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On the cobalt abundances of early-type stars

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Abstract. Photographic region high-dispersion high signal-to-noise spectra of A and F main sequence band stars which exhibit modest rotation show Co I lines. In the hottest of these stars, we also found weak Co II lines whose abundances are consistent with those from Co I lines. As a class the Am stars have cobalt abundances which are greater than solar while the normal stars have solar values.

Key words: stars: abundances – stars: chemically peculiar

1. Introduction

The stellar photospheric elemental abundances of the heavier iron peak elements are often less well known than those of the lighter iron peak elements. We study cobalt as an example. Both iron and cobalt have similar ionization potentials for their neutral atoms, 7.902 and 7.881 eV, respectively, and their singly ionized atoms, 16.16 eV and 16.98 eV, respectively. Thus their ionization fractions should be similar. However, there is a large difference in their cosmic abundances, a factor of 2.58 dex or 380 to 1. Two magnetic Chemically Peculiar (mCP) stars with very strong Co II lines in their spectrum HR 1094 (Sadakane 1992, Hill & Blake 1996) and HR 5049 (Dworetsky et al. 1980) are known. Both stars exhibit moderately broadened lines presumably due to rotation. Co II lines have been reported in other mCP stars including HD 200311 (Adelman 1974) and HD 110066 (Adelman & Adelman 1988). But why they are found in these mCP stars and not in others is not known. The appearance of Co II lines in the optical region spectra of normal stars is not well documented.

2. The spectrograms

The data examined were 2.4 Å mm^{-1} spectrograms, obtained with the coudé spectrograph of the 1.22-m telescope of the Dominion Astrophysical Observatory, which had been gathered for studies of normal and peculiar B, A, and F stars (see, e.g., Adelman 1998). They include coadditions of photographic IIa-O spectrograms with typical S/N of 80 and spectral coverage of $\lambda\lambda$3700–4640 and more recent spectrograms obtained with electronic Reticon and CCD detectors with typical S/N of 200 and spectral coverage usually of $\lambda\lambda$3830–4770. Many stars were sharp-lined with most of the rest having moderate rotational velocities. Only a few stars had v sin i values $\geq$ 50 km s^{-1}. In addition to the spectra of stars whose analyses had been published, we also examined those of stars whose set of electronic spectrograms is still incomplete or whose analyses had been started. The latter category includes S/N = 500+ spectrograms of γ Gem (A0 IV) and o Peg (A1 IV), both of which are ultra-sharp-lined stars.

Of the analyzed stars, those with derived abundances from at least two Co I lines had effective temperatures less than 9500 K. An examination of the spectra of the sharp-lined stars showed that two Co I lines were both very persistent and relatively blended free: λ3995.31 of multiplet 31 and λ4121.32 of multiplet 28. These lines are among those in the optical region with the strongest measured gf values (Fuhr et al. 1988). Their log gf values of -0.22 and -0.32, respectively, from Cardon et al. (1982), have accuracies of C+ and C (25% uncertainty), respectively. Further, their strengths (equivalent widths) correlate with those of other Co I lines.

Table 1 lists those stars with clearly present Co I lines. Effective temperatures and surface gravities using Strömgren uvbyβ photometry from Hauck & Mermilliod (1980) and the program of Napiwotzki et al. (1993) based on Moon & Dworetsky (1985) are also given. These values for normal stars have errors of $\pm$150 K and $\pm$0.2 dex, respectively (Lemke 1989). For the magnetic CP stars γ Equ and HR 8216, the errors may be larger. The spectral types and v sin i values from Hoffleit (1982) are inhomogeneous. With modern high dispersion spectrograms, many of the latter values are found to be too large. Still they indicate that stars with identifiable Co I lines have v sin i values less than about 55 km s^{-1}.

Two weak Co I lines with the same excitation potential and oscillator strength will have the same equivalent width. But if one of these lines has a significantly narrower hyperfine structure pattern, it will be easier to detect in sharp-lined stars. For strong lines the hyperfine structure delays saturation and should be included in the abundance derivations when it is known.

Grevesse et al. (1996) give the solar photospheric abundance of cobalt as log Co/N$_H$ = -7.08 ± 0.04. If we use this value and

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Table 1. Stars with Co I lines

Name	HR	T_{eff}	log g	Spectral Type	v sin i ($km\,s^{-1}$)
99 Her	6775	6052	3.41	F7V	3
ι Psc	8969	6177	3.95	F7V	6
γ Ser	5933	6302	4.22	F6V	8
η Ari	646	6422	3.95	F5V	9
α Per	1017	6481	3.52	F5Ib	18
Procyon	2943	6686	3.95	F5IV-V	6
σ Boo	5447	6744	4.35	F2V	3
θ Cyg	7469	6808	3.95	F4V	7
τ UMa	3624	6982	3.95	Am	18
η Lep	2085	7048	3.95	F1III	0
11 Del	7928	7113	3.50	A7IIIpδDel	41
HD 204485	8220	7242	4.27	F0V	...
28 And	114	7258	3.95	A7III	21
20 CVn	5017	7546	4.22	F3III	17
32 Aqr	8410	7851	3.61	A5m	19
γ Equ	8097	7872	3.67	F0p	8
15 Vul	7653	8041	3.61	A4III	23
2 UMa	3354	8053	3.95	A2m	17
τ^7 Ser	5845	8215	4.22	A2m	20
95 Leo	4564	8331	4.22	A3V	54
HD 204411	8216	8528	3.52	A6pCrEu:	9
68 Tau	1389	9025	3.95	A2IV	18
60 Leo	4300	9053	4.22	A1m	24
	6455	9134	3.46	A3III	11
γ Gem	2421	9227	3.67	A0IV	32
o Peg	8541	9591	3.64	A1IV	12

then predict the equivalent widths of the Co I λ3995.31 and λ4121.21 lines using the program WIDTH9 (Kurucz 1993), these lines have equivalent widths of order 1 mÅ for T_{eff} = 10000 K and main sequence band surface gravities (log g = 3.50 to 4.00). This is consistent with the stars in Table 1 being cooler than 10000 K as we can detect lines with equivalent widths of 0.5 mÅ in S/N = 500 spectra for sharp-lined stars.

3. A search for Co II lines

Pickering et al. (1998) recently reanalyzed the spectrum of Co II, determining the energy levels from the line spectrum. This study considerably extended previous studies particularly those of Iglesias (1972, 1979). Still it is very difficult to determine which Co II lines should be the strongest in A and F stars from Pickering et al. The only relatively comprehensive source of gf values is the semiempirical calculations of Kurucz (1994) which used the energy levels of Iglesias. As the strongest photographic region lines are likely to be produced from transitions between these levels, the omission of any recently found lines is probably not critical. However, the derived gf values may be systematically affected.

As for Co I, we calculated the expected equivalent widths for Co II lines for main sequence band stars with a solar Co abundance. The strongest lines had equivalent widths of a few mÅ. Thus it is likely that such lines can be found and used to derive abundances. Examining our two hottest stars with Co I lines γ Gem and o Peg, meant looking at the worst possible cases in terms of equivalent width. But major compensating factors were that the stars are very sharp-lined ($\leq$ 7 km s^{-1}) and the spectra had the highest S/N ratios of our study. Table 2 gives information on Co II lines in these stars and shows that there are 2 or 3 non-blended lines for each star.

Table 2. Search for Co II lines in γ Gem and o Peg

Laboratory λ (Å)	Stellar λ (Å)	W_λ (mÅ)	Blends and Comments
γ Gem			
3983.02	3982.995	1.9	
4040.03	4040.115	4.2	Zr II(54)4040.24(12)
4145.12	4145.113	3.2	S II(44)4145.067(22)
4160.67	4160.658	8.2	Fe II(39)4160.62(p)
4516.63	4516.702	5.4	
4533.21	4533.285	4.8	Ti I(42)4533.238(80)
4660.66	4660.740	2.1	slightly broad
o Peg			
3983.02	3983.009	3.5	from coaddition of plates
4040.03	4040.115	7.0	Zr II(54)4040.24(12)
4145.12	4145.129	10.1	S II(44)4145.067(22)
4160.67	4160.645	18.0	Fe II(39)4160.62(p)
4516.63	4516.635	3.3	
4533.21	4533.230	2.3	Ti I(42)4533.238(80)
4660.66	4660.660	3.5	

4. Cobalt abundances

To derive the abundances of cobalt from both neutral and singly lined lines, the effective temperature, surface gravity, microturbulence, and metallicity need to be adopted for each star. Adelman et al. (in preparation) have recently derived effective temperatures and surface gravities by comparing predicted fluxes and synthesized Hγ spectral regions with observations. For solar compositions they find T_{eff} = 9150 K, log g = 3.60 for γ Gem and T_{eff} = 9525 K, log g = 3.70 for o Peg, values close to those in Table 1. As the lines are weak, microturbulence is unimportant. Nevertheless we used 2.0 $km\,s^{-1}$ (Adelman & Philip 1996) for γ Gem and 1.3 $km\,s^{-1}$ (Adelman 1988) for o Peg. The measured equivalent widths were corrected for 3.5% scattered light (Gulliver et al. 1996).

For both γ Gem and o Peg, the agreement in the derived cobalt abundances from Co I and Co II lines is good (Table 3). Some lines initially thought to be usable were not, due most likely to blending. For o Peg the derived value is about 0.5 dex greater than solar.

We also examined the spectrum of the F2 V star σ Boo. Here the lines are much stronger in the optical region than those for early A dwarfs. The blending is also somewhat different. The only Co II line analyzed with a “head-on” identification, λ4516.63, has an equivalent width of 3.4 mÅ and a derived abundance of log Co/N_H = -6.81 compared to value derived from Co I lines of = -7.40 (Adelman et al. 1997). Considering the difficulties in placing the continuum and in measuring lines, this

Table 3. Derived cobalt abundances

Star	λ(Å)	log gf	Reference	W_λ(mÅ)	log Co/N_H
γ Gem					
Co I	log Co/H = −6.97±0.14				
	3845.46	+0.01	MF	6.7	−7.12
	3872.97	−0.66	MF	6.4	−6.78
	3995.31	−0.22	MF	6.9	−6.88
	4121.31	−0.32	MF	3.6	−7.10
Co II	log Co/H = −7.04				
	3983.02	−2.56	KX	1.9	−7.04
o Peg					
Co I	log Co/H = −6.43±0.25				
	3845.46	+0.01	MF	7.7	−6.76
	3872.96	−0.66	MF	5.6	−6.52
	3995.31	−0.22	MF	9.8	−6.43
	4045.39	−1.32	MF	2.5	−5.89
	4086.30	−0.88	MF	1.1	−6.21
	4110.53	−1.08	MF	1.2	−6.47
	4121.32	−0.32	MF	5.6	−6.60
	4530.93	+0.15	MF	1.3	−6.56
Co II	log Co/H = −6.55±0.18				
	4516.63	−2.56	KX	3.3	−6.30
	4660.66	−2.20	KX	3.9	−6.69

References: MF = Fuhr et al. (1988), KX = Kurucz (1994)

Table 4. Some Recent Cobalt Abundances and Equivalent Widths

Star	log Co/N_H	Refer.	W_λ(mÅ) λ3995.31	W_λ(mÅ) λ4121.32
ι Psc	−6.95	1	131	98
σ Boo	−7.40	1	...	64
θ Cyg	−6.80	1	95	...
32 Aqr	−6.47	1	115	81
15 Vul	−6.94	1	69	49
HD 204411	−6.43	2	30	38
68 Tau	−6.35	3	35	21
60 Leo	−6.64	4	18	14
o Peg	−6.54	5	10	6

References: 1. Adelman et al. (1997), 2. Caliskan (1995), 3. Adelman (1994), 4. Adelman et al. (1999), 5. Adelman (1988)

is not too bad. Analyses of such stars with spectrum synthesis techniques may be required to give more accurate comparisons.

In Table 4, cobalt abundances are given from abundance analyses using the DAO spectrograms which we examined for the stars of Table 1. The measured equivalent widths (W_λ) of Co I λ3995.31 of multiplet 31 and λ4121.32 of multiplet 28 are shown to give the reader a quantative impression of the ease of finding such lines as well as to indicate for which stars these lines are significantly strong that it is desirable to include the effects of hyperfine structure.

The cobalt abundances for normal stars have a range between −6.80 and −7.40 which spans the solar value. Since Am stars have values between −6.35 to −6.94, this indicates that these stars tend to have greater than solar cobalt abundances. HD 204411 is overabundant consistent with the cobalt rich mCP stars mentioned in the introduction. Additional stars analyzed using the DAO plate material with cobalt abundances include the Am stars ϵ Ser, −6.03, σ Aqr, −6.31 (Adelman & Albayrak 1998), π Dra, −6.34 (Adelman 1996), ϕ Aql, −6.45 (Caliskan & Adelman 1997), 21 Lyn, −6.67 (Adelman 1994), and θ Leo, −6.95 (Adelman 1988). These stars confirm the tendency for Am stars to be somewhat cobalt overabundant. In addition the cool HgMn star ν Cnc has a 4 mÅ λ3995 line which suggests cobalt is overabundant (Adelman 1989).

When one uses uvbyβ photometry to estimate the temperatures and surface gravities of the two known magnetic CP stars with strong Co II lines, one finds T_{eff} = 12900 K, log g = 4.30 for HR 1094 and T_{eff} = 11300 K, log g = 3.95 for HR 5049. These values are appropriate for order of estimate calculations. If we assume that cobalt is uniformly distributed and use a T_{eff} = 12000 K, log g = 4.0, 0 microturbulence, solar composition model atmosphere, then the average abundance of the two lines Co II analyzed in o Peg would be approximately the solar value for equivalent widths of 1 mÅ. Hence the appearence of strong Co II lines requires a large cobalt overabundance. We also calculated abundances for several other lines of Co II including those which had been blended. The strongest optical region lines are λ4160.67 and λ4145.41 which should have equivalent widths slightly greater than 1 mÅ for solar abundances.

5. Final comments

Hence for at least two early A stars, there are weak Co II lines which yield similar abundances to the Co I lines. The strongest

Co II lines are in the ultraviolet as are those for Fe II. The paucity of derived abundances from optical lines is due in large measure to the cosmic abundance of cobalt. We hope that the identification of the strongest expected Co II lines will help other spectroscopists to use them for analysis.

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