PART V

ABUNDANCES IN STELLAR POPULATIONS

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Abstract. Stellar abundances are reviewed with emphasis on large-scale effects which may yield clues to galactic structure and evolution. Spectroscopic and indirect photoelectric abundance criteria are discussed, and utilized.

The abundance statistics of nearby galactic disk stars, dominated by M dwarfs, but observed at spectral types F and GV and K III, suggest a weak age-abundance relationship with a substantial dispersion at any time. Very metal-poor stars are extremely rare. Spatial abundance gradients, with higher metal abundances occurring nearer the galactic centre, are indicated. Disk abundance gradients are prevalent for light elements in other Sb and Sc galaxies.

The confusing status of supermetallicity is again reviewed. The super-metal-rich (SMR) *giants* (like μ Leo) are either over-abundant because of self-N-enrichment (from C–N–O processing?)and boundary-temperature cooling, or are really SMR. Each case may be reasonably argued. The old galactic clusters M67 and NGC 183 seem, by recent *indirect* acclaim, to be only slightly more metal-rich than the Sun. The Spinrad-Taylor data on the M67 giants would still seem to superficially suggest over-abundances in Na and Mg, but other interpretations are possible.

SMR dwarfs, like HR 72, and subgiants, like 31 Aql are surely very old, and have metal abundances larger than the Hyades. However, they are, by number, only ≈ 5% of the local main sequence.

The galactic halo star tracers – red giants and RR Lyrae stars, have been observed extensively, lately. There is some indication of an abundance gradient from 5 or 10 kpc galactocentric radius out to $r \sim 100$ kpc. The most metal-poor stars observed in the Draco system are about 1000 times less abundant in heavy elements than is the Sun, and much of the galactic disk.

Abundances in other galaxies, as a function of their total mass, and stellar/gaseous composition are also reviewed. There is a clear dependence of abundance on galaxian total mass.

1. Introduction and Emphasis

This review will emphasize stellar abundance determinations on a large scale – as applied to the populations, which can yield large-scale information on the structure and past evolution of our Galaxy, and other galaxies.

Also since we deal with galactic archeology, I will almost ignore the problems of young stars and spectral types O, B, and A in this talk. All this means that we have to observe and also understand the spectra of many faint (distant) stars of spectral type F5 and later, or the integrated spectra of millions of stars. Then right away we have a strong operational constraint on the information content of the data and the depth of analysis to be expected. We have to look at indirect, coarse criteria for abundances – not the conventional, high-dispersion spectroscopic analysis. But large, homogeneous series of photoelectric observations of metallicity criteria (see the review by Bell in this Symposium) have advantages, too. As Williams (1974) states, the narrow-band technique has the advantage of speed, homogeneity and impersonal comparison. Of course, the detailed analysis of some interesting stars, difficult as they may be, is very necessary.

B. Hauck and P. C. Keenan (eds.), Abundance Effects in Classification, 183–204.

Now what are these indirect or semi-direct criteria we can use? Most closely aligned to conventional spectroscopic analysis are photoelectric measures of individual strong lines or groups of them – pioneered by the Cambridge group under Redman and Griffin, and recently by P. M. Williams (1971a, b). Then we have groups of weak lines, isolated by an echelle spectrograph, observed by Gustafsson *et al.* (1974); then the medium-resolution scans of Spinrad and Taylor (1969), and finally many other types of intermediate-band photometry – such as Strömgren photometry, DDO photometry which measures CN [*C(41–42)*], and recently a system extending to the near-IR developed by R. Canterna at the University of Washington. Even *UBV* photometry, or *RGU* photometry can be applied to stellar abundance determinations, perhaps in restricted parts of the HR diagram or together with other data. Naturally, we find the very narrow-band or single-line techniques applicable to mainly bright stars, and in the context of this talk, that usually means nearby K giants or a few very nearby G dwarfs. The broader-band, (often) less discriminating tests, can be applied to luminous stars almost across the galaxy, and to lots of main-sequence stars. What is desired is the best of the two worlds – and perhaps the next generation of digital, sky-subtracting scanners and panoramic detectors will provide the means. A start has been made by Butler and Kraft (1975).

Until then, we use what we can. An example of what can be done with the blanketing measures of, $U-B$, $B-V$ colours and the unique temperature dependence of $(R-I)$ or T (Spinrad and Taylor, 1969) follows:

If we examine the $U-B$, $B-V$ plane positions of nearby G-K dwarfs and K giants, vs the Hyades cluster sequence of Johnson and Knuckles (1955) and Johnson, Mitchell and Iriarte (1962), we note a large scatter, and rather poor separation of later-type stars of differing metal content. However, if we can group either dwarf or giant stars of nearly identical red colour (and therefore, effective temperature) together, we note that their *loci* in the $U-B$, $B-V$ plane are short lines, whose slope $S = \dfrac{\Delta(U-B)}{\Delta(B-V)}$, and is a function of T or $R-I$. Table I lists the results, seen in Figure 1. I call these slopes empirical blanketing vectors. In practice this is not very different from the work of Becker and Steinlin (1956).

The usefulness here is that abundances could probably be interpolated for stars with $B-V \geqslant 0.7$, with only a luminosity class, *UBV*, and T, or $R-I$ known. This is quite practical for stars to $V \simeq 15$, and thus a large fraction of the galaxy is available *in situ* for K0-K3 III types.

2. Abundance Results on Stars near the Sun – The Galactic Disk

Pagel and Patchett (1975) have recently compiled abundance data from several statistically complete samples of nearby dwarf stars.

They find for the long-lived G dwarfs the abundances, relative to the metal-rich Hyades cluster, were log-normal in [Fe/H], with a mean at $\simeq -0.3$. The age effect is

TABLE I

Empirical blanketing vectors for K stars

a) *K dwarfs:*

T	$(R-I)$	Equiv. Sp. Type	$S = \frac{\Delta\,(U-B)}{\Delta\,(B-V)}$
347	$0^{m}36$	G8V	4.0
376	$0^{m}40$	K0V	4.4
442	$0^{m}53$	K3V	6.7
485	$0^{m}55$	K4V	8.5
540	$0^{m}66$	K5V	10:

b) *K giant stars:*

T	$(R-I)$	Equiv. Sp. Type	$S = \frac{\Delta\,(U-B)}{\Delta\,(B-V)}$
392	$0^{m}47$	G9III	3.0
445	$0^{m}57$	K2III	4.5
500	$0^{m}70$:	K3-4III	6.6

present – a modest, but widely dispersed heavy element enrichment $Z(t)$ – with considerable scatter among field stars of a given age. The data are noisy, but according to Pagel and Patchett, there is a significant increase of Z with t – with no early peak. Note that the lowest mean Z considered is only at about 1/3 the *solar* metal abundance at an age of $l \simeq 10$ x 10^9 yr. Thus there is evidence, long known for clusters, that the metal-enrichment galaxy from some very low primordial level, was nearly half-complete when the disk stars formed. However, it has slowly increased since that time, if the Pagel and Patchett statistics are accurate and appropriate.

It is a pity that, at present, we cannot do more – on a quantitative level – with abundances for the M dwarfs. They are the vast, silent majority of stars in the solar neighbourhood and the nearby Universe. Scanner abundance determinations, such as those by Spinrad (1973) are a start – they show some strong – and some weak-line stars of both high and low velocity. It is difficult to use the scans alone for the badly needed quantitative analysis of M dwarfs. However, Barnard's star and Kapteyn's star, both high velocity M dwafs, have very different line strengths – presumably Barnard's is rich and Kapteyn's is metal-poor.

The oldest disk stars, as signified by their locations slightly above the main sequence (or as subgiants) have been observed spectroscopically by Hearnshaw (1972, 1973, 1974 and 1975). Other old stars (G and KV) can be found on the basis of abnormally weak chromospheric reversals at the centres of H and K; quantitative analysis by M. Penston shows many nearby stars to be older than the Sun, as expected.

The *oldest* disk stars have a rather large metallicity spread – from [Fe/H] $\simeq -0.8$ to even +0.44. Some of them are apparently SMR; we talk about this later.

Hearnshaw (1975) has suggested that old, higher velocity disk stars have higher [C/Fe] ratios than the average of disk stars with the same (low) iron abundance, but all the *Fe-rich* stars are carbon *overabundant*. The work of Oinas has suggested [Na/Fe] ≈

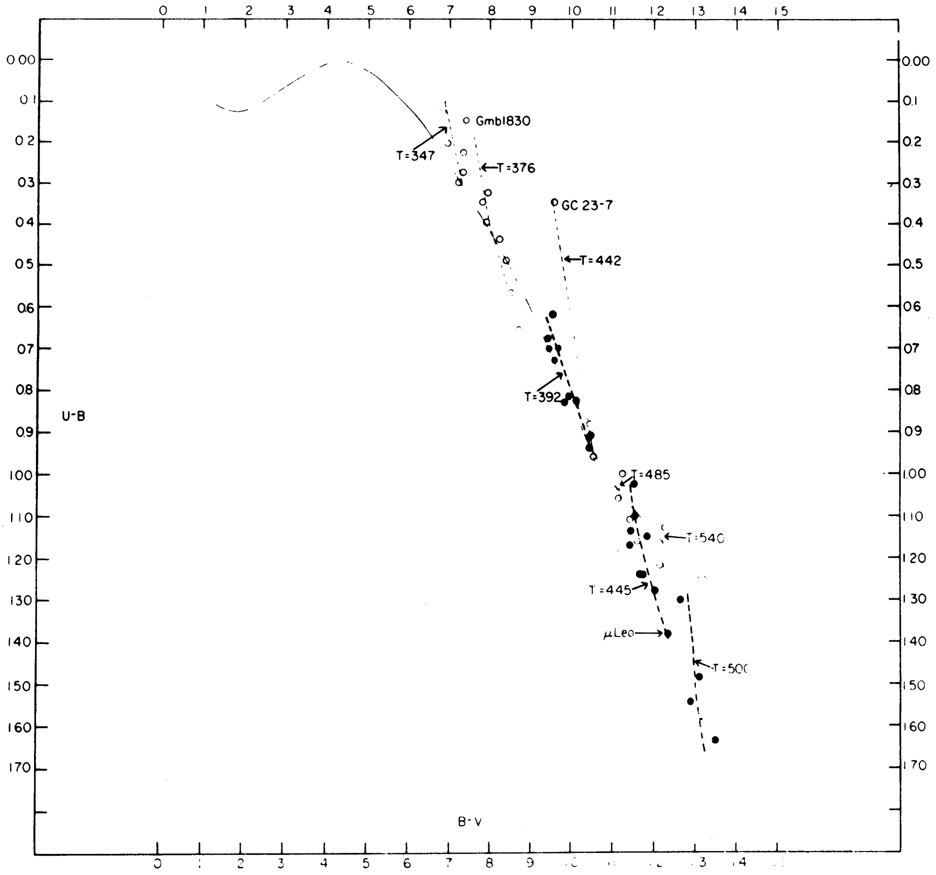

Fig. 1. Empirical blanketing vectors for K giants and late G-K dwarf stars. Points plotted and connected are stars with very similar red colour, *T*. The solid line in the Hyades main-sequence. Note the steepening of the vectors for the cooler stars.

[Fe/H]. Here we could begin to assemble clues important to early disk nucleosynthesis in the galaxy. Again the practical need to observe many faint stars suggests relative measures of CH (the G-band), Fe and T_{eff} by a (new) standard photoelectric system. That should be straightforward.

The statistics of normal disk K giants can now be studied with the large amount of data available on their DDO indices – mainly by Janes and McClure. In their 1971 and 1973 papers, Janes and McClure studied the kinematics of 799 K giants with photometry; the cyanogen index, their metallicity parameter, is rather well correlated with spectroscopic [Fe/H], except in some (unusual?)stars with N enrichment. Studying kinematics of their sample, they found that the K giants in the *weakest* CN group have a predominance of negative θ velocities – i.e. they are in rather eccentric orbits, and are likely old stars. However, the *strongest* CN stars also have predominantly negative θ velocities. These stars, with δCN > $0^{m}_{.}06$ (above the Hyades giants in CN) are 10% of the local K giants, in Janes (1972) thesis. Normal (δCN $\approx$ 0) giants cluster near the LSR in the Bottlinger diagram. However, in the Z velocity domain the situation is more conventional; the dispersion in Z velocities is a function of the CN anomaly, in the sense that the very weak CN stars have relatively high Z velocities, while the strong CN stars do not – they stay near the galactic plane. Thus the negative θ velocities (lag in rotation) of the strong-CN stars must be due to a *radial gradient* of CN strength in the *plane* of the galaxy. If these local gradients are blindly extrapolated to the centre of the galaxy, the population there – near the plane, would be dominated by the strong CN stars while in a larger volume around the nucleus the very weak CN stars would be very important. However, our galaxy must have a bulge population too, which we hardly sample out here, so this extrapolation in 10 kpc is too great. The Janes and McClure data yield a radial gradient in '[Fe/H]' of +0.023/kpc. Thus if R_0 = 9 kpc, the nuclear (*disk*) value of the CN-derived [Fe/H] would be +0.2, a modest overabundance. Data on other galaxies, mainly from H II region emission analysis, suggest that a linear extrapolation (at least for elemens O, N...) is too modest – I'll talk about that later.

The main thrust of this argument is to show that the heavy element abundance is a function of position of birth in the (exponential) disk for disk stars -- now relatively near the sun. This conclusion is strenghtened by the McClure *et al.* (1974) observation of the medium-age *galactic* cluster, NGC 2420 – toward the anti-centre. It has a low metal abundance, δCN = –0.06 which corresponds to [Fe/H] = –0.4, the lowest of any well-observed galactic cluster! Studies of other old to moderate age clusters, in the Perseus arm and beyond, are clearly desired.

3. The Status of Supermetallicity

I'd like to discuss the status and observed number of super-metal-rich (SMR), or apparently SMR stars, in 3 somewhat controversial or at least confused situations: They are:

1) The field K giants,
2) The old galactic clusters M67 and NGC 188,
3) The unevolved main sequence, F5-K7V.

In each section there are certain contradictions which I would like to mention – but cannot necessarily clarify!

It is surprising to this reviewer to find different rather sophisticated observations and analysis still yielding self-contradicting results for SMR K giants, especially the Spinrad-Taylor prototype star, μ Leonis (K2 III).

SMR stars are moderately rare, but a non-negligible fraction of nearby stars. Table II lists the proportions. Let's discuss recent work on field SMR K giants. There have been three major efforts to check on the abundances of prototype giants by conventional means. Blanc-Vaziaga *et al.* (1973) have analyzed ϕ Aur and μ Leo vs ϵ Vir, using high-dispersion spectra and theoretical line strength computations, based upon a grid of model

TABLE II

Percentages of stars classified 'SMR'*

Author(s)	% SMR	Technique or Parameters
1) *K giants:*		
Janes (1972)	10%	DDO CN index.
Spinrad and Taylor (1969)	~10%	Scanner line indices
Gustafsson *et al.* (1974)	~ 6%	Echelle spectrometry of metal lines.
Average =	9%	
2) *F-K dwarfs:*		
Taylor (1970)	4%	G-K5V scanner lines.
Raff (1975)	~5%	F5-G4V high-disp. spectra and models.
Average =	4,5%	

* Indirect or direct abundance ⩾ Hyades stars.

atmospheres. More recently, Ruth Peterson (1975) has obtained and analyzed high resolution spectra of μ Leo and two less-strong-line K2 III stars, κOph and ιDra. These stars have very similar red colours, and presumably the same T_e. Also, V. Oinas (1974) has utilized high-resolution coudé spectrograms of SMR giants (especially HR 8924, α Ser, μ Leo, HD 112127, 18 Lib A and θ UMi) and 'Atlas' models to compare red giants to the Hyades and the sun, and then to derive detailed abundances.

All three investigators need three basic and simple assurances to do their job:

(a) That the atmospheric structures of these giants are comparable,

(b) That the relative temperatures can be accurately determined (a negligible problem for Peterson), and

(c) That the equivalent width measurements are self-consistent among all compared stars.

It would seem that item (c) *should* be satisfactory, and I have not searched-out cross checks; (b) is crucial and everyone knows it or minimizes it by observing stars at a fixed red colour, and the first question (a) is assumed or anticipated, or tested later. Table III tabulates some recent spectroscopic and indirect results on SMR star abundances.

Blanc-Vaziaga, Cayrel and Cayrel's analysis suggests φ Aur is normal in Fe group elements, mildly overabundant in Na, while μ Leo is overabundant in Na and Ca, and normal in Fe and most other metals. They suggest that 'supermetallicity' is highly selective in the periodic table!

Oinas' technique is, with slight exceptions, very similar to the above; he used model atmospheres to compare the giants to the Sun. There may be some problem remaining, as Oinas found he had to alter the derived spectroscopic gravity to make abundances from ions and neutral coincident, and surprisingly, he found the most extreme K2-K3 III SMR stars to be modestly overabundant in Fe, Cr, Ti and V (averaging +0.2 dex), but up by 0.5 in [Na/H]. So at least Oinas found a substantial Na excess, in accord with Blanc-Vaziaga *et al.* But the basic conclusions differ for Fe and Cr; the situation (as I see it) is not clarified

TABLE III

Recent spectroscopic and photometric metallicities for SMR stars

Author(s)	Technique	Typical or maximum $[Fe/H]_\odot$	Stars involved
a) *Giants:*			
R. Griffin (1975)	Coudé spectra	−0.3	M 67, IV-202 Red Giant
R. Peterson (1975)	Coudé spectra	+0.0	μ Leo compared to ι Dra and κ Oph
P. Williams (1974)	Coudé spectra	+0.3	ι Dra
V. Oinas (1974)	Coudé spectra	+0.1, +0.2 (Na up)	μ Leo other SMR KIII
Blanc-Vaziaga *et. al.* (1973)	Coudé spectra	−0.10 (Na up)	μ Leo, ϕ Aur.
R. Canterna (1975)	Broad-Band Red-Green photom.	+0.3	Strong-CN stars, μ Leo, 20 Cyg
Gustafsson *et. al.* (1975)	Echelle Photo-electric spectra	∿+0.3	Strong-CN stars, μ Leo, 20 Cyg
b) *Dwarfs and some slightly evolved Sub-giants:*			
M. Raff (1975)	Coudé spectra	a few up to +0.4	η Boo, F8-G2V
J. Hearnshaw (1974, 1975)	Coudé spectra	5 with $>$ 0.3	G V and GIV
V. Oinas (1974)	Coudé spectra	+0.25, (Na up more)	K dwarfs, ρ, Cnc, Hr 1614
M. Grenon (1973)	Geneva Photometry	to +0.45	G-K V

by Peterson's result; μ Leo, κ Oph and ι Dra are all found to be at the solar level in [Fe/H]! She found that the weak (w_λ < 100 mÅ) lines for all three K2 III stars were about the same, and thus, since she found κ Oph had [Fe/H] = 0.0, so did μ Leo and κ Oph. However, she did find a strengthening of all lines formed near the boundary layer and suggests (as did Strom *et al.*, 1971) a lowered boundary temperature for the highly blanketed μ Leo. This is plausible, since μ Leo has very strong bands of CN. Thus Peterson concludes that μ Leo *appears* 'SMR' because of a low boundary temperature, which strengthens low-excitation lines of neutral atoms! This is a smooth scenario, but a likely flaw in the analysis is the choice of comparison stars, as both Spinrad-Taylor and Janes find that κ Oph has somewhat atypically strong blanketing in $U-B$, stronger-than-normal Ca I, Mg I and (slightly) Na I. Its DDO CN anomaly is +0.041, 2/3 the way to the Hyades! Moreover, Williams (1974) found ι Dra to be metal-rich by a factor of two, compared to ϵ Vir (usual ref. giant); the inconsistency in this result, the conclusion of Blanc-Vaziaga *et al.* and Peterson is sharpened when we note that Peterson finds the weak (W_λ < 100 mÅ) lines in the spectrum of ι Dra to be only 2% stronger than those in κ Oph, the standard of normalcy in her selection. Someone has to be incorrect!

Just as serious, in my thinking, is the difficulty of relating the relatively large narrow-band-indices for SMR giants to their detailed abundances. Do the correlations between spectroscopic [Fe/H] with an index, like CN or Canterna's $M-T_1$, break down only at $[\mathrm{Fe/H}]_\odot \gtrsim 0.2$? That would seem logical only if boundary cooling due to strong CN took over. However the high-resolution echelle spectrophotometry of Gustafsson *et al.* (1974) would seem to rely on lines near or strictly on the linear part of the curve-of-growth. These Fe lines are insensitive to boundary temperature fluctuations. These authors measured 80 G and K giants and utilized scaled solar model atmospheres, and found the Hyades to have $[\mathrm{Fe/H}]_\odot = +0.16$ (good agreement with previous conventional analysis). Some giants, including μ Leo, were found to be SMR. These procedures seem sound, too. I cannot reconcile their result with much of the conventional spectroscopy, of which we are familiar. Both seem to be credible.

Other narrow-band measures, such as the stronger Fe lines observed by Williams (1974), suggest SMR stars to be overabundant – as did Spinrad and Taylor for Na, Ca, and Mg.

One last remark on the SMR K giant problem should be re-stated; we probably cannot conclusively decide on how *superficial* 'SMR-ness' may be. It could represent a modest increase in Na and N and nothing else at all in an evolved star – or it could mean a primordial increase in abundance for almost all the elements. But we know quite empirically, that strong CN stars are more numerous toward the galactic centre (Janes and McClure 1973), so something physical is happening! If Grenon (1973) is correct and the same thing happens for G dwarfs and subgiants, we can be sure it's more basic and important than the CNO-generated N^{14} increase! On the other hand, the proportions of nearby SMR giants is twice that of the dwarf SMR sample (Table II), so that one could argue that half the SMR giants are, indeed, caused by self-enrichment in N^{14}, which makes strong CN. Then this yields a positive CN residual or overblankets the atmosphere of the K giant. Another counter argument: Dearborn *et al.* (1975) find μ Leo has even less C^{13} (relative to C^{12}) than does α Boo – μ Leo has a normal giant C^{12}/C^{13}, despite the strong CN bands, which imply much N^{14}. So the selfmixing arguments are not complete, for at least μ Leo.

The status of nearby SMR field *dwarfs* and slightly evolved subgiants is, for a change, almost unanimously in favour of finding a small percentage really SMR. Taylor and Raff each suggest ≈ 5% to be SMR. The most blatant examples are 31 Aql (Hearnshaw, 1972), HR 511 and HR 7670, (Hearnshaw, 1974), HR 72 (Spinrad and Luebke, 1970), ρ' Cnc, 14 Her, Hr 1614 (Taylor, 1970; Oinas, 1974), δ Pavonis (Harmer *et al.*, 1970) and η Boo (Raff, 1975).

I illustrate the spectrum of HR 72 and its Fe I curve-of-growth in Figures 2 and 3; the line strengths are really impressive. These are basically old to very-old stars, from the H-R diagram position of the subgiants, and the lack of measurable H and K reversals in the G-K dwarfs.

The actual abundances seem safe, because the stars are usually compared to the sun, and the comparisons often involve a small difference in temperature. Also we think that the atmospheres of solar-like stars are simpler or, anyway, more so than those of giants. Boundary temperature lowering by molecular blocking should be minimal, at least down to type K2 V.

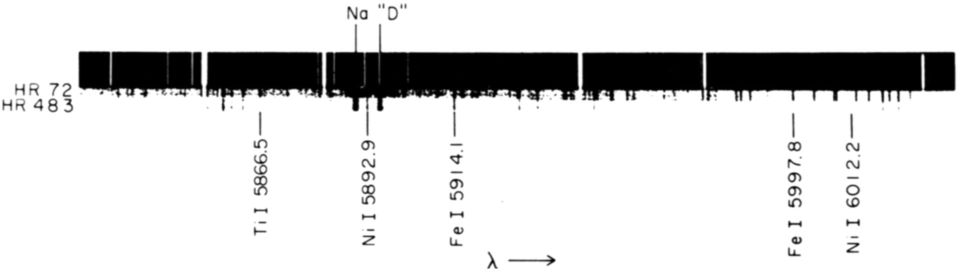

Fig. 2. A portion of the red spectra of HR72 (SMR G star) and HR483, a slightly metal-rich G2V. Note the strength of the weak lines and the strong, broad wings of Na 'D' in HR72. The original dispersion was 8 Å mm^{-1}.

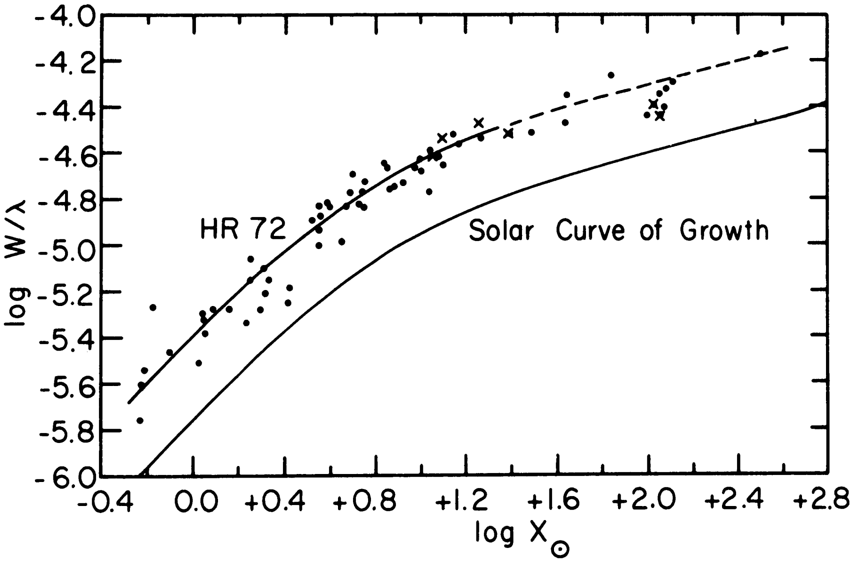

Fig. 3. The resulting curve-of-growth for HR72, compared to that for the Sun. From Spinrad and Luebke (1970). The overabundance of Fe is a factor of 2.5 in HR72.

Still, there are some surprises: Oinas still finds a Na-excess in the SMR dwarfs; [Na/Fe] $\simeq$ +0.2. Taylor's (1970) survey finds more K V stars with Na 'D' > (Na 'D')$_{\text{Hyades}}$, than stars with Fe I excesses. This might be an interesting lead to follow up.

Now the story of the old galactic clusters and supermetallicity: Spinrad and Taylor (ST) (1969) had suggested SMR line strengths for both M 67 and NGC 188, the oldest well-observed galactic clusters. This conclusion has been doubted and criticized ever since, and, I am sorry to say, has not been supported by any new evidence at all. I do *not* believe the ST scans of the M 67 giants have a systematic error, but I can't convince anyone. The old clusters are important – because of their age – and accurate abundances are needed.

The most direct new evidence on M 67 is the low-dispersion analysis of F and G dwarfs by Barry and Cromwell (1974) and the high-resolution spectroscopic work by R. Griffin

(1975) on the cool giant, M 67, IV – 202. Barry and Cromwell find M 67 only slightly metal-rich compared to nearby field dwarfs and the Coma cluster stars, while Griffin suggests the M 67 giant to be under-abundant by about a factor of 2 with respect to the Sun. Barry and Cromwell's H measuring technique can be used to derive the reddening to M 67, and they got rather lower reddening than do others. If we demand $E(B-V) = 0\overset{m}{.}06$ (Eggen and Sandage, 1964) or $E = 0\overset{m}{.}07$ (from HI in that direction – perhaps a risky correlation), then the abundances will go up somewhat, perhaps to $[\mathrm{Fe/H}]_{\odot} \simeq +0.1$ or $+0.2$, but probably not over the Hyades. The Griffin analysis seems straightforward enough, provided the relative stellar temperatures are well determined, and the abundance of α Boo is known. However the metal-deficiency of M 67 makes little sense if we examine the various cluster CN anomalies assembled by Boyle and McClure (1975). We tabulate in Table IV these results, in order of δ(CN).

TABLE IV

δ CN for Stars, Galactic and Globular Clusters

Star or Cluster	δ(CN)
μ Leo	$+0\overset{m}{.}11$
Praesepe-Hyades	$+0\overset{m}{.}07$
M67	$+0\overset{m}{.}03$
NGC 188	$+0\overset{m}{.}00$
[Field K giants]	$+0\overset{m}{.}00$
47 Tuc	$-0\overset{m}{.}07$

And also Pagel (1974) finds M 67 and NGC 188 to have CN indicative of metal abundances between the Hyades (+0.2) and the Sun (0.0).

Unless the average field giant is very metal-poor, then M 67 has to be intermediate on these CN systems. Of course a direct measurement of Fe would be better.

Probably what is really needed now, is a photoelectric measurement of medium-strength Fe I lines in M 67 stars below the turnoff, near G2V – where both the Sun or the Hyades can be used as controls.

In any case, a slightly-above-solar-abundance level for the old clusters is, perhaps, still a little uncomfortable for the gradual disk enrichment picture outlined earlier.

4. The Galactic Halo – Abundances from Tracers (and Occasional Field Samples)

It's been acknowledged that the halo population is quite metal-poor for some time (Lindblad 1922, Schwarzschild and Schwarzschild 1950). A considerable amount of qualitative information about [Fe/H] exists from the work of Mayall (1946), Morgan (1956) and Kinman (1959). Red giants in globular clusters were studied quantitatively by Helfer *et al.* (1959) and their very metal-poor field analogues were observed by Wallerstein *et al.* (1963).

There is a definite correlation between [Fe/H] and space motion for nearby halo stars, *selected* on the basis of proper-motions. These very high velocity stars are rare, per unit volume(~1% near us); however by the 1960s enough of them had been found, for which photometry was available, to allow Eggen, Lynden-Bell and Sandage (ELS) (1962) to correlate stellar ultraviolet excesses with space motions, especially the |W| (the *Z*-component). This led to the ELS picture of a rapid halo collapse with most nucleogenesis complete during the dynamically brief (~10^8 yr) collapse. The classic ELS paper is still important; it has set the stage for many important subsequent investigations and has carried over a few prejudices, too.

Now we have the technical capability to study a few nearby high velocity stars of the halo population in great detail (cf. Sneden, 1973 and Pagel, 1972), and many distant 'tracers' – RR Lyrae variables and globular cluster stars – in a coarse, comparative way. Despite the large distances involved, the study of luminous, evolved stars should allow us, in time, to map out the present distribution of metals in the galactic halo (presumably frozen in since the early days), and then evolutionary modelling should be successful.

The field halo star work I'd like to mention is a study by McClure (1973), complimenting the earlier work of Sturch and Helfer (1972). McClure noted that the CN anomalies of field K giants at the North Galactic Pole became more pronounced and negative (metal-poor) at heights of 1 kpc and more above the plane – but the dispersion in δ CN was still large at this distance – occasional strong-CN stars are still present in the near halo, although at $Z \geqslant 2$ kpc the few stars sampled seemed to be as metal-poor as Arcturus, judging from their CN bands. There are no extremely metal-deficient stars in this sample, or the one observed by Sturch and Helfer. Thus the halo stars selected by position *in situ* are moderately metal-poor – surprising no one. However, we recall that the *average metal-poor* star, selected not on the basis of motion or position far from the galactic plane, is in an almost circular orbit (Bond 1970)!

Unfortunately, to go further we have to pick on special tracer stars – variables in the field, in clusters, and globular cluster red giant stars. Some of the most recent work on these objects is by Butler (1975), Butler and Kraft (1975) and by Kraft (I thank Bob Kraft for many discussions and permission to quote some of his results of work in progress...).

The metal abundances of RR Lyrae stars, in the field and in clusters, were first studied by Preston (1959, 1961). This was done by estimating equivalent spectral types for both the H Balmer lines and the Ca II K-line. Preston's ΔS parameter, defined as ΔS = 10 [Sp(H)–Sp(K)] correlated with the periods of the nearby RR Lyrae type '*a*' variables, and their space motions. But because of the long exposure times demanded by a photographic spectral survey of distant RR Lyrae, this ΔS system hasn't enjoyed the popularity associated with intermediate-band photometric systems. The last few years Butler, and Butler and Kraft have used the new image-tube-scanner (ITS) (Robinson and Wampler 1972) at the Lick 120″ reflector to obtain low dispersion digital spectra of both field and cluster RR Lyrae stars. Under average observing conditions it takes 15^m to obtain a good ITS spectrum (in the blue) at $B \sim 15$. We illustrate in Figure 4 the spectra of some cluster RR Lyrae and 2 Coma main-sequence stars; note the relative weakness of.

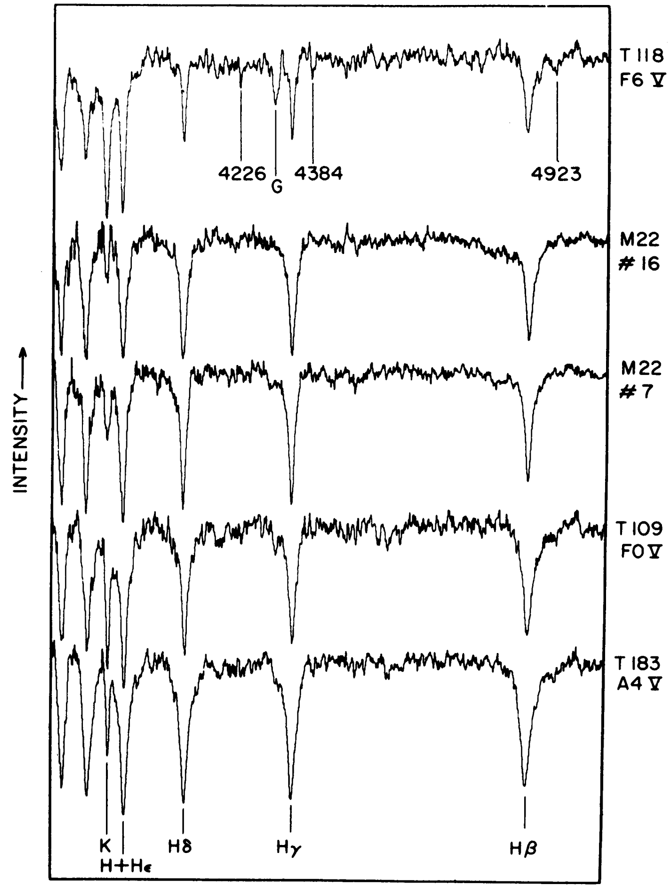

Fig. 4. ITS spectra of selected RR Lyrae stars in M22 illustrated with some Coma cluster A and F star standards. Note the weakness of Ca II K and the G-band in the metal-poor cluster variables. From Butler (1975).

Ca II in the M22 variables. Figure 5 shows Butler's plot of the equivalent widths of H Balmer lines and the K line, vs Spectral Type. The ΔS for distant globular clusters were corrected for the possible interstellar K-line components, and a calibration of the new photoelectric ΔS index was established by Butler from analysis of high-dispersion spectra of the brightest field RR Lyrae stars. The calibration was:

$$[\mathrm{Fe/H}] = -0.16\ \Delta S - 0.23 \tag{1}$$

The resulting abundances from ΔS correlate well with Sturch's (1966) $\delta\ (U-B)$ values and Jones (1971, 1973) K-line index. The most metal-poor field stars ($\Delta S \sim 12$) have $[\mathrm{Fe/H}] = -2.1$ while $\Delta S = -1$ applies to a star of nearly solar composition – and such field RR Lyrae do exist, although they haven't been located in any globular cluster.

The application of this technique to mapping out RR Lyrae abundances deep in the

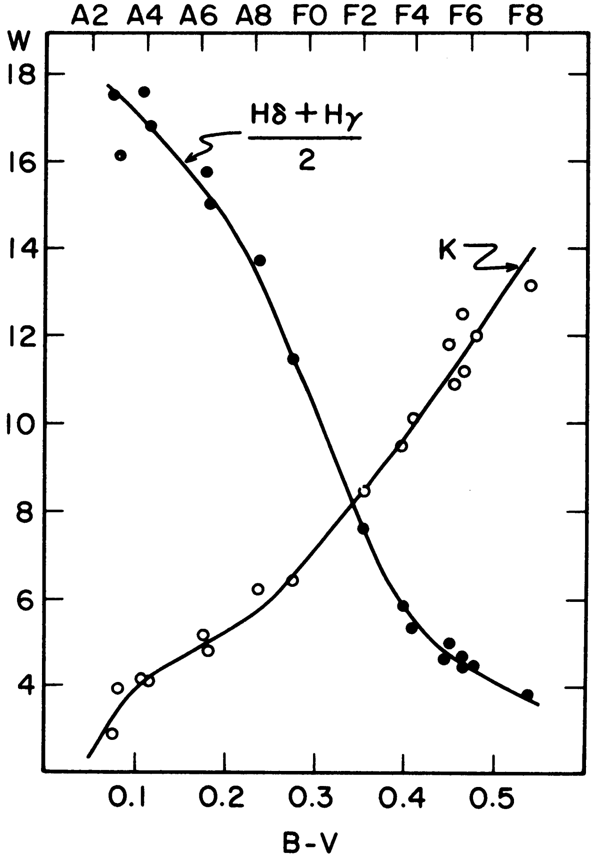

Fig. 5. Butler's plot of the equivalent widths of the H-Balmer lines and the Ca II K line, as a function of Spectral type, for normal stars. Such stars would have $\Delta S \simeq 0$.

halo is obvious; results so far on globular clusters compare well with Canterna's red-green photometry (1975) of the $(M-T_1)$ index. Table 5 lists abundances of globular clusters from Canterna's photometry of the giants (independent of C, N, O), Butler's [Fe/H] from RR Lyrae ΔS values, and the DDO CN photometry of Hartwick and McClure (1974) and Osborn (1973).

The agreement is fairly good. Under present investigation by Kraft are RR Lyrae near the galactic centre – in the field of NGC 6522. The period-frequency distribution of stars there (Hartwick, *et al.*, 1972) seems to mimic that of M5, for which $[Fe/H] \sim -1$. But the giants near the galactic centre, according to both Arp (1965) and van den Bergh (1972) are likely metal rich – as M67 or NGC 188. Do the RR Lyraes and giants of the galaxies nuclear bulge belong to a different population, or are there selection criteria – e.g. – *no large pulsations* in horizontal-branch stars if $[Fe/H] \gtrsim 0.0$? Anyway, Kraft's preliminary data show a few NGC 6522 field stars to have $\Delta S \simeq 3$, implying $[Fe/H] = -0.7$. This is pretty metal-poor!

Another project is to study selected halo fields (Kinman *et al.*, 1965) with RR Lyrae at varying distances from the plane and the galactic centre. The ultimate aim would be to directly map the metal-abundance gradient in the halo. The NGP field is under investigation now; the field 'below the anti-centre' ($\alpha \sim 2^h$, $\delta = +40°$) reaches RR Lyraes nearly 20 kpc away (and 10 kpc down), and so far the most metal-poor stars have only [Fe/H] = -1.5 (surprisingly high). This may be contrary to the Eggen, Lynden-Bell and Sandage picture. Why are not there stars as metal-poor as in M92?

The giants in globular clusters are attractively bright stars, and have been studied by several observers. However, some caution is necessary – work by Zinn (1973) on the G-band in subgiants and asymptotic branch giants in M92 and Kraft's recent digital spectra of M92 stars strongly suggests changes in the molecular bands of CH, CN and NH as the star evolves up the subgiant branch, reaches the red giant tip and goes back on the asymptotic giant branch of the HR diagram. There is good observational evidence in M92 that C and N are anti-correlated, mixing starts early, and C^{12} is gradually processed into N^{14}. So metal-abundances by photometry, measuring CN, could be pretty hazardous; luckily there is no indication of any change in *heavy* elements in the M92 stars (Fe, Ca, Na, etc, seem quite low throughout).

Some red giants in the Draco system (the nearest dwarf *E* galaxy dynamically bound to the Milky Way) have been observed by Canterna (1975) and by Hartwick and McClure (1974). Both suggest [Fe/H] for Draco is lower than that found for M92; an average of their scattered abundances suggests [Fe/H] $\doteq -2.9$, so these stars are really deficient in heavy elements – down a thousand times from a solar composition!

Draco is 68 kpc away now, and its tidal radius suggests that Draco couldn't have passed very close to the centre of our galaxy – it's always been way out in the halo, but is probably bound to the galaxy. If other distant systems like Sculptor or Pal 3 or Pal 4 also have extremely low abundances, there would be strong evidence for a halo abundance gradient extending from 10 to $\sim$100 kpc from the centre of our galaxy.

Canterna (1975) comments that any metal gradient established far out into the galactic halo is in agreement with the ELS model and a rapid collapse time; Larson's (1974) models for a spherical galaxy undergoing inhomogeneous collapse might be relevant too. In that case the radial dependence of Z (given mainly by *Draco*) would rule against Larson's models A-D, which predict [Fe/H] $\sim$ constant with distance for $r \geqslant 10^3$ pcs. However the Draco result would be consistent with models $E \rightarrow I$ with a collapse time $\sim 10^9$ yr, and a relatively *slow* and *low* star formation rate, which gives less metal production by stellar evolution in the early stages of the collapse when the stars of the outermost regions are formed.

Before we generalize too far from one beautiful, timely, pair of photometric observations, we should recall that the metallicity levels and gradients in globular clusters around other galaxies are probably different from our own. The Magellanic Cloud globulars are rather metal-poor. In the halo and disk of M 31 the known globular clusters are generally much more metal-rich than in our system (van den Bergh, 1969; Spinrad and Schweizer, 1972; Christensen, 1972), while the red colour of the M 87 globular clusters (Ables *et al.*,

1974) suggests they may be even systematically higher in heavy element abundances (cf. van den Bergh's 1975 review). I end this section with a query; much of our knowledge of the *halos* of other galaxies and our own comes from the study of globular clusters. Are these high density halo condensations typical of the surrounding sparse environs?

5. Abundances in Other Galaxies

Here we try to push to great distances and are often looking for rather subtle abundance effects. It is a challenge! Astronomers have begun to look at the abundances in other galaxies in a variety of complementary ways. On a small scale we can study individual luminous stars in the nearby Magellanic Clouds by conventional (but difficult) spectroscopy and comparison to (known?) galactic supergiants (cf. Fry and Aller, 1975; Przybylski, 1972; and Osmer, 1973).

Generally these spectroscopists found lower metals in both the LMC and the SMC, although the uncertainties are rather large. Van den Bergh (1975) and Gascoigne (1974) have suggested that classical Cepheids, whose mean period decreases from 6.1 days in the galaxy to 4.3 days in the LMC to 2.6 days in the SMC, indicate a lowering of the mean (internal) metal abundance in these *young* stars. Indeed, it appears as if stars of *any age*, apparently, have a low metal-abundance in the Magellanic Clouds. Cepheids' periods are an indirect, and easily-used, tool which should be also applied to abundance *gradients* in galaxies with a young-star population.

Most of the population/abundance work in other galaxies has been based upon integrated stellar spectra for the older-star dominated regions (nuclei of all types, bulges of Sa, Sb and SD galaxies, all over *E* galaxies) or in the interstellar medium (unborn new star population) – using H II region emission lines.

The analysis of the starlight shows line and band gradients in intermediate band photometry or low-resolution spectroscopy of the central parts of Sb-*E* galaxies. The CN bands have been fairly thoroughly studied by McClure (1969); Spinrad and Smith and Taylor (1972) and Spinrad and Stone (1975). That is because the λ 4200 CN band is wide and strong and relatively easy to measure in regions of low galaxies surface brightness.

Resually show a marked decrease in the CN [and when measured (cf. Welch and Forrester, 1972; Joly and Andrillat, 1973) strong neutral lines of Na, Fe and Mg] away from the nuclei of the galaxies. The scale length for 1/2 change from nucleus to a very low value, however, is variable – being as small as 100 pc in M 31 and 300 pc in N 3379 (EO). However, this could be deceptive, because of the limited nuclear angular resolution at 10–20 Mpc distance for giant *E* systems.

Spinrad *et al.* found variations in the CN gradients which correlated with the galaxies' radial drop in surface brightness. The *E* systems, which follow Hubble's law, generally show the steepest radial decline in CN, while the major axis of disk systems (Sa, SO galaxies) show little drop in metallicity with *r*. The SO system NGC 3115 has both populations; we therefore feel that the CN variation is associated with the old nuclear and halo populations, rather than the old disk. However that conclusion cannot be true for all E galaxies or most spirals, as recent Tololo CN measures by Spinrad and Stone seem to indicate a metal-rich halo to the Fornax EO galaxy NGC 1399 (halo CN≈nuclear value). Also as we note next, most spirals with gas and young stars show a sharp radial gradient in at least oxygen and nitrogen – from their H II region spectra.

Following the pioneering work of Peimbert (1968) on light-element abundances in the *nuclei* of M 81 and M 51, Searle (1971) made an extensive study of giant H II regions in several spiral galaxies. He confirmed the older Aller (1942) effect; the ratios of [N II]/Hα, Hβ/[O II] and [N II]/[O II] *decreased* from the centre outwards forming a neat, one-parameter family. The correlation holds from the inner H II regions (generally≈ 1 kpc from the nucleus) to the outermost regions. Searle concluded that these spectroscopic changes were most likely due to the presence of both O/H and N/H abundance gradients with the O^{16}, N^{14}/H ratios increasing inwards. We should remark that these results are only slightly model-dependent. This trend, if extrapolated to the nuclear regions (also see Warner, 1973) would agree with Peimbert's (1968), 1975) approximate factor of 6–12 overabundance of N, in particular. Recently H. E. Smith (1975) has obtained new observations of the H II regions of M 101 and M 33. He found a strong radial gradient in the O/H ratio, which decreased a factor of ∿10 across these two galaxy disks. The Ne/C and S/O abundance ratios are constant. The nitrogen abundances indicate a similar but weak gradient in the ratio of N/O (∿4 x over thehe disk).

TABLE V

Survey of selected Globular Cluster Abundances

Cluster	$[Fe/H]_{Canterna}$ indices	$[Fe/H]_{DDO}$	$[Fe/H]_{\Delta S}$
M92	−2.2 ± .4	−2.0	−2.2
M22	−2.0 ± .2		−1.7
M10	−1.7	−1.4	
M53	−1.6		−1.85
M3	−1.4	−1.0	−1.6
M71	−0.3 ± 0.2		−0.04

So for Sc galaxies all of this fits together pretty well – SMR nuclei-metal-rich inner regions – normal abundances≃ 0.5 Holmberg radius, and metal-poor exteriors!

Complications exist here too – galaxies with big bulges or less gas (H I/ star ratio lower), seemed to have H II regions with systematically stronger [N II] lines – in accord with the Burbidge's (1962, 1965) previous result for nuclei.

Finally, I'd like to discuss the evidence for a metal-abundance dependence on galaxy type and/or mass.

It is pretty clear now, that for *E* galaxies – with only old stars – that abundance at the nucleus and away from it depends on total galaxy mass. We go from the little dwarf spheroidal Draco ([Fe/H]$\cong$–3) to M 32 (nucleus$\approx$solar) to the giant NGC 4472 ([Fe/H]$\approx$ +0.3). These stellar determinations are upheld by the work of Jenner *et al.* (1973) who found [O/H] $\sim$–1 in the planetary nebulae of NGC 185, a dwarf *E* comparison to M 31.

Even better established are the gaseous composition differences between H II regions in small irregular galaxies (II Zw40, SMC) and our galaxy (near the Sun).

Dufour (1975), Aller *et al.* (1974) and Peimbert and Torres-Peimbert (1975) have observed H II regions in the Small Magellanic Cloud. I have averaged the well-determined ionic species (N, O, Ne) observed by these three sets of observers to form a mean comparison of the abundances of some light elements in the SMC, LMC and Orion-Carina of our Galaxy. Table VI lists these abundances.

This means the Small Cloud star-formation regions are down by 20 times in N, 6 times in O and 4 times in Neon! The overall metal abundance crudely-integrated over the periodic table, is about 1/5 solar! This seems to be well established.

TABLE VI

Total Chemical Abundances in the H II regions*

Galaxy	N	O	Ne
⟨SMC⟩	6.42	8.04	7.31
⟨LMC⟩	7.10	8.58	7.94
(Ori + Carina) in our galaxy	7.64	8.80	7.99

* Tabulated is log $N(X)$ with H = 12.00.

It does seem attractive to try to understand overall metal abundances and gradients in terms of theoretical stellar and galactic evolutionary models. The work of Talbot and Arnett (1973, 1975) for example, does indeed predict gradients in primary (O^{16}) and secondary (N^{14}) nuclei over disks of galaxies. The radial distribution of H I, H II regons and of colours is reproduced – so that we could infer that small, low mass, H I-rich irregulars like the SMC (or even the Markarians or II Zw40) are like the outer extremes of big spirals – and thus should be metal-poor. The star-evolution yield of heavy elements just has been too small (up to now).

Finally, I would like to close with a remark on the He-problem. This major abundant element has hardly been mentioned in my talk, or indeed as an effect on spectral classification [except for a few peculiar B stars] (but see Nissen, this Symposium).

I personally have had the prejudice of 'everywhere-constant Helium'; i.e., $Y = 0.28$ – 0.30. But the new and accurate spectrophotometry by the Peimbert's for the low-metal H II regions in the LMC and the SMC, are very suggestive of somewhat lower He, too. Peimbert and Torres-Peimbert (1975) suggest Y = 0.24 in the SMC; they propose a correlation of He and metals in galaxies.

This in turn, implies a primordial, or rather, *pregalactic*, He abundance rather lower than supposed to originate in the 'Big-Bang'. The pregalactic N(He)/N(H) is 0.074 ± 0.006, or $Y = 0.228$. So our galaxy and sun have benefited from star-produced He, too. This will, of course, have some considerable effect on our ideas of cosmology (an open universe if $H_0 > 20$ km s^{-1} Mpc^{-1}) and the luminosity of young galaxies! It definitely requires independent confirmation.

As you can see, the subject of abundances in stellar populations is still an open and active field, and one that interacts with a variety of other astronomical and physical disciplines.

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DISCUSSION

Griffin: In narrow-band photoelectric work it is generally appreciated that you measure *something* – that is, that you get numbers out of your machine but you are not always certain what the numbers mean. Although Arcturus was not included in the Spinrad-Taylor scanner studies, could you not measure it and compare your numbers with, say, the *Arcturus Atlas*? I am thinking in particular of the MG b-band region. Even in Arcturus, where Mg is known to be deficient, there is a surprisingly large number of strong MgH lines throughout that b-band region upon which you have based your Mg index. Incidentally, the strength of MgH may not necessarily be directly related to the Mg abundance, due to a variety of atmospheric effects upon the MgH dissociation equilibrium.

Spinrad: (1) It is too bright for the Lick equipment, unfortunately. (2) Maybe the MgH matters, but I doubt if it would vary out-of-phase with Mg I '*b*' in stars of similar temperature. Recall, the technique is differential.

Jaschek: Could you pleace quote average errors for the results you quoted? I am slightly surprised by the discussion of gradients of the order of $\Delta[\frac{\mathrm{Fe}}{\mathrm{H}}] = 0.023\ \mathrm{kpc}^{-1}$ since the errors of individual determinations are of the order of some tenths.

Spinrad: The errors are ***internally*** small in the DDO $\delta S(\mathrm{CN})$ measures. The gradient is that of the ***mean***; the dispersion is, of course, substantial.

Steinlin: There is no definite limit between disc stars of varying metal content on one side and a halo population on the other side, but a continuous distribution change with concentration to the plane of the disc strongly correlated with metal content. This means that lines of equal space density of stars go from extremely flat ellipsoids for high metal content to more and more spherical distribution for low metal content. The difficulty in observing the necessary large number of faint stars today is that broad-band systems are not well suited for the differentiation one has to be able to make and some new kind of system has to be found for this work.

Spinrad: The boundaries suggested in my talk are completely artificial.

Bidelman: It appears to me that we now have both direct and indirect evidence of appreciable nucleosynthesis of nitrogen in giant stars: the C^{13}/C^{12} ratios and the nitrogen-gradients found in galaxies. Thus it seems almost certain that the CN strengths measured in red giants are partly the result of primordial abundances and partly due to effects of evolution. I therefore feel rather strongly that one should not attempt to infer Fe/H ratios from observed strengths of CN. This is especially so in the case of the CN-rich stars.

Williams: I think any interpretation of the ΔS of RR Lyrae stars in terms of [Fe/H] should take into account the systematic dependence of [Ca/Fe] with [Fe/H] observed both in narrow-band and many spectroscopic analyses.

Spinrad: Yes, Butler tried to do this.

Walborn: Some caution may be required in deriving abundances from low-resolution observations of giant and supergiant H II regions such as the Carina Nebula and 30 Doradus. High-resolution observations show complex line profiles which vary with position, as well as regions of greatly different excitations. These effects may average out, but that should be checked with more detailed observations. Alternatively, less spectacular H II regions should be preferred for abundance studies.

Spinrad: OK; however some observations of different regions of large H II regions (with differing line strengths) by Peimbert and by Smith, each yield similar light-element abundance ratios.

Cayrel: I do not think that the enhancement of Na, Mg and Ca which we found in some 'Spinrad's SMR' stars could be explained by a lowering of surface temperature in these stars caused by CN-molecular absorption, because the overabundances of Na, Mg and Ca persist even if one uses only lines of higher excitation potential, formed in much deeper atmospheric layers.

Morgan: In the case of the globular clusters, how many individual stars would have to be observed with high dispersion to simulate the average characteristics of metallicity of the cluster as a whole?

Spinrad: I think for the Fe, Cr group of relatively heavy metals, a few stars scattered over the HR diagram would be sufficient.

For CNO elements, I fear the worst – it may take much observing of stars all over the subgiant, giant and asymptotic giant branches. Kraft is now working on this problem.

Bell: From nucleosynthesis calculations, it seems to be easier to get stars with high N and low C^{13} rather than high N and high C^{13}. This may explain why μ Leo, which must have enriched N, has $C^{12}/C^{13} = 18$, whereas Arcturus doesn't seem to have enriched N and has a lower C^{12}/C^{13} ratio.

Furenlid: You questioned the validity of Peterson's conclusions regarding the SMR phenomenon because the three stars investigated by her are all strong line stars. But is not the point of her paper that a range in SMR characteristics does not correspond to a range in [Fe/H], independent of the level of [Fe/H] in these stars?

Spinrad: Partly true, but indeed the ***photometric range*** of [Fe/H] or δCN or some other line strength parameter in between the 3 giant stars is small – ***none*** are normal, all have photometric abundance excesses. A bad choice of standard stars, I fear. However, Peterson's basic conclusion still could be correct.

Gustafsson: I would like to moderate your statement concerning the difficulties to reconcile the results for 'SMR' stars obtained by Kjaergaard, Andersen and me using very narrow-band photometry and those from conventional spectroscopy. The reason for this is the fact that there *are* lines from the flat part of the curve of growth within our abundance index for the most metal-rich stars, just because the photometric system was not mainly designed for studying the SMRs but giants in general. Therefore, a considerable surface cooling or a somewhat abnormal microturbulence could bring our [Fe/H] values for the SMRs down to the order of [Fe/H] for the Hyades. One way to clarify the situation would be to use the very-narrow-band technique with groups of still weaker lines if suitable groups can be found and the lines can be identified.

Spinrad: I agree!

Keenan: The M-dwarfs are being re-classified by Mrs Boeshaar at Perkins, and our plates show that Kapteyn's star is a subdwarf with very *strong* lines, particularly Ca 4226.

Spinrad: That's very important, and makes Kapteyn's star roughly similar in spectrum and M_V and motion to Barnard's star. Thanks.

Payne-Gaposchkin: Will you say something about planetary nebulae as tracers?

Spinrad: They have an excellent potential in this role, especially in the galactic bulge and halo. Quantitative spectra are now needed.

Stephenson: I have a brief comment plus a totally unrelated and somewhat awful question. *The comment*: I believe it is correct to assert, as a purely historical point, that the first published claim that there exists massive evidence for a nitrogen deficiency in the Small Magellanic Cloud was by Sanduleak.

The question: As many here are aware, Fred Hoyle has recently published a fascinating hypothesis to explain the solar neutrino deficiency, involving the survival of stellar nuclei from a previous generation of the Universe. If this is correct, it is highly relevant to the subject of stellar populations vs chemical abundances. Did you, in the course of the vast thinking that you did for this very excellent review, consider what you would have said about Hoyle's theory had you decided to include it?

Spinrad: (1) OK, Sanduleak's work on planetaries in the SMC did suggest a very low N abundance.
(2) I don't know enough about Hoyle's idea – sorry!

McCarthy: A question and a comment.

Question: Do you know whether the sodium line observations reported in your paper have been corrected in each case for the effects of Na in the night sky?

Comment: It seems important for us in discussions of galactic structure at high latitudes not to confuse the local structure in the direction of the NGP and SGP with much more extensive (and involved) region which is the galactic halo itself. We should try not to confuse a small part with a larger whole.

Spinrad: Yes.