HD 179821 (V1427 Aql, IRAS 19114+0002) – a massive post-red supergiant star?

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ABSTRACT
We have derived elemental abundances of a remarkable star, HD 179821, with unusual composition (e.g. [Na/Fe] = 1.0 ± 0.2 dex) and extra-ordinary spectral characteristics. Its metallicity at [Fe/H] = 0.4 dex places it among the most metal-rich stars yet analysed. The abundance analysis of this luminous star is based on high-resolution and high-quality (S/N ≈ 120–420) optical echelle spectra from McDonald Observatory and Special Astronomy Observatory. The data includes five years of observations over 21 epochs. Standard 1D local thermodynamic equilibrium analysis provides a fresh determination of the atmospheric parameters over all epochs: $T_{\text{eff}} = 7350$ ± 200 K, log $g$ = +0.6 ± 0.3, and a microturbulent velocity $\xi = 6.6$ ± 1.6 km s$^{-1}$ and [Fe/H] = 0.4 ± 0.2, and a carbon abundance $[\text{C}/\text{Fe}] = -0.19 ± 0.30$. We find oxygen abundance $[\text{O}/\text{Fe}] = -0.25 ± 0.28$ and an enhancement of 0.9 dex in N. A supersonic macroturbulent velocity of 22.0 ± 2.0 km s$^{-1}$ is determined from both strong and weak Fe I and Fe II lines. Elemental abundances are obtained for 22 elements. HD 179821 is not enriched in s-process products. Eu is overabundant relative to the anticipated $[\text{X}/\text{Fe}] ≈ 0.0$. Some peculiarities of its optical spectrum (e.g. variability in the spectral line shapes) is noticed. This includes the line profile variations for H α line. Based on its estimated luminosity, effective temperature and surface gravity, HD 179821 is a massive star evolving to become a red supergiant and finally a Type II supernova.

Key words: stars: abundances – stars: late-type – stars: massive.

1 INTRODUCTION

The spectral class of F–G luminous giants may encompass stars on two different evolutionary paths. Some stars may be massive stars evolving from the main sequence and some of these massive stars may now be in a post-red supergiant phase. Alternatively, other stars may be departing the asymptotic giant branch (AGB) evolving at roughly constant luminosity to hotter temperatures and the tip of the white dwarf cooling track. Unambiguous assignment of an F–G supergiant to the proper evolutionary path is not always immediately possible, even when a wide variety of observational techniques are applied and the electromagnetic spectrum is well sampled.

HD 179821, also known as V1427 Aql and IRAS 19114+0002, remains a supergiant of uncertain heritage despite a lengthy literature and frequent investigations into its status. Advocates for a post-AGB origin include Zač et al. (1996) and Reddy & Hrivnak (1999), who gave weight to their measurements of overabundances of s-process nuclides. Others have stressed the star’s distance as implied by its radial velocity and characteristics of its circumstellar gas and dust shell in suggesting that the star is a massive supergiant: see, for example, Jura & Werner (1999) and Jura, Velusamy & Werner (2001) with the latter paper carrying the provocative title “What next for the likely presupernova HD 179821?” Oudmaijer et al. (2009) confidently place HD 179821 among massive stars in a post-red supergiant phase.

An oft-stated assertion is that a star’s chemical composition provides clues to its evolutionary history. Certainly, one anticipates readily observable distinctive signatures between an evolved massive star and a mature post-AGB star (i.e. a star that left the AGB after experiencing many thermal pulses and extensive third dredge-up episodes). The massive star will have experienced mixing between envelope and interior at a minimum and, thus, readjustment of its surface C, N and possibly O abundances: a decrease in C abundance and an offsetting increase in N abundance is assured but with very few exceptions (Na, possibly) all other elements will retain their natal abundances. On the other hand, a mature post-AGB star

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will be markedly $s$-process enriched with a likely enrichment of $C$ accompanying the $s$-process enrichment. The contrasting compositions of massive and post-AGB stars surely represent a testable proposition. Unfortunately, some stars appear to evolve off the AGB before the third dredge-up has altered the surface abundances of the $s$-process nuclides (see De Ruyter et al. 2006, and references therein).

The paper is organized as follows: Section 2 discusses the high-resolution optical spectra obtained at the two observatories from 2008 to 2013; General properties of the spectra are discussed briefly in Section 3; Section 4 describes our abundance analysis and reanalyses previous analyses; Section 5 in a collection of concluding remarks places HD 179821 in its likely evolutionary status as a massive star evolving to become a red supergiant and finally a Type II supernova.

2 OBSERVATIONS

Our investigation of HD 179821 is based on high-resolution optical spectra obtained between 2008 and 2013 at two observatories: the McDonald Observatory (McD) and the Special Astrophysical Observatory (SAO). The log of observations is given in Table 1.

The character of HD 179821’s spectrum is displayed by Fig. 1. Some features are blended and require spectrum synthesis to yield useful abundance information. Many lines suitable for abundance analysis are apparently unblended.

2.1 McDonald Observatory’s Tull spectrograph

Spectra were obtained at the W.J. McDonald Observatory with the 2.7m Harlan J. Smith reflector and the Tull coudé echelle spectrograph (Tull et al. 1995). A single exposure covers the wavelength range from about 3800 to 10 500 Å. Spectral coverage is incomplete from about 5800 Å to longer wavelengths. A ThAr hollow cathode lamp provided the wavelength calibration. Exposures of 20 to 30 min provided a satisfactory S/N ratio over much of the captured spectrum.

### Table 1. Log of observations for HD 179821 obtained at the McDonald and the SAO. S/N ratios for the SAO spectra presents the S/N values at 5500 Å while in the McDonald spectra, the S/N values in the raw spectra are reported near 5000 Å.

| Obs. Period | Exposure (s) | Wave.Range Å | S/N | Notes |
|-------------|--------------|---------------|-----|-------|
| 21 Apr 2008 | 1 x 1800     | 3877–10 338   | 174 | McD   |
| 13 Jun 2008 | 1 x 1200     | 3832–10 339   | 193 | McD   |
| 11 Jul 2008 | 1 x 1800     | 3833–10 337   | 136 | McD   |
| 10 Aug 2008 | 1 x 1200     | 3833–10 337   | 154 | McD   |
| 17 Aug 2008 | 3 x 2400     | 4550–6000     | 252 | SAO   |
| 17 Sep 2008 | 3 x 1800     | 5260–6766     | 420 | SAO   |
| 13 Apr 2009 | 4 x 2400     | 5214–6688     | 385 | SAO   |
| 09 May 2009 | 1 x 1200     | 3832–10 338   | 172 | McD   |
| 09 May 2009 | 1 x 1200     | 3832–10 338   | 172 | McD   |
| 07 Nov 2009 | 3 x 3000     | 5220–6690     | 119 | SAO   |
| 21 Nov 2009 | 1 x 1500     | 3832–10 337   | 166 | McD   |
| 22 May 2010 | 1 x 1800     | 3833–10 337   | 123 | McD   |
| 22 May 2010 | 1 x 1800     | 3833–10 337   | 123 | McD   |
| 03 Jun 2010 | 3 x 2400     | 5210–6690     | 210 | SAO   |
| 30 Jul 2010 | 3 x 2700     | 4422–5930     | 324 | SAO   |
| 24 Sep 2010 | 3 x 1800     | 5220–6690     | 285 | SAO   |
| 17 Nov 2010 | 3 x 2400     | 5160–6689     | 352 | SAO   |
| 16 May 2011 | 1 x 1500     | 3832–10 338   | 208 | McD   |
| 30 May 2013 | 4 x 0900     | 3916–6980     | 260 | SAO   |
| 27 Aug 2013 | 4 x 2400     | 3917–6980     | 283 | SAO   |
| 08 Oct 2013 | 3 x 2400     | 3914–6077     | 201 | SAO   |

Figure 1. The spectrum for HD 179821 over the wavelength region 5300–5400 Å. The McDonald spectrum (2008 June 13) is plotted in black and the SAO spectrum (2010 November 17) in red.
Observations were reduced using the software package in IRAF.1 The bias level in the overscan area was modelled with a polynomial and subtracted. The scattered light was modelled and removed from the spectrum. In order to correct for pixel-to-pixel sensitivity variations, flat-field exposures from a halogen lamp were used. Individual orders were cosmic ray cleaned, and wavelength calibrated. The internal accuracy of the wavelength calibration via the ThAr lamp spectra was always better than on 0.003 Å rms. Rectification and merging of the individual orders into one spectrum were performed with bespoke echelle reduction software in IDL (Şahin 2008). The line equivalent widths (EWs) were measured in the same manner as in Şahin et al. (2011), however, one additional test was performed. The EWs were compared to those measured by using STARLINK spectrum analysis program DIPSO (Howarth et al. 1998), SPECTRE2 (Sneden 1973), and an in-house developed IDL package to check any systematic errors due to continuum placement in those measurements. The results for a representative sample of weak and strong lines agreed well within ± 5 mA. In EW measurements, the local continuum was fitted with a first-degree polynomial then EWs were measured using a Gaussian profile. For strong lines, a direct integration was preferred to the Gaussian approximation. The errors for each EW measurement were determined by using the prescriptions given by Howarth & Phillips (1986).

2.2 Special Astrophysical Observatory’s Nasmyth spectrograph
Spectra were obtained with the Nasmyth Echelle Spectrograph (NES) echelle spectrograph (Panchuk et al. 2007, 2009) mounted at the Nasmyth focus of the 6-m telescope of the SAO of the Russian Academy of Sciences. Observations were made with a 2048 × 2048 CCD and an image slicer. For the SAO spectra in 2013, a larger CCD (2048 × 4096) was employed. This provided an increase in the recorded spectral range. The spectrophotometric resolution and the signal-to-noise ratio are R ≥ 60 000 and S/N ≥ 100, respectively. A modified (Yushkin & Klochkova 2005) echelle context of the MIDAS package was used to extract 1D vectors from the 2D echelle spectra. Cosmic ray hits were removed via median averaging of two successively taken spectra. Wavelength calibration was performed using the spectra of a hollow-cathode ThAr lamp. The NES spectra cover the wavelength range 3916 to 6980 Å without gaps and, thus, provide lines that fall in the interorder gaps in the McDonald spectra up to almost 7000 Å.

3 GENERAL FEATURES OF HD 179821’S SPECTRUM
A partial glimpse into the spectrum of HD 179821 is provided by Fig. 1. Comparison of McDonald and SAO spectra shows that they are of matching quality. Comparison of EWs of unblended lines from the McDonald spectrum for 2008 August 17 and the SAO spectrum of 2008 August 17 (a one-week interval in which, we assume, the star’s spectrum varied very little) shows close agreement [EW(SAO) = 1.01(0.01)EW(McD)−5.95(1.94)] and, thus, spectra from the two observatories may be combined to study the star’s long-term behaviour.

Figure 2. The profile of the Hα line obtained in several observing runs. The profiles are plotted relative to photospheric velocity of the individual spectra. The ELODIE and the McDonald spectra analysed by Kipper (2008) and Reddy & Hrivnak (1999), respectively, are also presented. The profile of Hα in orange colour is 2010 July 21 spectrum obtained by the Hobby–Eberly Telescope (HET; Luck 2016, private communication). The dot–dashed line shows the 2001 August 6 McDonald spectrum (Reddy 2016, private communication).

3.1 Hα profiles
Photometric variability implies spectroscopic variability. Among the striking indicators of the variability is the changing profiles of Hα, a variation already noted by Kipper (2008). Fig. 2 shows a selection of Hα profiles. Weak emission in the blue or red wings is seen on occasions but a more striking change occurs in the width and radial velocity of the strong absorption line, for example, the 2010 May and July profiles are shifted to the blue by about 20 km s−1.

3.2 Radial velocities
Radial velocities for the McDonald spectra were measured using cross-correlation against a spectrum of Arcturus (Hinkle et al. 2000). The spectral range used for the cross-correlation was 5300–5500 Å. As a check, we also derived radial velocities from the central wavelengths of several unblended Fe i lines and the laboratory wavelengths (Nave et al. 1994). For a given spectrum, the two measurement techniques agreed to within about 0.4 km s−1. These velocities are based on the wavelength scale derived from exposures of a ThAr hollow cathode lamp observed during the same night but rarely either immediately before or after the HD 179821 exposure. To correct for a possible offset between stellar and ThAr lamp exposures, velocities were derived from telluric (H2O and O2) lines providing a correction of 0.1–0.4 km s−1.

Procedures for obtaining radial velocities from the SAO spectra are described by Klochkova et al. (2008). The list of selected lines is taken from the line list for the post-AGB F supergiant HD 56126 (Klochkova et al. 2007) and again the stability of the spectrograph was checked using telluric ([O i], H2O and O2) lines. An accuracy of 0.1–0.2 km s−1 is achieved.

The heliocentric velocities are listed in Table 2. A variable radial velocity is evident with a peak-to-peak amplitude of about 15 km s−1. The central velocity and amplitude are consistent with measurements in the literature from about 10 yr earlier. The mean

1 IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy (AURA), Inc., under cooperative agreement with the National Science Foundation.
2 http://www.as.utexas.edu/chris/spectre.html
velocity of 85.8 ± 0.8 km s$^{-1}$ ($V_{\text{LSR}} = 102.3 ± 0.8$ km s$^{-1}$) from Table 2 in good agreement with the systemic standard of rest (LSR) velocity (100 km s$^{-1}$) obtained from CO observations of the expanding circumstellar shell (Zuckerman & Dyck 1986; Likkel et al. 1987; van der Veen, Trams & Waters 1993; Fong et al. 2006; Castro-Carrizo et al. 2007).

Photometrically, HD 179821 is a semiregular variable. Arkhipova et al. (2001; see also Le Coroller et al. 2003) from photometric observations of the star between 1994–1999, found low-amplitude variations ($\Delta V \approx 0.05$–0.20 mag) and reported the periods for fundamental pulsation ($P_0$) and for the first overtone ($P_1$) as 205 and 142 d, respectively. Revised periods from $UBV$ photometry from 2000 to 2008 by Arkhipova et al. (2009) were $P_0 = 203 ± 5$ d and $P_1 = 141 ± 5$ d. The ratio $P_1/P_0 = 0.70$, a value of $P_1/P_0$ is close to 0.705 in classical Cepheids (Stobie et al. 1996; Likkel et al. 1997) is presented (fourth column). The number of identified DIB features is included in parenthesis.

Table 2. The measured heliocentric radial velocities $V_{\text{HEL}}$ in the McDonald and the S AO spectra of HD 179821. Also, a summary of the heliocentric radial velocities of identified DIBs (SAO velocities are corrected for an offset of 1.2 km s$^{-1}$) is presented (fourth column). The number of identified DIB features is included in parenthesis.

| Obs. Period | HJD 2450000+ | $V_{\text{HEL}}$ km s$^{-1}$ | DIB km s$^{-1}$ | Notes |
|-------------|--------------|-----------------|----------------|-------|
| 21 Apr 2008 | 4577.9       | 91.5 ± 0.2      | -8.4 ± 0.5 (5) | McD   |
| 13 Jun 2008 | 4630.9       | 82.2 ± 0.2      | -8.2 ± 0.5 (5) | McD   |
| 11 Jul 2008 | 4658.7       | 85.7 ± 0.2      | -8.7 ± 0.2 (6) | McD   |
| 10 Aug 2008 | 4688.6       | 87.9 ± 0.2      | -8.4 ± 0.7 (5) | McD   |
| 17 Aug 2008 | 4696.4       | 88.1 ± 0.1      | -7.8 ± 0.5 (6) | SAO    |
| 17 Sep 2008 | 4727.3       | 80.0 ± 0.1      | -9.4 ± 0.4 (14) | SAO   |
| 13 Apr 2009 | 4935.5       | 88.5 ± 0.1      | -8.7 ± 0.5 (9) | SAO    |
| 09 May 2009 | 4960.9       | 87.2 ± 0.2      | -8.3 ± 0.6 (5) | McD   |
| 09 May 2009 | 4960.9       | 87.3 ± 0.2      | -8.7 ± 0.4 (5) | McD   |
| 07 Nov 2009 | 5143.2       | 84.8 ± 0.2      | -8.0 ± 0.4 (16) | SAO   |
| 21 Nov 2009 | 5156.5       | 80.5 ± 0.3      | -8.5 ± 0.6 (5) | McD   |
| 22 May 2010 | 5338.9       | 85.9 ± 0.2      | -8.3 ± 0.7 (4) | McD   |
| 22 May 2010 | 5338.9       | 86.7 ± 0.2      | -8.3 ± 0.8 (5) | McD   |
| 03 Jun 2010 | 5351.5       | 82.1 ± 0.1      | -9.0 ± 0.3 (15) | SAO |
| 30 Jul 2010 | 5408.4       | 85.7 ± 0.1      | -9.0 ± 0.3 (2) | SAO   |
| 24 Sep 2010 | 5464.2       | 79.9 ± 0.1      | -9.0 ± 0.4 (9) | SAO   |
| 17 Nov 2010 | 5518.2       | 89.6 ± 0.1      | -8.9 ± 0.8 (9) | SAO   |
| 16 May 2011 | 5697.9       | 80.7 ± 0.3      | -9.1 ± 0.7 (4) | McD   |
| 30 May 2013 | 6425.2       | 98.1 ± 0.1      | -8.5 ± 0.4 (17) | SAO |
| 27 Aug 2013 | 6532.4       | 86.5 ± 0.1      | -8.1 ± 0.5 (10) | SAO |
| 08 Oct 2013 | 6574.3       | 83.5 ± 0.1      | -7.7 ± 0.5 (12) | SAO   |

3.3 Photospheric line profile variations

Asymmetric line profiles are almost a common property of the spectra over all epochs and also reported by Kipper (2008). In the 2009 McDonald spectrum, the lines have almost symmetric profiles and it was selected for the abundance analysis.

The shapes of the line profiles vary with their strengths. For several relatively high-excitation lines, the broadening of the line is seen to occur mainly at the long-wavelength side of the line profiles and the short-wavelength side of the line profiles remains almost static. On the other hand, for the low-excitation lines, the broadening is observed to occur mainly at the short-wavelength side of the line profiles.

Quantitative representation of the observed line profile variations are presented in Tables A1 and A2. In these tables, the measured EWs of neutral and ionized iron lines from the spectra over all epochs are listed and indicate notable changes in the spectra for 2008, 2010 and 2013 epochs. These changes seem to correlate with the episodic variation detected in the $H\alpha$ profile, for instance, for the 2010 May and July spectra.

3.4 Interstellar lines

Interstellar lines may prove relevant to the interpretation of HD 179821 in two ways: their radial velocities in conjunction with a model of Galactic kinematics place constraints on the star’s distance and the EWs of lines with an appropriate calibration may provide an estimate of the interstellar reddening, an essential ingredient in assessing the star’s luminosity. For HD 179821 with its circumstellar gas and dust, there is the possibility of contamination of interstellar lines by circumstellar components, especially in the case of the NaD lines with their complex profile.

Diffuse interstellar bands (DIBs) cross the optical spectrum, as noted previously, with Kipper (2008) providing the most complete discussion. The DIBs are assumed to be of interstellar origin. Mean radial velocities from 4 to 17 DIBs are given in Table 2. The rest wavelengths for DIBs are provided by Hobbs et al. (2008). As expected, the mean velocity does not vary from spectrum to spectrum. The mean is $-8.5 ± 0.5$ km s$^{-1}$ (over all epochs), a value consistent with that obtained by Kipper (2008). The corresponding LSR velocity is $8.1 ± 0.5$ km s$^{-1}$. An LSR velocity of $8−10$ km s$^{-1}$ is observed in the interstellar medium (ISM) in the direction of the star in the Galaxy (Brand & Blitz 1993). This permits us to conclude that the DIBs detected in spectra of HD 179821 are, indeed, formed in the ISM, however, the negative velocity measured for this principal ISM cloud cannot be used to estimate the distance of the star.

Kipper (2008) discusses two calibrations of the reddening $E(B−V)$ versus EWs of the measured DIBs. For the $-8.5$ km s$^{-1}$ leading component, we obtain $E(B−V) ≈ 1.0$, a value in fair agreement with the estimate of 0.7 from the broad-band colours (Arkhipova et al. 2009).

Profiles of the two NaD lines were illustrated by Zač et al. (1996), Reddy & Hrivnak (1999) and Kipper (2008) – see Fig. 3. The predicted photospheric NaD1 profile for 2009 May 9 is located between absorption components 4 and 5. Components 4 and 5 are seen to vary in intensity over all epochs. Varying intensity of these components may be an indication for a circumstellar component.

Velocities of the NaD components are constant to within the measurement errors and certainly independent of the varying photospheric velocity. Component 1 has a mean velocity of $-10.5 ± 0.8$ km s$^{-1}$. Given the uncertainty about the rest wavelengths of the DIBs, this represents satisfactory agreement between the NaD component and the principal DIB component. Components 2 to 5 may also be of interstellar origin. The Galactic rotation model of Brand & Blitz (1993) provides a crude estimate of distance to the component 2 as $\approx 1.5$ kpc and $\geq 6.9$ kpc for component 5.
The profile of the D₂ (solid) and D₁ (dotted) lines of Na I in the McDonald 2009 May 9 spectrum of HD 179821. Telluric H₂O lines have not been removed. Photospheric profile indicated with dotted line is computed for T_{eff} = 7350 K and log g = 0.64.

Kipper (2008) using a calibration by Munari & Zwitter (1997) estimated the reddening provided by each NaD component. If contributions from all components are summed, the total is E(B − V) ≃ 0.8, a value in agreement with estimates from the broadband colours and the DIBs. An identification of one or more of the NaD components with the circumstellar material could change this estimate.

4 THE ABUNDANCE ANALYSIS

All abundance analyses were performed using standard ATLAS9 local thermodynamic equilibrium (LTE) model atmospheres (Castelli & Kurucz 2004) and a recent version of the LTE line analysis MOOG code (Sneden 1973). All calculations assume a normal He abundance (He/H = 0.085). In the following subsections, we discuss the adopted line list, the derivation of the model atmosphere parameters, and comment briefly on the obtained abundances. Then, we compare our results with previously published abundances before presenting our conclusions in Section 5 about HD 179821’s composition and its evolutionary status.

4.1 The line list

An essential prerequisite for the abundance analysis of HD 179821 is a set of securely identified lines with reliable atomic data. Our line lists were generated from a systematic search for unblended lines. In about 30 per cent of the accepted lines, spectrum synthesis was preferred to a direct estimate of EW; known contaminating transitions in one or both wings were thus taken into account. Our final list covers 21 elements and 141 lines over the spectra range from about 4000 to 10 460 Å. The list of lines for elements other than Fe is provided in Table 3 with gf-values taken from the literature with references supplied in the notes to Table 3. Chosen lines of Fe I and Fe II are listed in Table 4 with gf-values taken from the critical compilation by Führ & Wiese (2006).

As a check on the line list and especially on the selection of gf-values, we have derived solar abundances using our list. Our lines were measured off the solar flux atlas of Kurucz et al. (1984) and analysed with the solar model atmosphere from the Castelli & Kurucz (2004) grid for T_{eff} = 5777 K and log g = 4.44. Our analysis gave a microturbulence of 0.87 km s^{-1} and the abundances in Table 5. The estimated solar abundances are compared with those from Asplund et al. (2009) in their critical review. The agreement is good but for two elements, e.g. N and Mn where our abundances are 0.25 dex greater. Perfect agreement is not expected because line lists, selection of gf-values and model atmospheres differ. In referencing stellar abundances to solar values, we use our solar abundances.

4.2 Model atmosphere parameters

Model atmosphere parameters – effective temperature, surface gravity, microturbulence, and metallicity – are determined from the Fe I and Fe II lines (Table 4). The selection of 28 Fe I lines range in lower excitation potential (LEP) from 1.0 to 4.6 eV with EWs of up to 270 mÅ but only four lines are stronger than 200 mÅ. 11 Fe II lines have LEPs from 2.8 to 6.7 eV with EWs of up to 239 mÅ. Observed and computed line profiles of the chosen Fe I and Fe II lines are shown in Figs 4 and 5.

First, the temperature is estimated by requiring that derived abundances are independent of the LEP. The microturbulence ξ is derived by requiring that the derived abundances are independent of line strengths. For our sample of Fe I lines, these two conditions are imposed simultaneously. We have used Fe II lines for measuring ξ microturbulence since appreciable departures from LTE may occur for Fe I lines (Boyarchuk, Lyubimkov & Sahibkullin 1985; Thévenin & Idiart 1999). In this calculation, ξ is assumed to be depth independent and isotropic. A check on the microturbulence is provided by the lines of other species using the dispersion in the abundances over a range in the ξ for a given model – see Fig. 6. The dispersion σ for Fe I, Fe II and Ca I lines are computed for two different effective temperature values: T_{eff} = 7350 K (e.g. black curve for Fe and Ca) and 5800 K (e.g. red curve for Fe and Ca) but since ξ far exceeds the thermal velocities, the result is essentially independent of T_{eff}. We adopt 6.6 ± 1.6 km s^{-1}. An estimate of the gravity is provided by the familiar requirement that Fe I and Fe II lines provide the same Fe abundance to maintain the ionization equilibrium (Fig. 7). Since these atmospheric parameter are interdependent, several iterations have been performed to determine a suitable model from the model atmosphere grid.

The atmospheric parameters obtained are T_{eff} = 7350 K, log g = 0.6, [Fe/H] = 0.4 and ξ = 6.6 km s^{-1}. The corresponding iron abundance is log ε(Fe) = 7.93 or [Fe/H] ≈ 0.4 for the solar abundance of derived log ε(Fe) = 7.50 (Asplund et al. 2009). The uncertainty in the derived surface temperature is provided by the error in the slope of the relation between the Fe I abundance and LEPs of the lines. A perceptible change of slope occurs for a variation of ± 200 K in the adopted model (see Fig. 7 top panel). In a similar way, 1σ abundance difference [X/H] between neutral and ionized lines of Fe corresponds to a change of 0.3 dex in log g. The abundances of other elements were derived (Table 6).

After having determined microturbulence, we attribute the residual broadening needed to fit the observed line profiles to macroturbulence. For determination of ξ_{max}, we used a sample of nine relatively low excitation lines of Fe I insensitive to collisional broadening located at 5300, 6000 and 6100 Å. For each line, we changed...
Table 3. Lines used in the analysis of McDonald and SAO spectra. Abundances for individual lines are those obtained for the 2009 May 9 spectrum and a model of $T_{\text{eff}} = 7350$ K, $\log g = 0.64$ and $\xi = 6.6$ km s$^{-1}$.

| Species | $\lambda$ (Å) | LEP (eV) | log (gf) | EW (mÅ) | log ($\chi$) (dex) | REFP |
|---------|---------------|---------|----------|---------|-------------------|-------|
| C$^+$   | 1197.98       | 7.49    | $-2.304$ | 115.0   | 9.14              | WFD   |
| C$^+$   | 6014.84       | 8.64    | $-1.58$  | 36.9    | 8.65              | WFD   |
| C$^+$   | 6829.18       | 8.53    | $-1.461$ | 118.7   | 9.13              | WFD   |
| C$^+$   | 7108.92       | 8.64    | $-1.594$ | 38.8    | 8.70              | WFD   |
| C$^+$   | 7111.45       | 8.64    | $-1.085$ | 88.9    | 8.66              | WFD   |
| C$^+$   | 7113.17       | 8.64    | $-0.773$ | 141.6   | 8.67              | WFD   |
| C$^+$   | 7115.17       | 8.64    | $-0.934$ | 136.1   | 8.80              | WFD   |
| C$^+$   | 7119.70       | 8.64    | $-1.159$ | 79.5    | 8.65              | WFD   |
| C$^+$   | 7476.15       | 8.77    | $-1.574$ | 36.7    | 8.77              | WFD   |
| C$^+$   | 7483.41       | 8.77    | $-1.372$ | 49.5    | 8.72              | WFD   |
| N$^+$   | 7442.29       | 10.33   | $-0.38$  | 995     | 9.95              | WFD   |
| N$^+$   | 8629.23       | 10.69   | 0.07     | 940     | 9.90              | WFD   |
| N$^+$   | 8594.01       | 10.68   | $-0.335$ | 980     | 9.90              | WFD   |
| O$^+$   | 6156.77       | 10.74   | $-0.694$ | 900     | 9.00              | WFD   |
| O$^+$   | 6158.18       | 10.74   | $-0.409$ | 908     | 9.08              | WFD   |
| Na$^+$  | 5682.63       | 2.10    | $-0.706$ | 768     | 7.68              | NIST  |
| Na$^+$  | 5688.21       | 2.10    | $-0.452$ | 766     | 7.66              | NIST  |
| Na$^+$  | 5688.19       | 2.10    | $-1.406$ | 766     | 7.66              | NIST  |
| Mg$^+$  | 4057.48       | 4.35    | $-1.190$ | 179.8   | 8.26              | THEV  |
| Mg$^+$  | 4167.23       | 4.35    | $-1.040$ | 229.2   | 8.42              | THEV  |
| Mg$^+$  | 4702.99       | 4.35    | $-0.550$ | 301.0   | 8.34              | THEV  |
| Mg$^+$  | 5528.41       | 4.35    | $-0.470$ | 308.6   | 8.24              | THEV  |
| Mg$^+$  | 7877.06       | 9.99    | 0.390    | 310.0   | 8.36              | KELP  |
| Mg$^{++}$ | 4481.13     | 8.86    | 0.749    | 83.3    | 6.86              | KELP  |
| Mg$^{++}$ | 4481.15     | 8.86    | $-0.553$ | 83.3    | 6.86              | KELP  |
| Mg$^{++}$ | 4481.33     | 8.86    | 0.594    | 83.3    | 6.86              | KELP  |
| Mg$^{++}$ | 5645.62     | 9.93    | $-2.141$ | 35.6    | 8.61              | KELP  |
| Si$^+$  | 5710.01       | 9.93    | $-2.050$ | 36.0    | 8.53              | KELP  |
| Si$^+$  | 5704.80       | 9.95    | $-1.470$ | 93.3    | 8.48              | NIST  |
| Si$^+$  | 5772.15       | 10.08   | $-1.750$ | 40.9    | 8.40              | KELP  |
| Si$^+$  | 5797.86       | 9.95    | $-2.050$ | 64.0    | 8.84              | KELP  |
| Si$^+$  | 6125.03       | 6.51    | $-1.540$ | 42.1    | 8.62              | REDH  |
| S$^+$   | 4694.12       | 6.52    | $-1.713$ | 65.2    | 7.99              | PODK  |
| S$^+$   | 4695.45       | 6.52    | $-1.871$ | 42.8    | 7.92              | PODK  |
| S$^+$   | 6743.57       | 7.86    | $-1.065$ | 63.5    | 8.32              | PODK  |
| S$^+$   | 6748.78       | 7.87    | $-0.638$ | 102.6   | 8.20              | PODK  |
| S$^+$   | 6757.19       | 7.87    | $-0.351$ | 124.1   | 8.04              | PODK  |
| Ca$^{++}$ | 4425.44     | 1.88    | $-0.358$ | 686     | 3.58              | THEV  |
| Ca$^{++}$ | 4585.87     | 2.52    | $-0.187$ | 57.7    | 6.58              | MCMW  |
| Ca$^{++}$ | 5581.98     | 2.52    | $-0.710$ | 59.5    | 7.06              | NIST  |
| Ca$^{++}$ | 5601.29     | 2.53    | $-0.690$ | 51.7    | 6.97              | NIST  |
| Ca$^{++}$ | 5857.46     | 2.93    | 0.230    | 127.3   | 6.90              | NIST  |
| Ca$^{++}$ | 6122.23     | 1.89    | $-0.315$ | 180.1   | 6.89              | NIST  |
| Ca$^{++}$ | 6162.18     | 1.90    | $-0.089$ | 234.3   | 6.98              | NIST  |
| Ca$^{++}$ | 6449.82     | 2.52    | $-0.552$ | 58.7    | 6.88              | NIST  |
| Sc$^{++}$ | 4420.66     | 0.62    | $-2.270$ | 197.6   | 4.05              | NIST  |

(a) References for the adopted gf values: WFD – Wise, Führ & Deters (1996); NIST – Atomic Spectra Database (http://physics.nist.gov/PhysRefData/ASD); KRCZ – KURUCZ Atomic Spectra Database (http://www.mp-mpi-hannover.de/projekte/kurucz/); THEV – Thévenin (1989); KELP – Kelleher & Podobedova (2008); REDH – Reddy & Hrivnak (1999); PODK – Podobedova, Kelleher & Wise (2009); SOLS – Sobeck, Lawler & Sneed (2007); SCOT – Scott et al. (2015); BIEG – Biémont & Godefroid (1980); HANN – Hannaford et al. (1982); LJUN – Ljung et al. (2006); MCMW – McWilliam et al. (1998); L001 – Lawler, Bonvallet & Sneed (2001); DEHG – Den Hartog et al. (2003); L013 – Wood et al. (2013).
Table 4. Fe i and Fe ii lines used in the analysis of McDonald and SAO spectra. Abundances for individual lines are those obtained for the 2009 May 9 spectrum and a model of $T_{\text{eff}} = 7350$ K, $\log g = 0.64$ and $\xi = 6.6$ km s$^{-1}$.

| Species | $\lambda$ (Å) | LEP (eV) | log (gf) | EW (mÅ) | log $\epsilon$(Fe) (dex) |
|---------|--------------|---------|----------|---------|--------------------------|
| Fe i    | 6024.07      | 4.55    | -0.06    | 96.8    | 7.91                     |
| Fe i    | 6207.06      | 4.08    | -0.19    | 43.5    | 8.16                     |
| Fe i    | 6108.86      | 3.61    | -1.53    | 70.0    | 7.68                     |
| Fe i    | 6193.61      | 2.43    | -1.58    | 87.3    | 7.70                     |
| Fe i    | 6200.10      | 3.60    | -0.29    | 122.9   | 7.54                     |
| Fe i    | 6411.66      | 3.65    | -0.72    | 98.6    | 7.88                     |
| Fe i    | 6592.91      | 2.73    | -1.47    | 71.7    | 7.72                     |
| Fe i    | 6841.34      | 4.61    | -0.60    | 50.3    | 8.15                     |
| Fe i    | 4893.82      | 2.83    | -4.27    | 238.5   | 8.06                     |
| Fe i    | 5247.80      | 6.72    | -1.58    | 91.1    | 7.58                     |
| Fe i    | 5813.67      | 5.57    | -2.75    | 86.4    | 7.89                     |
| Fe i    | 5823.18      | 5.57    | -2.99    | 67.9    | 7.99                     |
| Fe i    | 5991.38      | 3.15    | -3.65    | 223.0   | 7.59                     |
| Fe i    | 6113.33      | 3.22    | -4.23    | 137.7   | 7.84                     |
| Fe i    | 6116.06      | 3.23    | -4.47    | 87.3    | 7.82                     |
| Fe i    | 6129.73      | 3.20    | -4.74    | 111.0   | 8.20                     |
| Fe i    | 6179.40      | 5.57    | -2.80    | 69.4    | 7.83                     |
| Fe i    | 6331.95      | 6.22    | -2.07    | 124.7   | 7.94                     |
| Fe i    | 6464.40      | 6.22    | -2.08    | 89.4    | 7.75                     |

Table 5. Solar abundances obtained by employing the solar model atmosphere from Castelli & Kurucz (2004) compared to the photospheric abundances from Asplund et al. (2009). The abundances presented in bold typeface are measured by synthesis while remaining elemental abundances were calculated using the line EWs.

| Species | This work $\log \epsilon(X)$ (dex) | Asplund $\log \epsilon(X)$ (dex) | $\Delta \log \epsilon(X)$ |
|---------|-----------------------------------|----------------------------------|--------------------------|
| C       | 4.85 ± 0.15                       | 7                                | 0.02                     |
| N       | 8.08 ± 0.08                       | 2                                | 0.25                     |
| O       | 8.76 ± 0.21                       | 2                                | 0.07                     |
| Na      | 6.16 ± 0.01                       | 2                                | -0.08                    |
| Mg      | 7.60 ± 0.00                       | 1                                | 0.00                     |
| Mg      | 7.54 ± 0.01                       | 2                                | -0.06                    |
| Al      | 6.42 ± 0.00                       | 8                                | 0.00                     |
| Si      | 7.55 ± 0.07                       | 6                                | 0.03                     |
| S       | 7.12 ± 0.04                       | 4                                | 0.00                     |
| Ca      | 6.20 ± 0.23                       | 3                                | -0.14                    |
| Sc      | 3.11 ± 0.09                       | 4                                | 0.00                     |
| Ti      | 5.01 ± 0.15                       | 5                                | 0.06                     |
| Cr      | 5.54 ± 0.10                       | 3                                | 0.09                     |
| Mn      | 5.62 ± 0.04                       | 3                                | 0.00                     |
| Fe      | 7.40 ± 0.01                       | 2                                | 0.00                     |
| Ne      | 7.50 ± 0.08                       | 7                                | -0.00                    |
| Zn      | 4.66 ± 0.26                       | 2                                | 0.10                     |
| Y       | 2.35 ± 0.19                       | 3                                | 0.14                     |
| Zr      | 2.71 ± 0.10                       | 2                                | 0.13                     |
| Ba      | 2.13 ± 0.00                       | 1                                | -0.05                    |
| La      | 1.03 ± 0.00                       | 1                                | -0.07                    |
| Nd      | 1.37 ± 0.00                       | 1                                | -0.05                    |
| Eu      | 0.43 ± 0.02                       | 3                                | -0.09                    |

The mean $\xi_{\text{mac}}$ resulting from this procedure after correcting for the microturbulence (6.6 km s$^{-1}$) and the instrumental width (5 km s$^{-1}$), is $\xi_{\text{mac}} = 22.0 \pm 1.7$ km s$^{-1}$. Projected rotational velocity is assumed to be negligible.

Following analysis of the 2009 May 9 McDonald spectrum, we determined model atmosphere parameters from all McDonald and SAO spectra – see Table 7. There is no secular trend in any of the atmospheric parameters. Therefore, one can conclude that the line profile variations are not reflected in the atmospheric parameters. For instance, the 2010–2011 episode of H α broadening presented in Fig. 2 is not seen in the model parameters from the McDonald and SAO spectra.

4.3 Balmer and Paschen lines

Additional information about the atmosphere is provided by the hydrogen Balmer and Paschen lines. At the parameters of HD 179821, the line profiles are sensitive to temperature and gravity. The variable H α profiles (Fig. 2) are clearly highly distorted modifications of the photospheric profile. Thus, we seek to constrain the atmospheric parameters using the Balmer lines H β, H γ and H δ and the Paschen lines P8 at 10 049 Å and P11 at 8863 Å. These profiles appear immune to the extreme variations exhibited by H α – see Fig. 8 (right) for a selection of spectra around the H β line.

In the top left panel of Fig. 8, we superimpose on the H β profile for the McDonald 2009 May 9 spectrum theoretical profiles for [Fe/H] = +0.4 models for $T_{\text{eff}} = 7350$ K and $\log g = 0.4$ and 0.6 and $T_{\text{eff}} = 7550$ K and $\log g = 0.4$. The observed red wing is shallower than predicted suggesting that emission is affecting this wing. Predicted profiles were computed with SYNTE and convolved

5 The MOOG code computes a $\xi^2$ radial-tangential macroturbulence profile based on the work of Gray (1992), in 'The Obs. & Anal. of Stell. Phot', p. 409.
Figure 4. The observed (filled circles) and computed (full red line) line profiles for neutral Fe lines used for model parameter determination from the McDonald spectrum for 2009 May 9. Their wavelengths and measured EW are indicated at the top of each panel. The computed profiles show synthetic spectra for the abundances listed in Table 4 and blending lines included as necessary.

with a Gaussian profile in DIPSO to simulate the instrumental broadening. For all predicted profiles, blending lines were computed with abundances scaled to the metallicity [Fe/H] = +0.4. These are LTE profiles but non-LTE profiles for similar supergiant atmospheres suggest that corrections for non-LTE effects affect the core of the line and are likely to be very small if collisions with hydrogen atoms are included in the statistical equilibrium calculations for the H atom (Barklem 2007; Barklem 2016, private communication). The best fit to H β’s blue wing is found for $T_{\text{eff}} = 7550 \pm 200$ K and $\log g = 0.4 \pm 0.3$. These parameters are in fair agreement with the spectroscopic values from iron lines. Examination of a family of predicted profiles shows that H β can be fit by profiles along a locus in the $(T_{\text{eff}}, \log g)$ plane from (7350, 0.3) to (7750, 0.6) through (7550, 0.4). H γ and H δ as well as Paschen lines are well fitted also by the (7550, 0.4) model and other models along the locus of best fits to the H β line. Emission in the red wings is absent for H β and H γ but, perhaps, weakly present for the Paschen lines (Fig. 8).

Previous fits to the Balmer line, H δ gave lower temperatures which were considered to be at odds with the spectroscopic determination: Reddy & Hrivnak (1999) gave (6750, 0.5) and Kipper (2008) obtained (6000, 2.0). These estimates straddle the locus found from our fit to the H β line.

4.4 The chemical composition

In Table 6, we present a summary of the elemental abundances based on the LTE-based model parameters. In Table 6, log $\epsilon$ is the logarithm of the abundances. The $\sigma_{\text{line}}$ is the 1σ line-to-line scatter in the abundances. The $[X/H]$ is the logarithmic abundance ratio with hydrogen relative to the corresponding solar value, and $[X/Fe]$ is the logarithmic abundance with respect to the Fe I abundance. Estimated formal errors for the abundances arising from uncertainties of the atmospheric parameters $T_{\text{eff}}, \log g$ and $\xi$ are summarized in Table 8 for changes with respect to the model of $+200$ K, $+0.3$ cgs units and $\pm 1.6$ km s$^{-1}$. From the uncertainties listed in Table 8, we find the total absolute uncertainty ($\sigma_{\text{abs}}$) to range from 0.06 for O I to 0.36 for La II by taking the square root of the sum of the quadrature of the errors in [X/H] and [Fe/H].
a sample of 451 F, G and K stars of luminosity classes I and IIa of which the vast majority are evolved intermediate-mass stars and not post-AGB stars. A handful had [Fe/H] of 0.4 or greater but in conformity with expectation these stars were at Galactocentric...
Table 6. Abundances of the observed species for HD 179821 are presented for the 2009 May 9 McDonald spectrum and the model atmospheres of $T_{\text{eff}} = 7350$ K, $\log g = 0.64$, $\xi = 6.6$ km s$^{-1}$.

| Element | log $\epsilon$(X) (dex) | $\sigma_{\text{line}}$ (dex) | $\sigma_{\text{abs}}$ (dex) | N | [X/H] (dex) | $\sigma_{[X/H]}$ (dex) | [X/Fe] (dex) | $\sigma_{[X/Fe]}$ (dex) | log $\xi$ (X) (km s$^{-1}$) |
|---------|-----------------|-----------------|-----------------|---|-------------|-----------------|-------------|-----------------|-----------------|
| C I     | 8.79            | 0.19            | 0.18            | 10| 0.34        | 0.24            | -0.19        | 0.30            | 8.45 ± 0.15     |
| N I     | 9.48            | 0.14            | 0.24            | 3 | 1.40        | 0.16            | 0.87         | 0.24            | 8.08 ± 0.08     |
| O I     | 9.04            | 0.06            | 0.06            | 2 | 0.28        | 0.22            | -0.25        | 0.28            | 8.76 ± 0.21     |
| Na I    | 7.67            | 0.01            | 0.31            | 2 | 1.51        | 0.01            | 0.98         | 0.18            | 6.16 ± 0.01     |
| Mg I    | 8.32            | 0.08            | 0.32            | 4 | 0.72        | 0.08            | 0.19         | 0.20            | 7.60 ± 0.00     |
| Mg II   | 8.40            | 0.10            | 0.23            | 3 | 0.86        | 0.10            | 0.33         | 0.21            | 7.54 ± 0.01     |
| Al I    | 6.78            | 0.01            | 0.20            | 2 | 0.36        | 0.01            | -0.17        | 0.18            | 6.42 ± 0.00     |
| Si I    | 8.58            | 0.15            | 0.23            | 6 | 1.03        | 0.17            | 0.50         | 0.25            | 7.55 ± 0.07     |
| Si II   | 8.13            | 0.17            | 0.21            | 7 | 1.01        | 0.17            | 0.48         | 0.25            | 7.12 ± 0.04     |
| Ca I    | 6.89            | 0.14            | 0.33            | 8 | 0.69        | 0.27            | 0.16         | 0.32            | 6.20 ± 0.23     |
| Ca II   | 3.90            | 0.18            | 0.17            | 4 | 0.79        | 0.20            | 0.26         | 0.27            | 3.11 ± 0.09     |
| Ti II   | 5.80            | 0.13            | 0.21            | 2 | 0.79        | 0.20            | 0.26         | 0.27            | 5.01 ± 0.15     |
| Cr I    | 6.04            | 0.04            | 0.29            | 3 | 0.50        | 0.11            | -0.03        | 0.21            | 5.54 ± 0.10     |
| Cr II   | 6.16            | 0.04            | 0.15            | 4 | 0.48        | 0.07            | -0.05        | 0.19            | 5.68 ± 0.06     |
| Mn I    | 5.86            | 0.04            | 0.27            | 3 | 0.19        | 0.06            | -0.34        | 0.19            | 5.67 ± 0.05     |
| Fe I    | 7.93            | 0.14            | 0.26            | 28| 0.53        | 0.18            | 0.00         | 0.25            | 7.40 ± 0.11     |
| Fe II   | 7.93            | 0.19            | 0.09            | 11| 0.43        | 0.21            | -0.10        | 0.28            | 7.50 ± 0.08     |
| Ni I    | 7.03            | 0.14            | 0.25            | 7 | 0.81        | 0.24            | 0.28         | 0.30            | 6.22 ± 0.19     |
| Ni II   | 7.15            | 0.00            | 0.19            | 1 | 0.93        | 0.00            | 0.40         | 0.18            | -              |
| Zn I    | 5.08            | 0.15            | 0.26            | 2 | 0.42        | 0.30            | -0.11        | 0.35            | 4.66 ± 0.26     |
| Y I     | 2.84            | 0.11            | 0.21            | 4 | 0.49        | 0.22            | -0.04        | 0.28            | 2.35 ± 0.19     |
| Zr I    | 3.53            | 0.12            | 0.15            | 7 | 0.82        | 0.16            | 0.29         | 0.24            | 2.71 ± 0.10     |
| Ba II   | 2.65            | 0.00            | 0.29            | 1 | 0.52        | 0.00            | -0.01        | 0.18            | 2.13 ± 0.00     |
| La II   | 2.08            | 0.04            | 0.32            | 3 | 0.71        | 0.04            | 0.18         | 0.18            | 1.37 ± 0.00     |
| Eu II   | 1.65            | 0.12            | 0.20            | 3 | 1.22        | 0.12            | 0.69         | 0.22            | 0.43 ± 0.02     |

Galactocentric distances of 7 kpc have [Fe/H] of 0.3 or greater, and these values are in excess of those expected from the gradient and [Fe/H] = 0 at the Sun’s Galactocentric distance of 8.5 kpc. Thus, at [Fe/H] = +0.4, HD 179821 may not be an unusual supergiant.

What may be thought unusual is that the metallicity [Fe/H] = +0.4 is significantly higher than all previous spectroscopic determinations. Considering that such determinations have used spectra of comparable quality to our and methods of similar approach, it is necessary to re-examine published metallicity determinations which we do in the next section.

4.5 The metallicity [Fe/H]

Determinations of HD 179821’s composition from high-resolution optical spectra have been reported by Začs et al. (1996), Reddy & Hrivnak (1999), Kipper (2008) and Luck (2014). Behind these (and our) analyses is a common framework involving the combination of plane–parallel model atmospheres in LTE and hydrostatic equilibrium with a line analysis programme also based on the assumption of LTE. Analyses differ by dates of the observations, the wavelength coverage of the spectra, the selection of lines and gf-values.

HD 179821 has presented two different faces to the quantitative spectroscopist: it is either metal-poor with [Fe/H] $\lesssim -1.0$ to $-0.4$ with atmospheric parameters $T_{\text{eff}} \approx 6800$ K and log $g \approx 0.5$ to 1.3 (Začs et al. 1996; Reddy & Hrivnak 1999; Kipper 2008) or it is metal-rich with [Fe/H] $\geq +0.4$ with atmospheric parameters $T_{\text{eff}} \approx 7300$ K with log $g \approx 0.6$ to 1.0 (Luck 2014; this paper).

\footnote{\textsuperscript{6} The Thévenin, Parthasarthy & Jasniwicz (2000) analysis of a low-resolution spectrum ($R \approx 8000$) gave [Fe/H] = $-0.5$ and $T_{\text{eff}} = 5660$ K and $\log g = -1.0$.}

\textsuperscript{\textnormal{distances inside the solar circle. At HD 179821’s Galactic longitude of 36\degree, the line of sight at closest approach to the Galactic Centre is at 5 kpc for a distance from the Sun of slightly less than 7 kpc. Given that there is an abundance gradient with higher metallicities towards the Galactic Centre, a positive [Fe/H] is not unexpected. Luck & Lambert (2011) from Cepheid variables obtained the slope d[Fe/H]/d$R_G$ = $-0.061$ dex kpc$^{-1}$ which gives [Fe/H] $\approx 0.2$ for a star at 5 kpc. In Luck’s sample, almost all supergiants inside}}
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Figure 8. The left-hand panel shows the observed (black dotted) and the model line profiles for H β. The theoretical profiles have been generated for a surface gravity log $g = 0.4$ and 0.6 dex, $T_{\text{eff}} = 7350$ and 7550 K, and [Fe/H] = +0.4. The right-hand panel shows the observed H β profiles for the 1997 October McDonald spectrum (Reddy 2016, private communication), the 2000 Oct ELODIE spectrum (Kipper 2008), the 2001 August McDonald spectrum (R16: Reddy 2016, private communication), and the 2009 and 2010 May McDonald spectra. The lower panels shows the observed and the model line profiles for the Paschen lines Pδ at 10 049 Å and P11 at 8863 Å.

Začs et al. (1996) analysed a spectrum from 1992 August 17 obtained at the SAO. Abundances were given relative to those of the G8IIIab giant ϵ Vir. With parameters $T_{\text{eff}} = 5130$ K, log $g = 2.5$, $\xi = 2.0$ km s$^{-1}$ and [Fe/H] = 0, HD 179821 was found to be slightly Fe-poor with [Fe/H] = −0.1. However, chosen parameters for the star do not satisfy ionization equilibrium for either Fe or Cr: the reported mean Fe abundance was 7.31 from Fe I and 7.69 from Fe II lines. In light of this discrepancy, we reanalysed the Začs et al. (1996) line list, and obtained the model parameters: $T_{\text{eff}} = 7300$ K, log $g = 0.60$, [Fe/H] = +0.40 and $\xi = 6.50$ km s$^{-1}$. These parameters are compatible with our results from McDonald and SAO spectra (Table 7).

The McDonald spectra of 1997 October 15–16 taken by Reddy and Hrivnak were analysed using our line list. Parameters: $T_{\text{eff}} = 7150$ K, log $g = 0.60$, [Fe/H] = +0.20 were obtained. This temperature is 400 K hotter and the metallicity 0.3 dex greater than reported by Reddy and Hrivnak. Examination of the Fe lines chosen by Reddy and Hrivnak found that 9 of 23 Fe I and 3 of 9 Fe II did not meet our criteria of a measurable and unblended line. We suggest that the subsolar Fe abundance reported by Reddy and Hrivnak likely arises from an imperfect list of Fe lines.

Kipper (2008) analysed spectra acquired in 2000 September and October and stored in the ELODIE archive (Moultaka et al. 2004). He compiled an extensive line list which was analysed using the model selected by Reddy & Hrivnak (1999): $T_{\text{eff}} = 6750$ K, log $g = 0.5$ but with a slightly higher microturbulence $\xi = 6.6$ km s$^{-1}$. He reported a mean Fe abundance of log $\epsilon$(Fe) = 7.00 ± 0.20 from 36 Fe I lines and 11 Fe II lines but ionization equilibrium was not achieved: the Fe abundance was 6.90 from Fe I and 7.16 from Fe II lines. Relative to the Asplund et al. (2009) solar Fe abundance, Kipper’s mean value corresponds to [Fe/H] = −0.5.

On subjecting Kipper’s line list to our analysis procedures, we found a model providing excitation and ionization equilibrium, namely $T_{\text{eff}} = 7450$ K, log $g = 0.60$, $\xi = 8.6$ km s$^{-1}$ with Fe abundances of 7.88 ± 0.17 and 7.87 ± 0.22 from the Fe I and Fe II lines, respectively, i.e. [Fe/H] = +0.47. These parameters and Fe abundance are thoroughly compatible with our results from McDonald and SAO spectra (Table 7).

When we ran Kipper’s Fe line list through the Reddy and Hrivnak model, we found the same lack of ionization equilibrium but higher Fe abundances than reported by Kipper. On examination of the complete line list, we found that our abundances were 0.44 ± 0.05 dex greater across the array of elements; this surprising difference comes from using the same line list as Kipper in every respect and a Kurucz model with Kipper’s adopted parameters. This 0.4 dex difference is not understood. (In order to satisfy a curiosity, we extracted the 2000 ELODIE spectra used by Kipper from the archive and measured a set of clean lines and compared EWs. Our measurements are in fair agreement with Kipper’s: EW(K) = 1.3(±0.07)EW(Us) + 1.6(±6.9). Such EW differences have nothing to do with the 0.44 dex difference above.)
Table 8. Sensitivity of the derived abundances to the uncertainties of $\Delta T_{\text{eff}} = \pm 200$ K, $\log g = +0.3$, and $\xi = \pm 1.6$ in the model atmosphere parameters for $T_{\text{eff}} = 7350$ K, $\log g = 0.64$, and $\xi = \pm 1.6$.

| Species | $\Delta T_{\text{eff}}$ | $\Delta \log g$ | $\Delta \xi$ | $\Delta \xi$ |
|---------|-----------------|----------------|--------------|--------------|
|         | (K)             | (cgs)          | (km s$^{-1}$) | (km s$^{-1}$) |
| CI      | +0.15            | -0.09          | -0.03        | +0.05        |
| N1      | -0.01            | -0.03          | -0.24        | +0.37        |
| O1      | -0.04            | 0.00           | -0.05        | +0.04        |
| Na1     | +0.31            | +0.01          | -0.04        | +0.45        |
| Mg1     | +0.20            | -0.13          | -0.21        | +0.42        |
| Mg II   | +0.02            | +0.05          | -0.22        | +0.41        |
| Al1     | +0.17            | -0.10          | 0.00         | +0.02        |
| Si1     | +0.20            | -0.12          | -0.01        | +0.03        |
| S1      | +0.15            | -0.14          | -0.06        | +0.02        |
| Ca1     | +0.29            | -0.16          | -0.04        | +0.11        |
| Sc II   | +0.12            | -0.04          | -0.12        | +0.13        |
| Ti II   | +0.15            | +0.03          | -0.15        | +0.29        |
| Cr I    | +0.27            | -0.10          | 0.00         | +0.07        |
| Cr II   | +0.11            | +0.03          | -0.10        | +0.26        |
| Mn I    | +0.24            | -0.12          | -0.02        | +0.07        |
| Fe I    | +0.22            | -0.13          | -0.07        | +0.12        |
| Fe II   | +0.07            | +0.02          | -0.06        | +0.11        |
| Ni I    | +0.20            | -0.14          | -0.04        | +0.02        |
| Ni II   | +0.10            | -0.05          | -0.15        | +0.40        |
| Zn I    | +0.23            | -0.12          | -0.02        | +0.05        |
| Y II    | +0.21            | -0.01          | -0.04        | +0.12        |
| Zr II   | +0.14            | -0.01          | -0.06        | +0.09        |
| Ba II   | +0.26            | -0.12          | -0.04        | +0.06        |
| La II   | +0.35            | -0.02          | -0.07        | +0.05        |
| Nd II   | +0.25            | -0.10          | 0.00         | +0.00        |
| Eu II   | +0.17            | -0.09          | -0.05        | +0.03        |

Table 9. Comparison of abundances of the observed species for HD 179821.

| Element | This work | Luck (2014) |
|---------|-----------|-------------|
|        | [X/Fe]    | [X/Fe]$^a$  |
|        | (dex)     | (dex)       |
| CI      | -0.19     | -0.58       |
| N1      | 0.87      | 1.78        |
| O1      | -0.25     | -0.38       |
| Na1     | 0.98      | 1.01        |
| Mg1     | 0.19      | 0.17        |
| Al1     | -0.17     | 0.16        |
| Si1     | 0.50      | 0.26        |
| S1      | 0.48      | 0.50        |
| Ca1     | 0.16      | 0.18        |
| Sc II   | 0.26      | 0.29        |
| Ti II   | 0.26      | 0.05        |
| Cr I    | -0.03     | 0.68        |
| Cr II   | -0.05     | 0.17        |
| Mn I    | -0.34     | 0.13        |
| Fe I    | 0.00      | 0.06        |
| Fe II   | -0.10     | 0.08        |
| Ni I    | 0.28      | 0.26        |
| Zn I    | -0.11     | 0.09        |
| Y II    | -0.04     | 0.26        |
| Zr II   | 0.29      | 0.15        |
| Ba II   | -0.01     | 0.31        |
| La II   | 0.01      | 0.17        |
| Nd II   | 0.18      | 0.01        |
| Eu II   | 0.69      | 0.20        |

$^a$Mean abundances for HD 179821 from 2010 HET spectrum; Luck (2014).
$^b$Mean abundances from Luck (2014) for a subsample of eight stars analysed with MARCS grids and with [Fe/H] $> 0.6$ dex and $\sigma_2$ is star-to-star scatter in [X/Fe] values.

Our final comparison is with Luck (2014), who analysed ELODIE spectra$^7$ and one taken with the high-resolution spectrograph at HET at the McD (Tull 1998). The HET spectrum is from 2010 July 21. Luck analysed both the ELODIE and the HET spectra using models from two grids: the Kurucz ATLAS and the Uppsala MARCS grids. The selected ATLAS model had $T_{\text{eff}} = 6997$ K, $\log g = 0.62$ and $\xi = 4.76$ km s$^{-1}$. The chosen MARCS model was similar with $T_{\text{eff}} = 7107$ K, $\log g = 1.0$ and $\xi = 4.74$ km s$^{-1}$. The metallicity [Fe/H] was +0.5 from the ELODIE spectrum with just a 0.03 dex difference between the values from the ATLAS and MARCS models. A slightly lower [Fe/H] value of +0.35 was obtained from the HET spectrum, again with a 0.03 dex difference between the two models. Thus, Luck’s analyses confirm our results for the atmospheric parameters and metallicity [Fe/H].

In short, reanalysis of published spectroscopic analyses show that there is general agreement that HD 179821 is metal-rich [Fe/H] $\simeq +0.4$. In the next section, we discuss relative abundances [X/Fe].

4.6 Relative abundances [X/Fe]

In principle, HD 179821’s chemical composition may offer insights into the status of the star: a massive post-main-sequence star or a lower mass post-AGB star. Obviously, such insights are compromised by uncertain and erroneous abundances. In order to minimize compromises, we pursue a multipart discussion. We compare our abundances (Table 6) with those from Luck (2014) who, as noted above, undertook a large survey of F–G supergiants and included HD 179821. In Table 9, we compare our [X/Fe] with the average provided by Luck from the HET spectrum and the MARCS model. Given the estimated $\sigma_\xi$ the comparison suggests fair agreement. A notable feature is the agreement that Na (relative to Fe) is highly overabundant, a feature noted by all previous analyses of HD 179821. In the case of Cr where Luck’s [Cr/Fe] is 0.7 dex greater than ours and his [Cr/Fe] from Cr i and Cr ii lines differ by 0.6 dex, it is possible that his limited selection of Cr i lines contains blended lines.

HD 179821’s sample of supergiants is dominated by evolved massive stars and many have higher surface gravities than HD 179821. Yet, it is instructive to compare abundances obtained for HD 179821 with selected samples drawn from Luck’s large survey. The sample of eight stars represented in Table 9 have $T_{\text{eff}}$ from 6600–7200 K and $\log g$ from 1.1–2.0. There is general agreement with our results for HD 179821, notably for C, N and O but interesting disagreements for Na, S and Y. The high Y abundance in the sample is likely a matter of line selection, given that Zr does not share the apparent overabundance.

HD 179821’s [X/Fe] may be judged against expected values for a star with [Fe/H] $\sim +0.4$. Abundance analyses of local dwarfs and giants show that for Na to Zn, relative abundances [X/Fe] do not differ greatly from zero, even at [Fe/H] $\sim +0.4$, the metallicity of HD 179821 – see, for example, Bensby, Feltzing & Oey 2014 for dwarfs and Luck & Heiter (2007, their table 10) for giants. Although HD 179821’s metallicity places it at or even beyond the

$^7$ EWs averaged over seven ELODIE spectra, including the same spectrum as that analysed by Kipper (2008), with the two highest S/N (153 and 180) having weight 2 and the others weight 1. (Luck 2016, private communication.)
high-metallicity limit of these samples, [X/Fe] \sim -0.0 might be expected. With respect to this baseline, inspection of our and Luck’s results in Tables 6 and 9 shows that the one outstanding anomaly is for Na with [Na/Fe] \sim 1.0. Possible additional anomalies include [Si/Fe], [S/Fe], [Sc/Fe] and [Ni/Fe] with [X/Fe] \sim +0.3 to +0.5. Table 6 shows that HD 179821 is not enriched in s-process products. Eu, an r-process product, appears overabundant relative to the anticipated [X/Fe] \sim -0.0.

The assumption of LTE was adopted in the construction of the model atmosphere and in the analysis of the absorption lines. Given the low particle densities in the atmosphere, one should be concerned about the effects of departures from LTE on the atmospheric structure and the formation of the lines. We are unaware of supergiant atmospheres constructed in non-LTE. There are some calculations of line formation in relevant atmospheres which suggest approximate corrections to [X/H] and [X/Fe] for HD 179821. Fortunately, some results are available for the interesting light elements C, N and O. Venn (1995) in her analyses of A and F supergiants computed non-LTE corrections for selected lines of C I and N I and her stellar sample included four stars with T_eff between 7400 and 7600 K and surface gravities log g from 1.1 to 1.6 with approximately solar metallicities. Considering our chosen lines and assuming that Venn’s quartet are representative of HD 179821, Venn’s calculations imply that the non-LTE abundance is about 0.3 dex for both C and N smaller than the tabulated LTE abundances. Takada & Takada-Hidai (1998) provide non-LTE predictions for the 6157 Å lines in A–F supergiants. At the atmospheric parameters of HD 179821, their calculations show that the LTE O abundance should be reduced by 0.1 to 0.2 dex.

For abundances of species from Na to Zn, the outstanding abundance anomaly is held by Na with a 1.0 dex enrichment which may be an indicator for a high-luminosity status of the star, hence operation of the Ne–Na cycle (Denissenkov & Ivanov 1987; Denissenkov 2005). The Lind et al. (2011) extensive non-LTE calculations for Na I lines did not cover the atmospheric parameters of HD 179821 as the most extreme supergiant model was a relatively cool T_eff = 5500 K at log g = 1.0. By extrapolation, it would seem that the non-LTE correction to HD 179821’s Na abundance is small. This suspicion is confirmed by pioneering calculations by Boyarchuk et al. (1988a,b,c); Korotin (2016, private communication) predicts Δ([Na/H]) = -0.14 dex.8 The Venn (1995) estimates for a few Mg I lines in late-F and early-F supergiants suggest only a 0.1 dex reduction of the LTE abundances but her and our selections of Mg I lines show little overlap. Extensive calculations of Mg I line formation in cool stellar atmospheres have been reported by Osorio & Barklem (2016) for many Mg I lines. Inspection of their predictions for four strong lines in Table 3 show that the non-LTE Mg abundances for a HD 179821-like model atmosphere9 are about +0.2 dex greater than the LTE value. The highest correction is needed for 5528 Å Mg I line with +0.2 dex and the corrections for 4057, 4167 and 4702 Mg I lines are about +0.1 dex. These corrections are less than the uncertainty arising from the microturbulence. Non-LTE calculations for Zn I lines (Takeda et al. 2005) show a very small non-LTE abundance correction. Non-LTE effects for prominent Ba II lines in cool stars have been calculated by Korotin et al. (2015). The examined grid of stellar atmospheres extends up to 6500 K and down to log g = 0 and to stars as Fe-rich as [Fe/H] = +0.5. For the model parameters reported in Section 4.2, the non-LTE Ba abundance from the 5853 Å Ba II line for HD 179821 is +0.3 dex greater than the LTE abundance listed in Table 6 (Korotin 2016, private communication). In interpreting [X/Fe], one obviously must consider the non-LTE corrections to the Fe abundance. In the case of Fe, a leading non-LTE effect is the overionization of neutral iron atoms leading to an underestimate by the LTE analysis of the Fe abundance from Fe I lines, Lind, Bergemann & Asplund (2012) extensive calculations of non-LTE effects across the Fe I spectrum did not unfortunately extend to an atmosphere representative of HD 179821. At T_eff > 7000 K, models considered had log g \geq 3 and [Fe/H] \leq +0.25. A necessarily crude extrapolation suggests the LTE Fe abundance is underestimated by less than 0.1 dex. Species similar to Fe (e.g. Ni) will presumably be affected similarly and [X/Fe] will require an even smaller non-LTE correction.

In the quest for more accurate abundance determinations for HD 179821, incorporation of non-LTE effects in the interpretation of the absorption lines and even in the construction of a model atmosphere may not provide the biggest leap to the end. The star’s atmosphere violates the standard assumption of uniform plane-parallel (or spherical) layers in hydrostatic equilibrium. A supersonic macroturbulence of 22 km s^{-1} starkly contradicts this assumption and challenges theoretical stellar astrophysicists to build more inclusive model atmospheres. The important STAGGER grid (Magic et al. 2013) does not intrude into the domain belonging to HD 179821; models at 7500 K refer to main-sequence stars and the lowest gravity models (log g = 1.5) are no hotter than 4500 K. Realistic atmospheres of supergiants will have many applications including the extension of determination of analyses of supergiants to several galaxies beyond the Galaxy.

5 CONCLUDING REMARKS

There is no question but that HD 179821 is a luminous star. Possible identifications of the star include two possibilities: (i) a massive star evolving from the main sequence at approximately constant luminosity to the red supergiant phase or on a post-red supergiant loop back to the blue or (ii) a lower mass star evolving at roughly constant luminosity from the AGB to the tip of the white dwarf cooling track.

The mass–luminosity relations for these alternative identifications overlap for a range of masses. Above a certain luminosity, the more likely identification is a high-mass star. This critical luminosity is set by the maximum mass – the Chandrasekhar mass – of a post-AGB star which may become a white dwarf. At the Chandrasekhar mass, the luminosity of a post-AGB star is M_{bol} \sim -7.1 or log L / L_{\odot} \sim 4.7 (Wood, Bessell & Fox 1983). Therefore, if it can be shown that HD 179821’s luminosity exceeds the latter limit by a clear margin, one may identify the star as a massive star.
Estimations of HD 179821’s absolute magnitude from an apparent magnitude are fraught with uncertainty owing to an uncertain correction for interstellar extinction with the possibility of an additional correction for circumstellar extinction. As previous investigators of the star have appreciated (Reddy & Hirvnak 1999; Kipper 2008; Oudmaijer et al. 2009), the absolute magnitude of HD 179821 may be estimated from the EW of the OI triplet at 7770–7774 Å. The $M_I$–EW calibration for warm supergiants comes from Kovtyukh, Gorlova & Belik (2012), who assembled EW measurements for supergiants with known luminosities. Our measurement of the oxygen triplet’s EW is 2.7 Å. The Kovtyukh et al. calibration has few stars with such strong EW but mild extrapolation of the calibration gives $M_I \simeq -8.9$ or $\log L/L_\odot \simeq 5.5$. This absolute magnitude is nearly two magnitudes brighter than the maximum for a post-AGB star and slightly fainter than the Humphreys–Davidson (Humphreys & Davidson 1979) limit of $M_{\text{bol}} \simeq -9.5$ for the most luminous warm Galactic supergiants such as $\rho$ Cas and HR 8752.

Absolute luminosities for post-AGB stars are poorly known, in general. Arellano Ferro, Giridhar & Arellano (2003) incorporated five post-AGB stars into their calibration of $M_I$–EW relation based primarily on normal supergiants. The two post-AGB star with estimated luminosities close to the luminosity limit for post-AGB stars had EWs of the triplet of 2.0 and 1.7 Å, values similar to EWs of normal supergiants of the same luminosity. Thus, it appears that normal supergiants and post-AGB stars of type F–G satisfy similar $M_I$–EW relations for the oxygen triplet.

The effective temperature and surface gravity provide a check on the conclusion that HD 179821 is a massive star. By combining the relations $L \propto R^2 T^4_{\text{eff}}$ and $g \propto M/R^2$, one obtains

$$\log L/L_\odot = \log M/M_\odot + 4 \log T_{\text{eff}} - \log g - 10.61.$$  

On substituting $T_{\text{eff}} = 7350$ K, $\log g = 0.64$ and $\log L/L_\odot = 5.5$, a mass $M = 19 M_\odot$ is obtained. Stellar evolutionary tracks (e.g. Iben 1985) imply that such a luminosity is achieved at a higher mass – say, $30 M_\odot$ – but an adjustment of $\log g$ by just 0.2 dex provides just such a mass.\(^{10}\)

It remains to consider HD 179821’s composition in light of the proposed identification as a massive star which has evolved beyond core H-burning on the main sequence to an He-core burning warm supergiant (and possibly beyond this phase). A massive star observed as a warm supergiant may be expected to have shuffled at a minimum its C and N abundances as CN-processed material reached the surface by rotationally induced mixing and the first dredge-up with the latter a contributor if the star is now evolving to the blue after a red supergiant phase. Present C/N/O abundances are taken from our analysis summarized in Table 6 with the approximate non-LTE corrections listed in Section 4.6, i.e. $C = 8.5$, $N = 9.2$ and $O = 8.9$. On the assumption that initial abundances satisfied the condition $[X/Fe] = 0.0$ and $[Fe/H] = +0.4$, $C = 8.9$, $N = 8.5$ and $O = 9.2$ were the starting abundances; relative to these values $N$ is clearly enriched, $C$ and $O$ are depleted. Assuming that the envelope has been mixed with CN-processed material from the interior, the CN-cycle’s catalysts of C and N are required to be conserved. The initial (logarithmic) sum is 9.0 and the observed sum is 9.3 with conservation satisfied within the measurement uncertainties and including the rough corrections for non-LTE effects. For more severe mixing, ON-cycled products may be involved but the conserved quantity is the sum of the C, N and O abundances. In this case, the initial value is 9.4 and the observed value is 9.3 which surely represents a case of fortuitous agreement. (Note: the analysis does not consider enhancement of the surface He abundance during evolution.)

Sodium overabundances in F–G supergiants have been the subject of several observational and theoretical investigations. As an observational reference point for HD 179821, we take the survey by Andrievsky et al. (2002) of Na abundances in F–G Ib-II giants which showed $[Na/Fe]$ increasing with decreasing log $g$ reaching $[Na/Fe] = +0.3$ at $\log g = 1.0$. Non-LTE calculations show that the departures from LTE on the observed Na i lines at 6154 and 6160 Å are small ($\sim 0.1$ dex) for supergiants with $T_{\text{eff}} \sim 7000$ K. The Na enrichment is attributed to operation of the H-burning NeNa chain in which $^{22}$Ne is converted to $^{23}$Na. Denissenkov (2005) argued that observed levels of Na enrichment required massive stars to undergo mixing between core and the radiative envelope in their main-sequence progenitor.

Inspection of the Andrievsky et al. (2002) list of stars showed that just one was as Fe-rich as HD 179821. A reference sample of four stars was selected with the conditions that $T_{\text{bol}} \geq 6500$ K and $\log g < 1.0$. For this quartet, mean values are $[Fe/H] = -0.24$ and $[Na/Fe] = +0.37$ with a small star-to-star scatter. If we assume that the $^{22}$Ne abundance scales with $[Fe/H]$, and the conversion of $^{22}$Ne to Na with subsequent mixing of Na to the surface are independent of metallicity, HD 179821 with $[Fe/H] \simeq +0.4$ and $[Na/Fe] \simeq +0.4$ for an unmixed star is expected to have $[Na/Fe] \simeq -0.7$, a value close to the observed value in Table 6.

An alternative identification of HD 179821 as a post-AGB star might appear to be excluded on the grounds that key signatures of post-AGB stars are absent, i.e. a C-rich and s-process atmosphere and envelope are clearly not a feature of HD 179821. This exclusion supposes that all AGB stars experience third dredge-up (i.e. envelope enrichment with C and s-process nuclides) before evolving off the AGB. The case of RV Tauri stars as post-AGB stars provides common examples of without carbon and s-process enrichment.

In such situations, when chemical composition is not a definitive way to distinguish massive evolved from post-AGB stars, other observed characteristics may be invoked. For example, the circumstellar CO expansion velocity for HD 179821 exceeds the typical velocity for post-AGB stars and likely requires a very luminous (i.e. a massive) star in order to drive the expansion by radiation pressure (Jura et al. 2001; Oudmaijer et al. 2009). But, obviously, among the other characteristics the absolute luminosity plays a key role, one looks forward to a precise trigonometric parallax. Until then, HD 179821 may be considered to be a warm Galactic supergiant like $\rho$ Cas and HR 8752.

\(^{10}\)An independent estimate of the mass was also provided by Parsec isochrones (Bressan et al. 2012) with the solar metal content of $Z_{\odot} = 0.0152$ and using a $Z = 0.03$ ([Fe/H] = $\log (Z/Z_{\odot})$) isochrone (http://stev.oapd.inaf.it/cgi-bin/cmd-2.7). This isochrone, based on model atmosphere parameters reported in Section 4.2, provided a mass of $30 M_\odot$ for HD 179821.

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APPENDIX: EQUIVALENT WIDTH MEASUREMENTS OF NEUTRAL AND IONIZED FE LINES OVER THE 18 EPOCHS LISTED IN TABLE 1

| Wave. (Å) | Spec. | LEP (eV) | log g | EW15Oct97 (mÅ) | EW13Sep00 (mÅ) | EW21Apr08 (mÅ) | EW13Jun08 (mÅ) | EW11Jul08 (mÅ) | EW10Aug08 (mÅ) | EW17Aug08 (mÅ) | EW17Sep08 (mÅ) | EW14Apr09 (mÅ) |
|-----------|-------|---------|------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| 4484.23   | 26.0  | 3.60    | −0.86| 89.7           | 89.4           | 118.6          | 120            | 128.8          | −              | −              | −              | −              |
| 4602.95   | 26.0  | 1.49    | −2.22| 277.7          | 142.9          | 152.3          | 156.3          | 152.7          | 136.5          | 119.6          | −              | −              |
| 4643.47   | 26.0  | 3.65    | −1.15| 46.3           | 28.5           | 37.8           | 47.1           | 32.5           | 51.1           | 29.9           | −              | −              |
| 5090.77   | 26.0  | 4.26    | −0.44| 76.7           | 73.8           | 54.3           | 105.1          | 98.9           | 118.4          | 87.9           | −              | −              |
| 5353.37   | 26.0  | 4.10    | −0.68| 103.9          | 55.6           | 64.0           | 77.9           | −              | 70.4           | 66.2           | 45.6           | 63.6           |
| 5364.88   | 26.0  | 4.45    | 0.23 | 209.0          | 148.8          | 145.0          | 167.4          | 158.0          | 152.4          | 147.4          | 117.3          | 134.2          |
| 5367.48   | 26.0  | 4.42    | 0.44 | 215.4          | 144.6          | 196.0          | 172.5          | 161.0          | 154.7          | 149.8          | 137.3          | 160.5          |
| 5373.71   | 26.0  | 4.47    | −0.84| 14.8           | 12.4           | 17.4           | 21.6           | 19.3           | 21.9           | 11.4           | 24.0           | −              |
| 5393.18   | 26.0  | 3.24    | −0.72| 103.7          | 147.7          | 130.9          | 128.9          | 121.8          | 114.5          | 88.4           | 180.9          | −              |
| 5434.53   | 26.0  | 1.01    | −2.12| 273.5          | 213.4          | 284.9          | 257.9          | 213.0          | 228.3          | 213.5          | 190.3          | 226.2          |
| 5569.63   | 26.0  | 3.42    | −0.49| 175.2          | 108.9          | 135.0          | 152.9          | 143.2          | 138.5          | 137.5          | 107.5          | 119.8          |
| 5572.85   | 26.0  | 3.40    | −0.28| 178.0          | 154.4          | 194.8          | 201.9          | 187.7          | 187.2          | 181.7          | 162.1          | 179.6          |
| 5816.38   | 26.0  | 4.55    | −0.60| 33.3           | 36.0           | 38.0           | 33.6           | 30.4           | 26.3           | 35.7           | 21.2           | 26.8           |
| 6020.17   | 26.0  | 4.61    | −0.21| 57.3           | 28.9           | 42.5           | 48.7           | 54.6           | 41.1           | −              | 27.8           | 39.0           |
| 6024.07   | 26.0  | 4.55    | −0.06| 101.1          | 68.3           | 87.3           | 94.8           | 92.2           | 82.2           | −              | 68.2           | 77.6           |
| 6027.06   | 26.0  | 4.08    | −1.09| 51.7           | 25.6           | 42.9           | 46.3           | 43.6           | 34.8           | −              | 22.8           | 32.2           |
| 6065.49   | 26.0  | 2.61    | −1.53| 52.9           | 64.6           | 80.2           | 63.6           | 60.2           | −              | 34.0           | 50.5           | −              |
| 6393.61   | 26.0  | 2.43    | −1.58| −              | 91.0           | 99.1           | 82.6           | 76.3           | −              | 47.0           | 60.4           | −              |
| 6411.66   | 26.0  | 3.65    | −0.72| 70.1           | 88.1           | 101.1          | 91.8           | 86.1           | −              | 68.9           | 76.9           | −              |
| 6592.91   | 26.0  | 2.73    | −1.47| −              | 70.5           | 97.2           | 57.2           | 60.9           | −              | −              | 47.8           | −              |
| 6814.34   | 26.0  | 4.61    | −0.60| −              | 37.8           | 42.6           | 39.5           | 36.8           | −              | −              | −              | −              |
| 4893.82   | 26.1  | 2.83    | −4.27| 272.3          | 222.9          | 228.5          | 229.8          | 212.7          | 211.9          | 221.8          | −              | −              |
| 5427.80   | 26.1  | 6.72    | −1.58| 74.1           | 94.6           | 115.5          | 86.9           | 74.0           | 72.0           | 89.1           | 83.0           | 76.6           |
| 5813.67   | 26.1  | 5.57    | −2.75| 68.4           | 65.6           | 83.2           | 83.9           | 78.4           | 79.2           | 85.5           | 85.0           | 77.6           |
| 5823.83   | 26.1  | 5.57    | −2.99| 59.1           | 33.0           | 47.1           | 66.8           | 48.7           | 45.7           | 49.9           | 37.9           | 54.3           |
| 5991.38   | 26.1  | 3.15    | −3.65| 242.6          | −              | 215.8          | 295           | 245.2          | 250.6          | 239.1          | 248.1          | 253.5          |
| 6113.33   | 26.1  | 3.22    | −4.23| 133.7          | 125.8          | 145.7          | 145.7          | 130.5          | 131.6          | −              | 129.4          | 138.9          |
| 6129.73   | 26.1  | 3.20    | −4.74| 118.8          | 103.1          | 90.1           | 104.1          | 96.4           | 87.7           | −              | 72.4           | 67.3           |
| 6179.40   | 26.1  | 5.57    | −2.80| 85.4           | 76.8           | 82.4           | 58.0           | 69.1           | −              | 56.8           | 66.6           | −              |
| 6446.40   | 26.1  | 6.22    | −2.08| −              | 86.0           | 97.5           | 98.7           | 104.6          | −              | 74.9           | 92.9           | −              |
Table A2. EW measurements of neutral and ionized Fe lines over the 18 epochs listed in Table 1.

| Wave. (Å) | Spec. | LEP | log $g_f$ | EW 9May09 (mÅ) | EW 7Nov09 (mÅ) | EW 21Nov09 (mÅ) | EW 22May10 (mÅ) | EW 3Jun10 (mÅ) | EW 24Sep10 (mÅ) | EW 17Nov10 (mÅ) | EW 16May11 (mÅ) | EW 27Aug13 (mÅ) |
|-----------|-------|-----|-----------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| 4484.23   | 26.0  | 3.60| −0.86     | 102.8          | −              | 174.2          | 167.1          | −              | 74.8           | −              | −              | 151.2          |
| 4602.95   | 26.0  | 1.49| −2.22     | 151.2          | −              | 146.6          | 197.6          | −              | 115.1          | −              | −              | 155.6          |
| 4643.47   | 26.0  | 3.65| −1.15     | 47.8           | −              | 34.3           | 45.8           | −              | 20.4           | −              | −              | 36.3           |
| 5090.77   | 26.0  | 4.26| −0.44     | 101.1          | −              | 115.0          | 121.2          | −              | 60.9           | −              | −              | 69.5           |
| 5353.37   | 26.0  | 4.10| −0.68     | 77.2           | 60.7          | 69.0           | 102.6          | 93.3          | 56.0           | 70.4          | 94.7           | 72.4           |
| 5364.88   | 26.0  | 4.45| 0.23      | 157.0          | 147.5          | 179.8          | 192.0          | 181.5          | 121.1          | 148.0          | 218.8          | 178.7          |
| 5367.48   | 26.0  | 4.42| 0.44      | 190.7          | 146.4          | 160.3          | 188.1          | 188.0          | 140.6          | 158.9          | 221.0          | 168.1          |
| 5377.91   | 26.0  | 4.47| −0.84     | 26.5           | 15.9           | 27.4           | −              | 26.6           | 24.7           | 19.7           | 22.5           | 27.1           |
| 5393.18   | 26.0  | 3.24| −0.72     | 133.9          | 98.9           | 126.6          | 168.7          | 153.1          | 102.5          | 112.0          | 157.0          | 127.2          |
| 5434.53   | 26.0  | 1.01| −2.12     | 234.4          | 218.0          | 196.6          | 316.9          | 315.2          | 200.1          | 238.8          | 301.7          | 230.0          |
| 5569.66   | 26.0  | 3.42| −0.49     | 149.4          | 126.5          | 143.4          | 154.0          | 175.7          | −              | 137.5          | 176.6          | 148.5          |
| 5572.85   | 26.0  | 3.40| −0.28     | 209.4          | 194.2          | 185.6          | 227.1          | 219.5          | −              | 181.9          | 224.0          | 199.6          |
| 5816.38   | 26.0  | 4.55| −0.60     | 35.0           | −              | 23.8           | 45.0           | 34.8           | −              | 27.1           | 39.1           | 28.4           |
| 6020.17   | 26.0  | 4.61| −0.21     | 56.9           | −              | 46.5           | 66.4           | 62.1           | −              | 43.7           | 75.1           | 46.2           |
| 6024.07   | 26.0  | 4.55| −0.06     | 96.8           | −              | 96.4           | 107.6          | 102.8          | −              | 87.5           | 108.3          | 85.1           |
| 6027.06   | 26.0  | 4.08| −1.09     | 43.5           | −              | 33.3           | 59.5           | 52.0           | −              | 33.3           | 52.8           | 39.1           |
| 6065.49   | 26.0  | 2.61| −1.53     | 70.0           | −              | 65.1           | 93.4           | 93.5           | −              | 62.1           | 87.9           | 60.9           |
| 6393.61   | 26.0  | 2.43| −1.58     | 87.3           | −              | 83.3           | 124.7          | 112.4          | −              | 70.9           | 119.2          | 68.8           |
| 6411.66   | 26.0  | 3.65| −0.72     | 98.6           | 66.6           | 88.9           | 111.8          | 100.3          | −              | 86.6           | 104.8          | 87.4           |
| 6592.91   | 26.0  | 2.73| −1.47     | 71.7           | −              | 58.7           | 106.9          | 87.7           | −              | 64.6           | 102.0          | 68.1           |
| 6841.34   | 26.0  | 4.61| −0.60     | 50.3           | −              | 18.8           | 40.1           | −              | −              | −              | −              | 51.3           |
| 4893.82   | 26.1  | 2.83| −4.27     | 238.5          | −              | 228.4          | 212.5          | −              | 230.1          | −              | −              | 252.2          |
| 5427.80   | 26.1  | 6.72| −1.58     | 91.1           | 80.9           | 95.4           | 91.0           | 85.4           | 98.1           | 81.1           | 95.7           | 88.3           |
| 5813.67   | 26.1  | 5.57| −2.75     | 86.4           | −              | 83.7           | 93.1           | 70.9           | −              | 88.3           | 82.8           | 94.9           |
| 5823.18   | 26.1  | 5.57| −2.99     | 67.9           | −              | 44.4           | 63.2           | 50.8           | −              | 38.5           | 46.0           | 42.3           |
| 5991.38   | 26.1  | 3.15| −3.65     | 223.0          | −              | 266.0          | 281.5          | 286.0          | −              | 240.7          | 264.4          | 268.7           |
| 6113.33   | 26.1  | 3.22| −4.23     | 137.7          | −              | 145.4          | 147.2          | 152.2          | −              | 133.5          | 143.4          | 132.6           |
| 6129.73   | 26.1  | 3.20| −4.74     | 111.0          | −              | 105.6          | 118.2          | −              | 89.8           | 101.8          | 95.5           | 106.5           |
| 6179.40   | 26.1  | 5.57| −2.80     | 69.4           | −              | 76.3           | 68.3           | 74.7           | −              | 71.2           | 80.6           | 80.2           |
| 6446.40   | 26.1  | 6.22| −2.08     | 89.4           | 89.6           | 97.1           | 103.2          | 91.5           | −              | 85.4           | 86.6           | 74.3           |

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