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Atmospheric Abundances of Light Elements in the F-Type Star Procyon

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Abstract

High-dispersion spectra in the near-infrared region of the F-type star Procyon (α CMi, F5 IV–V) were obtained and the absorption lines of eight light elements, including phosphorus P and potassium K were analyzed with ATLAS9 model atmospheres. The LTE abundance was found to be solar for N, Mg, Al, Si, and P, which is consistent with previous studies in the visible region. However, two C I lines, triplet lines of O I at λ7771–5 Å, and the resonance line of K I at λ7699 Å are fairly strong; their estimated LTE abundances are greater than the solar values by more than 0.2 dex. These discrepancies are discussed in terms of non-LTE line formation.

Key words: Stars: abundances — Stars: atmospheres — Stars: invidual (Procyon)

1. Introduction

This paper discusses the abundance analysis of light metals (with atomic number Z smaller than 20) in the atmosphere of the F-type spectroscopic standard star Procyon (α CMi = HR 2943 = HD 61421). This work was initiated in an attempt to extend our previous abundance analyses of Procyon (Kato, Sadakane 1982, 1986; Kato 1987) into the near-infrared region and to detect absorption lines of light elements so far unexplored in this star.

Most of the deduced abundances of light elements in the atmosphere of Procyon have values very close to those of the Sun. Exceptions are light elements, such as Li and Be (e.g., Conti, Danziger 1966; Boesgaard 1976). Extensive abundance analyses made by Griffin (1971), Kato and Sadakane (1982), Steffen (1985), and Lane and Lester(1987) include such elements as C, N, O, Na, Mg, Al, Si, and S. Tomkin and Lambert (1978) and Altas (1987) studied the abundances of C, N, and O. They found that their abundances are very close to the solar values. In their elaborate work for 189 F and G disk dwarfs, Edvardsson et al. (1993) obtained the abundances of 13 elements, whose deviations from solar values are within 0.11 dex. Takeda (1992, 1994) recently carried out detailed investigations of non-LTE effects for neutral lines of C, N, and O in this star, demonstrating fairly large deviations from LTE, amounting to 0.36 dex for stronger lines.

2. Observations and Data Reduction

Spectroscopic observations of Procyon in the near-infrared region, ranging from 6700 Å to 9800 Å, were carried out during a nine-night observing run in 1994 February, with the 0.65 m solar coudé telescope at the Okayama Astrophysical Observatory, a branch of the National Astronomical Observatory of Japan. The spectrograph was used with a 1200 groove mm^{-1} grating, and the spectra were recorded with a LN$_2$-cooled CCD camera of Osaka Kyoiku University. The CCD (EEV 88200) has an effective imaging area of 1152 × 790 pixels, and the pixel size is 22.5 μm. This configuration yielded a linear dispersion of 0.017 Å pixel^{-1} = 0.72 Å mm^{-1}. The shutter durations of individual stellar exposures were fixed at 10 min. The spectral resolution, defined as the FWHM of thorium-argon lines, was close to 45 mÅ, corresponding to 2.7 pixels on the CCD chip.

Data reduction was carried out using the IRAF software following the standard procedure, including bias subtraction, trimming, flat-fielding, and extracting stellar and comparison spectra into one-dimensional data. The wavelength calibration was carried out with Th–Ar comparison lines. Individual stellar spectra were adjusted in the wavelength scale, and then co-added in order to increase the S/N ratio. The measured S/N ratio in our final spectrum is about 150. This was certainly valid when we could achieve complete flat-fielding. In some cases, weak wavy interference patterns, which were

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Table 1. Effective tempeartures derived from various methods.*

Integrated flux	6510(1)	6520(2)	6427(9)	6420(9)	6560(16)
IR flux method	6359(3)	6421(5)	6601(10)		
Bolometric correction	6450(9)				
Continuum flux visual	6500(6)	6650(9)	6550(9)	6560(13)	
Continuum flux visual–UV	6400(8)	6500(11)			
Continuum flux UV	6340(15)				
Four color $(b-y)$	6600(4)	6650(6)	6650(12)	6704(14)	
UBVRIJKL colors	6470(9)				
13 colors	6500(9)				
UV color	6550(7)	6370(13)			
$R-I$ color	6500(13)				

* The number in parentheses indicates reference.

1. Code et al. (1976)
2. Beeckmans (1977)
3. Blackwell and Shallis (1977)
4. Tomkin and Lambert (1978)
5. Blackwell et al. (1980)
6. Kato and Sadakane (1982)
7. Böhm-Vitense (1982)
8. Lane and Lester (1984)
9. Steffen (1985)
10. Saxner and Hammarbäck (1985)
11. Theodossiou (1985)
12. Moon and Dworetsky (1985)
13. Kato and Kuroda (1992)
14. Edvardsson et al. (1993)
15. Sokolov (1995)
16. Smalley and Dworetsky (1995)

probably produced in the thin surface layer of the CCD chip or in the cover glass of the dewer, remained on the final spectra. Unfortunately, we failed to completely remove the wavy pattern in the region of the O I triplet lines near to 7774 Å.

3. Abundance Analysis

The equivalent widths of the absorption lines for light metals were measured using an IRAF routine *splot.* We also measured the Fe I lines in order to utilize them for checking the result of abundance computations.

We adopted a set of model parameters: ($T_{\rm eff}$, log g, $\xi_{\rm t}$) = (6500 K, 4.0, 1.8 km s^{-1}). The surface gravity log g and microturbulent velocity $\xi_{\rm t}$ were the same as those used in Kato and Sadakane (1982), while the effective temperature $T_{\rm eff}$ was lower by 150 K. In table 1, we summarize the effective temperatures of Procyon derived by various methods within the past 20 years. The simply averaged effective temperature and RMS scatter are 6512 K and 97.0 K, respectively. We can see that the temperatures deduced from flux data point toward $T_{\rm eff}$ $\sim$ 6500 K, while those from the $(b-y)$ index indicate a higher value. Kato and Sadakane (1982) found that the effective temperature of Procyon determined from flux data is cooler by 100 K – 400 K than that deduced from the ionization balance of iron-group elements. This discrepancy in the effective temperature was also found by Steffen(1985). During the final stage of the abundance analysis, Kato and Sadakane (1982) as well as Steffen (1985) chose $T_{\rm eff}$ = 6650 K and 6750 K, respectively, to minimize the abundance differences between those derived from neutral and from ionized species. However, the stellar effective temperature should be determined from the flux data following its definition. Therefore, we adopted $T_{\rm eff}$ = 6500 K in this study. Further discussions concerning the effective temperature of Procyon are given in Lane and Lester (1984, 1987) as well as Drake and Martin Laming (1995).

Most of the gf values for each line were taken from the literature. When reliable data were not available, solar gf values were empirically deduced from the equivalent widths measured on the Solar Flux Atlas from 296 to 1300 nm (Kurucz et al. 1984).

To calculate the elemental abundances, fully line-blanketed ATLAS9 model atmospheres (Kurucz 1993) were used, which were computed by adopting the convection of mixing length l/H = 1.25 (H represents the pressure scale height) and the solar metallicity. The elemental abundances were computed using the program WIDTH9, a companion to the program ATLAS9, assuming LTE line formation.

Table 2 contains an analysis of the light elemental lines in Procyon. The consecutive columns give the wavelengths (in Å), lower excitation potentials (in eV), log gf values, sources of the gf values, the measured equivalent widths (in mÅ, the lines with lower accuracy are marked with a colon), the derived LTE abundances [in the usual scale where log ε(H)= 12.00], and the solar-abundance values. All of the solar abundances were taken from Anders and Grevesse (1989), except for iron. The solar iron abundance is from Holweger et al. (1995). For recent

Table 2. Measured equivalent widths and derived LTE abundances.*

Species	λ(Å)	χ(eV)	log gf	Ref†	W_λ (mÅ)	log ε	log ε(Sun)
C I							8.60
	8335.13	7.68	−0.46	BHGV	203:	8.81:	
	9111.80	7.49	−0.32	BHGV	270:	8.86:	
N I							8.00
	8216.35	10.34	0.147	HBGV	31	8.13	
O I							8.93
	7771.94	9.15	0.35	BHGVF	174:	9.37:	
	7774.17	9.15	0.21	BHGVF	155:	9.32:	
	7775.39	9.15	−0.02	BHGVF	124:	9.19:	
Mg I							7.58
	8213.03	5.75	−0.67	sol	100	7.54	
Al I							6.47
	6695.97	3.14	−1.60	BC	21	6.48	
	6698.42	3.14	−1.90	BC	12	6.52	
	7835.39	4.02	−0.68	sol	26	6.37	
	7836.15	4.02	−0.54	sol	38	6.46	
Si I							7.55
	8215.15	6.26	−0.90	sol	27	7.45	
P I							5.45
	9750.75	6.95	−0.17	BMQZ	9:	5.29:	
	9796.91	6.99	0.26	BMQZ	23	5.37	
K I							5.12
	7698.96	0.00	−0.168	M	138	5.51	
Fe I							7.51
	6703.56	2.76	−3.060	MRW	15	7.51	
	6705.10	4.61	−1.073	CCC	28	7.47	
	7832.24	4.43	0.018	K	98	7.37	
	8220.44	4.32	0.249	K	124	7.32	
	9800.36	5.09	−0.394	K	83	7.88	

* Values of lower accuracy are marked with a colon.

† gf values references.

BC : Burkhart and Coupry (1989)
BMQZ : Biémont et al. (1994)
M : Morton (1991)
sol : solar gf values
BHGV : Biémont et al. (1993)
CCC : Cayrel et al. (1985)
MRW : May et al. (1974)
BHGVF : Biémont et al. (1991b)
HBGV : Hibbert et al. (1991)
K : Kurucz (1994)

investigations of solar iron, see, for instance, Biémont et al. (1991a), Holweger et al. (1991), Blackwell et al. (1995), and Holweger et al. (1995).

4. Abundance Results

4.1. C I

Two fairly strong neutral carbon lines were analyzed. The van der Waals interaction with hydrogen atoms is important for these lines, and an enhancement of $\Delta \log C_6 = +1.0$ is applied to the collisional damping term in the WIDTH9 program. This correction factor was empirically determined in order to bring the abundances derived from the weak lines and those from the strong lines into agreement for the Sun. The solar line data for neutral carbon were taken from Biémont et al. (1993). The resulting carbon abundance in Procyon is higher by 0.24 dex with respect to the Sun, contradicting the previous results.

From an analysis of the near-infrared C I lines, Tomkin and Lambert (1978) deduced the solar abundance for carbon in Procyon. Studies of the neutral carbon lines in the visual region also show the solar abundance. According to Steffen (1985), the logarithmic abundance relative to the Sun is −0.03. Altas (1987) and Kato (1988) concluded that although the carbon in Procyon is slightly underabundant, the dicrepancy disappears after applying new gf values of Biémont et al. (1993). From an analysis of the forbidden line at λ8727.13 Å, Andersson and Edvardsson (1994) gives a logarithmic carbon abundance with respect to the Sun $[\varepsilon(\mathrm{C})]$ of −0.01. Based on the observation of 7100 Å C I lines, Tomkin et al. (1995) obtained a $[\varepsilon(\mathrm{C})]$ value of −0.22 by adopting model parameters of (T_{eff}, log g) = (6704, 4.03). The abundance will increase to $[\varepsilon(\mathrm{C})] = -0.10$ when we make a calculation employing the same line data and model parameters (T_{eff}, log g) = (6500, 4.0) as those used in the present analysis.

The departure from LTE for the C I lines in Procyon was investigated by Takeda (1994). His non-LTE computations found no significant departures from LTE for the weak C I lines ($W_\lambda \leq 52$ mÅ). However, his recent computations (Takeda 1995, private communication) including the strong C I lines show that non-LTE effects are fairly large for the two lines in table 2, where the corrections are 0.23 and 0.38 dex for the 8335.13 and 9111.80 Å lines, respectively. After the correction for the non-LTE effects noted above, the final carbon abundance would be solar, which is consistent with the previous studies.

4.2. N I

We used a weak neutral nitrogen line at 8216.35 Å. Its equivalent width (31 mÅ) is slightly larger than the measurement (26 mÅ) given in Tomkin and Lambert (1978). The derived abundance of nitrogen seems to be somewhat higher than that in the Sun. According to Takeda (1994), the non-LTE correction for this line is 0.11 dex in Procyon. His elaborate work using a very detailed model atom of nitrogen shows that the non-LTE effect in the atmosphere of Procyon reduces the abundance systematically with respect to the LTE abundance from 0.09 to 0.13 dex, even for weak lines ($W_\lambda = 12$–32 mÅ). By applying the non-LTE correction to the value given in table 2, an agreement with the solar nitrogen abundance was achieved.

4.3. O I

The oxygen abundance was derived from the strong triplet lines at 7771–5 Å. We used the radiative damping, log $\gamma_{\mathrm{rad}} = 8.04$; the Stark broadening, log $C_4 = -14.46$; and the van der Waals broadening, log $C_6 = -30.87$, following Baschek et al. (1977). The spectral data in this region suffered from interference features produced in the thin surface layer of the CCD chip. Even if we take the uncertainty due to the noise into account, the abundances derived from these lines are evidently higher than the solar value. The differences range from +0.27 to +0.44 dex, corresponding to the estimation of [O(7774)/O(6300)] = 0.35 dex (normalized to the Sun) by Nissen and Edvardsson (1992). Since it is well known that the O I triplet lines are fairly strong in early-type stars, especially in supergiants, they have been used as a luminosity indicator. The unusual strength is now explained as an effect of departures from local thermodynamic equilibrium (e.g., Baschek et al. 1977; Eriksson, Toft 1979; Faraggiana et al. 1988; Kiselman 1991, 1993; Takeda 1992; Nissen, Edvardsson 1992). Takeda (1992, 1994) performed detailed non-LTE computations of the O I triplet lines for Procyon by adopting a realistic model atom of oxygen (86 terms and 294 transitions), and found that the LTE abundances deduced from the triplet were overestimated by 0.3 to 0.4 dex. Previous LTE studies in the visual region (Griffin 1971; Tomkin, Lambert 1978; Steffen 1985; Altas 1987; Kato 1988) show no significant departure from the solar composition. The apparent overabundance of oxygen given in table 2 can be interpreted as the effect of non-LTE. The correction necessary to the LTE abundance is around ∼ 0.3 dex, which is much less than the results of, for example, Baschek et al. (1977), and is very close to those of Takeda (1992, 1994).

4.4. Mg I, Al I, and Si I

The solar gf values for the Mg I and Si I lines were obtained from the equivalent widths (151 and 41 mÅ for Mg I and Si I lines, respectively) measured on the Solar Flux Atlas (Kurucz et al. 1984) by adopting the ATLAS9 solar model atmosphere, where a microturbulence of 0.85 km s^{-1}, an enhancement of $\Delta \log C_6 = +1.0$, and the solar composition given by Anders and Grevesse (1989) were used. For the two Al I lines at 7835.39 Å and 7836.15 Å, their solar gf values were also derived in the same way. The final abundances for these elements are consistent with those obtained in the visible region, and coincide with the solar abundances.

4.5. P I

The two lines of P I were identified and used in the present analysis. Since the weaker line at 9750.75 Å is located on a noisy continuum, its equivalent width may be less reliable. The derived abundance of phosphorus appears to be slightly underabundant when compared to that of the Sun. More analyses based on higher quality data are necessary to confirm this conclusion.

4.6. K I

The LTE abundance of potassium has been determined from the strong resonance line of K I at 7698.96 Å by applying $\Delta \log C_6 = +1.0$ to the van der Waals damping term. The resulting abundance, log $\varepsilon(\mathrm{K}) = 5.51$, is fairly larger than the solar value of 5.12. Bedford et al. (1994) measured the weak magnetic fields of Procyon by observing the circular polarization in the wings of this potassium line. The measured magnetic fields were so weak that no significant enhancement of the line due to the Zeeman splitting is expected (e.g., Takeda 1993).

Table 3. Comaprison of the derived abundances relative to the Sun.*

Species	N		This study	TL78	KS82	S85	A87	LL87	E93
		$T_{\rm eff}$	6500	6600	6650	6750	6500	6400	6704
		log g	4.0	4.0	4.0	4.04	4.0	3.95	4.03
		$\xi_{\rm t}$	1.8	2.0	1.8	2.1	2.1	1.80	2.4
C I	2		+0.22	+0.07	...	−0.03	−0.16	...	...
N I	1		+0.13	+0.07	...	+0.07	−0.02	...	...
O I	3		+0.36	+0.07	...	−0.08	−0.13	...	−0.05
Mg I	1		−0.04	...	−0.04	+0.07	...	−0.24	+0.07
Al I	4		−0.01	...	−0.05	−0.01	...	+0.40	0.00
Si I	1		−0.10	...	0.00	+0.12	...	−0.07	+0.01
P I	2		−0.12	...	...	...	...	...	...
K I	1		+0.39	...	...	...	...	...	...
Fe I	5		0.00	−0.14	−0.01	−0.02	...	−0.11	−0.02

* N is the number of lines used in this analysis.

TL78: Tomkin and Lambert (1978) KS82: Kato and Sadakane (1982) S85 : Steffen (1985)
A87 : Altas (1987) LL87: Lane and Lester (1987) E93 : Edvardsson et al. (1993)

It is unlikely that potassium is heavily overabundant in the atmosphere of Procyon, because no other metallic elements show such a large anomaly. It is reasonable to assume that the overabundance is due to the non-LTE effect which appeared in the strong resonance line. Takeda's recent non-LTE computation demonstrates that the line at 7698.96 Å is very sensitive to the radiation field in the atmosphere of Procyon, and its correction to the LTE abundance amounts to ∼ 0.7 dex !

We can therefore conclude that the overabundance of potassium given in table 2 is superficial due to the non-LTE effect. Details concerning a non-LTE analysis of the K I line are discussed in a separate paper (Takeda et al. 1996).

4.7. Fe I

The gf values for the Fe I lines in table 2 were taken from May et al. (1974), Cayrel et al. (1985, solar gf values), and Kurucz (1994). The averaged iron abundance derived after applying $\Delta \log C_6 = +1.0$ is 7.51, which is in good agreement with previous analyses and identical to the current solar value.

5. Conclusions

The final LTE abundances of eight light elements in Procyon with respect to the Sun are summarized in table 3 together with the results of previous studies. Fairly good agreements are found, except for C and O, which probably reflect the non-LTE effect. The iron abundance is also solar one, which indicates that our analysis is consistent with previous studies. Some of the remaining abundance differences are partly due to the choice of the model parameters, as well as the atmospheric structure corresponding to these parameters. A difference of 500 K in the effective temperature changes the abundance from 0.01 to 0.38 dex, depending on the elements. Particularly, neutral nitrogen, potassium, and iron are very sensitive to a change in the effective temperature. Taking into account the ambiguities involved in an abundance analysis, we conclude that the final abundances including newly derived phosphorus and potassium are solar. The apparent overabundances of carbon, oxygen, and potassium deduced from the stronger lines are caused by a departure from LTE for these lines.

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