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THE OLD DISK METAL-RICH SUBGIANT 31 AQUILAE

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ABSTRACT

A differential coarse curve-of-growth analysis has been carried out with respect to the Sun for the high-velocity field subgiant 31 Aql. The results show most metals to be 4 times as abundant as in the Sun. The age of 31 Aql is probably similar to that of NGC 188, the oldest open cluster known. The results for 31 Aql are contrary to the hypothesis that the oldest stars in the Galaxy should be metal poor.

I. INTRODUCTION

Recently, Spinrad and Taylor announced the existence of a substantial number of metal-rich stars (i.e., stars having metal-to-hydrogen ratios greater than that of the Hyades) among both giants (Spinrad and Taylor 1969) and dwarfs (Taylor 1970), based on narrow-band scanner observations of spectral features. One of the important conclusions from their observations was that the old clusters M67 and NGC 188 are also metal rich (see also Spinrad *et al.* 1970), in spite of their great age. Under existing techniques, stars in these clusters are somewhat too faint for detailed curve-of-growth analyses to test this conclusion. However, the present paper describes such an analysis of the high-velocity field G star 31 Aql, which according to its parallax lies on the subgiant branch of the older of the clusters mentioned (NGC 188).

Details of the colors, motion, and parallax of 31 Aql are given in Table 1. The star has an ultraviolet deficiency, so it is a possible candidate for a metal-rich star. Jenkins (1952) lists three widely differing parallaxes, but only one of high weight, and all substantially less than the value required to bring the star to the main sequence.

II. OBSERVATIONS AND REDUCTIONS

The plate material used was obtained on the coudé spectrograph of the 74-inch telescope at Mount Stromlo Observatory, and consisted of two 103a-F emulsion red plates at 10.2 Å mm^{-1}, and single baked IIa-O emulsion blue plate at 6.7 Å mm^{-1}, all three of excellent quality. In addition, two plates in each color were obtained of the daytime sky at the same dispersions. The stellar spectra were widened to about 0.8 mm, the solar ones to about 2.5 mm. The plates were traced on the Hilger microphotometer at Mount Stromlo Observatory, and equivalent widths were obtained by using a triangle approximation to the line profiles for about seventy lines in each plate. The remainder of the lines were measured after setting up a relation between central depth and equivalent width ($-\log W/\lambda$) for each plate, and interpolating in this relation. Blue lines measured were in the wavelength range 4468–4923 Å; red ones in the range 5497–6810 Å.

Scans were obtained of 31 Aql at the scanner wavelengths of Hayes (1970), using 50 Å bandpasses and an ITT FW130 S-20 tube attached to the spectrum scanner on the 50-inch telescope at Mount Stromlo. They were reduced by means of the Hayes (1970) α Lyr calibration. The scans were deblanketed by using a semiempirical method to be described in more detail in a later paper. It involves measuring the blanketing in a single blue band (that at 4464 Å) from the blue plate, and then applying a nonlinear correction to the solar blanketing in all the other bands on the basis of the blanketing at 4464 Å.

TABLE 1

DETAILS OF 31 AQUILAE

Parameter	Value	Source
Galactic coordinates (1900)	$\alpha = 47°21'$, $\delta = -1°51'$	1
Proper motion (μ_α, μ_δ)	(0″.719, 0″.636)	1
Trigonometric parallax π	0″.059	2
Parallax to be on main sequence	0″.12	
Radial velocity (km sec^{-1})	−99.8	3
Velocity components (U, V, W) (km sec^{-1})	(+123, −24, −24)	4
Apparent visual magnitude V_E	5.17	4
$(B-V)$	+ 0.78	4
$(U-B)$	+ 0.43	4
$(B-V)_c$	+ 0.75	4
$\delta(U-B)$	− 0.03	4
$(R-I)_k$	+ 0.21	5
R_k	4.92	5
M_v	+ 4.0	4
Sp. type (MK system)	G8 IV	4

SOURCE.—
1. Hoffleit (1964). 2. Jenkins (1952). 3. Wilson (1953). 4. Eggen (1964). 5. Eggen (1970).

III. EFFECTIVE TEMPERATURE

The effective temperature of 31 Aql has been measured in three ways. (*a*) Scan of blue (3862 Å) to near-infrared region (7550 Å), and comparison with the flux-constant model atmospheres computed by the author from the program of Brooke (1969), Hain (1969), and Schmidt (1969). (*b*) The $(R - I)$ color index, and use of Johnson's (1966) calibration of $(R - I)$ versus effective temperature. (*c*) The Hα profile, obtained from the coudé plates, and compared with the profiles computed by the author for the model atmospheres using a program due to Schmidt (1969). This program uses Griem's (1964) formulation of linear Stark broadening in hydrogen lines.

The scans of 31 Aql were obtained on two independent nights, with four scans per night (1969 August 6 and 9). However, the mean results have random errors of 0.02 mag. A differential effective temperature with respect to the Sun was obtained by using the solar-flux data of Labs and Neckel (1968) for the integrated solar disk. Because of the uncertainties in the author's scans and the use of an approximate deblanketing procedure, the temperature of

$$\Delta\theta_{\rm eff} = +0.03$$

could be in error by ± 0.02 in θ. The value quoted allows a back warming of 0.03 to be added to the solar temperature derived from the line-free models (Oke and Conti 1966), and of 0.04 to be added to the solar temperature of 31 Aql. The addition of 0.01 excess back warming was felt to be a reasonable guess in view of the fact that 31 Aql is known (from the *UBV* photometry) to be a highly blanketed star.

The Kron, Gascoigne, and White (1957) $(R - I)$ index of 31 Aql has kindly been obtained for me by Professor Eggen. This index has been transformed to the $(R - I)$ system of Johnson (1964) using Eggen's (1971) Kron-Johnson $(R - I)$ conversion relation, and then into an effective temperature using the $(R - I)$ versus temperature calibration of Johnson (1966) for normally blanketed stars. However, 31 Aql has excess blanketing, and 0.01 has been added to the temperature so derived, as described for the scanner temperature. The solar $(R - I)$ color is subject to uncertainty; if $(R - I)_J^{\odot} = 0.32$ is adopted as being the mean color of solar spectral type dwarfs (Johnson 1965), then one obtains for 31 Aql

$$\Delta\theta_{\rm eff} = +0.01 \,.$$

The total width of the Hα profile, on both plates taken, was measured at residual intensities of 0.80, 0.85, and 0.90 and compared with the widths from two sets of models—one with solar metal abundances, the other with 3 times these abundances. A cooler temperature is obtained with the former calibration, because the H^- opacity is lower in normal stars than in metal-rich stars, resulting in a broader hydrogen line. The results are

$$\Delta\theta_{\rm eff} = +0.04 \quad \text{(normal abundance calibration)} \,,$$

$$\Delta\theta_{\rm eff} = +0.02 \quad \text{(3 times normal abundance calibration)} \,.$$

In each case the differential temperature has been obtained by using the solar Hα profile measured from the day-sky plates with the normal abundance calibration. The same back-warming corrections were applied as with the scans. The random errors are less than ± 0.01 in θ.

Combining these three determinations of effective temperature, and anticipating that 31 Aql is metal rich in the case of the Hα temperature, one obtains

$$\Delta\theta_{\rm eff} = +0.02 \pm 0.01$$

for 31 Aql with respect to the Sun. The final abundances derived did not warrant a correction to be applied to the Hα temperature adopted.

IV. CURVE OF GROWTH

Values of $\log \eta_0^{\odot}$ were found for each line by interpolating in Wrubel's (1949) curve of growth for pure absorption on the Milne-Eddington model with $B^0/B^1 = \frac{2}{3}$, in which we used $\log a = -1.8$ and a solar microturbulent velocity of 1.3 km sec^{-1} after Allen (1962). For 31 Aql, $-\log W/\lambda$ was plotted against $\log \eta_0^{\odot}$ for fifteen groups of red Fe I lines, grouped according to their lower excitation potentials, and the horizontal shifts for each group determined. The excitation temperature was found from a least-squares plot of shift versus potential χ. The result was

$$\Delta\theta_{\rm ex} = +0.03 \pm 0.02 \,.$$

Next, $-\log W/\lambda$ was plotted against $(\log \eta_0^{\odot} - \chi\Delta\theta_{\rm ex})$ for each element (seventeen in all) and ionization state (I or II). The electron pressure $[P_e]$ was found from

$$[P_e] = \text{shift}_{\rm I} - \text{shift}_{\rm II} - I\Delta\theta_{\rm eff} - 2.5[\theta_{\rm eff}] \,,$$

where I is the ionization potential for each of Fe, Ti, and Cr. The mean electron pressure from each of these three elements was taken, after giving Fe double weight. The value was

$$[P_e] = +0.08 \,.$$

The opacity was determined by assuming the dominance of the H^- opacity and using the Saha equation for H^-. One obtains

$$[K] = [P_e] + 0.75\Delta\theta_{\rm eff} + 2.5[\theta_{\rm eff}] \,.$$

Partition functions were taken from Drawin and Felenbok (1965) or from Aller (1963), and abundances were obtained by using

$$[\mathrm{N/H}] = \mathrm{shift} + [VUK] .$$

The velocity V was computed from the temperature, microturbulence, and atomic weight for each element. The microturbulent velocity measured from the Fe I curve of growth was 1.3 km sec^{-1}, equal to the solar value adopted. Uncertainty in the microturbulence produces an error in all abundances; in a metal-rich star, where there are few weak lines which are also measurable in the Sun, the resulting uncertainty must be larger than normal, but the possibility of 31 Aql not being metal rich is inconsistent with the data.

A correction to all abundances was made for the degree of ionization x for each element, which is a function of $\Delta\theta$ and $[P_e]$, so as to obtain the total metal-to-hydrogen ratio for each element. The equations are

$$[M_{\mathrm{total}}/\mathrm{H}] = [M_{\mathrm{I}}/\mathrm{H}] - [1 - x]$$

and

$$[M_{\mathrm{total}}/\mathrm{H}] = [M_{\mathrm{II}}/\mathrm{H}] - [x] .$$

It is necessary, for this purpose only, to adopt mean values for the solar ionization temperature and electron pressure; $\theta_{\mathrm{ion}} = 0.89$ and $\log P_e = 1.51$ were chosen after Unsöld (1955). Throughout $\Delta\theta_{\mathrm{ion}} = \Delta\theta_{\mathrm{eff}}$ has been assumed.

Results of the analysis are given in Table 2. It is found that 31 Aql has an average overabundance of metals of about 4 times relative to the Sun. Magnesium appears to be less overabundant, and sodium and zinc more so. Copper and yttrium were inconsistent with the general trend. These are both based on single lines, however, and in the case of copper the line at 5782 Å may be affected by hyperfine structure, for which no correction was applied.

V. DISCUSSION

Since 31 Aql is both a high-velocity star and an evolved G star about 1.5 mag brighter than the main sequence, it is certainly very old. It may have an age of about 10^{10} years, but the exact value depends rather critically on both the parallax and evolutionary theory. The existence of very old metal-rich stars certainly presents a difficult problem,

TABLE 2

ABUNDANCES IN 31 AQUILAE

Element	No. of Lines	$[M_{\mathrm{total}}/\mathrm{H}]$	Element	No. of Lines	$[M_{\mathrm{total}}/\mathrm{H}]$
Fe I	178	+0.50	Na I	7	+0.84
Fe II	18	+0.53	V I	6	+0.74
Cr I	22	+0.57	Cu I	1	(+1.45)
Cr II	7	+0.60	Mn I	11	+0.64
Ti I	21	+0.64	Al I	2	+0.53
Ti II	9	+0.57	Zn I	2	+0.88
Si I	15	+0.68	Sc II	5	+0.58
Si II	1	(+0.61)	Ba II	3	+0.56
Mg I	4	+0.26	Ce II	1	(+0.61)
Ni I	41	+0.64	Y II	1	(+0.29)
Ca I	21	+0.49			

NOTE.—The last column (doubtful values in parentheses) lists the abundance after correcting ionic or neutral element abundances for their degree of ionization.

as it would indicate that at least some parts of the Galaxy went through a phase of enriched metal content during the early collapse. The possibility that all metal-rich objects in the Galaxy are also very old has been discussed by Spinrad and Taylor (1969).

Narrow-band observations of 31 Aql by Spinrad and Taylor (1969) indicate that the Na D-lines are strong, which agrees with the present analysis, but their results for CN, Mg I, and Ca I (their Figs. 16, 17, and 18) appear inconclusive, as their mean "normal" abundance loci are taken from only a handful of subgiants. If these loci are accepted, then 31 Aql appears to have marginally strong CN, Mg I, and Ca I with respect to the Sun.

It is noteworthy that 31 Aql has an ultraviolet deficiency, whereas the M67 stars considered by Spinard *et al.* (1970) do not. The value of $\delta(U - B)$ must depend mainly on the line blanketing. The subgiant 31 Aql has a higher electron pressure than normal-abundance dwarfs of the same temperature, so the possibility that this deficiency is due to its evolved status (low gravity) would appear to be ruled out. The problem of how the cluster stars can have ultraviolet excesses, even if they are metal rich, thus remains. The effect on $\delta(U - B)$ of helium abundance, and of heavier elements which may contribute to the continuous opacity, should be investigated.

Note added in proof.—From the Fe I curve of growth, it was estimated that the abundance uncertainty, due to the microturbulence uncertainty, is about ± 0.1 in the logarithm; it is not as large as ± 0.2. This result is based on the measurement of twenty Fe I lines with log W/λ -5.05. The total uncertainty in [Fe/H], arising from random errors in the horizontal and vertical curve of growth shifts and in the temperature determination, was estimated to be ± 0.2.

The high electron pressure, for a star of this temperature and luminosity (from the parallax) supports the evidence of a high metal abundance rather than high microturbulence. Actually $[P_e]$ is about 0.1 larger than it should be for the abundance, but the uncertainty in the parallax, or in $[P_e]$, could account for this.

The Li line at 6708 Å could not be detected in either red plate.

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A table of lines used, together with equivalent widths and log $\eta_0^{\odot}$ values, is available from the author.

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