

*Letter to the Editor***Parent stars of extrasolar planets III:  $\rho^1$  Cancri Revisited**Guillermo Gonzalez<sup>1</sup> and Andrew D. Vanture<sup>1,2</sup><sup>1</sup> Astronomy Department, University of Washington, Box 351580, Seattle, WA 98195, USA<sup>2</sup> Science Division, Everett Community College, 801 Wetmore Ave., Everett, WA 98201, USA

Received 31 August 1998/ Accepted 21 September 1998

**Abstract.** New values of the atmospheric parameters of  $\rho^1$  Cnc are derived. From spectroscopic analysis of very high S/N, high resolution spectra, we obtain:  $T_{\text{eff}} = 5250 \pm 70$  K,  $\log g = 4.40 \pm 0.15$  (cgs),  $\xi_t = 0.80 \pm 0.09$  km s<sup>-1</sup>, and  $[\text{Fe}/\text{H}] = 0.45 \pm 0.05$ . This temperature estimate is consistent with other recent determinations by Gonzalez and Fuhrmann et al.

We have also derived CNO abundances and set a new upper limit on the lithium abundance of  $\log \epsilon = 0.50 \pm 0.15$ . From an analysis of the CN bands near 8000 Å, we set a lower limit on the <sup>12</sup>C/<sup>13</sup>C ratio of 30.

**Key words:** stars: abundances – planetary systems**1. Introduction**

Gonzalez (1997, 1998, hereafter Papers I & II) reported the results of spectroscopic analyses of the parent stars of the then known extrasolar planet candidates. The primary finding was that on average the parent stars are metal-rich compared to nearby stars. The results of Papers I & II are generally in agreement with those of other recent studies of these stars, but there remain a few discrepancies. The most serious one concerns  $\rho^1$  Cnc. The temperature estimate of Fuhrmann et al. (1998) differs from that of Paper II by nearly 200 K. The method of temperature determination differs between the two studies. While the standard technique of using Fe I lines with a wide range in lower excitation potential,  $\chi_{\text{low}}$ , is used in Papers I & II to determine  $T_{\text{eff}}$ , Fuhrmann et al. model the H $\alpha$  and H $\beta$  profiles to determine this quantity. Of the 8 stars studied in Paper II,  $\rho^1$  Cnc was the most difficult to analyze and its parameters the most sensitive to changes in the number of lines employed. Fuhrmann et al. encountered difficulties in trying to measure the H $\beta$  profile, which they had measured in their other stars, due the very strong metal lines. So, their temperature estimate is based only on the H $\alpha$  profile, leading to a larger uncertainty compared to their other stars.

Our goal in deriving more accurate values for the atmospheric parameters is to use them to better constrain the location of  $\rho^1$  Cnc in the HR diagram. This, in turn, will lead to a more

accurate determination of its age and mass. Accurate temperatures are essential for deriving reliable age estimates for stars on the lower main sequence, due to the convergence of evolutionary tracks there. As shown graphically by Fuhrmann et al., age estimates for  $\rho^1$  Cnc range from a few Gyr to far beyond the age of the universe! An accurate age estimate will allow us to compare  $\rho^1$  Cnc's metallicity to Galactic chemical evolution predictions, so that we can determine if it really is anomalous. Such comparisons will also help to decide between the two main hypotheses proposed in Papers I & II to account for the high metallicities of these stars: primordial or self-pollution.

For these reasons we have obtained new spectra of  $\rho^1$  Cnc of higher quality than those used in Paper II. In addition, we derive accurate values for the abundances of the CNO elements, set a new limit on the lithium abundance, and set a limit on the <sup>12</sup>C/<sup>13</sup>C ratio for the first time.

**2. Observations**

High quality spectra of  $\rho^1$  Cnc were obtained by David Lambert, Leonid Lyubimkov, and Sergey Rostopchin at our request in Dec. 1997 and by one of us (GG) in June 1998 with the McDonald Observatory 2.7 m telescope equipped with an echelle spectrograph at the coudé focus (Tull et al. 1995), and a 2048x2048 pixel Tektronix CCD. This setup resulted in a resolving power, R, of 64,000 and a S/N ratio of 550 for the 1997 spectrum and R = 68,000, S/N = 300 for the 1998 spectrum at 6500 Å. The spectral coverage is complete between 3700 and 5600 Å, with gaps between orders redward of 5600 Å. The spectrograph settings were slightly different for the two runs, resulting in slightly different spectral coverage beyond 5600 Å. In addition, a spectrum of a high rotation velocity hot star was obtained during the June run for the purpose of removing telluric absorption lines. The procedures followed in reducing the spectra are the same as those described in Paper I.

**3. Analysis***3.1. Method and line selection*

Our method of abundance analysis closely follows that used in Papers I and II. Like them, this analysis is a differential one with respect to the Sun. We employ the Kurucz (1993) model atmospheres; the effective temperature,  $T_{\text{eff}}$ , surface gravity,

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$g$ , and depth-independent microturbulence parameter,  $\xi_t$ , are estimated in the standard way using Fe I and Fe II line equivalent width measurements. The oscillator strengths of the Fe lines are taken from Papers I (Table 1) and II (Table 2) and from a new inverted solar analysis. We used the same solar spectra as employed in Paper I (two spectra of Vesta obtained in July 1996 with the 2.7 m) and also the Kurucz et al. (1984) Solar Flux Atlas. Most of the new lines were measured on all three solar spectra. The differences in the equivalent width values for the same lines in the three spectra lead to a scatter in the derived abundances of about  $\pm 0.02$  dex.

In order to improve on the analysis of  $\rho^1$  Cnc presented in Paper I, we have greatly increased the number of Fe I, Fe II lines used; the results of Paper I for this star were based on only 19 Fe I and 6 Fe II lines. In the present study we employ 49 Fe I and 10 Fe II lines.

New lines were selected based on the following criteria: 1) there must be a “continuum window” within a few Å 2) the line must be isolated or easily deblended both in the spectra of  $\rho^1$  Cnc and the Sun, 3) the equivalent width must be less than about 100 mÅ in both sets of spectra. The Fe I lines in the new list span the range in  $\chi_{\text{low}}$  from 0.09 to 5.02 eV, and the equivalent widths range from 15 to 100 mÅ. The typical absolute value of the differences in the equivalent widths of those lines common to both spectra are 2–7 mÅ (with most being 2–3 mÅ). In addition, we compared the average equivalent widths of several lines from the new spectra to those from an  $R = 180,000$  spectrum of  $\rho^1$  Cnc (with much smaller spectral coverage) used in Paper II to determine  $v \sin i$ ; the average difference in the equivalent widths between these spectra is about 1.5 mÅ. This shows that spectra with  $R \sim 60,000$  are adequate to reliably measure equivalent widths for this star.

### 3.1.1. Model atmosphere selection and Fe abundances

The final model atmosphere parameters were arrived at iteratively, approached slightly differently and conducted independently by each of us (GG and ADV). We employed slightly different versions of the line list (differing by four Fe I lines), yet we arrived at nearly identical solutions. The final parameters fulfill the standard constraints noted earlier for the Fe-line analysis. Plus, we performed a simple check: the standard deviation of the Fe I line-derived abundances must reach a minimum value in the  $T_{\text{eff}}\text{-}\log g$  plane at the same values of  $T_{\text{eff}}$  and  $\log g$  that fulfill the standard constraints. Our final results for  $\rho^1$  Cnc are:  $T_{\text{eff}} = 5250 \pm 70$  K,  $\log g = 4.40 \pm 0.15$ ,  $\xi_t = 0.80 \pm 0.09$  km s $^{-1}$ ,  $[\text{Fe}/\text{H}] = 0.45 \pm 0.03$ . This solution is independent from the analysis of Paper II (note that the  $gf$ -values employed in the two studies for this star are different, but some of the same lines are used). Note that these are formal uncertainties only; to account for possible systematic errors in the zero-point of the metallicity scale relative to the Sun, we adopt  $[\text{Fe}/\text{H}] = 0.45 \pm 0.05$ .

In order to check for possible systematic errors due to non-LTE effects on Fe I lines, we also performed an Fe-line analysis on  $\alpha$  Cen B using the equivalent width measurements of Neu-

forge & Magain (1997). This star is very similar to  $\rho^1$  Cnc, except that it is not quite so metal-rich. Neuforge & Magain derived the same value of  $[\text{Fe}/\text{H}]$  for each component of the system (A and B), giving confidence to the consistency of their LTE analysis. They derive the following parameters for  $\alpha$  Cen B, based on 58 Fe I and 4 Fe II lines:  $T_{\text{eff}} = 5255 \pm 50$  K,  $\log g = 4.51 \pm 0.08$ ,  $\xi_t = 1.00 \pm 0.08$  km s $^{-1}$ ,  $[\text{Fe}/\text{H}] = 0.24 \pm 0.03$ . The results of our analysis of their data (using our  $gf$ -values) for 20 Fe I and 4 Fe II lines in common between our studies are:  $T_{\text{eff}} = 5180 \pm 110$  K,  $\log g = 4.50 \pm 0.15$ ,  $\xi_t = 1.00 \pm 0.13$  km s $^{-1}$ ,  $[\text{Fe}/\text{H}] = 0.26 \pm 0.04$ . Using the recently revised dynamical mass and luminosity and their spectroscopic temperature estimate, Neuforge et al. (1998) calculated  $\log g = 4.51 \pm 0.08$ . With our temperature estimate, this value must be decreased by 0.02 dex. Hence, the spectroscopic and dynamical surface gravity values are in agreement.

Neuforge & Magain also derived  $T_{\text{eff}} = 5180 \pm 30$  K for  $\alpha$  Cen B from an analysis of its H $\alpha$  profile. While this is 75 K less than their Fe-line based estimate, it is exactly equal to our estimate. This shows that discrepancies between H $\alpha$ -based and Fe-based  $T_{\text{eff}}$  estimates are not restricted to  $\rho^1$  Cnc.

The uncertainties in the atmosphere parameters were estimated in the same way as Neuforge & Magain: the uncertainty in  $\xi_t$  was determined from the standard deviation in the slope of the least-squares fit of abundance versus reduced equivalent width, the uncertainty in  $T_{\text{eff}}$  was determined from the uncertainty in the slope of the least-squares fit of abundance versus  $\chi_{\text{low}}$  in addition to the uncertainty in the slope due to the uncertainty in  $\xi_t$ , the uncertainty in the Fe abundance a combination of the uncertainties in  $T_{\text{eff}}$ ,  $\xi_t$ , and the scatter of the individual Fe I abundances (standard deviation of the mean), all added in quadrature. However, in calculating the uncertainty in  $\log g$ , we include the contribution from the uncertainty in  $T_{\text{eff}}$  in addition to the scatter in the Fe II line abundances; Neuforge & Magain only included the second source in their estimation of the uncertainty in  $\log g$ .

### 3.1.2. Other elements

We have determined the abundances of the light elements Li, C, N, and O. The O abundance is based on the [O I] line at 6300.3 Å, for which we measured an equivalent width of 13.4 mÅ, resulting in  $[\text{O}/\text{H}] = 0.55 \pm 0.08$ . The C abundance was determined in three ways: C I at 5380 Å (equivalent width = 21.0 mÅ), the C $_2$  bandhead at 5635 Å, and the CH clump at 4323 Å. The C abundances from the C $_2$  and CH molecular lines were determined by comparing the observed spectrum with synthetic spectra. The linelists had been used previously in a study of FG Sge (Gonzalez et al. 1998). The values of  $[\text{C}/\text{H}]$  resulting from these three C species are  $0.33 \pm 0.10$ ,  $0.54 \pm 0.10$ , and  $0.54 \pm 0.10$ , respectively. Hence, the C abundance derived from the atomic C I line is marginally inconsistent with the abundances derived from the molecular lines. A reduction in  $T_{\text{eff}}$  by about 100 K would bring them into agreement, but note that the abundance derived from atomic C is based on only one line. It is unlikely that differential non-LTE corrections between  $\rho^1$  Cnc and the Sun can account

for this difference. The N abundance was determined from a synthesis of the CN lines between 7995 and 8015 Å; we employed the same linelist used by Gilroy & Brown (1991) in their study of giants in M67. Adopting  $[C/H] = 0.54$ , we get  $[N/H] = 0.71 \pm 0.14$ . The same synthesis was used to set an upper limit on the  $^{12}C/^{13}C$  ratio of 30.

The upper limit on the Li abundance was determined in the same way as in Paper II. We find,  $\log \epsilon(Li) < 0.50 \pm 0.15$ .

## 4. Discussion

### 4.1. Comparison with recent studies

The uncertainties quoted in Paper II for the atmospheric parameters of  $\rho^1$  Cnc were probably underestimated, as indicated by the high sensitivity of those results to a small change in the linelist (which was discussed in that study). Instead of 75 K, the uncertainty in  $T_{\text{eff}}$  is closer to 100 K. Regardless of which uncertainty is chosen, the  $T_{\text{eff}}$  estimate of Paper II is consistent with the present one. Also, the uncertainty in  $\log g$  was underestimated in Paper II; a more accurate estimate is about 0.15, rather than 0.05. Taking this into account, the differences between the two surface gravity estimates are not discrepant. There is no significant systematic difference in the equivalent widths between the two studies; the mean difference is  $0.4 \pm 3.6$  mÅ.

Given that the present analysis is completely independent from that in Paper II, we can combine the results from both analyses, as well as the results of Fuhrmann et al., to reduce the uncertainties. Weighting each value according to the uncertainties (and adopting the revised uncertainties for the results from Paper II), we obtain:  $T_{\text{eff}} = 5251 \pm 48$  K,  $\log g = 4.38 \pm 0.07$ ,  $\xi_t = 0.80 \pm 0.06$  km s $^{-1}$ ,  $[Fe/H] = 0.40 \pm 0.04$ , where the standard deviations of the mean are quoted for the uncertainties. This mean value of  $[Fe/H]$  is nearly identical with Taylor's (1996) estimate,  $0.414 \pm 0.096$ .

### 4.2. Status of $\rho^1$ Cnc

With these new mean values for the atmospheric parameters of  $\rho^1$  Cnc, we can derive new values for its age and mass from theoretical evolutionary tracks. Using Fig. 5 of Fuhrmann et al., we find: mass =  $1.05 \pm 0.03 M_{\odot}$  and age =  $3.6 \pm 3.0$  Gyr. The models of Ford et al. (1998) are not quite consistent with this combination of parameters; the closest match (with  $T_{\text{eff}} = 5280$  K) yields: mass =  $0.91 \pm 0.06 M_{\odot}$ , age =  $12.5 \pm 5$  Gyr. The disagreement between the two studies is due mostly to their different assumptions concerning the He abundance: Fuhrmann et al. assume a solar He abundance, and Ford et al. assume the He abundance scales with metal abundance. The models of Ford et al. yield results very close to those of Fuhrmann et al. when they assume a solar He abundance (Ford, private communication). Baliunas et al. (1997) estimate an age of 5 Gyr from the mean level of chromospheric activity; the measured rotation period, 41.7 days, is also indicative of old age.

The agreement between the C abundances derived from the CH and C<sub>2</sub> bands argues for a solar He abundance in the atmosphere of  $\rho^1$  Cnc. The well-known weakness of the CH band in

comparison with the C<sub>2</sub> bands in R CrB stars is often cited as evidence of their extreme H-deficient atmospheres.

Taylor claims that  $\rho^1$  Cnc is a subgiant both on spectroscopic and astrometric grounds. We do provide weak confirmation of this in that the surface gravity of  $\rho^1$  Cnc is slightly less than that of  $\alpha$  Cen B. However, Strömgren et al. (1982) showed that the surface gravity of a cool dwarf is a sensitive function of the assumed He abundance; use of a model atmosphere with a solar He abundance to analyze a He-rich star will result in an overestimate of the surface gravity (see their Table II). The slightly low value of  $\log g$  for  $\rho^1$  Cnc might be cited as evidence for a He deficit in its atmosphere.

The lack of detectable lithium argues against both youth and recent accretion of high-Z material. Our upper limit for the lithium abundance is similar to that quoted for  $\alpha$  Cen B by Chmielewski et al. (1992). Compared to the Li abundance trends in open clusters studied by Jones et al. (1997), the Li abundance upper limit of  $\rho^1$  Cnc constrains it to an age greater than that of the Hyades. However, more metal-rich stars have deeper outer convection zones than their solar metallicity counterparts, so lithium destruction may have been accelerated in the envelope of  $\rho^1$  Cnc.

The lack of  $^{13}C$  enhancement argues against pollution of  $\rho^1$  Cnc's atmosphere by nuclear processed material (either from its interior or from another star).

Is the value of  $\xi_t$  for  $\rho^1$  Cnc unusually small? The three recent independent analyses of this star all obtained nearly identical values of  $\xi_t$ . Compared with  $\alpha$  Cen B,  $\rho^1$  Cnc has a marginally smaller value of  $\xi_t$ . However, very few stars in  $\rho^1$  Cnc's temperature range have been analysed with the required precision, so, at this time, we cannot answer this question with certainty. An anomalous value of  $\xi_t$  might have significant consequences on the diffusion rate of He and Li ions in the envelope.

The hypothesis proposed in Paper II that  $\rho^1$  Cnc is a nearly pole-on system is rendered less necessary, as the revised age estimates are not so extreme as that of Paper II. Also, the probability is only 1 in 10,000 that the observed radial velocity variations are due to a companion star with a mass near  $0.1 M_{\odot}$  ( $\sin i \sim 0.01$ ).

It is clear from the present results that  $\rho^1$  Cnc belongs to a very small group of extremely metal-rich stars. Castro et al. (1997) find that there are only 5 stars known in the solar neighborhood with  $[Fe/H] \geq +0.4$ . Now there are 6.

## 5. Summary

We have derived new values for the atmospheric parameters of  $\rho^1$  Cnc from high quality spectra. The new results are consistent with other recent analyses and confirm  $\rho^1$  Cnc's highly anomalous metallicity. The presence of a planet around what is possibly the most metal-rich star in the solar neighborhood strongly implies that there is a causal link between planets and the metallicity of the parent star. However, the direction of the link is not yet known.

*Acknowledgements.* We thank David Lambert, Leonid Lyubimkov, and Sergey Rostopchin for obtaining a spectrum of  $\rho^1$  Cnc at our request. We are also grateful to Eric Ford and Geoff Marcy for their helpful comments. The research has been supported in part by the Kennilworth Fund of the New York Community Trust.

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