A Very Metal-poor RR Lyrae Star with a Disk Orbit Found in the Solar Neighborhood

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Abstract

Metal-deficient stars are important tracers for understanding the early formation of the Galaxy. Recent large-scale surveys with both photometric and spectroscopic data have reported an increasing number of metal-deficient stars whose kinematic features are consistent with those of the disk stellar populations. We report the discovery of an RR Lyrae variable (hereafter RRL) that is located within the thick disk and has an orbit consistent with the thick-disk kinematics. Our target RRL (HD 331986) is located at around 1 kpc from the Sun and, with \( V \sim 11.3 \), is among the \( \sim130 \) brightest RRLs known so far. However, this object has scarcely been studied because it is in the midplane of the Galaxy, at a Galactic latitude around \( -1^\circ \). Its near-infrared spectrum shows no absorption line except hydrogen lines of the Paschen series, suggesting [Fe/H] \( \lesssim -2.5 \). It is the most metal-deficient RRL, at least among RRLs whose orbits are consistent with the disk kinematics, although we cannot determine to which of the disk and the halo it belongs. This unique RRL would provide us with essential clues for studying the early formation of stars in the inner Galaxy with further investigations, including high-resolution optical spectroscopy.

Unified Astronomy Thesaurus concepts: RR Lyrae variable stars (1410); Spectroscopy (1558); Milky Way disk (1050); Surveys (1671); Milky Way formation (1053); Metallicity (1031)

1. Introduction

It is possible to investigate stellar populations in the Galaxy with various detailed observations thanks to relatively small distances to individual stars. For example, the positions and motions of billions of stars provided by the Gaia satellite (see Gaia Collaboration et al. 2021, for the latest data release, EDR3) have revolutionized our understanding of the Galactic structure and evolution. In particular, streams and substructures that are clearly detected with the Gaia data allow us to build up a scenario of accretions and mergers in the early history of the Galaxy (Helmi 2020). Another vital material for characterizing the Galactic stellar populations is being brought by detailed elemental abundances based on high-resolution spectroscopy (Jofré et al. 2019; Matteucci 2021, and references therein). Metal-deficient stars are especially important for understanding the early Galactic evolution (Frebel & Norris 2015), and tremendous efforts have been devoted to identifying metal-deficient stars (see, e.g., Starkenburg et al. 2017; Da Costa et al. 2019, for recent large-scale surveys). An exciting discovery through these surveys is the presence of metal-deficient stars in the Galactic disk (Sestito et al. 2020).

The presence and the characteristics of metal-deficient stars in the disk provide us with crucial clues to the formation of the Galactic disk and its history. A strong merger at an early stage, for example, would have disrupted the disk, and metal-deficient stars that were present at the time of the merger could lose their disk kinematics except those in the inner Galaxy, where the gravitational potential was deep enough to trap the stars. Recent studies equipped with the Gaia data suggest that such a merger occurred \( \sim10 \) Gyr ago, triggered the growth of the thick disk (Helmi et al. 2018; Gallart et al. 2019; Helmi 2020), and is
imprinted in the kinematics of halo stars as a feature called Gaia Enceladus or the Gaia Sausage. Metal-deficient stars with disk orbits such as the stars with \([\text{Fe/H}] \lesssim -2.5\) discussed in Sestito et al. (2020) can be considered relics of the protodisk that was present before the merger. Further identification of such stars over a wide range of metallicity, together with characterization of halo stars in the same spatial volume, is crucial to establishing (or rejecting) such a formation scenario of the thick disk.

This study focuses on RR Lyrae stars (RRLs) to investigate the old and metal-deficient populations located in the Galactic disk. RRLs are pulsating stars in the Cepheid instability strip and at the horizontal branch phase evolved from low-mass stars \((\lesssim 1 M_\odot)\). They are exclusively old \((>10\text{ Gyr})\) and thus trace old stellar populations in galaxies. General views on the characteristics of RRLs are found in a review by Beaton et al. (2018) and in references therein. The majority of RRLs belong to old stellar spheroids, i.e., the halo and the bulge, though a disk population of RRLs has also been found (Layden 1995; Prudil et al. 2020; Zinn et al. 2020). Other than the differences in spatial distribution and kinematics, an essential difference between the halo and disk groups of RRLs is the metallicity distribution. Disk RRLs are predominantly metal-rich, \([\text{Fe/H}] \gtrsim -1\), while halo RRLs are less metal-enriched. In this study, we report the discovery of an RRL with \([\text{Fe/H}] \lesssim -2.5\) that has a disk orbit.

The rest of this paper is organized as follows. First, we discuss the photometric properties of our target in Section 2. We first identified this object as a bright but unexplored RRL through our variability survey, the KWFC Intensive Survey of the Galactic Plane (KISOGP), described in Section 2.1. Combined with other photometric data (Section 2.2) and the Gaia-based distance, we give an estimate of its metallicity by making use of the period–luminosity–metallicity (PLZ) relation of RRLs (Section 2.3). Then, in Section 3, we present an analysis of the near-infrared spectrum obtained with the WINERED spectrograph. We detected hydrogen lines of the Paschen series, which enabled us to measure the radial velocity (Section 3.2), but detected no metallicity lines, which gives only upper limits of abundance (Section 3.3). In Section 4, we discuss the kinematics and the low metallicity of the target RRL in the context of the Galactic structure and evolution. Finally, Section 5 concludes the paper.

2. Photometric Data

2.1. KISOGP

KISOGP is a large-scale survey of variable stars in the northern Galactic plane using the Kiso Wide Field Camera (KWFC) attached to the 105 cm Schmidt telescope at Kiso Observatory, Japan. KWFC is a mosaic CCD camera with eight CCD chips having a total of 8k \(\times\) 8k pixels covering a field of view of 2.2 deg\(^2\) (0\(^\prime\)946 pix\(^{-1}\)) on the sky. See more details of the KWFC in Sako et al. (2012).

To discover and characterize variable stars in the Galactic plane, we started KISOGP in 2012 and made \(I_c\)-band time-series observations for the 80 KWFC fields of view covering \(\sim 330 \text{ deg}^2\) between 60\(^\circ\) and 210\(^\circ\) deg in Galactic longitude (Matsunaga 2017). The analysis for publishing the catalog of variables detected in KISOGP is in progress, but a study on eclipsing binary systems has been published by Ren et al. (2021).

![Figure 1. Finding chart of our target RRL (HD 331986), indicated by a red circle with a radius of 10\(^\prime\), on a KISOGP \(I\)-band image (3 arcmin\(^2\), north up and east left).](image)

| Table 1 Properties of the Target RRL |
|--------------------------------------|
| **Item(s)**                      | **Value(s)** | **References** |
|----------------------------------|--------------|----------------|
| KISOGP ID                        | KISOJ 201241.60+321242.4 | 1               |
| Aliases                          | HD 331986, NSVS 8487853 | 2               |
| Gaia EDR3 source ID              | 2054159819759156992 | 3               |
| Eq. coordinates (deg)            | \(\alpha = 303.17334, \delta = 12.21177\) | 2               |
| Gal. coordinates (deg)           | \(l = 70.40915, b = -1.05159\) | 2               |
| Variability type                 | RRc          | 1, 2           |
| Period (days)                    | 0.371197     | 1              |
| 2MASS magnitudes                 | \(J = 9.954, H = 9.663\) | 4               |
| \(K_s = 9.577\)                 |              | 5              |
| Astrometric distance (kpc)       | 1.042 \pm 0.015 | 5               |
| Proper motion (mas yr\(^{-1}\))  | \(\mu_x = 11.76, \mu_y = -5.09\) | 3               |
| \(\mu_x \cos b = 2.23, \mu_y = -12.62\) | 3           |

References. (1) This work, (2) Simbad, (3) Gaia EDR3, (4) Skrutskie et al. (2006), and (5) Bailier-Jones et al. (2021).

During our early attempt to identify periodic variables, we discovered a bright but scarcely investigated RRL and made a spectroscopic observation in 2015 (Section 3.1). The properties of this RRL variable, HD 331986 (finding chart presented in Figure 1), are summarized in Table 1. The KISOGP \(I\)-band light curve of this object is presented in Figure 2 together with light curves in other wavelengths (see Section 2.2).

We fitted the discrete Fourier series to the photometric points:

\[
m(t) = A_0 + \sum_{j=1}^{3} A_j \sin \left[ \frac{2\pi j}{P}(t - t_0) + \phi_j \right]
\]

where \(t\) indicates the heliocentric Julian date of each photometric measurement and \(t_0\) is the reference epoch, 2,456,000.519, which we determined to put the maximum of the \(I_c\)-band light curve at phase zero. We obtained the period,
in the NSVS images with a pixel size of 14′′ (Kinemuchi et al. 2006). The same applies to the data from the All-sky Automated Survey for Supernovae (ASAS-SN) with 8′0 pixels (Jayasinghe et al. 2018). There is no optical data set, other than the Gaia DR2, that was published before and gives a high-quality light curve of this object in the V or other bands. We considered the data of the Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006) and NEOWISE (Mainzer et al. 2011, 2014) for the infrared range. While 2MASS gives the JHK_s magnitudes at a single epoch (1999 June 22), NEOWISE gives time-series data collected between 2014 May and 2020 October in the two mid-IR bands, W_1 (3.4 μm) and W_2 (4.6 μm). The available time-series data are presented in Figure 2, but the 2MASS magnitudes are not included because we cannot determine the precise pulsation phase for this data set ~30 yr ago. We fitted the three-term Fourier series (Equation (1)) to the photometric points in each band and estimated the intensity mean and amplitude (Table 2). The NEOWISE data include many outliers, and we made a 2σ clipping for fitting the Fourier series. Although we did not find good V-band photometry free from the blending effect as mentioned above, the mean magnitudes in the Gaia bands give a mean V-band mean magnitude of 11.32 and a maximum magnitude of 11.01 according to the formula in Evans et al. (2018). Maintz (2005) compiled a catalog of well-identified RRLs brighter than V = 12.5 at the maximum phase, and there are 132 RRLs brighter than our target RRL.

2.3. PLZ Relation

RRLs are established distance indicators although the correlation between their periods and absolute magnitudes is significantly affected by metallicity (Beaton et al. 2018). We considered the PLZ relations obtained by Neeley et al. (2019) to see if the photometric data are consistent with the geometric distance and to give a constraint on the metallicity of our target. Following a theoretical study on the PLZ relation in Neeley et al. (2017, 2019) we used the Gaia DR2 trigonometric distances of 55 RRLs with [Fe/H] between −2.56 and −0.07 to obtain the empirical PLZ relations from the optical to the mid-IR photometric bands. The PLZ relation in each band is in the form of

\[ M_\lambda = a + b(\log P_F + 0.30) + c([\text{Fe/H}] + 1.36), \]  

where \( P_F \) is the “fundamentalized” period given by \( \log P_F = \log P + 0.127 \) for an RRc star (\( \log P_F = -0.303 \) for our target). The mid-IR bands used in Neeley et al. (2019) are those of the Spitzer Space Telescope, but we used their PLZ relations for the WISE data. The Spitzer [3.6] and [4.5] bands correspond to the WISE W_1 and W_2 bands, respectively. The theoretical result by Neeley et al. (2017) suggests that the relations in the Spitzer bands and those in the WISE bands are identical, within 0.003 mag, to each other at each wavelength. In addition to W_1, W_2, and \( L_i \) in Table 2, we consider the single-epoch 2MASS magnitudes in JHK_s in the following analysis.

![Figure 2. Light curves of our target RRL (HD 331986).](image)

Figure 2. Light curves of our target RRL (HD 331986). The upper panel presents optical data, i.e., KISOGP (I), and Gaia DR2 (RP, G, and BP), while the lower panel presents the infrared data from NEOWISE (W_1 and W_2). The dashed curves indicate the fitted discrete Fourier series (Equation (1)). The gray strip indicates the duration of the WINERED spectroscopic observation (Section 3.1).

2.2. Other Photometric Data Sets

Our target star was first identified as a candidate RRL by Kinemuchi et al. (2006) based on the Northern Sky Variability Survey (NSVS). Hoffman et al. (2009) also reported this star as an RRL based on the automated classification with the NSVS data. It has also been included as an RRL in the Gaia Data Release 2 (Clementini et al. 2019) and in a variability catalog based on the Wide-field Infrared Survey Explorer (WISE) (Chen et al. 2018). However, no detailed follow-up study has been done, and its kinematic and chemical features remain to be revealed.

As seen in Figure 1, there is a similarly bright star at ~10^6, Gaia EDR3 ID 2054159819759157504 with \( G = 11.56 \). This star is at 0.35 kpc (Bailer-Jones et al. 2021) and has a higher proper motion ~20 mas yr^{-1}. It does not affect the KISOGP photometry of the target RRL, but severe contamination occurs
Combining an observed magnitude \( m_\lambda \) and the PLZ relation (Equation (2)), we can calculate the distance modulus as a function of [Fe/H]:

\[
\mu_\lambda = \mu_0 + A_\lambda = m_\lambda - M_\lambda,
\]

where \( \mu_\lambda \) and \( \mu_0 \) are called apparent and true distance moduli, respectively, and \( A_\lambda \) indicates the interstellar extinction at each wavelength. In the upper panel of Figure 3, the apparent distance moduli with different [Fe/H] are compared with each other and also with the distance modulus corresponding to the astrometry-based distance in Bailer-Jones et al. (2021). We adopted the extinction law obtained by Wang & Chen (2019), i.e., \( A_J / A_V = 0.559, A_H / A_V = 0.243, A_K / A_V = 0.131, \) \( A_m / A_V = 0.078, A_W / A_V = 0.039, \) and \( A_{W3} / A_V = 0.026. \)

We can predict a model of \( A_\lambda \) for a given set of \( A_V \) and [Fe/H], like the one indicated by the orange curve in Figure 3, and we searched for the best set with the least-squares method. We used the error of 0.10 mag for 2MASS \( JHK_s \), and 0.03 mag for the other bands considering that the 2MASS data are single-epoch magnitudes. We then obtained \( A_V = 1.01 \) and [Fe/H] = −2.55 by searching for the best set of these parameters that makes the six-band photometry in Figure 3 consistent with the true distance modulus based on the astrometry-based distance. This result indicates that our target RRL is very metal-poor ([Fe/H] < −2), according to the terminology in Beers & Christlieb (2005), which is consistent with the spectroscopic analysis we present in Section 3. A higher [Fe/H] would require a smaller distance as illustrated in Figure 3. This estimate is subject to the systematic uncertainty and the intrinsic scatter of the PLZ relations given by Neeley et al. (2019) in addition to the uncertainty in the Gaia-based distance by Bailer-Jones et al. (2021). It is not straightforward to estimate the error in our estimate considering the various uncertainties discussed in Neeley et al. (2019). We roughly estimate that the distance modulus based on the PLZ relation has an error of 0.1 mag, which dominates the error ∼0.03 mag from the Gaia-based distance, and the error of 0.1 mag corresponds to the error of ∼0.5 in [Fe/H].

The light-curve shape can be used to infer the metallicity of RRab-type variables (see Mullen et al. 2021, and references therein) but not of RRc-type ones. Nevertheless, the period and amplitudes indicate that this RRc star is metal-deficient compared to typical RRLs. Although there is a star-to-star scatter, Figure 7 of Sneden et al. (2018) clearly suggests that RRc stars with longer periods tend to have lower metallicity. Among the sample they considered, the relatively long period, 0.371197 days, of the target RRL was not found among metal-rich RRc stars ([Fe/H] > −1). Furthermore, Fabrizio et al. (2021) illustrated that metal-deficient RRLs tend to have larger amplitudes at a given period (see their Figure 7). Although we have no good V-band light curve, the amplitudes in the Gaia bands suggest a large V-band amplitude, 0.55–0.65 mag, which is found among metal-deficient RRLs ([Fe/H] ≤ −1.5).

3. Spectroscopic Data

3.1. The WINERED Spectrum

We observed the target RRL on 2015 August 15, 14:55 to 16:20 (UT), with WINERED attached to the 1.3 m Araki telescope at Koyama Observatory, Kyoto Sangyo University in Japan. WINERED is a near-infrared high-resolution spectrograph covering 0.90–1.35 μm (\( z', Y, \) and \( J \) bands) with a resolution of \( R = \lambda / \Delta \lambda = 28000 \) with the WIDE mode (Ikeda et al. 2016, 2022). We carried out eight 600 s exposures, giving a total integration time of 4800 s, with the ABBA nodding pattern having the target within the slit in all the exposures. The eight exposures within ∼1.4 hr cover the phases between 0.47 and 0.63 along the pulsation cycle (Figure 2).

The raw spectral data were first reduced by the pipeline developed by the WINERED team (S. Hamano et al. 2021, in preparation). The pipeline outputs one-dimensional spectra for individual exposures and combined spectra along with supplementary information. Avoiding spectral parts with too much telluric absorption, we considered the following echelle orders in the subsequent analysis: 43rd to 48th (11560–13190 Å in the \( J \) band), 51st to 57th (9760–11150 Å in the \( Y \) band), and 61st (9120–9280 Å in the \( z' \) band).
and spectra with $\lambda_{\text{air}}$ adjusted to the observed spectrum considering the differences between the mean radial velocity, $\langle c \rangle$, and the median of the pixel-by-pixel errors in the normalized spectrum. We then performed telluric correction using the synthetic WINERED spectrum. The vertical line corresponds to the air wavelength, $\lambda_{\text{air}}$, of each line at rest. The wavelength scale of the observed spectrum (Obs) is after the mean radial velocity, $-85.5 \text{ km s}^{-1}$, was subtracted. Four synthetic spectra with $\log g = 2.6$ and $[\text{Fe}/\text{H}] = -2$ but with different $T_{\text{eff}}$ were adjusted to the observed spectrum considering the differences between the mean velocity and $v_j$ in Table 3.

The reduced spectrum is featureless except for strong hydrogen lines and spurious noises that are mainly caused by residuals of telluric lines and OH airglow lines (Oliva et al. 2015). We used the hydrogen lines to measure the radial velocity (Section 3.2), and we estimated the upper limits of chemical abundance with the help of theoretical synthetic spectra (Section 3.3).

### 3.2. Hydrogen Lines

There are four hydrogen lines situated within the wavelength range of our interest, and we detected all of them (Figure 4). Pa ε at 9545.973 Å is located in the 59th order of our spectrum, but it is highly contaminated by telluric absorption between the $z'$ and $J$ bands. We measured the central wavelength ($\lambda_{\text{air}}$) and FWHM by fitting a Gaussian function to 20 pixels, corresponding to $\pm 50 \text{ km s}^{-1}$, around each of the four hydrogen lines. Table 3 lists the $\lambda_{\text{air}}$ and the air wavelength at rest, $\lambda_{\text{air}}$, together with the radial velocity and the FWHM. The velocity error in the fitting of a Gaussian is smaller than $1 \text{ km s}^{-1}$.

In order to calculate the barycentric motion of the object, however, we needed to consider the pulsational effect in addition to the heliocentric correction (i.e., the correction taking into account the motion of the observing facility around the Sun). The amplitude of the radial velocity ($\Delta V_{\text{hel}}$) is, at least approximately, proportional to the $V$-band amplitude ($\Delta V$) (Sneden et al. 2017; Magurno et al. 2019). Recently, Braga et al. (2021) thoroughly investigated the amplitudes and shapes of velocity curves obtained with different absorption lines in the optical range and provided templates of velocity curves. The ratio $\Delta V_{\text{hel}}/\Delta V$ depends on the line being measured. In particular, $H_\alpha$ gives a high ratio, $\Delta V_{\text{hel}}/\Delta V \approx 107$, compared to other Balmer lines and metallic lines, which give ratios $\sim 55$ with some scatter for RRc stars. Unfortunately, the ratios for Paschen lines have not been studied well. Therefore, we made a simple correction by ignoring the difference between the velocity curves of the four Paschen lines and assuming $\Delta V_{\text{hel}}/\Delta V = 55$. This ratio is also consistent with the ratios reported by Sneden et al. (2017) and Magurno et al. (2019).

The amplitudes in the Gaia bands indicate that the $V$-band semi-amplitude is $\sim 0.3 \text{ mag}$, leading to a semi-amplitude of velocity $\sim 16.5 \text{ km s}^{-1}$. The radial velocity of an RRc star gets most redshifted at around the minimum phase with respect to the mean velocity (e.g., Benkő et al. 2021). Thus, we applied a correction of $-16.5 \text{ km s}^{-1}$ in addition to the heliocentric correction ($-2.4 \text{ km s}^{-1}$), resulting in a heliocentric velocity $V_{\text{hel}} = -104.4 \text{ km s}^{-1}$ and a velocity with respect to the local standard of rest (LSR) $V_{\text{LSR}} = -86.7 \text{ km s}^{-1}$. Because of the lack of a velocity template and because only a single-epoch velocity measurement was available, the correction of the pulsational effect introduced a dominant error in our estimate of the barycentric radial velocity (or the so-called gamma...

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**Figure 4.** Four hydrogen lines, from Pa $\zeta$ (top) to Pa $\beta$ (bottom), located within the WINERED spectrum. The vertical line corresponds to the air wavelength, $\lambda_{\text{air}}$, of each line at rest. The wavelength scale of the observed spectrum (Obs) is after the mean radial velocity, $-85.5 \text{ km s}^{-1}$, was subtracted. Four synthetic spectra with $\log g = 2.6$ and $[\text{Fe}/\text{H}] = -2$ but with different $T_{\text{eff}}$ were adjusted to the observed spectrum considering the differences between the mean velocity and $v_j$ in Table 3.

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**Table 3**

| Line    | $\lambda_{\text{air}}$ (Å) | $\lambda_{\text{air}}$ (Å) | $v_j$ (km s$^{-1}$) | FWHM (km s$^{-1}$) |
|---------|----------------------------|----------------------------|---------------------|---------------------|
| Pa $\zeta$ | 9229.017                  | 9226.247                  | -90.0               | 78.6                |
| Pa $\delta$ | 10049.373                | 10046.462                | -86.9               | 60.8                |
| Pa $\gamma$ | 10938.093                | 10934.966                | -85.8               | 62.1                |
| Pa $\beta$ | 12818.077                | 12814.689                | -79.3               | 51.2                |
| Mean    | ...                      | ...                      | -85.5               | ...                |

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#### Notes:

- $\lambda_{\text{air}}$ is the center wavelength of the air absorption line.
- $v_j$ is the velocity of the $j$th pixel.
- FWHM is the full width at half maximum of the Gaussian fit.
velocity, \( V_\odot \)). Considering the scatter of \( \Delta RV/\Delta V \) observed in different RRc stars and the line-to-line difference presented in Braga et al. (2021; see their Figure 15), we conservatively estimate its error to be 10 km s\(^{-1}\).

### 3.3. Metallic Lines

We detected no metallic lines, and we cannot make any solid estimate of the chemical abundance of the target RR. Instead, we estimated the upper limits of the equivalent widths (EWs) and the corresponding limits of abundance for the strongest absorption lines expected in the WINERED range.

#### 3.3.1. Spectral Synthesis and Stellar Parameters

In the subsequent analysis, we used the MOOG tool for spectral synthesis (Sneden et al. 2012) together with the ATLAS9 atmosphere models extended by Mészáros et al. (2012). They provided models with different \([\alpha/Fe]\) and \([C/Fe]\) for a wide range of metallicity, and we assumed \([\alpha/Fe]\) and \([C/Fe]\) are both enhanced by +0.3 dex. Together with an atmospheric model, spectral synthesis requires a list of absorption lines. We considered the Vienna Atomic Line Database (VALD; Ryabchikova et al. 2015) and the list of Meléndez & Barbuy (1999, hereinafter referred to as MB99), and synthesized two spectra for a given atmospheric model by using the two line lists separately.

We needed stellar parameters such as the effective temperature to decide which atmosphere models to use. The WINERED observation was carried out over \( \sim 1.4 \) hr, within which 10 minute exposures were repeated eight times. This corresponds to a significant fraction of the pulsation cycle, 0.473 < \( \phi \) < 0.630 (Figure 2). Nevertheless, the variation of stellar parameters is expected to be small because the exposures were made at around the minimum phase (e.g., Govea et al. 2014). Therefore, we decided to ignore the variation of stellar parameters during the eight exposures.

It was, however, not easy to obtain a precise estimate of the stellar parameters of our target. In Section 2.3, we used the PLZ relations to estimate the interstellar reddening. This means that we assumed that the intrinsic color of our target is consistent with the prediction of the PLZ relations for which only mean magnitudes are used. On the other hand, the lack of metallic lines prevented us from estimating the stellar parameters with the various methods used in common spectral analyses. Therefore, we considered the \( T_{\text{eff}} \) and \( \log g \) expected for RRc-type variables allowing relatively large errors.

Govea et al. (2014) found that the \( T_{\text{eff}} \) of RRc are concentrated between 7000 and 7500 K. This is consistent with the \( T_{\text{eff}} \) of a larger sample of RRc stars in Crestani et al. (2021b) considering the uncertainties. At around the minimum phase, the effective temperature is expected to be at the low extreme. We considered three temperatures, i.e., 6750, 7000, and 7250 K, where we needed to evaluate the effect of \( T_{\text{eff}} \) on the upper limits of abundance. Concerning other stellar parameters necessary for the spectral synthesis, we used a surface gravity \( \log g = 2.6 \), microturbulence \( v_{\text{mic}} = 2.5 \) km s\(^{-1}\), and additional Gaussian broadening \( v_{\text{broad}} = 25.0 \) km s\(^{-1}\) including macroturbulence and instrumental factors. Figure 4 compares the observed spectrum with synthetic spectra with \( \log g = 2.6 \) and \([Fe/H] = -2\) but with four different \( T_{\text{eff}} \) between 6000 and 7500 K. The relative strengths of the four Paschen lines support the adopted temperature range. The constraint is, however, not very strong because it is hard to reproduce the broad profile of hydrogen lines accurately with high-resolution echelle spectra like the WINERED one.

#### 3.3.2. Upper Limits of EW

We first listed up the supposedly strongest absorption features in the synthetic spectrum with \( T_{\text{eff}} = 7000 \) K, \( \log g = 2.6 \), and \([Fe/H] = -1\) created with the line list of VALD or MB99. Then, we identified the absorption lines that form the selected features (Tables 4 and 5). Multiple lines can contribute to each feature. Among the selected features, the one at 11659.5 Å is formed by two C I lines, and the one at 12083.5 Å by two Mg I lines according to VALD. In addition, Mg II 10914.244 and Sr II 10914.887 could have formed the feature at \( \sim 10914.5 \) Å together. We excluded this mixed feature from the subsequent analysis to avoid the blending effect on the upper limits of abundance.

For each selected feature, we evaluated the upper limits of the EW as follows. First, we calculated the weighted mean and its error of the pixel counts within \( \pm 150 \) km s\(^{-1}\) around each line but with the pixels within \( \pm 25 \) km s\(^{-1}\) of the features in Tables 4 and 5 excluded from the calculation. The weighted mean was considered as the local continuum level, \( f_\odot \) (with the error, \( e_\odot \)), in the wavelength range around the feature. If the continuum normalization for each order were perfect in the spectral reduction (Section 3.1), \( f_\odot \) should be 1, and it is actually consistent with 1 within the error in most cases. Then, we

| ID | Species | \( \lambda_{\text{abs}} \) (Å) | EP (eV) | \( \log gf \) | \( W_{\text{exp}} \) (mA) | [X/H]_{\text{upp}} |
|----|---------|----------------|--------|------------|-----------------|--------------|
| V01 | Si I | 9212.8630 | 6.524 | 0.470 | 52 | -1.72 |
| V02 | Mg II | 9218.2500 | 8.655 | 0.270 | 85 | -1.08 |
| V03 | Sr II | 10585.141 | 4.954 | 0.012 | 28 | -1.99 |
| V04 | C I | 10683.080 | 7.483 | 0.079 | 86 | -2.10 |
| V05 | C I | 10685.340 | 7.480 | -0.272 | 103 | -1.57 |
| V06 | C I | 10691.245 | 7.488 | 0.344 | 72 | -2.51 |
| V07 | C I | 10707.320 | 7.483 | -0.411 | 48 | -2.05 |
| V08 | C I | 10729.529 | 7.488 | -0.420 | 38 | -2.18 |
| V09 | Si I | 10827.088 | 4.954 | 0.302 | 44 | -2.03 |
| V10 | Si I | 10868.789 | 6.191 | 0.206 | 39 | -2.11 |
| V11 | Mg II | 10914.244 | 8.864 | 0.020 | 39 | -1.03 |
| V12 | C I | 11658.820 | 8.771 | -0.278 | 144 | -1.03 |
| V13 | C I | 11659.680 | 8.647 | 0.028 | ... | ... |
| V14 | C I | 11748.220 | 8.640 | 0.375 | 61 | -1.78 |
| V15 | C I | 11753.320 | 8.647 | 0.691 | 46 | -2.35 |
| V16 | Mg I | 11828.171 | 4.346 | -0.333 | 57 | -1.89 |
| V17 | Ca II | 11838.997 | 6.468 | 0.312 | 90 | -1.66 |
| V18 | Si I | 11984.198 | 4.930 | 0.239 | 70 | -1.69 |
| V19 | Si I | 12031.504 | 4.954 | 0.477 | 351 | ... |
| V20 | Mg I | 12083.278 | 5.753 | 0.450 | 52 | -2.03 |
| V21 | Mg I | 12083.649 | 5.753 | 0.410 | ... | ... |

**Notes:**

1. No constraint was obtained for this feature with multiple elements’ contribution.
2. No constraint stronger than \([X/H] \leq -1\) was given.

**Table 4**

Upper Limits of EW (W) and [X/H] for the Metallic Lines Selected from VALD

*The Astrophysical Journal,* 925:10 (11pp), 2022 January 20

Matsunaga et al.
that we found with the synthetic spectra, we give no constraint on the abundance for a given line.

Figure 5 plots the upper limits of abundance. For most of the lines included in both VALD (Table 4) and MB99 (Table 5), the log gf in the two lists agree with each other within 0.1 dex, and the difference in the line list is not important for the upper limits in Figure 5. Neutral carbon lines give the strongest constraints in terms of [X/H], i.e., |C/H| ≤ −2.5. A couple of lines of other elements (Mg, Si, and Ca) indicate [X/H] ≤ −2. We have no direct constraint on [Fe/H] because no iron line in the WINERED wavelength range is expected to be as strong as the lines in Tables 4 and 5. There have been several reports of carbon-enhanced stars among metal-deficient RRLs (e.g., Preston et al. 2006; Kimman et al. 2012; Kennedy et al. 2014). In contrast, Andrievsky et al. (2020) found [C/Fe] < 0 for a few RRLs with −1.7 < [Fe/H] < −1.2 based on non-LTE analysis. We simply give an upper limit of −2.5 dex and use it in the subsequent discussion. According to the terminology defined by Beers & Christlieb (2005), the target RRL is a very metal-poor star ([Fe/H] < −2) if not an extremely metal-poor star ([Fe/H] < −3).

4. Discussion

Combining the radial velocity estimated with the four Paschen lines (Section 3.2) with Gaia’s distance and proper motions, the six-dimensional information (i.e., the position and space velocity) is available for our target. We computed the target’s orbital and kinematic properties by taking into account the observational uncertainties. We used the AGAMA package (Vasiliev 2019) with Galactic constants adopted from

Table 5

| ID | Species | λ_{νs} (Å) | EP (eV) | log gf | W_{νp} (mA) | [X/H]_{νp} |
|---|---|---|---|---|---|---|
| M01 | C I | 10123.87 | 8.54 | −0.09 | 51 | −1.44 |
| M02 | Si I | 10585.14 | 4.93 | −0.06 | 28 | −1.92 |
| M03 | C I | 10683.09 | 7.48 | 0.03 | 86 | −2.05 |
| M04 | C I | 10685.36 | 7.48 | −0.30 | 103 | −1.54 |
| M05 | C I | 10691.26 | 7.49 | 0.28 | 72 | −2.45 |
| M06 | C I | 10707.34 | 7.48 | −0.41 | 48 | −2.05 |
| M07 | C I | 10729.54 | 7.49 | −0.46 | 38 | −2.14 |
| M08 | Si I | 10749.39 | 4.93 | −0.21 | 46 | −1.49 |
| M09 | Si I | 10827.10 | 4.95 | 0.23 | 44 | −1.95 |
| M10 | Si I | 10869.54 | 5.08 | 0.36 | 39 | −2.09 |
| M11 | Mg II | 10914.24 | 8.86 | 0.00 | 39 | ...
| M12 | C I | 11658.85 | 8.77 | −0.36 | 144 | ...
| M13 | C I | 11659.70 | 8.65 | −0.07 | ...
| M14 | C I | 11753.32 | 8.65 | 0.51 | 42 | −2.29 |
| M15 | Mg II | 11754.79 | 8.64 | 0.51 | 42 | −2.29 |
| M16 | Mg I | 11828.19 | 4.35 | −0.50 | 57 | −1.72 |
| M17 | Ca II | 11838.97 | 6.47 | 0.24 | 90 | −1.59 |
| M18 | Ca II | 11949.76 | 6.47 | −0.04 | 43 | −1.92 |
| M19 | Si I | 11984.23 | 4.93 | 0.12 | 70 | −1.57 |
| M20 | Si I | 12031.53 | 4.95 | 0.24 | 351 | ...

Notes.

a No constraint was obtained for this feature with multiple elements’ contribution.

b No constraint stronger than [X/H] ≤ −1 was given.

obtained the EW (W) and its error (E_{νp}) by

\[ W = \sum_{i=1}^{n} \left( 1 - \frac{f_i}{f_c} \right) \Delta \lambda_i \]  \hspace{1cm} (4)

\[ E_{νp} = \frac{1}{f_c} \sum_{i=1}^{n} \sigma_i^2 (\Delta \lambda_i)^2 + \frac{e_x}{f_c} \sum_{i=1}^{n} f_i \Delta \lambda_i \]  \hspace{1cm} (5)

where the sum is taken over the n pixels (1 ≤ i ≤ n, with the flux f_i and the noise \sigma_i at each pixel) within ±25 km s⁻¹ around the line center and \Delta \lambda_i indicates the width of each pixel in units of mA. We estimated the upper limit of the EW by

\[ W_{νp} = \begin{cases} 
W + 3 E_{νp} & \text{(if } W \geq 0) \\
3 E_{νp} & \text{(if } W < 0) 
\end{cases} \]  \hspace{1cm} (6)

for each feature (Tables 4 and 5).

3.3.3. Upper Limits of Elemental Abundance

We estimated the upper limits of chemical abundance based on the upper limits of the EW. This was done with the help of synthetic spectra. For each feature in Tables 4 and 5, except the mixed feature of Mg II and Sr II at 10914.6 Å, we calculated the EWs in the synthetic spectra with different abundances of each species over −3 ≤ [Fe/H] ≤ −1. This enabled us to draw the curve of growth and estimate the upper limit, which corresponds to \( W_{νp} \). We estimated the abundance upper limits with the models at three different temperatures (6750, 7000, and 7250 K), and took the highest upper limit of the three as the final estimate, [X/H]_{νp} in Tables 4 and 5, based on the given feature. The maximum metallicity of the synthetic spectra we considered is −1 dex. If \( W_{νp} \) is larger than the maximum EW

![Figure 5. Upper limits of [X/H] given by individual lines in Table 4 (VALD) and those in Table 5 (MB99).](Image)
Table 6
Kinematic Properties of the Target RRL

| Parameter                      | Value                      |
|--------------------------------|----------------------------|
| \( D_0 \) — geometric distance | 1.042 ± 0.015 (kpc)        |
| \( v_{\text{LSR}} \) — radial velocity | \(-104 ± 10 \) (km s\(^{-1}\)) |
| \( \mu_\alpha \cos \delta \) — proper motion along \( \alpha \) | \(11.76 ± 0.01\) (mas yr\(^{-1}\)) |
| \( \mu_\delta \) — proper motion along \( \delta \) | \(-5.09 ± 0.02\) (mas yr\(^{-1}\)) |

\( \eta \) — pericenter distance 3.71 ± 0.38 (kpc)
\( \eta_{\text{max}} \) — apocenter distance 8.36 ± 0.01 (kpc)
\( z_{\text{max}} \) — maximum height 1.18 ± 0.01 (kpc)
\( e \) — eccentricity 0.39 ± 0.04
\( v_R \) — radial velocity 52.9 ± 2.2 (km s\(^{-1}\))
\( v_\theta \) — azimuthal velocity 143.5 ± 9.8 (km s\(^{-1}\))
\( v_Z \) — vertical velocity 53.6 ± 0.3 (km s\(^{-1}\))
\( v_{\text{pec}} \) — peculiar velocity 118.7 ± 8.4 (km s\(^{-1}\))
\( E_\text{tot} \) — total orbital energy \(-118.9 ± 1.3\) (10\(^7\) km\(^2\) s\(^{-2}\))
\( L_\phi \) — azimuthal angular momentum 1135 ± 77 (kpc km s\(^{-1}\))

Note. The given errors are the standard deviations observed in our Monte Carlo calculation and do not include the systematic errors. The velocity and proper motion of the input parameters are given with respect to the Sun, while the velocities of the output parameters are given with respect to the Galactic center.

Zinn et al. (2020): the distance to the Galactic center \( D_0 = 8.2 \) kpc, the velocity of the LSR \( v_{\text{LSR}} = 232 \) km s\(^{-1}\), and the solar velocity with respect to the LSR \( (U_\odot, V_\odot, W_\odot) = (-11.1, 12.24, 7.25) \) km s\(^{-1}\) (Schönrich et al. 2010). We used the Galactic potential called MWPotential2014 available in the galpy library (Bovy 2015), which is composed of three axisymmetric potentials for a spherical power-law bulge with an exponential cutoff, a Navarro–Frenk–White halo potential, and a Miyamoto–Nagai disk.

We randomly drew 10,000 samples from the error distribution of the position and velocity and integrated the orbit forward in time for a long enough period of time (100 Gyr). The average and standard deviation of the orbital parameters from individual Monte Carlo samples are given in Table 6. The eccentricity is defined by \( e = (r_{\text{max}} - r_{\text{min}}) / (r_{\text{max}} + r_{\text{min}}) \). The positive azimuthal velocity \( (v_\theta) \) and angular momentum \( (L_\phi) \) correspond to the prograde rotation. With the maximum height \( z_{\text{max}} = 1.18 \) kpc from the Galactic plane, the orbit of the target RRL is accommodated within the stretch of the thick disk, whose vertical scale length is about 0.9 kpc (Bland-Hawthorn & Gerhard 2016).

In Figures 6 and 7, we compare the properties of our target RRL with those of 463 RRLs compiled by Zinn et al. (2020), but we recalculated their parameters except [Fe/H] and the V-band magnitudes. We combined the radial velocities adopted from Zinn et al. (2020) with the astrometric data from the Gaia EDR3 and the EDR3-based distances from Bailer-Jones et al. (2021) to calculate the current positions \( (X, Y, Z) \), the velocities \( (v_X, v_Y, v_Z) \), the apocenter distance \( r_{\text{max}} \), the maximum height \( z_{\text{max}} \), the angular momenta \( (L_\phi) \), and the total orbital energies \( E_\text{tot} \), the sum of kinetic and potential energies. The total orbital energies show a systematic offset, \( \sim 7 \times 10^6 \) km\(^2\) s\(^{-2}\), between our calculation and that of Zinn et al. (2020) because of the difference in Galactic potential. The distributions in the other parameters do not show such systematic offsets but the parameters of individual objects are expected to be improved by using the Gaia EDR3.

Figure 6 includes 360 RRLs with \( V < 13 \), while our RRL is located at \( V = 11.32 \), obtained in Section 2.2 using the Gaia photometry. We highlight eight bright and metal-deficient \([\text{Fe/H}] \lesssim -2.3\) objects selected within Figure 6 and list their names in the caption. Three of them (V338 Pup, X Ari, and UY Boo) are fundamental-mode pulsators (i.e., RRab type), while the other five are first-overtone pulsators (RRc, same as the target RRL). The metallicities of the eight RRLs have been measured and reported recently in Beers et al. (2014), Snedden et al. (2017), Andrievsky et al. (2018), Chadid et al. (2017), and Zinn et al. (2020). The brightest four RRLs (Nos. 1–4) are located at 0.4–0.6 kpc from the Sun, while the faintest four are located further, at 0.95–1.3 kpc, according to Baier-Jones et al. (2021). The distance to our target RRL is among the farthest ones, and its metallicity is as low as those of the eight RRLs.

Figure 7(a) presents a Toomre diagram, in which the semicircle contours indicate constant peculiar velocities,

\[
v_{\text{pec}} = \sqrt{v_R^2 + (v_\theta - v_{\text{LSR}})^2 + v_Z^2},
\]

with respect to the LSR corresponding to 75 and 150 km s\(^{-1}\). Panel (b) shows that RRLs with relatively low \( v_{\text{pec}} \) tend to be metal-rich (Layden 1995). In Figure 7, except in panel (c), halo stars show more or less symmetric distributions of \( v_\theta \) and \( L_\phi \), and they overlap with the disk component at around the position of our target. The bright and metal-deficient RRLs highlighted in Figures 6 and 7 can be classified as halo objects according to their \( v_{\text{pec}} \). The motion of our RRL deviates significantly from the Galactic rotation with \( v_{\text{LSR}} = 232 \) km s\(^{-1}\), but the star is, with a peculiar velocity of 116.6 km s\(^{-1}\), indistinguishable from thick-disk stars in regard to kinematics (Figure 7(a)). Our RRL may still belong to the halo and its motion is at the prograde-side tail of halo orbits. Two metal-deficient bright RRLs highlighted, V338 Pup and V701 Pup (Nos. 2 and 5), are located at around the opposite point on the retrograde side.

Panel (c) plots \( z_{\text{max}} \) against the \( r_{\text{max}} \) estimated with the orbit calculation. Like that of our RRL, the orbits of the four bright, metal-deficient RRLs highlighted are within the stretch of the thick disk, although three of them show retrograde motion. In addition, the four RRLs have larger eccentricity than our RRL:
Figure 7. Properties of the target RRL in comparison with the known RRLs compiled by Zinn et al. (2020). The target RRL is indicated by the star symbol, and the arrow in panel (b) means that its metallicity is given as the upper limit. The orange semicircles in panel (a) indicate the peculiar velocities \( v_{pec} \) of 75 and 150 km s\(^{-1}\). RRLs with \( v_{pec} \) lower than 75 km s\(^{-1}\) are indicated by blue circles, those with \( v_{pec} \) between 75 and 150 km s\(^{-1}\) are indicated by green circles, and the other RRLs from Zinn et al. (2020) are indicated by gray crosses. The same bright and metal-deficient RRLs in Figure 6 are indicated by red circles with the number IDs labeled. The orange line in panel (b) indicates the threshold, \( v_p = -400 [\text{Fe/H}] - 300 \), used for selecting disk RRLs by Layden et al. (1996), while the regions enclosed by orange lines in panel (d) indicate the “plume” (center) and the “disk” (right).

0.53 (V338 Pup), 0.60 (V701 Pup), 0.79 (TV Boo), and 0.83 (X Ari) in contrast to 0.39 for our RRL. Nevertheless, the kinematics of all these very metal-poor RRLs, including our target RRL, is consistent with that of similarly metal-deficient stars investigated by Chiba & Beers (2000), who concluded that the disk population is negligible at \( [\text{Fe/H}] \lesssim -2.2 \). In a recent study on a large sample of stars toward the Galactic anticenter, Fernández-Alvar et al. (2021) detected metal-poor stars belonging to the thin disk well down to \( [\text{Fe/H}] \simeq -2 \) but the situation of more metal-deficient stars was not conclusive.

Figure 7(d) plots \( E_{tot} \) against \( L_Z \). Zinn et al. (2020) found that, in addition to RRLs that may be related to moving groups like the Helmi stream (Helmi et al. 1999), there are two major groups, i.e., “disk” RRLs with prograde rotation and “plume” RRLs with \( L_Z \sim 0 \). These two groups of RRLs were also found by Prudil et al. (2020) and Iorio & Belokurov (2021). The plume structure of halo stars was discovered by Dinescu (2002), and recent studies based on Gaia data have identified the very prominent feature called Gaia Enceladus or the Gaia Sausage (Belokurov et al. 2018; Helmi et al. 2018). This prominent feature is considered to originate from an accreted galaxy that contributed many halo objects, including globular clusters such as \( \omega \) Cen, after a major merger with the Milky Way (Belokurov et al. 2018; Helmi et al. 2018). Zinn et al. (2020) found that plume RRLs include fewer objects with \([\text{Fe/H}] < -2\), and, among the eight highlighted objects, UY Boo (No. 6) is the only one located within the plume region in Figure 7(d).

Our RRL does not belong to the plume but is associated with, or at least closer to, the disk populations as discussed above. There are accumulating reports and discussions on the presence of metal-deficient stars in the thick disk (Di Matteo et al. 2020; Sestito et al. 2020; Limberg et al. 2021). The latter two groups of authors used large samples of more than 1000 candidates of metal-deficient stars and found a limited but significant fraction of stars with disk orbits \( (z_{max} < 3 \) kpc and \( 6 \lesssim r_{max} \lesssim 13 \) kpc) and low metallicity \( ([\text{Fe/H}] < -2.5) \). Our target RRL may belong to the same population. There are a few scenarios to explain the metal-deficient disk population (see, e.g., Sestito et al. 2020). Such a population could have composed the ancient disk of the Galaxy before the severe merger that created the plume structure (or the Gaia Sausage/Enceladus) around 10 Gyr ago. The formation of the stars contributing to the ancient disk may be in situ (within the preexistent disk) or external. Alternatively, metal-deficient stars with external origins could be quietly merged into the Galactic thick disk even after the severe merger (Gómez et al. 2017; Karademir et al. 2019). If membership to the thick disk is confirmed, the target RRL would be a unique object representing the population of the metal-deficient thick disk.
Otherwise, the target may be giving a hint as to the contamination of halo stars into the disk population.

5. Concluding Remarks

We have presented photometric and spectroscopic analyses on an RRL, KISOJ 201241.60+321242.4 or HD 331986, located in the Galactic plane at 1 kpc from the Sun. Although this star was found to be an RRL by some previous surveys and is bright (V ∼ 11.3), no study has investigated its detailed characteristics. We confirmed its classification as an RRC-type variable and discovered that it is a very metal-poor star. The near-infrared spectrum taken with the WINERED spectrograph covering 0.9–1.35 μm shows only hydrogen lines and no metallic lines. We estimated the upper limit of metallicity to be [Fe/H] = −2.5. This upper limit is consistent with the metallicity inferred from the PLZ relation, although there remains a large uncertainty, ~0.5 dex, in the latter estimate. We conclude that the object is among the known RRLs with the lowest metallicities, around ∼−3.0 to −2.5 dex (Hansen et al. 2011; Crestani et al. 2021a).

This RRL is located within the thick disk and its kinematics is consistent with that of thick-disk objects, which makes it an even more interesting object. While RRLs with [Fe/H] < −1 tend to have disk orbits (Layden 1995; Layden et al. 1996; Prudil et al. 2020; Zinn et al. 2020), metal-deficient RRLs have been regarded as halo objects. Recent studies (e.g., Sestito et al. 2020; Limberg et al. 2021) have found metal-deficient stars (but not RRLs) in the thick disk, which has a large impact on our understanding of Galactic formation. Finding the origin of the target RRL would give an essential insight into the early history of the Galaxy.

Detailed elemental abundances are crucial for disclosing the origins of stars. However, without any metallic lines detected, we have no clues to the abundance pattern of the target. It is of vital importance to make follow-up spectroscopic observations in the optical range, in which much stronger lines of various elements are present (e.g., Hansen et al. 2011; Crestani et al. 2021b). The origin of our target may be revealed by comparing its abundance pattern with those of RRLs and other stars with similarly low metallicity in different groups including the halo and the thick disk. Furthermore, the census of RRLs in the Galactic plane region has been limited, and future surveys including Gaia observations would reveal more metal-deficient RRLs that are constrained in the disk. A larger sample of such objects and follow-up observations would enable us to understand the initial environment and formation of the ancient Galactic disk.

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Software: AGAMA (Vasilevly 2019), IRAF (Tody 1986, 1993), MOOG (1990 November version; Sneden et al. 2012), WINERED pipeline (S. Hamano et al. 2021, in preparation).

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