) compared to HN/SN yields of Nomoto et al. (2006). Error bars account for statistical and systematic uncertainties of 0.1 dex, summed in quadrature. See text for details.

et al. 2008) and a stratified abundance distribution in the ejecta. Hydrodynamic instabilities at the trailing edge of the SN shell will preferentially lead to an accretion of material from the inner shell, which is rich in Si and depleted in Mg (e.g., Maeda et al. 2002), on the secondary (FA81). Tailored nucleosynthesis calculations for this particular case, a detailed hydrodynamical simulation of the SN-shell–secondary interaction, and a comprehensive modeling of the subsequent mixing of the accreted material with the secondary's envelope are desirable.

4. CONCLUSIONS

An accurate determination of the surface composition of the HVS HD 271791 in the present work confirmed the low [Fe/H] expected for a star born in the outer Galactic rim (Paper I). The finding of α-enhancement allowed the acceleration mechanism to be identified as an extreme case of the runaway scenario (Blaauw 1961). The evolution of a binary with a very massive primary ($M \gtrsim 55\ M_\odot$) can lead to a suitable progenitor system of a close WR + B main-sequence star that can account for both, the observed α-enhancement and ejection at high orbital velocity. The collapse of the WR star into a black hole gave rise to either an (aspherical) SN or a more energetic HN (which may be accompanied by a gamma-ray burst of the long-duration/soft-spectrum type; Woosley & Bloom 2006), in which the system was disrupted. A simple model for accretion from the SN shell and subsequent mixing with pristine envelope material can qualitatively explain the observed abundance pattern of HD 271791. Only one fact remains to be explained: the difference between the kick velocity from the binary disruption ($v_{\rm kick} \approx 400$ km s^{-1}) and the Galactic rest-frame velocity of HD 271791 ($v_{\rm grf} = 530$–920 km s^{-1}).

Inspection of Figure 4 in Paper I shows that HD 271791 was ejected from the Milky Way in the direction of the Galactic rotation. A rough alignment of the orbital velocity vector of the secondary with the Galactic rotation direction at the moment of system disruption is therefore sufficient to explain the space motion of HD 271791 if it is on the lower end of the observed range. Numerical kinematic experiments using the Galactic potential of Allen & Santillan (1991) imply a minimum $v_{\rm kick} \approx 380$ km s^{-1} to obtain the minimum $v_{\rm grf}$ of HD 271791 (~530 km s^{-1}) that is consistent with the observed proper motion, radial velocity, distance, and age. For the "best" proper motion of Paper I ($v_{\rm grf} =$ 630 km s^{-1}) a $v_{\rm kick} \approx 460$ km s^{-1} would be required. We conclude that the proposed SN runaway scenario can reproduce all observational constraints, the kinematics, and the abundance pattern. Extreme cases of the runaway scenario of Blaauw (1961) therefore pose an alternative to the Hills mechanism for the acceleration of some HVSs with moderate velocities. As HD 271791 is escaping from the Galaxy, it could be termed a hyperrunaway star, the first of its class.

We thank R. Napiwotzki for valuable discussions on the kinematics of HD 271791 and the ESO staff at La Silla for support with the observations. M. F. N. gratefully acknowledges financial support by the Deutsche Forschungsgemeinschaft (grant HE 1356/45-1).

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