CU COMAE: A NEW FIELD DOUBLE-MODE RR LYRAE VARIABLE, THE MOST METAL-POOR DISCOVERED TO DATE

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ABSTRACT

We report the discovery of a new double-mode RR Lyrae variable (RRd) in the field of our Galaxy: CU Comae. CU Com is the sixth such RRd identified to date and is the most metal-poor RRd ever detected. Based on $BV$ CCD photometry spanning 11 years of observations, we find that CU Com has periods $P_0 = 0.5441641$ days ($\pm 0.0000049$) and $P_1 = 0.4057605$ days ($\pm 0.0000018$). The amplitude of the primary (first overtone) period of CU Com is about twice the amplitude of the secondary (fundamental) period. The combination of the fundamental period of pulsation $P_0$ and the period ratio of $P_1/P_0 = 0.7457$ places the variable on the metal-poor side of the Petersen diagram, in the region occupied by M68 and M15 RRd's. A mass of 0.83 $M_\odot$ is estimated for CU Com using an updated theoretical calibration of the Petersen diagram. High-resolution spectroscopy ($R = 30,000$) covering the full pulsation cycle of CU Com was obtained with the 2.7 m telescope of the McDonald Observatory and has been used to build up the radial velocity curve of the variable. An abundance analysis performed on the four spectra taken near minimum light ($0.54 < \phi < 0.71$) confirms the metal-poor nature of CU Com, for which we derive $[\text{Fe/H}] = -2.38 \pm 0.20$. This value places this new RRd at the extreme metal-poor edge of the metallicity distribution of the RR Lyrae variables in our Galaxy.

Key words: stars: abundances — stars: fundamental parameters — stars: horizontal-branch — stars: individual (CU Comae) — stars: oscillations — stars: variables: other

1. INTRODUCTION

Double-mode RR Lyrae variable stars (RRd's) play a fundamental role in astrophysics because they can be used to estimate the mass and the mass-metallicity relation of horizontal-branch stars, and because they can provide information on the direction and rate of evolution across the horizontal branch. RRd's are variables that pulsate in both the fundamental and first-overtone radial pulsation modes. The evolutionary interpretation of the double-mode phenomenon suggests that these stars are changing their pulsation mode while evolving across the RR Lyrae instability strip. The mixing of the two pulsation modes produces cycle-to-cycle amplitude changes and a large scatter in the observed light curves, much larger than accounted for by observational errors alone.

First discovered in 1977 (AQ Leo; Jerzykiewicz & Wenzel 1977), about 40 RRd's have been detected so far in a number of globular clusters of our Galaxy (e.g., M15, $[\text{Fe/H}] = -2.12$; M68, $[\text{Fe/H}] = -1.99$; IC 4499, $[\text{Fe/H}] = -1.26$ on the Carretta & Gratton 1997, hereafter CG97, metallicity scale). Less than a hundred are hosted in dwarf spheroidal (Draco, $[\text{Fe/H}] = -2.0$; Sculptor, $[\text{Fe/H}] = -1.8$; from Mateo 1998) and irregular galaxies of the Local Group; in particular, 73 double-mode RR Lyrae stars have recently been detected by the MACHO experiment (Alcock et al. 1997) in the Large Magellanic Cloud (LMC). However, double-mode RR Lyrae stars seem to be rather rare in the field of our Galaxy, where only five RRd's have previously been detected (Jerzykiewicz & Wenzel 1977; Clement, Kinman, & Sunzteff 1991; Garcia-Melendo & Clement 1997; Moskalik 2000). All of the double-mode RR Lyrae variables have been so far generally found in metal-poor stellar systems ($[\text{Fe/H}] \lesssim -1.3$ dex, CG97 scale, or $-1.5$ dex, Zinn & West 1984 scale). The metal abundance estimated by Clement et al. (1991) for three of the five Galactic RRd's known so far ($-1.81$, $-1.90$, $-1.91$ for AQ Leo, RR VIII-58, and RR VIII-10, respectively, on the Zinn & West 1984 scale) confirms this finding. However, since the metallicity distribution of the RR Lyrae variables in the Galaxy extends to metal abundances both much lower and much higher than in globular clusters, it is very important to identify RRd's among the field RR Lyrae population in order to test the mass-metallicity distribution on a much wider metallicity interval. Applying the $\Delta S$ method (Preston 1959) to low-resolution spectroscopic observations of RRd's in the bar of the LMC, Bragaglia et al. (2000) inferred metallicities in the range $-1.09$ to $-1.78$ dex and found that the LMC field RRd's do not show any systematic difference in the derived masses with respect to the Galactic cluster double-mode pulsators. However, with so few RRd stars identified in the field of our Galaxy, it is not possible to assess whether Galactic field and cluster RRd's actually
behave alike in the mass-metallicity plane. The discovery of any new Galactic field RRd helps set important constraints on the mass-metallicity distribution; the discovery of this particular extremely metal-poor RRd also sets a new boundary condition.

In this paper, we present results based on new photometric data for the RR Lyrae variable CU Comae taken from 1995 to 1999, combined with published photometry of this object taken from 1989 to 1994 (Clementini et al. 1995b), together with high-resolution spectroscopy obtained in 1999 that covers an entire pulsation cycle. Section 2 presents the observations and data sets. In § 3, we give our results from the analysis of the entire photometric data set of CU Com (467 V, 172 B, and 167 I data points), which spans 11 years of observations. In § 4, we report the results of our spectroscopic analyses. We have both derived a radial velocity curve of the full pulsation cycle (§ 4.1) and performed an elemental abundance analysis of the spectra of CU Com taken near minimum light (§ 4.2). In § 5, we estimate the mass of CU Com using a new theoretical calibration of the Petersen diagram (Petersen 1973), summarize the main derived quantities of CU Com, and discuss the impact of this new discovery on both the mass-metallicity distribution and the evolutionary interpretation of the double-mode pulsation for RR Lyrae variables.

2. OBSERVATIONS AND REDUCTIONS

In the fourth edition of the General Catalogue of Variable Stars (GCVS4, Kholopov et al. 1985), CU Com (x = 12h24m47s, δ = 22°24′29″, J2000.0) is classified as an ab-type RR Lyrae variable with P = 0.416091 days and amplitude of the photographic light variation of 0.5 mag. Clementini et al. (1995b) presented observations of CU Com taken during the years 1989–1994. Their V light curve (121 data points) has a sinusoidal shape (see their Fig. 3b) reminiscent of a c-type pulsator; however, the region around maximum light is split into two separate branches about 0.15 mag apart. They also derived a shorter period of P = 0.405749 days and a larger (V) amplitude of 0.58 mag compared with the GCVS4 values. The irregular nature of the CU Com light curve is confirmed by the much less sampled photometry of Schmidt, Chab, & Reiswig (1995, 26 data points; see their Fig. 2). However, neither the Clementini et al. (1995b) nor the Schmidt et al. (1995) photometry was sufficient to address the issue of whether CU Com was exhibiting double-mode or non–radial mode pulsation (Olech et al. 1999), or whether it might be affected by the Blazhko effect (Blazhko 1907).

A new observing campaign was conducted on CU Com from 1995 to 1999, collecting data on several consecutive nights of each run and in two to three runs about 1 month apart, to test the possibility both of double-mode or non–radial mode pulsation (which both are known to occur on cycle-to-cycle timescales) and of the Blazhko effect (whose periodic modulation of the light curve typically has timescales of tens of days). Moreover, during the 1999 campaign, coordinated observations at the 1.52 m telescope of the Osservatorio Astronomico di Bologna and at the Southwestern University; they were organized to obtain continuous photometry with time coverage longer than 12–16 hours. High-resolution spectroscopy was also secured in order to check whether CU Com might be the component of a spectroscopic binary system, to obtain its radial velocity curve, and to perform an abundance analysis of the variable. Uneven weather conditions at the various sites prevented us from getting long-span photometric observing nights; however, we succeeded in obtaining simultaneous photometry and spectroscopy with the 40 cm Southwestern University and the 2.7 m McDonald telescopes, on the night of 1999 February 12.

2.1. Photometry

The new photometric observations of CU Com were obtained over 21 nights from 1995 March to 1999 April. They consist essentially of BV I CCD observations in the Johnson-Cousins system obtained with the Loiano 1.52 m telescope operated by the Osservatorio Astronomico di Bologna and are complemented by 17 V and eight B frames obtained with the Southwestern University 40 cm. The journal of the new photometric observations is given in Table 1.

The photometric data were tied to the Johnson-Cousins system obtained with the Loiano 1.52 m telescope operated by the Osservatorio Astronomico di Bologna and are complemented by 17 V and eight B frames obtained with the Southwestern University 40 cm. The journal of the new photometric observations is given in Table 1. Observations at the 1.52 m telescope were obtained with two different instrumental setups, (1) with an RCA CCD for direct imaging having a 4.3 × 2.7 arcmin² field of view and a 0.5 pixel⁻¹ scale, and (2) with BFOSC (Bologna Faint Object Spectrograph and Camera) equipped with a Thomson 1K × 1K CCD with 0.5 pixel⁻¹ scale, giving a field of view of 9.6 × 9.6 arcmin². A filter wheel for the Johnson-Cousins photometric system was used with both setups. A 2.3 × 2.8 arcmin² CCD image of the CU Com field is shown in Figure 1. Four stars besides CU Com are marked on the image. These are nonvariable objects that were used as reference stars. The light curve of CU Com is derived in terms of differential magnitude with respect to these comparison stars (whose constancy has been accurately checked); hence, no concern arises when observations were performed in conditions that were not strictly photometric. Observations at the 40 cm Southwestern University telescope were obtained using standard Johnson B and V filters and a Pictor 416XT CCD camera coupled to a Celestron f/6.3 focal reducer. This configuration gives a scale of 0.8 pixel⁻¹, resulting in a 7.4 × 10.1 arcmin² field of view. Data were prereduced, and instrumental magnitudes of the variable and its comparison stars were derived by direct photon counting using standard routines for aperture photometry in IRAF. The photometric data were tied to the standard photometric system through observation of 35 standard stars selected from Landolt (1983, 1992).

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| TABLE 1 |
| --- |
| **NEW PHOTOMETRIC OBSERVATIONS** |

| YEAR   | B   | V   | I   | OBSERVED INTERVAL (HJD − 2,400,000) |
|--------|-----|-----|-----|-----------------------------------|
| 1995   | 8   | 16  | 7   | 49,789–49,846                     |
| 1996   | 23  | 21  | 22  | 50,130–50,195                     |
| 1997   | 14  | 27  | 16  | 50,550–50,551                     |
| 1998   | 1   | 1   |     | 50,842                            |
| 1999   | 126 | 281 | 113 | 51,220–51,301                     |
| Total  | 172 | 346 | 158 |                                   |
Table 2

| Star | N_GSC  | V     | B     | I     |
|------|--------|-------|-------|-------|
| C1... | 0144701247 | 14.08 ± 0.03 | 14.89 ± 0.03 | 13.19 ± 0.04 |
| C2... | 0144700851 | 15.27 ± 0.03 | 15.88 ± 0.03 | 14.62 ± 0.04 |
| C3... | 0144701207 | 15.12 ± 0.03 | 15.80 ± 0.03 | 14.40 ± 0.04 |
| C4... | 0144701193 | 14.60 ± 0.03 | 15.31 ± 0.03 | 13.87 ± 0.04 |

Calibrated magnitudes of the four comparison stars are given in Table 2. Comparison stars are identified in the second column of the table by their numbers in the 1.2 version of the Hubble Space Telescope Guide Star Catalog. Within the quoted photometric uncertainty, the V magnitude of star C1 given in Table 2 agrees with the value published by Clementini et al. (1995b); however, the present value, being the average of several measurements obtained in four independent calibration nights, supersedes the 1995 estimate. The B, V, and I magnitudes of CU Com relative to the primary comparison star C1 are listed in Table 3 along with the Heliocentric Julian Date at midexposure. Only data corresponding to the first night of observations of the 1995–1999 span are listed in the table. According to the errors quoted in Table 2, we estimate that the photometric accuracy of each individual data point is ±0.03 mag in V and B, and ±0.04 mag in I. For sake of homogeneity, instrumental magnitudes of CU Com and of its comparison stars in the 1989–1994 data published by Clementini et al. (1995b) were all remeasured in order to reduce any systematic effect that might arise in the analysis of the photometric data from inhomogeneities in the magnitude measuring procedure.

2.2. Spectroscopy

CU Com is the first double-mode RR Lyrae variable for which high-resolution spectroscopy is available. Fifteen spectra evenly covering the full pulsation cycle of CU Com were obtained with the cross-dispersed echelle spectrometer at the coude f/32.5 focus of the 2.7 m Harlan J. Smith Telescope at the McDonald Observatory in west Texas during the nights of 1999 February 12 and 13. Seeing conditions during the nights varied from 1′5 to 2′7. Exposures of a ThAr lamp were taken at beginning, middle, and end of each night, in order to secure the absolute wavelength cali-

Fig. 1.—A 2.3 × 2.8 arcmin² CCD image of the CU Com field. The four stars marked besides CU Com are nonvariable objects that were used as reference stars to obtain differential measurements of the magnitude variation of CU Com.
vation. Observations of the radial velocity standard star HD 58923 \((RV = +17.8 \text{ km s}^{-1}\); Wilson 1953) were also obtained in order to use them during the cross-correlation measure of the radial velocities of CU Com and to set the radial velocity zero point.

The “2dcoudé” spectrograph (Tull et al. 1995) was operated using the E2 echelle grating (52.6759 grooves mm\(^{-1}\) with a blaze angle of 65°293), which yields a 2 pixel resolving power at the CCD of \(R = \lambda/\Delta \lambda = 63,000\). Our wavelength coverage extended from 3670 to 9900 Å (with interorder gaps in wavelength coverage redward of 5600 Å), with the data from about 4400 to 5300 Å and from 3924 to 8465 Å used in the radial velocity and metallicity determinations, respectively.

Given the faintness of our target \((\langle V \rangle \sim 13.3 \text{ and } V_{\text{min}} \sim 13.6 \text{ mag})\) and the severe constraints on the exposure length (exposures of CU Com could not exceed 20–30 minutes, in order to avoid phase blurring on the pulsation cycle of this short-period variable star), we used a 1010 μm slit (which projects to 2° on the sky) and performed a 2 × 2 binning during the readout of the CCD in order to increase the signal-to-noise ratio. The FWHM measured from the ThAr comparison lamp lines is \(\sim 0.2\) Å. The data were taken on a 2048 \(\times\) 2048 thinned, grade 1 Tektronix CCD.

Data were reduced using standard IRAF processing tools to correct and calibrate for various detector effects. The overscan region of each image was used to determine the bias level to subtract from each frame. We then trimmed the overscan region from the individual images. Identification of the locations of “bad” pixels was made by means of long-exposure dark frames, as well as flat-field frames. Bad-pixel values were replaced using interpolated values from neighboring pixels. We then divided the stellar and comparison lamp spectra by a scaled “flat-field” image (comprising 20 spectra taken with a quartz lamp through a blue-pass filter) in order to correct for the relative differences in pixel response of the detector. The minimum order separation was 10°, leaving sufficient interorder background free of contamination from starlight in order to adequately remove the (small) scattered-light contribution. Cosmic-ray excision was performed using LINECLEAN.

We extracted the flux in the individual orders of the two-dimensional data to obtain one-dimensional summed spectra of the stellar and comparison lamp spectra. Using the ThAr comparison lamp emission spectra, we determined and applied the dispersion relation to the stellar spectra, interpolating in time over shifts in the comparison line positions on the chip through the course of a night. We verified that the resulting wavelength solutions gave correct positions of known atmospheric emission and absorption features on each spectrum. Geocentric and Heliocentric Julian Dates were computed and the information implanted in the file headers. The information was then used to compute the corrections to the observed radial velocity due to the diurnal, monthly, and yearly motions.

3. ANALYSIS OF THE PHOTOMETRIC DATA

Using the differential photometry of CU Com with respect to the reference star C1 and the full 1989–1999 data set (the present new photometry together with that of Clementini et al. 1995b), we performed a period search with GRATIS (graphical analyzer time series), a code being developed at the Osservatorio Astronomico di Bologna that employs two different algorithms: (1) a Lomb periodogram (Lomb 1976; Scargle 1982) and (2) a best fit of the data with a truncated Fourier series (Barning 1963). The adopted period search procedure was to perform the Lomb analysis on a wide period interval first and then to use the Fourier algorithm to refine the period definition and find the best-fitting model. The period search employed each of the complete \(B, V,\) and \(I\) data sets. Figure 2 shows the periodograms of the CU Com \(V, B,\) and \(I\) data obtained using the Lomb algorithm to identify the most probable frequency of the data on a wide period interval of 0.2–0.7 days. The highest peaks at \(\omega = 2.46\) (\(P \sim 0.406\) days) correspond to the primary periodicity of the data; the two lower peaks at \(\omega = 1.46\) and \(\omega = 3.46\) are aliases of the primary periodicity, while the peaks at \(\omega = 1.84\) are the signature of a second periodicity present in the data.

We then reduced the interval around the primary periodicity using the Fourier algorithm to find the best fit. The period obtained using a three-harmonic best-fitting Fourier series on the \(V\) data and a two-harmonic series on the \(B\) and \(I\) data is \(P = 0.405759 \pm 0.000001\) days. Shown in Figure 3 are the \(V, B,\) and \(I\) light curves of CU Com obtained by phasing the data according to this periodicity, together with the best-fitting models. Filled circles mark data obtained with the 40 cm Southwestern University telescope.

The rms deviation from the best-fitting model is \(\pm 0.083\) mag in \(V, \pm 0.109\) mag in \(B,\) and \(\pm 0.056\) in \(I\). These residuals are much larger than expected from observational errors alone (\(\pm 0.03\) mag in \(V\) and \(B,\) and \(\pm 0.04\) mag in \(I\)) and provide us with clues that a second periodicity may be present in the data. The amplitude of the light variation ranges from 0.63 to 0.30 mag in \(V,\) from 0.82 to 0.45 in \(B,\) and from 0.41 to 0.20 in \(I.\) Data corresponding to consecutive nights show that the amplitude variation takes place on a cycle-to-cycle

![Figure 2](image-url)
timescale (see Di Tomaso 2000 for details). This occurrence definitely rules out the Blazhko effect as an explanation of the irregular behavior of CU Com. Since the residuals and amplitude of the light variation of CU Com cannot be described by a single periodicity, and the variation occurs on cycle-to-cycle basis, we proceeded to look for a second periodicity in the data on timescales of the order of 1 day. Data were prewhitened using the best-fitting models in Figure 3, and a new period search was performed on the residuals with respect to the models. Figure 4 shows the periodograms of the residuals of the V, B, and I data obtained from the Lomb algorithm on a wide period interval of 0.1–0.9 days. Strong peaks are present at ω = 1.84 (P ∼ 0.54 days) in all the three periodograms, which clearly mark the secondary periodicity present in the data of CU Com. We further refined the secondary period by restricting the period search interval and using a three-harmonic best-fitting Fourier series in V and a two-harmonic model in B and I and then performed an iterative refinement of both primary and secondary periodicities. At the end of the trial procedure (conducted on the V, B, and I data independently), the final adopted periodicities of CU Com were P₁ = 0.4057605 ± 0.0000018 days and P₀ = 0.5441641 ± 0.0000049 days. We also conducted another independent period search on the CU Com V data set using the date-compensated discrete Fourier transform algorithm (DCDFT; Ferraz-Mello 1981) and the CLEANest routine (Foster 1995). Its results (P₁ = 0.405760 ± 0.000001 days and P₀ = 0.544166 ± 0.000003 days with DCDFT; P₁ = 0.405761 ± 0.000001 days and P₀ = 0.544164 ± 0.000003 days with CLEANest) fully confirm the periodicities found by the GRATIS algorithms.

The ratio of the first to second period of CU Com is P₁/P₀ = 0.745658 ± 0.000007, which is a typical value for double-mode RR Lyrae stars. The top panels of Figures 5, 6, and 7 show the V, B, and I light curves of CU Com phased according to the primary (first overtone) period of pulsation P₁ = 0.4057605 days and the epoch of maximum light E = HJD 2,450,142.5860390. The middle panels give the light curves of the primary period after prewhitening of the secondary (fundamental) period P₀ = 0.5441641 days, and the bottom panels show the light curves of the secondary period after prewhitening of the primary periodicity. The rms deviations of the best-fitting models of the prewhitened data (Figs. 5b, 6b, and 7b) are about halved with
respect to the original data (0.049 mag in \( V \), 0.069 in \( B \), and 0.034 in \( I \)). The amplitudes of the primary variation are 0.43, 0.55, and 0.27 mag in \( V \), \( B \), and \( I \), respectively, and the corresponding amplitudes of the secondary (fundamental) variation are 0.22, 0.25, and 0.14 mag. Since the quoted photometric errors, we investigated whether a third periodicity might be present in the data. Indeed, several low peaks around 0.233 days were found. Inclusion of a third period (which is the average of the third periodicities that are the average of the \( P_0 \) and \( P_2 \) values found from each of the three data sets independently (0.047 mag in \( V \), 0.065 in \( B \), and 0.034 in \( I \)).

On the other hand, these “large” residuals might partially be caused by the lower accuracy of some of the photometric data (particularly data obtained in full Moon nights with very poor seeing conditions). In order to investigate this possibility further, we restricted the analysis to the data for which the difference between comparison stars (C1 and C4, in particular) remained constant within \( \pm 0.03 \) mag, which is the typical photometric error both in \( V \) and \( B \). The data set was thus restricted to 378, 116, and 134 data points in \( V \), \( B \), and \( I \), respectively. While periodicities found with this data subset fully confirm the results obtained with the complete data set, the residuals are indeed slightly reduced (0.043 mag in \( V \), 0.067 in \( B \), and 0.031 in \( I \)). A search for a third periodicity was conducted also on this small data set. Again, several low peaks around 0.233 days were found. While inclusion of a third periodicity (which is the average of the \( P \)-values found from the \( V \), \( B \), and \( I \) data independently) in the analysis of the data reduces the residuals to the fit to 0.38 mag in \( V \), 0.059 in \( B \), and 0.025 mag in \( I \). However, the patterns of the peaks in the 0.233 day area are somewhat confused. Overall, this third periodicity is not very strongly supported by the data.

### 4. Analysis of the Spectroscopic Data

#### 4.1. Radial Velocity Curve

Radial velocities were measured from the reduced wavelength-calibrated spectra of CU Com using a cross-correlation technique (FXCOR in IRAF). Twelve orders containing weak metal lines (the best suited to measure radial velocities) in the spectra of CU Com were cross-correlated against the same orders in the spectra of the radial velocity standard star HD 58923. Table 4 lists the derived heliocentric radial velocities of CU Com and corresponding errors, along with the heliocentric phases of the spectra, computed according to the final adopted primary period of pulsation and the epoch of CU Com (\( P_1 = 0.4057605 \) days and \( E = \) HJD 2,450,142.5860390). Neither splitting of lines nor double cross-correlation peaks were

### Table 4

| Spectrum (2,400,000+) | HJD 2,450,142.5860390 | RV (km s\(^{-1}\)) | Error (km s\(^{-1}\)) |
|----------------------|-----------------------|-------------------|---------------------|
| W1       | 51,222.750103         | 0.073             | -69.94              | 3.97                |
| W2       | 51,222.765833         | 0.112             | -69.96              | 2.94                |
| W3       | 51,222.780487         | 0.148             | -69.17              | 3.75                |
| W4       | 51,222.795855         | 0.192             | -67.37              | 3.54                |
| W5       | 51,222.820304         | 0.246             | -61.83              | 2.90                |
| W6       | 51,222.841913         | 0.299             | -58.99              | 1.84                |
| W7       | 51,222.868628         | 0.365             | -54.85              | 2.94                |
| W8       | 51,222.892935         | 0.425             | -50.24              | 3.77                |
| W9       | 51,222.916663         | 0.483             | -48.41              | 4.45                |
| W10      | 51,222.938504         | 0.537             | -44.14              | 3.71                |
| W11      | 51,222.961503         | 0.594             | -41.50              | 2.14                |
| W12      | 51,222.983263         | 0.647             | -39.62              | 1.99                |
| W13      | 51,223.009931         | 0.713             | -37.96              | 2.64                |
| W14      | 51,223.894986         | 0.895             | -56.13              | 2.56                |
| W15      | 51,223.907752         | 0.931             | -63.12              | 4.68                |
observed, which would otherwise provide a hint of a spectroscopic binary system. Errors in the measured radial velocities of CU Com (see last column of Table 4) are larger than found for two other RR Lyrae stars observed in the same observing run (CM Leo and BS Com, an RRc and an RRab, respectively). These slightly large uncertainties (typical errors of 3 instead of 2 km s\(^{-1}\), despite CU Com’s being about a half-magnitude brighter than CM Leo) can be attributed to the extremely low metal abundance of the star (see § 4.2). The bottom panel of Figure 8 shows the radial velocity curve of CU Com obtained by phasing the data according to its primary period of pulsation, while the top panel shows the simultaneous \(V\) light curve obtained with the 40 cm Southwestern University telescope. The shape and amplitude of the radial velocity curve (\(A_{V} = 32.73\) km s\(^{-1}\)) are typical of a c-type pulsator. The systemic velocity \(\gamma\) of CU Com was calculated by integration of the radial velocity curve on the full pulsation cycle and corresponds to \(-54.13\) km s\(^{-1}\).

### 4.2. Metallicity of CU Com

Four spectra of CU Com taken at or near the minimum light (0.54 < \(\phi\) < 0.71) were used to measure the metal abundance of the variable from the following line analysis procedure.

First we derived the effective temperature \(T_{\text{eff}}\) from the dereddened \(B - V\) and \(V - I\) colors of CU Com at minimum light. A reddening value of \(E(B - V) = 0.023\) mag was estimated for CU Com from Schlegel, Finkbeiner, & Davis (1998) reddening maps. Table 5 lists the dereddened \(B - V\) and \(V - I\) photometric colors corresponding to the four exposures of CU Com close to minimum light, derived from the \(B\) and \(V\) light curves simultaneous with the spectroscopic data and from the total \(I\) light curve (since no simultaneous \(I\) photometry is available), along with the corresponding temperatures as estimated using the color-temperature calibration and procedure of Clementini et al. (1995a). The average photometric temperature we derive is \(T_{\text{eff}} = 6286 \pm 112\) K, where according to Clementini et al. (1995a; see their § 3.4.2) the mean temperature derived from individual \((B - V)_{\text{b}}\)'s was lowered by 49 K, and that from the \((V - I)_{\text{b}}\)'s was lowered by 97 K, before averaging them together, to tie them to the \((V - K)\)-temperature calibration for RR Lyrae stars, since this calibration is not affected by the discrepancy between synthetic (Kurucz 1993a, 1993b) and observed colors (see Fig. 3 of Clementini et al. 1995a) and it is less metallicity dependent (see Fernley 1989 and references therein). Within the errors, there is no difference between the mean temperature estimated using colors at minimum light derived from the total \(B\), \(V\), and \(I\) light curves and the temperature obtained from the simultaneous photometry.

As an alternative approach, temperatures were also estimated by fitting the profile of the H\(\beta\) line (the Hz profile is usually used in this technique but was not observed with the adopted wavelength setup) in the four spectra. We devised the following effective technique to remove the characteristic wavelength response induced by the echelle blaze function: a pseudo-flat-fielding was obtained by dividing the spectrum of the order including H\(\beta\) by the average of the two adjacent orders (this division was made using the pixel values, ignoring the wavelength calibration); before this division was made, cosmic rays and strong absorption lines (other than H\(\beta\)) were excised, and the spectra of the adjacent orders were Gaussian-smoothed with a FWHM of 1 Å. This procedure works quite well because the instrumental response has no strong wavelength dependence other than the echelle blaze function. The continuum was traced far from the center of H\(\beta\) and normalized to a value of unity, and the H\(\beta\) feature and surrounding regions were then compared with line profiles obtained following the precepts described in Castelli, Gratton, & Kurucz (1997).

![Fig. 8. Radial velocity curve (bottom) and simultaneous V light curve of CU Com (top), obtained with the 2.7 m McDonald telescope and the 40 cm of the Southwestern University, respectively.](image-url)

Table 5: Temperatures Derived from CU Comae Dereddened Colors at Minimum Light

| Spectrum | \(\phi\) | \((B - V)_{\text{b}}\) | \((V - I)_{\text{b}}\) | \((B - V)_{\text{I}}\) | \((V - I)_{\text{I}}\) |
|----------|---------|----------------|----------------|----------------|----------------|
| W10...... | 0.537   | 0.369          | 0.495          | 6305          | 6550          |
| W11...... | 0.594   | 0.400          | 0.506          | 6130          | 6513          |
| W12...... | 0.647   | 0.411          | 0.525          | 6070          | 6448          |
| W13...... | 0.713   | 0.355          | 0.519          | 6385          | 6470          |

Figure 9 shows the result of this comparison obtained using the Kurucz (1993a, 1993b) model atmospheres, with the overshooting option switched on (these models are used for consistency with the analysis of Clementini et al. 1995a; temperatures obtained with the Kurucz model atmospheres without overshooting are lower by about 250 K). The average spectroscopic temperature we obtained for the four spectra taken close to minimum light is \(6400 \pm 150\) K. Within their quoted uncertainties, photometric and spectroscopic temperatures agree well. The temperature from H\(\beta\) is about 100 K higher than the photometric one. Adopting the photometric temperature in our analysis permits us to stay on the same scale of Clementini et al. (1995a), so that the new abundances can be directly compared with those, and avoids any lingering doubts about the effectiveness with which we determined the continuum region near H\(\beta\). Furthermore, the photometric temperature is less sensitive to...
Comparison of the observed Hβ line profiles and synthetic spectra computed using Kurucz (1993a, 1993b) model atmospheres, with the overshooting option switched on (see text). Labels indicate the spectra according to their identification in Table 5. The average temperature we obtained for the four spectra taken close to minimum light is $6400 \pm 150$ K.

We then summed the four individual spectra (after excision of the cosmic rays and shift to zero radial velocity). The co-added spectrum was convolved with a Gaussian having a FWHM of 0.3 Å to enhance the signal-to-noise ratio and allow us to measure faint, unsaturated lines with confidence. Finally, we measured equivalent widths of 15 Fe i and eight Fe II lines on the co-added spectrum. Table 6 gives the line list, the assumed $\log gf$'s, and the corresponding equivalent widths we measured. A full discussion of the reliability of these adopted atomic parameters to determine abundances of RR Lyrae variable stars can be found in § 4.1.1 of Clementini et al. (1995a).

We obtained average abundances of $[\text{Fe/H}] = -2.35 \pm 0.026$ (with $\sigma = 0.10$ dex) from the Fe i lines and $[\text{Fe/H}] = -2.40 \pm 0.028$ (with $\sigma = 0.08$ dex) from the Fe ii lines, using a stellar atmosphere model with the following parameters: $T_{\text{eff}} = 6286$ K, a surface gravity of $\log g = 3.2$, and a microturbulent velocity of $V_t = 3.5$ km

**TABLE 6**

| Species | $\lambda$ (Å) | EP (eV) | $\log gf$ | EW (Å) | $\log n$ |
|---------|----------------|---------|-----------|--------|---------|
| Fe i... | 4005.24        | 1.56    | -0.57     | 111.10 | 5.28    |
| Fe i... | 4045.81        | 1.49    | -0.22     | 159.10 | 5.23    |
| Fe i... | 4073.74        | 1.61    | -0.02     | 137.50 | 5.23    |
| Fe i... | 4132.06        | 1.61    | -0.63     | 86.10  | 5.03    |
| Fe i... | 4143.87        | 1.56    | -0.44     | 102.70 | 5.03    |
| Fe i... | 4235.95        | 2.43    | -0.34     | 47.90  | 5.06    |
| Fe i... | 4383.56        | 1.49    | 0.20      | 159.50 | 5.13    |
| Fe i... | 4415.13        | 1.61    | -0.61     | 109.40 | 5.28    |
| Fe i... | 4415.13        | 1.61    | -0.61     | 109.40 | 5.28    |

**Note.**—Table 6 is presented in its entirety in the electronic edition of the Astronomical Journal. A portion is shown here for guidance regarding its form and content.
of CU Com near the Mg temperature. Figure 10 shows a comparison of the spectrum deduced in the analysis, confirming the adopted photometric strength or excitation or ionization state were easily satisfied (abundance results that show no trends with either line RR Lyrae stars at minimum light (see also Clementini et al. 1995a). These two latter have been shifted vertically for clarity. Note that the iron-group lines in the spectrum of CU Com have strengths similar to those in the spectrum of X Ari and are much weaker than those in ST Boo, in agreement with the metallicity given by our analysis. 

s\(^{-1}\). The model parameters we derived, with the exception of the very low metallicity we find, are typical of c-/d-type RR Lyrae stars at minimum light (see also Clementini et al. 1995a). Standard spectroscopic abundance constraints (abundance results that show no trends with either line strength or excitation or ionization state) were easily satisfied in the analysis, confirming the adopted photometric temperature. Figure 10 shows a comparison of the spectrum of CU Com near the Mg \(b\) lines with analogous spectra for two other RR Lyrae variables (X Ari, [Fe/H] = \(-2.52\); ST Boo, [Fe/H] = \(-1.80\)) from Clementini et al. (1995a). Iron-group lines in the spectrum of CU Com have strengths similar to those in the spectrum of X Ari and are much weaker than those in ST Boo, in agreement with the metallicity given by our analysis. Note that while weak lines in CU Com appear stronger than in X Ari (because of the slightly higher metal abundance), the stronger lines (noticeably the Mg \(b\) ones) are somewhat shallower; this is due to the lower microturbulent velocity of CU Com (an RRd) with respect to X Ari and ST Boo (both RRab's).

Uncertainties in the derived abundances are mainly due to possible errors in the atmospheric parameters (\(+100\,\text{K}\) in \(T_{\text{eff}}\), \(+0.3\) dex in \(\log g\), \(+0.5\,\text{km\,s}^{-1}\) in \(V_r\), and \(+0.2\) dex in [A/H]) and on the adopted model atmospheres (Kurucz 1993a, 1993b). Our estimate of the random error contribution (including errors in measuring individual lines) is 0.13 dex. However, the adopted model atmospheres may contribute an additional 0.15 dex. Thus, our conservative estimate of the metallicity and of the total error for CU Com is [Fe/H] = \(-2.38 \pm 0.20\). This metallicity is on the scale of Clementini et al. (1995a) for RR Lyrae variables. On these same scales X Ari, the most metal-poor RR Lyrae star of any type known so far, has a metal abundance of \(-2.52\) dex, and M15, the most metal-poor globular cluster in which RRd variables have been found, has a metal abundance [Fe/H] = \(-2.15\). CU Com thus becomes the most metal-deficient double-mode RR Lyrae star ever detected.

Table 7 shows the abundance ratios with respect to iron that we derive for a few other elements. As a comparison, in the last column are listed the same abundance ratios as obtained by Clementini et al. (1995a) for X Ari: we find a very similar abundance pattern, namely, an overabundance of \(\alpha\)-elements by about 0.4 dex and a large deficiency of Mn and of Ba. This is the typical abundance pattern for very metal-poor stars ([Fe/H] < \(-2\)). We also obtain a very low Al abundance from the resonance lines, a result shared by other extremely metal-poor stars (Gratton & Sneden 1988).

5. DISCUSSION AND CONCLUSIONS

CU Com is the sixth double-mode RR Lyrae variable identified in the field of our Galaxy. As is true of most of the RRd's known so far, the amplitude of the primary (first overtone) period is about twice the amplitude of the secondary (fundamental) period. Final periods and epoch, as well as the average quantities derived for CU Com from both the photometric and spectroscopic analyses, are given in Table 8. According to the period ratio \(P_1/P_0 = 0.7457\) and the secondary period (\(P_o\)), CU Com falls on the metal-poor side of the Petersen diagram, in the region populated by the M68 and M15 double-mode pulsators (see Fig. 11). This is confirmed by the extremely low metallicity ([Fe/H] = \(-2.38 \pm 0.20\)) derived for CU Com from the abundance analysis of the spectra taken at minimum light, making it the most metal-poor double-mode RR Lyrae known so far.

An estimate for the mass of CU Com has been obtained from the Petersen diagram, following Alcock et al. (1997) and adopting the Bono et al. (1996) theoretical mass calibration. Following the suggestion by Cox (1991) that the inclusion of new opacity evaluations (Rogers & Iglesias 1992) in the computation of pulsation models allows one to reconcile pulsational and evolutionary predictions for the stellar mass of double-mode RR Lyrae stars, Bono et al. (1996) investigated the Petersen diagram predicted for Oosterhoff I and Oosterhoff II cluster pulsators on the basis of their nonlinear convective pulsation models with updated input physics. The properties of these models, as well as the adopted physical and numerical assumptions, are extensively discussed by Bono & Stellingwerf (1994) and Bono et
al. (1996, 1997b, 1997a). The main result found by Bono et al. (1996) was that the Petersen diagram based on nonlinear computations is able to provide valuable constraints on the mass and on the luminosity level of double-mode RR Lyrae variables belonging to Oosterhoff I and Oosterhoff II clusters.

The comparison between the predictions of Bono et al. (1996) and the location of CU Com in the Petersen diagram indicates for this star a mass larger than 0.80 $M_\odot$ (see Fig. 11), placing it among the most massive double-mode RR Lyrae variables. In order to better constrain the “pulsational” mass of CU Com, new sequences of nonlinear models with 0.83 and 0.85 $M_\odot$, respectively, have been computed, using exactly the same code and the same physical inputs as in Bono et al. (1996). The behavior of these new models in the Petersen diagram is shown in Figure 11 (short-dashed and long-dashed lines) for the computed luminosity levels $[\log (L/L_\odot) = 1.72$ and 1.81 for the 0.83 $M_\odot$ model, and only the $[\log (L/L_\odot) = 1.81$ level for the 0.85 $M_\odot$ model]. CU Com, as well as most of the M68 and M15 RRd's, is very well fitted by the new pulsational models, which indicate a mass of $0.830 \pm 0.005 M_\odot$ and a luminosity level close to 1.81. A relation between mass and metallicity was suggested to exist among RRd variables in globular clusters and possibly in the field in our Galaxy, in Local Group dwarf spheroidal, and in the LMC (see discussion in Bragaglia et al. 2000), and CU Com is at the lowest metallicity end. In Figure 11, there are a couple of field RRd stars that are less massive than those in IC 4499; these are NSV 09295 (Garzia-Melendo & Clement 1997; bottommost triangle in Fig. 11) and VIII-58 (Clement et al. 1991). No metal abundance is available for NSV 09295, while according to its metallicity VIII-58 is about 0.4 dex more metal-poor than IC 4499. Given the small number of RRd's in the field of our Galaxy, we think that no firm conclusion can be reached on whether the Galactic field RRd's do or do not follow mass-metallicity relation.

According to the evolutionary models consistent with ours (Cassisi et al. 1998, 1999), a stellar mass of about 0.8 $M_\odot$ is expected to populate the RR Lyrae gap for a metallicity $Z = 0.0001$. Hence, the expected stellar mass populating the RR Lyrae instability strip in metal-poor globular clusters such as M15 and M68 is close to 0.80 $M_\odot$ with a luminosity level between 1.75 and 1.8, depending on the assumed efficiency of element diffusion. Model isochrones by the same authors (Cassisi et al. 1998, 1999) suggest a turnoff age of 11.6 Gyr and a turnoff mass of 0.80 $M_\odot$ for a red giant mass of 0.83 $M_\odot$ (when diffusion and mass loss are neglected) with the typical low metallicities of clusters such as M15.

Taking into account an $\alpha$-enhancement contribution of $\sim 0.4$ dex, which is typical of the lowest metallicity stars in the solar neighborhood and in globular clusters, such as, for instance, M68 (see, e.g., Carney 1996), and which is also shared by CU Com (see § 4.2), and including it in the global metallicity computation following the relation provided by Salaris, Chieffi, & Straniero (1993), one would obtain for these stars a metallicity $Z = 1.5 \times 10^{-4}$. This tiny metallicity increase with respect to $Z = 0.0001$ is not expected to change the results of the pulsation analysis. On the other hand, model isochrones for $Z = 0.0002$ predict an age ranging from 10.9 to 11.2 Gyr, depending on the efficiency of element diffusion, and a turnoff mass of 0.80 $M_\odot$ for a red giant mass of 0.83 $M_\odot$. Indeed, adopting this metallicity Cassisi et al. (1999) estimated an age of 11 $\pm 1$ Gyr for M68. It is also worth noting that the luminosity level of CU Com, of the M68 and M15 RRd's, inferred from the Petersen approach is in good agreement with the evolutionary predictions one may extrapolate, for a mass of $\sim 0.83 M_\odot$, from updated horizontal-branch evolutionary models (Cassisi et al. 1998).

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**TABLE 8**

| Property       | Value          |
|----------------|----------------|
| Type           | RRd            |
| [Fe/H]         | $-2.38 \pm 0.20$ |
| Epoch (HJD)    | 2,450,142.5860390 |
| $P_1$ (days)   | 0.4057605 $\pm 0.0000018$ |
| $P_0$ (days)   | 0.5441641 $\pm 0.0000049$ |
| Mass ($M_\odot$) | $0.830 \pm 0.005$ |
| $\langle V \rangle$ | 13.34 |
| $\langle B \rangle$ | 13.67 |
| $\langle T \rangle$ | 12.88 |
| $\langle V \rangle - \langle B \rangle$ | 0.33 |
| $A_V$ | 0.46 |
| $A_B$ | 0.43 |
| $A_K$ | 0.22 |
| $A_L$ | 0.55 |
| $A_T$ | 0.25 |
| $A_H$ | 0.27 |
| $A_B$ | 0.14 |
| $A_{\nu}$ (km s$^{-1}$) | 32.73 |
| $\gamma$ (km s$^{-1}$) | $-54.13$ |

*Fig. 11.—Position of CU Com on the Petersen diagram. Data shown in the figure are from Walker & Nemec (1996; IC 4499), Walker (1994; M68), Nemec (1985b; M15), Nemec (1985a; Draco), Clement, Ferance, & Simon (1993; AQ Leo, VIII-10, and VIII-58), Garcia-Melendo & Clement (1997; NSV 09295), and Alcock et al. (1997; LMC). Dash-dotted, solid, and dotted lines represent Bono et al. (1996) pulsational models for masses of 0.65, 0.70, and 0.80 $M_\odot$ and log$(L/L_\odot) = 1.72$ (upper portions of the curves) and log$(L/L_\odot) = 1.81$ (lower portions), respectively. The short-dashed and long-dashed lines show our new pulsational models for 0.83 and 0.85 $M_\odot$, respectively. Only the log$(L/L_\odot) = 1.81$ luminosity level is shown in the latter case.*
Thus, if the pulsational masses estimated from Figure 11 are correct, the M68 and M15 RRd's should have masses around 0.83 \( M_\odot \) and luminosities of about \( \log (L/L_\odot) = 1.81 \). This would imply that almost no mass loss occurs during the red giant branch evolution of these very metal-poor cluster stars.

Unfortunately, no firm constraint on the red giant phase mass loss can be inferred from the large pulsational mass of CU Com, because, at variance with the double-mode pulsators in globular clusters, we do not have any information on its age or, hence, on its turnoff mass. However, (1) given the similarity of CU Com's mass to masses of double-mode pulsators in M68 and M15, (2) given its extremely low metal abundance, and (3) given the direct dependence of mass loss upon metal abundance predicted by canonical mass-loss relations such as those by Reimers (1975) and Maeder (1992), it is probable that CU Com has not lost a large amount of mass during its red giant branch evolution.

The synthetic horizontal-branch distributions computed by Rood (1973) first showed the need for an average mass loss of about 0.2 \( M_\odot \) prior to the horizontal-branch phase, coupled with a ~10% dispersion of 0.025 \( M_\odot \), in order to reproduce the color extension of the horizontal branch of metal-poor globular clusters (see also Renzini & Fusi Pecci 1988; Chiosi 1998). Reimers's (1975) empirical formula predicts that the mass loss needed to reproduce the observed horizontal-branch morphologies at \( Z \approx 0.001 \) is obtained for a value of 0.40 ± 0.04 for the mass-loss rate efficiency parameter \( \eta \) (see Renzini & Fusi Pecci 1988). Thus, if the 0.83 \( M_\odot \) we derive for CU Com is correct, its turnoff mass could range from 0.83 \( M_\odot \), in the case of no mass loss, up to 0.93 \( M_\odot \) for an assumed mass loss of 0.1 \( M_\odot \) (a reasonable assumption given the overall uncertainties). Correspondingly, CU Com's age could range from ~10 to 6.5 Gyr, the turnoff ages of a 0.83 and a 0.93 \( M_\odot \) model, respectively, according to Cassisi et al. (1998) at \( Z = 0.0002 \) and including diffusion.

In this framework, the implication of the high mass and low metallicity of CU Com on the evolutionary interpretation of the double-mode phenomenon is that, if its estimated metallicity and mass are correct, CU Com is a massive, overluminous RR Lyrae variable almost as old as M68, sharing the typical \( \alpha \)-element overabundance of very metal-poor stars, which started its horizontal-branch evolution on the very red side of the instability strip and is now moving blueward across the strip while evolving from the \( ab \) to the \( c \) type region.

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