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THE CHEMICAL COMPOSITION OF POLARIS

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ABSTRACT

From high-signal-to-noise coudé Reticon spectra obtained at Lick Observatory, we have determined the chemical composition of the bright Population I Cepheid Polaris (α UMi).

The chemical abundances in Polaris are found to be completely typical of normal F–G supergiants. The iron abundance is solar ([Fe/H] = 0.0), and other metals are present in essentially solar ratios. Carbon is deficient ([C/H] = −0.4) and nitrogen overabundant ([N/H] = +0.4) relative to solar abundances indicating the presence of CN-cycle products at the surface. Oxygen shows an underabundance ([O/H] = −0.2) that is also typical of F–G supergiants, but is not as easily understood.

Key words: supergiants: composition–supergiants: Cepheids

I. Introduction

Polaris (α Ursae Minoris) is the nearest and apparently brightest of the Cepheid variables. It is also the Cepheid with the lowest light amplitude (Arellano Ferro 1983, 1984), a fact generally attributed to a location in the H-R diagram near the red edge of the instability strip (e.g., Sandage and Tammann 1971). Kraft (1960) assigns a spectral-type range of F7 I*b*–II to F8 I*b*–II.

In the older literature, and even in the 1969 *General Catalogue of Variable Stars*, Polaris has been classified as a Population II (W Virginis) Cepheid. This attribution was apparently based solely on the high galactic latitude (b = +26°); however, Polaris is so nearby that its distance above the galactic plane is only ~ 35 pc (Eggen 1985*a*), and the star is now considered to be a normal Population I object (cf. Fernie 1966). More recently, however, it has been suggested that the spectrum of Polaris may be abnormal in having a weak G band of CH (Schmidt 1971).

Chemical abundances, including those of the important elements carbon, nitrogen, and oxygen, have been determined for a number of bright Cepheids and nonvariable F–G supergiants by combining high-signal-to-noise spectroscopic observations with model-atmosphere analysis techniques (Luck 1978; Luck and Lambert 1981, 1985). Polaris was not included in these studies, in spite of its brightness, largely because of its inconvenient location in the sky. We have now obtained the necessary spectroscopic observations, and in this paper we will discuss the composition of Polaris.

II. Observational Data

The data for this study were acquired by H.E.B. with the 3-m Shane telescope of Lick Observatory and the coudé Reticon detector described by Vogt (1981). The wavelengths of the observations were chosen to cover features of C I, [C I], N I, O I, and [O I], as well as representative lines of heavier elements. In all cases, the signal-to-noise ratio achieved was greater than 100. Details of the observations are given in Table I, and Figures 1–4 show portions of some of the spectra.

III. Method of Analysis

Equivalent widths for metallic lines were determined

TABLE I

Lick Reticon Observations of Polaris

Date (UT)	Phase	Central Wavelength (Å)	Coverage (Å)	Resolution (Å)
1982 Nov 25	0.64	5400	250	0.30
	0.59	6330		
	0.57	6600		
1983 Apr 27	0.09	5380	125	0.15
	0.08	6195		
	0.08	6300		
	0.08	6460		
	0.07	6590		
	0.10	8700		

Phases from maximum light given in Table I were calculated from the ephemeris of Arellano Ferro (1983).

from the data by R.E.L. The spectra were first smoothed with a fast-Fourier transform technique, and then the Gaussian approximation was assumed for the determination of equivalent widths for individual lines. The abundances of C, N, and O were determined from spectrum-synthesis fits, as described below.

The same analysis techniques as described by Luck and Lambert (1981, 1985) were employed in the present study, so only a brief outline will be given here. Basically, the abundances of the elements are determined by computing theoretical equivalent widths (or synthetic spectra) via integration through a model stellar atmosphere, and then repeating the calculation, changing the abundance of the element in question, until a match with the observed equivalent width (or spectrum) is achieved.

The model atmospheres, which were calculated using the MARCS code of Gustafsson *et al.* (1975), are based on the assumption of local thermodynamic equilibrium (LTE) and a static atmosphere. Oscillator strengths were determined from an inverted solar analysis, as discussed by Luck (1982) and Luck and Lambert (1985). These papers may be consulted for the justification for assuming a static atmosphere for the analysis of Cepheid variables.

Since the observations on the two nights were made in succession, the spectra were taken to refer to mean phases of 0.62 and 0.08, respectively, and the data for the two nights were then analyzed independently. The effective temperatures were determined by forcing Fe I lines of various excitations to yield the same abundances. The adopted parameters are given in Table II. The effective temperatures are uncertain by about ± 0.04 in units of $H = 5040/T$, or about ± 275 K. Since $(B-V)$ varies by only 0.03 mag over the entire pulsation cycle (Arellano Ferro 1983), and differs by only 0.02 mag for the two phases in question, it is not surprising that we detected no difference in effective temperature.

The mean $(B-V)$ color index of Polaris is 0.59 (Fernie 1966; Arellano Ferro 1984), and the $(b-y)$ index on the Strömgren system is 0.345 (Eggen 1985*b*). We will adopt a reddening of $E(B-V) = 0.01$, following the discussion of Gauthier and Fernie (1978). Then we find the following effective temperatures from the indicated theoretical calibrations: 5825 K ($(B-V)$, Buser and Kurucz 1978, $\log g = 1.5$); 5850 K($(B-V)$, Bell and Gustafsson 1978, $\log g = 2.25$); 6025 K ($(b-y)$, Relyea and Kurucz 1978, $\log g = 1.5$). The agreement with our adopted spectroscopic effective temperature is well within our quoted error.

The surface gravities in Table II were determined by forcing Fe I and Fe II to yield the same abundances. These $\log g$ values are believed to be accurate to ± 0.3 dex; see Luck and Lambert (1985) for a critical examination of gravity determinations in F–G supergiants.

The microturbulent velocities were determined by forcing Fe I lines of various equivalent widths to give the same abundances. These values are accurate to about ± 0.5 km sec^{-1}. The values obtained agree well with those for other F–G supergiants (Luck and Bond 1980; Luck and Lambert 1981, 1985; Luck 1982).

TABLE II

Parameters for Polaris

Date (UT)	Mean Phase	T_{eff} (K)	log(g) (cgs)	Turbulence Micro (km s^{-1})	Turbulence Macro (km s^{-1})
1982 Nov 25	0.62	6000	1.5	3.5	12
1983 Apr 27	0.08	6000	1.7	3.5	12

IV. Chemical Abundances in Polaris

The abundances of the elements Na through Eu (except for S) are listed in Table III. They are expressed as [M/H] values, i.e., the logarithmic metal-to-hydrogen ratios relative to those in the Sun. The abundances are listed separately for the two phases at which Polaris was observed. The standard deviations and number of lines used in the analysis are given.

Errors in the metallic abundances arise primarily from

TABLE III

Abundances for Polaris

Species	Phase = 0.62 [M/H]	σ	N	Phase = 0.08 [M/H]	σ	N
Na I	0.32	.00	2			
Mg I	0.08	.24	2			
Al I				0.05	.18	2
Si I	0.09	.17	12	0.16	.14	6
Si II	0.03		1	0.15	.04	2
Ca I	0.17	.26	13	0.10	.25	4
Sc II	-0.17	.20	6	0.07	.27	8
Ti I	0.04	.24	10	0.30	.28	9
Ti II	-0.16	.12	3	0.08	.20	4
V I	0.18	.32	11	0.16	.19	9
V II	-0.46	.28	3	0.14	.43	2
Cr I	-0.03	.30	7	0.10	.14	5
Cr II				0.06	.21	7
Mn I	-0.07	.27	5	0.03	.24	6
Fe I	-0.04	.20	84	0.04	.28	113
Fe II	0.01	.19	20	0.05	.16	13
Co I	0.06	.21	10	0.37	.20	8
Ni I	-0.07	.22	22	0.02	.20	19
Zn I	0.07		1	0.37		1
Sr I				0.63		1
Y II	-0.17		1	0.11	.15	2
La II	0.08		1	0.24	.33	4
Ce II	-0.08	.09	2	0.01		1
Pr II	-0.15		1	0.07		1
Nd II	-0.21	.21	5	0.11	.24	8
Eu II	-0.07		1	0.01		1

line-to-line scatter and from errors in the stellar parameters. The first source may be evaluated directly from Table III; a typical standard deviation is 0.2–0.3 dex for well-represented species. For Fe I, which has numerous lines, this translates into an error in the mean of less than ± 0.06 dex. As discussed in the papers by Luck, and Luck and Lambert cited above, parameter uncertainties increase the error in the iron abundance to about ± 0.2 dex. Species represented by only a few lines have considerably more uncertain abundances, by up to ± 0.4–0.5 dex. Comparison of the results for the two phases shows agreement that is generally well within the errors quoted above.

The abundances of C, N, and O as well as Li and S were determined from spectrum-synthesis fits. Figures 1 through 4 show repesentative examples of such fits, and the results are given in Table IV on the usual log H = 12 scale. Also included in Table IV are equivalent widths for representative abundance indicators.

V. Discussion

Table III shows that Polaris has a solar metallicity ([Fe/H] = 0.0). The other metals show no significant departures from the solar ratios relative to iron. The lithium abundance given in Table IV shows that Polaris has a significant Li depletion relative to the Sun, but the magnitude of the depletion is as expected based on results for late-type evolved stars, both from an observational (Luck 1977; Luck and Lambert 1982) and a theoretical (Iben 1967*a*,*b*) point of view.

Table IV reveals that Polaris shows the carbon depletion and nitrogen enhancement typical of F–G supergiants and attributed to the dredge-up of material from layers that have undergone CN-cycling. Although Polaris is indeed carbon-deficient relative to the Sun, its carbon content is completely typical of stars in its region of the H-R diagram, and we do not confirm Schmidt's (1971) suggestions of an abnormally low C abundance.

The oxygen content in Polaris is also lower than solar. This again is typical of F–G supergiants, but it is not as readily understood as the carbon depletion/nitrogen enhancement, since the dredge-up is not expected to reach material that has undergone ON-cycling. The question of oxygen depletions in F–G supergiants has been discussed exhaustively by Luck and Lambert (1985), and the reader is referred to the paper for details; Luck and Lambert tentatively favor the conclusion that young stars have initial oxygen abundances that are lower than solar.

An abundance analysis of Polaris has recently been published by Giridhar (1985). She obtained photographic spectra at three different phases, and analyzed the data in a manner very similar to ours. Similar effective temperatures, gravities, microturbulent velocities, and abundances to ours were found, except that only a slight oxygen underabundance ([O/H] = −0.05) was reported. Using her parameters and oxygen abundance we derive an equivalent width of 33 mÅ for [O I] 6300 Å in excellent

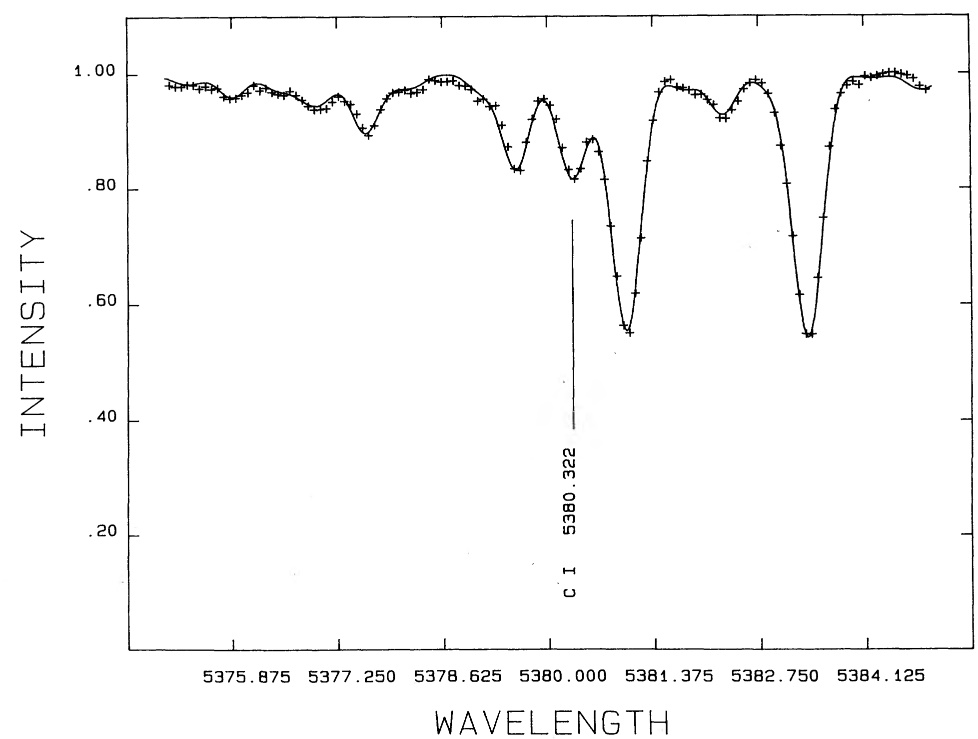

FIG. 1–Polaris at phase 0.09 superposed by a synthetic spectrum. The feature indicated at 5380.322 Å is C I. Points are the observed spectrum, and the continuous line is the calculated synthetic spectrum.

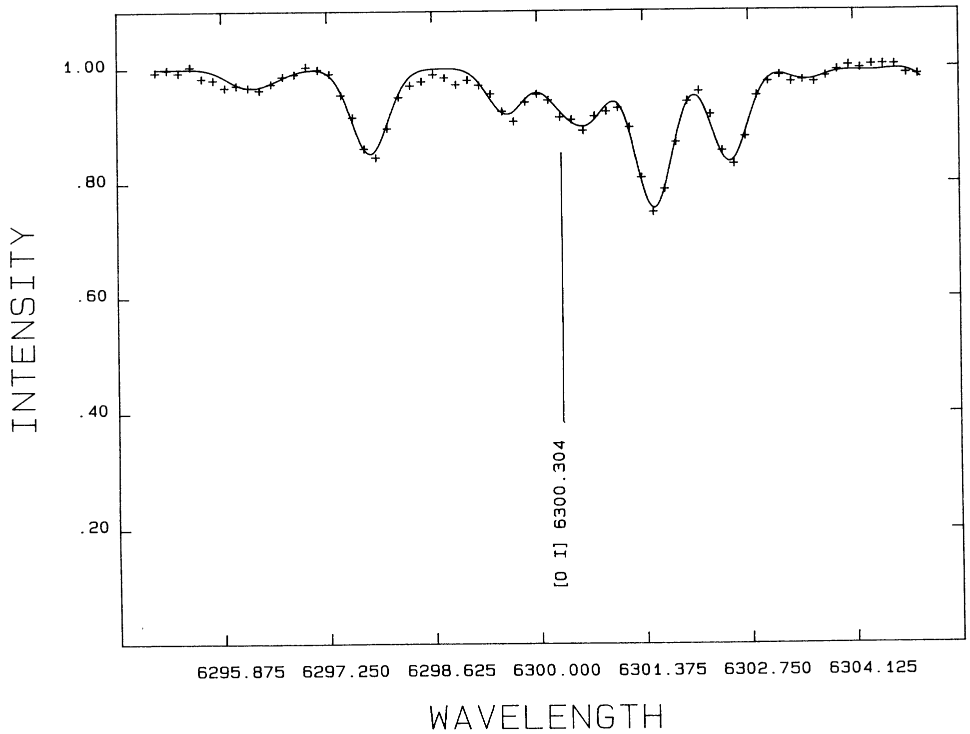

FIG. 2–Polaris at phase 0.59 superposed by a synthetic spectrum. The feature indicated at 6300.304 Å is [O I]. Points are the observed spectrum, and the continuous line is the calculated synthetic spectrum.

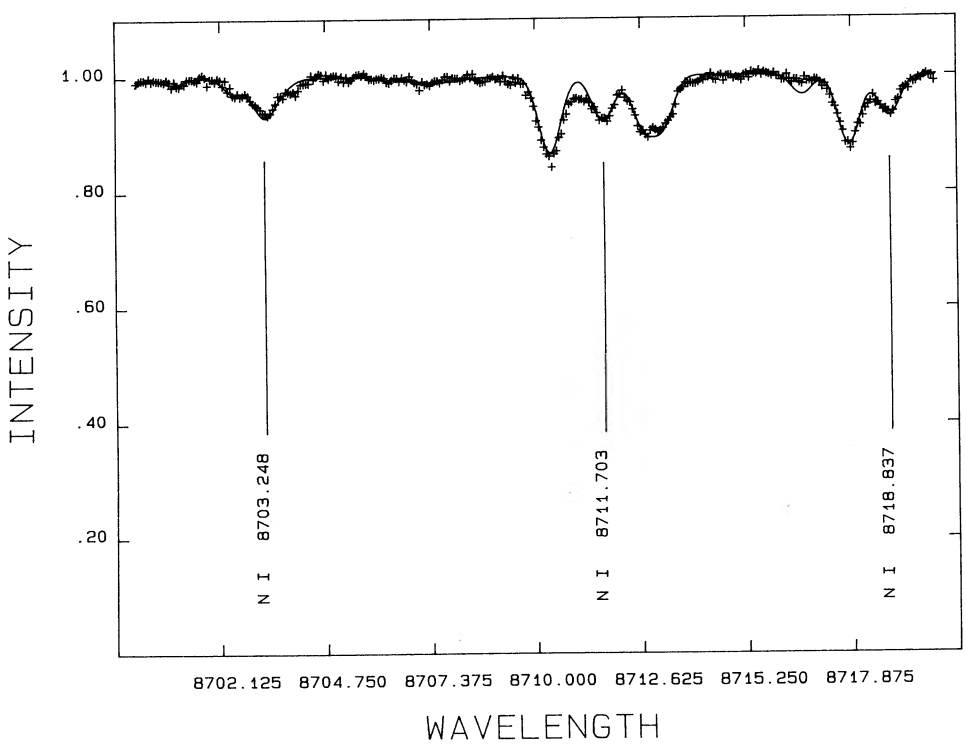

FIG. 3–Polaris at phase 0.10 superposed with a synthetic spectrum. All features indicated are N I. Points are the observed spectrum, and the continuous line is the calculated synthetic spectrum.

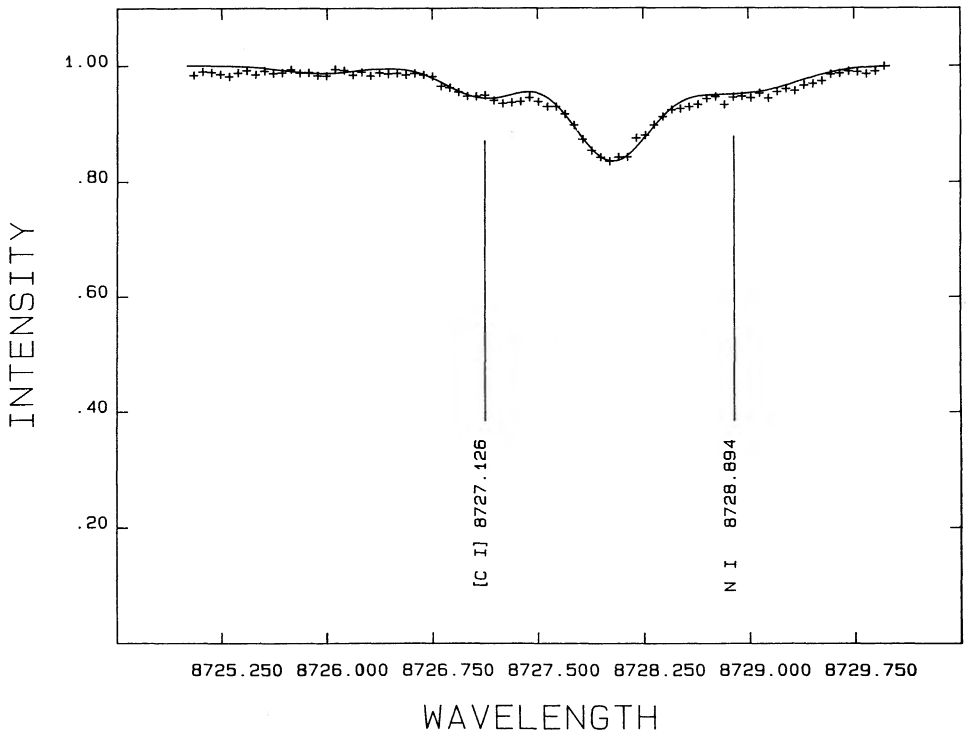

FIG. 4—Polaris at phase 0.10 superposed with a synthetic spectrum. The [C I] feature at 8727.126 Å is indicated as is a N I line at 8728.894 Å. Points are the observed spectrum, and the continuous line is the calculated synthetic spectrum.

TABLE IV

Light Element Abundances in Polaris

Feature		Phase = 0.62 EW	Phase = 0.62 Abundance	Phase = 0.09 EW	Phase = 0.09 Abundance
Li I	6707Å	≤1.4	≤0.80		
C I	5380Å	63	8.17	76	8.37
[C I]	8727Å			38	8.31
		Mean = 8.28 ([C/H] = -0.39)			
N I	8683Å			75	8.37
		([N/H] = +0.38)			
O I	6158Å			34	8.90
[O I]	6300Å	34	8.61	34	8.68
		Mean = 8.73 ([O/H] = -0.19)			
S I	8694Å			125	7.32
		([S/H] = +0.09)			

Notes:

1) The equivalent widths (in mÅ) refer to the line of these species at the quoted wavelength.

2) The abundances of Li I, N I, O I, and S I are best fit values respectively to multiplets 1, 1, 10, and 6. The other species refer to an abundance computed based on the quoted line.

agreement with our data; therefore, we attribute the higher oxygen abundance derived by Giridhar solely to differences in adopted parameters.

In summary, our abundance analysis of Polaris shows it to have a chemical composition that is entirely typical of Population I F–G supergiants.

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