The Metal Abundances of NGC 188 and NGC 6791 from Low Resolution Spectra

Guy Worthey and Kelly J. Jowett

Program in Astronomy, Washington State University, Pullman, WA 99164-2814

ABSTRACT

Analysis of low resolution spectra of K giants in old open clusters NGC 188 and NGC 6791 yields [Fe/H] = $0.075 \pm 0.045 \pm \sigma_{sys}$ for NGC 188 and [Fe/H] = $0.320 \pm 0.023 \pm \sigma_{sys}$ for NGC 6791. The term σ_{sys} represents the drift between our underlying star catalog's abundance scale and the true abundance scale. Star R23 in NGC 6791 has [Fe/H] > 0.6 according to our analysis and deserves further study.

Subject headings: stars: abundances — stars: giant — open clusters and associations: NGC 6791 and NGC 188

1. Introduction

The open cluster NGC 6791 is old, rich with stars, and rich with heavy elements, making it an excellent analog to the kind of stellar population present in spiral bulges and the bright regions of S0 and elliptical galaxies. A third of its horizontal branch stars are much hotter than the typical red clump (Kaluzny & Rucinski 1995). These stars are of the type thought to give rise to the bulk of the "UV upturn" in elliptical galaxies (Ferguson 1999; Landsman et al. 1998). Elliptical galaxies are also thought to be fairly ancient on average, with central metal abundances significantly greater than solar (Trager et al. 2000). NGC 6791 seems to be a good stellar evolutionary template for understanding the stellar content of early type galaxies if its abundance is a good match. Open cluster NGC 188 is nearer and better studied. It is also old, with an abundance around solar (Hobbs et al. 1990; Twarog & Anthony-Twarog 1989)

In order to try to fill a relative dearth of reddening-independent, isochrone-independent abundance estimates, we use low-resolution spectroscopy of K giants in these two clusters in a technique to recover atmospheric parameters (T_{eff}, log g, [Fe/H]) via absorption feature index strengths. Under the assumption that all stars in each cluster should have the same abundance, we find median cluster [Fe/H] values. We describe our observations and analysis and discuss the results below.

2. Observations

Stellar spectroscopic data of field stars and stars in the clusters NGC 188 and NGC 6791 were obtained during a four-night run at the Michigan-Dartmouth-MIT observatory 2.4-meter telescope 1994 October 10-11 through 13-14. The Mark III spectrograph with a 600 line/mm grism blazed at 4600 Å and the "Charlotte" thinned Tektronics 1024 CCD were employed for spectral coverage of approximately 3700-6000Å at 2.3Å per pixel. The slit was 1.68 arcseconds wide, typically oriented north-south. Wavelength dependencies in the spectrograph camera optics rendered the portion of the spectrum bluer than about 4000Å unusable.

Besides the usual array of calibration images (lamps, flat fields, dark frames, and twilight frames), multiple spectra were taken of 11 Lick/IDS stars in order to assure that the spectra could later be transformed to the Lick/IDS system (Worthey et al. 1994). The spectra were not fluxed, as this step is superfluous for accurate Lick/IDS index measurements unless the spectral response curves sharply within the confines of a single index (Worthey & Ottaviani 1997). 23 stars in NGC 6791 and 14 stars in NGC 188 were observed.

The spectra were extracted using IRAF routines and smoothed to the wavelength-dependent Lick/IDS resolution recommended in Worthey & Ottaviani (1997). The index values were integrated using González (1993) quadratic interpolation for fractional pixels to account correctly for their binned nature. When compared to the standard stars, 8 indices required additive corrections to bring them into conformity. Such corrections are due to differing local spectral response between the original Lick/IDS and the new spectra. 23 of the 25 defined indices were measured: the 2 TiO indices lie beyond the red limit of the spectra. The indices near 4000Å (Hδ and CN) suffer from low signal and focus blur, and are not used to derive conclusions in this study. The final index values and errors are listed in Table 1. The value of N referred to in Table 1 is the number of exposures, up to three of which could have been taken of any given star on any given night (line strength standards may have more than that).

More stars are presented in Table 1 than are analyzed here. Extra FG dwarfs in the field and in NGC 188 and an M giant sequence in NGC 6791 are included. The results will be used in future versions of the Worthey et al. (1994) fitting functions. The star labeled "Worthey 1" is a previously uncataloged star found in unpublished nonphotometric images taken at the MDM 1.3m telescope. It has $m_I \approx 11.9$ (Cousins) and $V - I \approx 1.8$, which puts it squarely on the giant branch in the CMD of NGC 6791. The spectrum we analyze was obtained to see if the star belonged to the cluster. Its FK5 epoch 2000 coordinates are 19 21 01.4, +37 58 29.

3. Abundance Results

In order to derive atmospheric parameters from Lick/IDS indices, we seek a method to invert the fitting functions of Worthey et al. (1994). These give (Lick/IDS) index strengths as a function of atmospheric parameters T_{eff}, log g, and [Fe/H]. They are based on literature values primarily, although some values of log g were derived from $V-K$ color, literature [Fe/H], and observed Mg_2 line strength (Gorgas et al. 1993). The fits cover a large array of K giants from metal-poor globular cluster giants to metal-rich field giants. The temperatures for the giants used in the fits come primarily from the $V-K$ to T_{eff} calibration of Ridgway et al. (1980). This temperature calibration is essentially identical to those derived from more extensive data sets of stellar radii (Dyck et al. 1996). The values of [Fe/H] are from heterogeneous sources, and systematic effects are possible, as discussed later in this article.

To invert the fitting functions, we define a figure of merit and look for its minimum within the parameter space. The figure of merit for one star with m indices subjected to scrutiny is

$$G_x^2 = \sum_m (I_m - P_{m,x})^2/\sigma_m^2 \tag{1}$$

Where I_m is the observed index with error σ_m, and $P_{m,x}$ is the predicted index given an assumed set of atmospheric parameters x (computed via the fitting functions). G_x is computed for many trial sets of atmospheric parameters and the minimum G indicates the best match for the particular set of indices considered.

The covariances are easy to visualize using this approach. Figure 1 gives an example for program star I-105 in NGC 188 in the abundance, temperature plane for several values of log g. A higher temperature (which would weaken most lines) can be counteracted by either an increase in abundance or an increase in surface gravity. The covariance between abundance and gravity is so mild it is hard to detect in the figure.

Errors in the results are computed by Monte Carlo techniques. Two hundred realizations of the set of input indices were processed with artificial Gaussian random errors superimposed on the fiducial. Atmospheric parameters were derived from each realization and errors were computed statistically from the 200 data points. Such a technique automatically includes all of the covariances.

The sets of indices used for the abundance analysis were chosen by examining tables like Table 2. This table shows index values computed from the fitting functions (column 2) and typical errors for well-observed stars in the present data set (column 3). Index sensitivity-to-atmospheric-parameters values are shown in the remaining columns. For instance, column 4 is the index variation in units of observational error if the temperature changes by 100 K.

Scanning through this table, one can pick out collections of indices that complement each other by being sensitive to different atmospheric parameters. Orthogonality is impossible, but some index combinations fit well together. For instance, Ca4227 is fairly temperature sensitive, Fe4668 is sensitive to abundance, and Hβ is gravity-sensitive. These three were adopted as one valid index set from which atmospheric parameters were derived. Two others were used: a set of five indices (Fe4383, Fe4668, Hβ, Mg b, Fe5406) and a set of six indices (Ca4227, Fe4668, Hβ, Mg b, Fe5406, Na D). The effectiveness of the various index sets as measured by the Monte Carlo error estimate is a function of temperature. For most stars, all three index sets were used and a weighted mean gave the final values for the atmospheric parameters.

The variance-weighted means were computed assuming Gaussian statistics, with $w_i = 1/\sigma_i^2$. The mean and its variance are given by

$$\overline{x} = \frac{\sum w_i x_i}{\sum w_i} \tag{2}$$

$$\overline{\sigma^2} = \{\frac{\sum w_i}{(\sum w_i)^2 - \sum w_i^2}\} \times \sum w_i (x_i - \overline{x})^2 \tag{3}$$

Table 3 gives atmospheric parameters for Lick/IDS standard stars along with literature means from Worthey et al. (1994) for purposes of comparison. We were especially keen to discover if temperatures and gravities were recovered with suitable accuracy because the method of inverting Lick/IDS indices is relatively untested. The majority of parameters agree within one observational sigma, and this sigma is less than 100 K except for HR 7576. Table 4 lists the derived atmospheric parameters for the program stars in NGC 188 and NGC 6791.

To double-check our temperatures and gravities, we derived temperatures from (the heterogeneous) available photometry and gravities using M_I or M_V to obtain luminosity. Temperatures were obtained with the fitting functions given by von Braun et al. (1998) except for the two warmest stars in NGC 188. For these, Worthey et al. (1994) temperatures were retained. For gravities, bolometric corrections and masses were obtained by using isochrones from Worthey (1994) that match the color-magnitude diagrams. We adopted { $E(B-V)$, $(m-M)$ } = { 0.09, 11.4 } for NGC 188 and { 0.12, 13.2 } for NGC 6791 (von Hippel & Sarajedini 1998; Friel & Janes 1993; Garnavich et al. 1994). The results are plotted in Figure 2 and show good systematic agreement except for a couple of outliers. The low lying open square in the temperature plot is R25, which has $V-I$ error of 0.7 mag in Garnavich et al. (1994). If $(B-V)_0 = 1.22$ ($B-V$ from SIMBAD) is used for this star, then its temperature is 4440 K, only 28 K warmer than the spectroscopic estimate. We conclude that the spectroscopic temperature is accurate. The labeled outlier is R24. The SIMBAD

$B-V = 1.46$ temperature of R24 is 4270 K, only 20 K cooler than the temperature derived from von Braun et al. (1998) $V-I$. With the photometry apparently solid, we conclude that the spectroscopy is the most probable culprit here, especially as we only obtained one spectrum of R24, and the abundance error for this star is almost certainly larger than that listed in Table 4.

All of the NGC 188 stars observed are confirmed cluster members with probability greater than 94% (Upgren et al. 1972; Dinescu et al. 1996) except I-85 and I-88, which are members according to Gorgas et al. (1993) (but this appears to be a mistake in Gorgas et al.). Retaining all 10 stars, the median of the data set is [Fe/H] = 0.075. To compute errors about this median, we used bootstrap resampling (Efron 1979) of several thousand realizations, and found the standard deviation of the results was 0.045 dex.

In NGC 6791, R18 is known to be a probable nonmember on the basis of radial velocity (Garnavich et al. 1994), while R8, R9, R12, and R19 are members. K. Cudworth (private communication) kindly provided preliminary proper motion membership probabilities for about half the stars in our sample. No star was unambiguously identified as a nonmember, so we retain all Cudworth stars except R24, for which our spectroscopic data is probably in error due to incorrect convergence on the other atmospheric parameters (see Figure 2 and discussion). The median of the NGC 6791 [Fe/H] data excluding R18 and R24 is 0.320 with bootstrap standard deviation of 0.023 dex.

4. Discussion

The method we use for obtaining abundance is independent of reddening and distance modulus and does not depend on stellar evolutionary isochrones. In light of this, we limit literature comparisons to spectroscopic determinations of abundance. High resolution spectroscopy of NGC 188 dwarfs (Hobbs et al. 1990) yields [Fe/H] = -0.12 ± 0.16 (for microturbulent velocity of 1 km s^{-1}) or [Fe/H] = -0.01 ± 0.15 (for microturbulent velocity of 0.5 km s^{-1}). Friel & Janes (1993) find [Fe/H] ≈ -0.06 from low resolution spectra rather like ours. Our estimate is a shade more metal-rich, but agrees with the literature estimates within the quoted errors.

For NGC 6791, Friel & Janes (1993) gives [Fe/H] = $+0.19 \pm 0.19$ while Peterson & Green (1998) gives [Fe/H] = $+0.4 \pm 0.1$ on the basis of high resolution spectroscopy of one warm horizontal branch star. Taylor (2001) has critically reviewed metallicity determinations of NGC 6791, especially as regards statistical treatment, and arrives at a literature mean of [Fe/H] = $+0.16 \pm 0.44$. Taylor's paper had the additional effect that we made sure we explicitly stated how our errors were estimated in the present paper. Our value agrees with the literature estimates, but promises to be more accurate.

We have shown that low-resolution spectroscopy can give extremely high *precision* abundance results (e.g. ≈5% from 26 spectra of 16 stars in NGC 6791), but *accuracy* also depends on the systematics of the underlying calibration. In the present case, the calibration is a collection of 400-odd stars (Worthey et al. 1994) with literature abundance values, some of which stretch back to the 1970s. The quality of data for K giants is generally quite high, and there are lots of them so that statistical fluctuations should be largely smoothed away, but the possibility remains that, due to incomplete understanding of metal-rich stellar atmospheres, we have not set the metal-rich end of the abundance scale with perfect solidity. The best we can do so far is to intercompare different data sets by splitting the Cayrel de Strobel et al. (2001) catalog by author, and intercomparing objects in common for the larger data sets. This has been done by us and by S. C. Trager (unpublished) but we have been unable to come to a crystal clear conclusion. We can show that the Worthey et al. (1994) catalog is off by less than 0.1 dex (high confidence) of the current literature mean at the metal-rich end, but we cannot show that the community is reaching consensus. The abundance results are thus dominated by what one might term "real uncertainty," the fact that, even with perfect high resolution data and the best atmosphere models available, the models still are not "good enough" for our craving for accuracy.

In closing, we would like to draw attention to stars that stand out in some way. NGC 6791 star R23 appears to be a member of the cluster according to K. Cudworth's preliminary proper motion reductions, but it appears to be twice as metal rich as the cluster median. It is possible that a particularly devious cosmic ray is responsible for this high-seeming abundance, since only one spectrum was taken of this star. In any event, this star is worth further study. NGC 6791 star R6 has no membership information from any source, but with [Fe/H] $= -0.42$ we doubt very much it belongs. It appears to a clump star in the NGC 6791 color-magnitude diagram, but because metal-poor giant branches are warmer it is more probably a field giant higher on the giant branch, and thus it is more distant than the cluster. Star Worthey 1 also has doubtful membership credentials. It appears on the NGC 6791 giant branch a magnitude above the clump, but it is very far from the cluster center and our [Fe/H] $= 0.02$ is also several sigma below the cluster median. The only other star that is suspicious for reason of low abundance is R24 at [Fe/H] $= 0.08$, but this is the star that appears to have ill-converged atmospheric parameters (Figure 2). Stars that are "metallicity members" with no previous membership information are NGC 188 stars I-85 and I-88, and NGC 6791 stars R2, R11, and R21.

This work is based on observations obtained at MDM Observatory through the auspices of the University of Michigan. Partial funding for this project was granted by NASA's Jet Propulsion Laboratory, contract 1236947 in support of the SIM open cluster project. Invaluable were the software and services of NOAO's IRAF, NASA's ADC and ADS, and the SIMBAD database. Thanks go to S. C. Trager for sharing his hard work on abundance systematics, to K. Cudworth for sharing preliminary results, and to the helpful anonymous referee.

REFERENCES

Cayrel de Strobel, G., Soubiran, C., & Ralite, N. 2001, A&A, 373, 159

Dinescu, D. I., Girard, T. M., van Altena, W. F., Yang, T.-G., & Lee, Y.-W. 1996, AJ, 111, 1205

Dyck, H. M., Benson, J. A., van Belle, G. T., & Ridgway, S. T. 1996, AJ, 111, 1705

Efron, B. 1979, Ann. Stat., 7, 1

Ferguson, H. C. 1999, Ap&SS, 267, 263

Friel, E. D., & Janes, K. A. 1993, A&A, 267, 75

Garnavich, P. M., VandenBerg, D. A., Zurek, D. R., & Hesser, J. E. 1994, AJ, 107, 1097

Geisler, D. 1988, PASP, 100, 338

González, J. J. 1993, Ph. D. Thesis, University of California, Santa Cruz

Gorgas, J., Faber, S. M., Burstein, D., González, J. J., Courteau, S., & Prosser, C. 1993, ApJS, 86, 153

Hobbs, L. M., Thorburn, J. A., & Rodriguez-Bell, T. 1990, AJ, 100, 710

Kaluzny, J., & Rucinski, S. M. 1995, A&AS, 114, 1

Landsman, W., Bohlin, R. C., Neff, S. G., O'Connell, R. W., Roberts, M. S., Smith, A. M., & Stecher, T. P. 1998, AJ, 116, 789

McClure, R. D., & Twarog, B. A. 1977, ApJ, 214, 111

Ridgway, S. T., Joyce, R. R., White, N. M., & Wing, R. F. 1980, ApJ, 235, 126

Peterson, R. C., & Green, E. M. 1998, ApJ, 502, L39

Sandage, A. 1962, ApJ, 135, 333

Taylor, B. J. 2001, A&A, 377, 473

Trager, S. C., Faber, S. M., Worthey, G., & González, J. J. 2000, AJ, 119, 1645

Twarog, B. A., & Anthony-Twarog, B. J. 1989, AJ, 97, 759

Upgren, A. R., Mesrobian, W. S., & Kerridge, S. J. 1972, AJ, 77, 74

von Braun, K., Chiboucas, K., Minske, J. K., Salgado, J. F., & Worthey, G. 1998, PASP, 110, 888

von Hippel, T., & Sarajedini, A. 1998, AJ, 116, 1789

Worthey, G. 1994, ApJS, 95, 107

Worthey, G., Faber, S. M., González, J. J., & Burstein, D. 1994, ApJS, 94, 687

Worthey, G., & Ottaviani, D. L. 1997 ApJS, 111, 377

This preprint was prepared with the AAS LaTeX macros v5.0.

Table 1. Indices and Errors for Stars

Star	N	CN_1	CN_2	Ca4227	G4300	Fe4383	Ca4455	Fe4531	Fe4668	Hβ	Fe5015	Mg_1	Mg_2	Mg b	Fe5270	Fe5335	Fe5406	Fe5709	Fe5782	Na D	Hδ_A	Hγ_A	Hδ_F	Hγ_F
HR 489	6	0.201	0.248	2.522	6.415	8.028	2.570	4.735	6.155	0.817	6.561	0.183	0.324	3.613	3.870	3.436	2.541	1.507	1.292	3.678	-5.788	-9.821	-1.069	-2.796
		0.0019	0.0051	0.0676	0.0647	0.1148	0.1103	0.0639	0.0517	0.0274	0.0565	0.0048	0.0042	0.0245	0.0302	0.0557	0.0179	0.0273	0.0116	0.0604	0.2010	0.0528	0.1651	0.0259

Note. — This is a sample only. The full table is available electronically.

Table 2. Index Sensitivities at $\{T_{eff}, \log g, [\mathrm{Fe/H}]\} = \{4200, 2, 0\}$

Name	Value	$\bar{\sigma}$	$\frac{dI/\sigma}{dT/100\mathrm{K}}$	$\frac{dI/\sigma}{d(\log\ g)/0.5\mathrm{dex}}$	$\frac{dI/\sigma}{d[\mathrm{Fe/H}]/0.25\mathrm{dex}}$
1. CN_1	0.216	0.009	1.697	-2.548	7.380
2. CN_2	0.268	0.016	1.040	-1.854	4.652
3. Ca4227	2.634	0.170	-2.890	1.203	1.254
4. G4300	6.546	0.161	0.757	-1.373	-0.048
5. Fe4383	8.009	0.209	-0.620	-0.166	3.864
6. Ca4455	2.488	0.224	-0.542	0.077	0.815
7. Fe4531	4.756	0.187	-1.171	0.198	1.192
8. Fe4668	7.323	0.221	-0.278	-1.489	8.403
9. $H\beta$	0.727	0.072	1.845	-2.525	0.722
10. Fe5015	6.884	0.134	-0.588	-2.194	4.064
11. Mg_1	0.209	0.014	-2.001	1.804	1.450
12. Mg_2	0.350	0.014	-2.124	1.646	2.562
13. Mg b	4.131	0.127	-1.851	2.474	3.111
14. Fe5270	3.895	0.079	-0.883	-0.380	4.082
15. Fe5335	3.656	0.116	-1.702	0.862	3.539
16. Fe5406	2.613	0.052	-2.881	0.852	5.044
17. Fe5709	1.486	0.069	-0.089	-0.490	1.786
18. Fe5782	1.339	0.051	-0.672	-0.569	2.590
19. Na D	3.644	0.114	-1.336	0.191	7.683
22. $H\delta_A$	-6.548	0.601	-0.151	0.355	-1.779
23. $H\gamma_A$	-10.300	0.220	0.920	0.000	-3.005
24. $H\delta_F$	-1.399	0.254	-0.031	0.447	-1.321
25. $H\gamma_F$	-3.281	0.118	0.438	-1.161	-2.034

Note. — The σ in column 3 refers to the average error of bright standard stars for the data presented in this paper. The partial derivatives in columns 4, 5, and 6 utilize these σ values.

Table 3. Standard Field Star Atmospheric Parameters

Star	T_{eff}	σ_T	log g	σ_g	[Fe/H]	σ_{Fe}
HR 489	4103	49	1.1	0.3	-0.23	0.029
	4133	···	1.2	···	-0.11	···
HR 1805	4247	20	1.8	0.2	0.35	0.032
	4156	···	1.2	···	0.21	···
HR 2002	4797	···	2.3	···	0.15	···
	4751	···	2.2	···	0.03	···
HR 2600	4573	76	2.6	0.2	-0.36	0.030
	4381	···	2.2	···	-0.35	···
HR 7429	4551	92	3.0	0.3	0.20	0.025
	4428	···	2.45	···	0.22	···
HR 7576	4296	130	1.8	0.9	0.48	0.007
	4355	···	2.15	···	0.42	···

Note. — For each star, the first line indicates atmospheric parameters derived from the present data set. The second line of each entry lists the literature compilation adopted in Worthey et al. 1994 used to compute fitting functions. The parameters for HR 2002 did not automatically converge, which made computing errors in the same way as the other stars impossible. Table 1 dwarfs HR 7126, HR 7373, HR 7503, HR 7504, and HR 7560 are too hot to be included here.

Table 4. Program Star Atmospheric Parameters

Star	T_{eff}	σ_T	log g	σ_g	[Fe/H]	$\sigma_{\rm Fe}$	Note
I-55	5545	32	2.7	0.2	0.202	0.034	2
I-61	4745	41	3.1	0.3	-0.011	0.061	2
I-69	4380	92	1.9	0.5	0.065	0.021	2
I-75	4729	37	3.0	0.1	0.045	0.021	2
I-85	4853	74	3.5	0.2	0.099	0.027	
I-88	5146	108	3.0	0.9	0.223	0.105	
I-97	4878	178	3.4	1.0	-0.006	0.016	2
I-105	4781	68	2.4	0.2	0.204	0.011	2
I-116	4992	111	2.9	0.4	-0.021	0.146	2
II-181	4448	91	2.0	0.5	0.085	0.011	2
R2	3910	101	1.4	0.9	0.438	0.118	
R3	3924	115	2.1	0.7	0.417	0.101	2
R6	4261	89	1.0	0.2	-0.419	0.072	
R8	3987	33	1.1	0.3	0.285	0.024	1,2
R9	3966	79	1.9	0.8	0.300	0.111	1,2
R10	4077	0	1.2	0.3	0.202	0.146	
R11	4148	43	1.1	0.4	0.281	0.026	
R12	3900	···	0.8	···	0.290	0.050	1,2
R16	3982	42	0.9	0.7	0.356	0.048	
R17	4076	42	1.1	0.6	0.320	0.014	2
R18	4140	107	2.1	0.8	-0.143	0.079	
R19	3935	81	1.0	0.9	0.319	0.104	1,2
R21	4157	110	1.9	0.8	0.349	0.058	
R22	4425	150	2.2	0.5	0.475	0.024	2
R23	4575	···	2.3	···	>0.6	···	2
R24	3972	54	0.7	0.4	0.080	0.052	2
R25	4413	51	2.7	0.2	0.341	0.026	2
Worthey1	4135	47	1.5	0.4	0.019	0.018	

Note. — NGC 6791 star R12 is near the cool cutoff for the fitting functions, but we think its [Fe/H] measurement is robust. Star R23 exceeds the range of the fitting functions in the [Fe/H] dimension. R18 is a probable radial velocity nonmember according to Garnavich et al. (1994). Table 1 stars II-52, II-64, II-67, and II-69 are too warm to be included here. Table 1 stars R1, R4, R5, R7, and R14 are too cool to be included here. NOTES: (1) Radial velocity member from both Garnavich et al. (1994) and Geisler (1988). (2) Proper motion membership available from Cudworth (private communication), Upgren et al. (1972), or Dinescu et al. (1996).

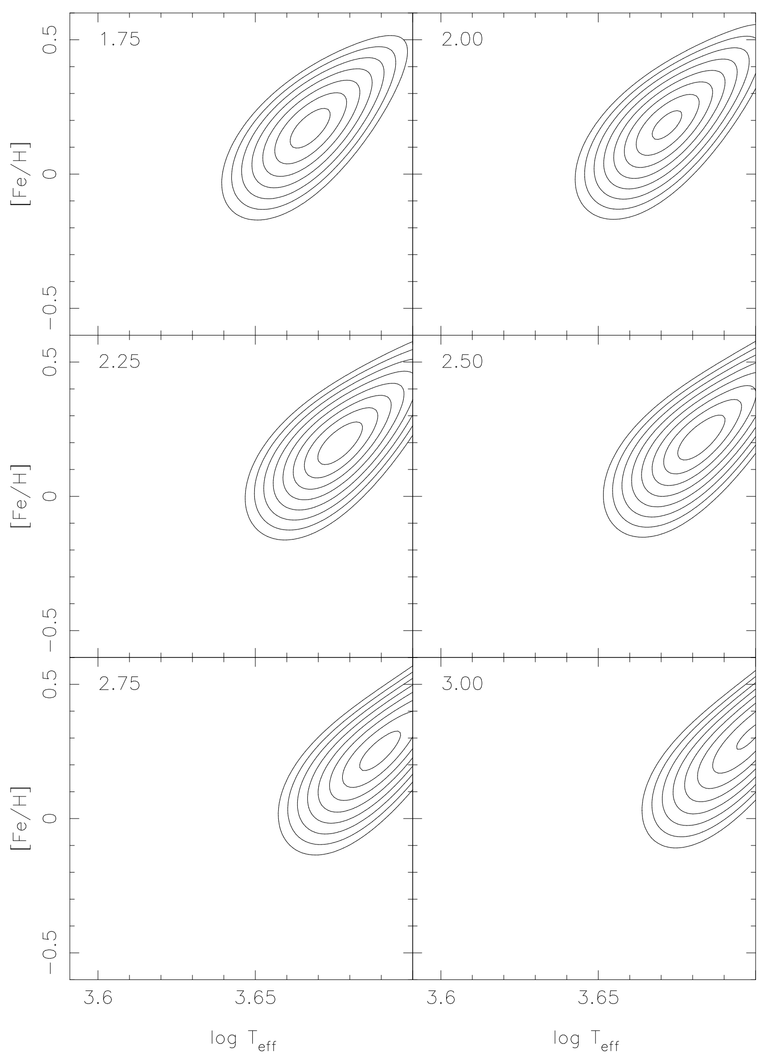

Fig. 1.— To illustrate covariances, contours of $G \times 6^{-1/2}$ for NGC 188 star I-105 are shown in the abundance-temperature plane for the 6-index set. Contours are set at 0.5-σ intervals, and the centermost contour is at 2.0σ (this is one of our worst-fitting stars: a typical star has $\sim$3 more inner contours). Different panels correspond to different values of log g, labeled in the upper left corners of each panel. The log g = 2.25 panel is the tightest fit. The tilt of the contours indicate a mild covariance between temperature and abundance. The drift of the locations of the best fits between panels shows that log g also covaries such that a higher temperature can be compensated for by a higher surface gravity. The log g, [Fe/H] covariance is more subtle.

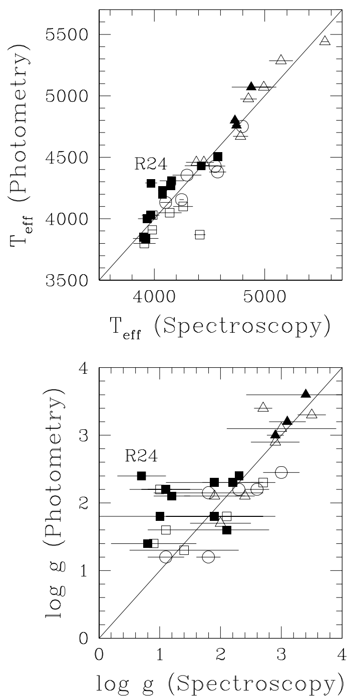

Fig. 2.— Temperatures and gravities as deduced from photometry are plotted as a function of the same quantities from Tables 3 and 4. Triangles are NGC 188 stars, filled if $V-I$ photometry from von Hippel & Sarajedini (1998) was employed, open if $B-V$ photometry from McClure & Twarog (1977) or SIMBAD was used. Circles are field giants using Table 3 data. Squares are NGC 6791 stars, filled if von Braun et al. (1998) data was used, open if the lower-precision Garnavich et al. (1994) data was used. See the text for a discussion.

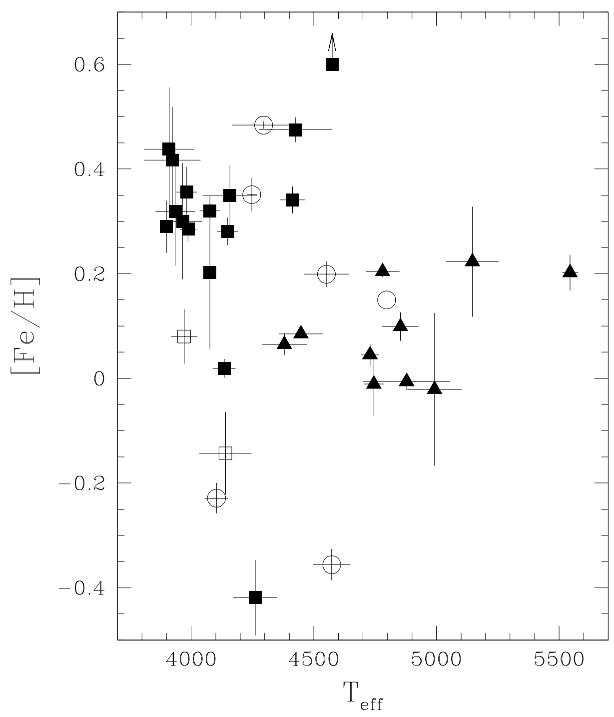

Fig. 3.— Abundance results as a function of temperature. Squares are stars from NGC 6791, filled if they were used to compute the cluster median abundance. Circles are Lick/IDS standard field stars. Triangles are NGC 188 stars.