Elliptical Galaxies: Abundance Ratio Trends and Implications

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Abstract. In large elliptical galaxies, Mg, Na, and N appear overabundant compared to Ca and Fe. There is a probable variation of (Sc + V)/Ti. It is clear that smaller ellipticals have a stellar population age spread larger than large ellipticals, but further progress in age determination is hampered by abundance ratio effects, which are the single most serious barrier to the estimation of mean ages. Isochrone grids allowing for the variation of many individual elements (He, O, C, and N at least) are needed to quantitatively estimate the overabundances and mean ages of ellipticals. The abundance pattern in elliptical galaxies matches neither the disk, nor the halo, nor the bulge of our own galaxy, although the bulge appears to come the closest.

1. The Spectrum of an Elliptical Galaxy

In concentrating on the abundance ratio variations in elliptical galaxies (Es), I am skipping virtually all of the vast literature available on these deceptively simple-appearing galaxies. As Arimoto (this volume) shows, the question of age in elliptical galaxies is a lot more slippery than some of us would have liked to believe. We remain frustrated in being able to quantitatively specify the star formation history of an E even in two-bin histograms of "old" or "young" stars due to the complication of metallicity and its nearly overwhelming similarity to age effects (Aaronson et al. 1978, Worthey 1994).

The spectrum of an elliptical can be viewed only at resolutions appropriate to the velocity dispersion of the individual stars within it due to the smearing effect of the combined stellar doppler shifts. This resolution is on the order of 10 Å (at ~5000Å) for the largest galaxies. Such a resolution swamps many weak features and makes even strong features blend with neighbors. Many index systems have been devised to measure the stronger absorption features in the optical spectrum (I will confine myself to the optical for this paper) with the intent to study galaxies. Narrow-band photometric indices were devised by, for example, Spinrad & Taylor (1969, 1971), Faber (1973), and O'Connell (1976). As observational techniques improved, it became possible to do higher resolution spectrophotometry, and some authors have taken advantage of this to define

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indices measured from polynomial-drawn continua (e.g. Bica 1988, Sil'chenko & Shapovalova 1989). Others define purely local measures of the continuum (e.g. Rose 1994; Burstein et al. 1984).

Most of the conclusions in this article rest on the large collection of data collected at Lick Observatory from 1972 to 1984 with the same telescope, instrument, and IDS detector. In the Lick scheme, flanking "pseudocontinuum passbands" are defined to either side of the feature of interest. The average fluxes in these bands are found, and a straight line is drawn from midpoint to midpoint that represents the pseudocontinuum. The missing flux in the "index passband" is added up and expressed as either an equivalent width or a flux ratio in magnitudes.

Each index is measured in a large collection of stars that cover the metallicity range in addition to gravity and temperature. Index behavior is summarized by polynomial fitting functions and incorporated into evolutionary population models. The models which appear in this article are the Worthey (1994) models, but the results are independent of isochrone author.

The indices are summarized in Table 1, where all indices except those marked "new" are found in Worthey et al. (1994). The indices are grouped into 10 families according to what species they measure. The information on what species are present comes largely from the theoretical work of Tripicco & Bell (1996). Parentheses in the "other species" column indicate that addition of that element contributes negatively to that index. The column of "metal sensitivities" are partial derivatives of the population models (d log age / d log Z at constant index) giving the relative sensitivity of the index to metallicity compared to its sensitivity to age. Broadband colors have sensitivities near 1.6 (the "3/2 rule," Worthey 1994), and it is useful to note how the indices do or do not break the age-metallicity degeneracy.

2. The Question of Elliptical Age

In particular, in Table 1, notice that compared to metal-sensitive indices like Fe4668, the Balmer features are relatively metal-insensitive, or age-sensitive, thus opening the possibility that some metal-Balmer index pairs can break the otherwise omnipresent age-metal degeneracy. At first glance (at Fig. 1) this appears to be the case. In the Balmer-metal diagrams shown, the models do indeed occupy a *region* rather than a *locus*, and the galaxies tend to fill the region.

However, in the top panels of Fig. 1, notice how the median galaxy drifts from panel to panel. Versus <Fe>, the galaxies look as old as the universe and just under solar metallicity. Versus Mg_2, the galaxies appear a lot more metal rich than the model grid can cover (maybe +1.0 dex) and about 2 Gyr old. Versus Fe4668, the ages and metallicities come out to be about the same as the geometric mean of <Fe> and Mg_2. This large (a factor of 10!) spread in age estimates is caused (see below) by abundance ratios that differ from those in the solar neighborhood, so that Mg strength is anomalously great compared to Fe strength, seriously skewing the age estimate because of the residual interdependency of age and metallicity. This result is model-independent.

Table 1. Lick/IDS index families

		dom.	other species	sensitivity	
1.	CN_1	CN	C, N, (O)	1.9	
	CN_2	CN	C, N, (O)	2.1	
2.	Ca4227	Ca	(C)	1.5	weak
3.	G 4300	CH	(O)	1.0	
4.	Fe4383	Fe	C, (Si)	1.9	
	Fe5270	Fe	C, (Mg), Ca	2.3	
	Fe5335	Fe	(C), (Mg), Cr	2.8	
	Fe5406	Fe	(Mg), Cr, C	2.5	
5.	Ca4455	mix	Cr, Ca, Fe, Ni	2.0	
	Fe4531	Ti	Cr, Fe, (Si)	1.9	small range
	Fe5015	mix	Ti, (Mg), Fe	4.0	O III in sideband
	Fe5709	mix	(C), Fe, Ti, Cr	6.5	weak
	Fe5782	Cr		5.1	weak
6.	Fe4668	C_2	(O), (Si)	4.9	
7.	Mg_1	C	Mg	1.8	
	Mg_2	Mg	C	1.8	
	Mg b	Mg	(C)	1.7	
8.	Na D	Na	C	2.1	interstellar extinction
9.	TiO_1	TiO	Ti, (Fe)	1.5	
	TiO_2	TiO	V, Sc, Ti	2.5	
10.	$H\delta_A$	H		0.9	new
	$H\delta_F$	H		1.1	new
	$H\gamma_A$	H		1.0	new
	$H\gamma_F$	H		1.2	new
	$H\beta$	H	(Mg), (Cr), C	0.6	

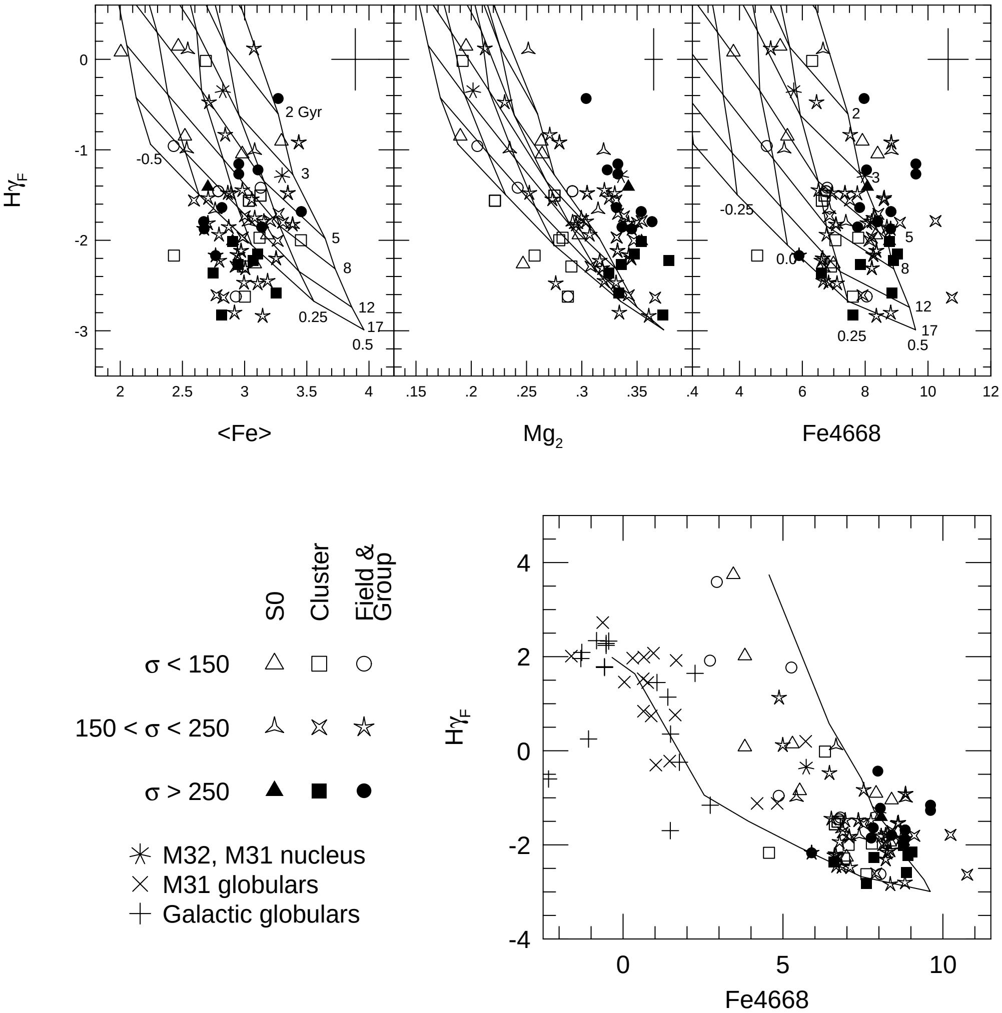

Figure 1. The index $H\gamma_F$ is shown versus <Fe> (an average of Fe5270 and Fe5335), Mg_2, and Fe4668. Lick/IDS data is shown with Worthey (1994) models. The model grid ages and scaled-solar [Fe/H] values are marked. Symbols for galaxies of different types and of differing central velocity dispersion are shown. Notice how dramatically the median age shifts from metal-feature to metal-feature. In the lower panel, Galactic and M31 globular clusters are also shown along with an abbreviated model sequence (17 Gyr models with $-1.5<[Fe/H]<0.5$ and +0.5 models with ages between 0.8 and 17 Gyr) in order to illustrate the strong empirical separation of the galaxian sequence and the cluster sequence. The models would indicate that the galaxian sequence is primarily caused by age differences, and the cluster sequence is primarily caused by metallicity differences.

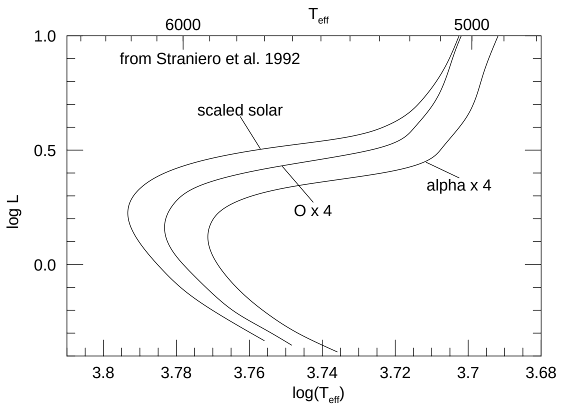

Figure 2. Tracks from Straniero et al. (1992) illustrating the effect that changing element ratios has on isochrone temperature. In particular, adding Oxygen lowers the turnoff temperature by about 150 K, leaving the RGB unchanged. As discussed in the text, the tolerance for relative temperature changes as a function of age, metallicity, or abundance ratio is on the order of 7 K if 5% accuracy in age estimates is desired.

It should be noted that there are some indices, mostly undiscovered ones, which appear to measure *only* age (e.g. the $H\gamma_{HR}$ index; Jones & Worthey 1995; Jones, this volume) but even these indices which cleanly measure the difference in temperature between the main sequence turnoff and the RGB will be modulated by variations in those abundance ratios which affect that temperature difference (Oxygen at least does this [see Fig. 2], and apparently helium does as well [Weiss et al. 1995]).

A rough estimate of the tolerance for uncertainty in isochrone temperature is easy to come by. One way is to note how much cluster RGB temperatures shift with metallicity and apply the 3/2 rule to convert a metallicity shift to an age shift. Another way is to use the models to note that a global shift of the whole isochrone by 100 K leads to an age estimate which is off by about 70%. This means that if we want ages accurate to 5% we need isochrones which are accurate to 7 K. This is obviously a rough estimate, but it should provide a useful guide for deciding whether candidate opacity sources are significant or not when calculating stellar structure.

Several other things are apparent in Fig. 1. First, there is a strong relation between Mg_2 and velocity dispersion which is utterly missing in <Fe>. Nobody knows what this means yet, but there is *some* sort of communication between Mg and galaxy size, while Fe is left out of the conversation. Second, we look at the lower panel in which globular clusters also appear. The sequence defined by the globular clusters is empirically distinct from the sequence defined by the galaxies. We *know* that the globular sequence is driven by metallicity, and we are pretty sure that even small Es have overall abundances near the solar value. The models (anybody's models) would indicate that the galaxy sequence is primarily an age sequence. Finally, the sample of galaxies is not statistically complete, but there would appear to be *many* young ellipticals out there. There is a tendency for the young ones to be the smaller ones, but there are some old & small ones as well.

On the topic of ages of elliptical galaxies, the literature contains a confusing array of opinions. Most (but not all) authors who have specifically addressed the question from a stellar populations standpoint have come to the conclusion that intermediate age subpopulations do exist in Es. Rather than give long lists of references, I would refer readers to O'Connell (1994) for a nice conference review article, to Rose (1994) for a recent comparitive study of M32 and Galactic globular clusters, and to Buzzoni (1995) for alternative viewpoints.

For rich cluster Es (this qualification excludes about 95% of the Es I plot in Figs. 1 and 3), there is some independent support for a small age spread from a "tightness constraint," imposed by the small scatter of M/L_B in the fundamental plane (16%; Faber et al. 1987). For Es of all environments there is another tightness constraint from the Mg_2-σ (where σ is the assumed-gaussian line-of-sight central stellar velocity dispersion) relation, which is tighter at the larger-galaxy end than at the small-galaxy end (Bender et al. 1993 and references therein). To be fair, it must be noted that <Fe> varies only extremely weakly with σ with constant scatter, and to equate σ with metallicity is a mistake from the start.

Nevertheless, under simple (naïve?) assumptions (working through population models) the tightness constraints tend to limit the RMS age spreads to less than 20% under the assumption that metallicity does not vary at all. If, on the other hand, one assumes a prolonged and complex history of star formation in Es, then the increase in chemical abundance with time will tend to tighten the fundamental plane and the Mg_2-σ relation (Worthey et al. 1995). Although this is a cloudy issue, hopes remain alive that at least *some* of the very large ellipticals typically found in rich clusters are in fact basically old galaxies. All that can be shown at present is that *the largest Es show more age homogeneity than smaller Es,* which may be a useful clue for galaxy formation modeling.

What have we learned about elliptical galaxy ages? It seems ironclad that significant mean age spreads exist among (at least) smaller Es. Age spreads among the largest ellipticals are smaller, but *how much* smaller is not known. Getting beyond the qualitative is tough. The measurement of absolute mean ages with spectral features is blocked at present by abundance ratio effects. Let us therefore look more closely at the abundance ratios.

3. Abundance Ratio Trends

The pointer to non-solar abundance ratios come from the blatant mismatch between scaled-solar population models and galaxies (Fig. 3). Many index-index pairs are very well reproduced by the models (for instance, in all intercomparisons of Table 1 families 2, 4, and 5 the models fall on top of the galaxies; see Worthey 1994 for illustrations), but not magnesium. Historically, Mg was singled out because the Fe features are immediately adjacent, thus eliminating any possible wavelength dependence of the models. As our confidence in the basic correctness of the models has grown, additional features can be highlighted.

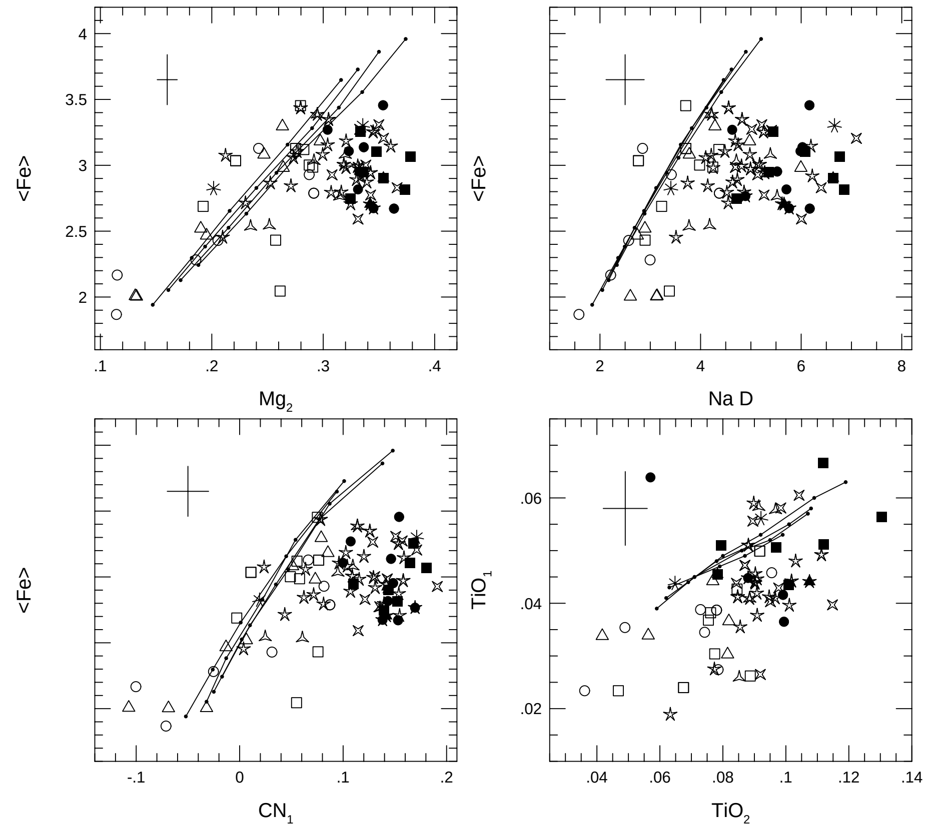

Figure 3. Abundance ratio differences in early type galaxies show up in plots of average Fe indices versus indices of lighter elements. Galaxy data is shown with the same symbols as in Fig. 1. Scaled-solar-ratio models of ages between 5 and 17 Gyr, and metallicities between −0.5 and +0.5 (lines connect models of one age) fail to track the galaxies in these diagrams, but do track intercompared Fe indices at all wavelengths (see Worthey 1994). Neither spreads in age, spreads in metallicity, changes in helium abundance, changes in mixing length, temperature shifts, horizontal branch morphology, stellar evolutionary timescales, nor IMF changes affects the overall locus of the models trajectories, so modest changes in element abundance ratios are implicated. Na D is affected by interstellar absorption upscatter, but this effect is probably less than 1 Å, on average. Since galaxies highest in CN are not also high in CH or C_2 index measurements, the CN enhancement is being driven by N enhancement. In the TiO_1-TiO_2 diagram, the mismatch appears to be driven by V and Sc (in TiO_2) versus atomic Ti (in TiO_1).

The basic logic is presented in the figure caption: all of the many changes that were tried, physical and unphysical, induce changes in the index-index diagram that are along the age-metal slope. Composite subpopulations add approximately as vectors, but are located along the same age-metallicity slope and hence cannot induce off-slope changes. The galaxies, however, stubbornly remain nearly horizontal, with Mg strength growing stronger without changing Fe. The straightforward implication is that the Mg abundance is enhanced relative to the scaled-solar ratio. The same logic applies to Na and CN. In the case of CN, we can pinpoint N rather than C because the CN-strongest galaxies are *not* strong in the G band (CH) or Fe4668 (C_2) indices. In the case of the TiO_1-TiO_2 diagram, the mismatch is clear, but the cause involves homework. Tripicco & Bell (1996) do not include TiO absorption in their calculations. Worthey (1994) looked at the spectrum of β Peg, an M2 giant (Davis 1947) to find that, besides TiO absorption, the TiO_1 index has additional contributions from atomic Ti, while the TiO_2 index has additional contributions from V and Sc. It is quite probable that [V + Sc / Ti] is the culprit variable.

The final thing to note in Fig. 3 is that it is preferentially the high-σ galaxies which are most light-element overabundant. In the TiO plot, both indices seem to have roughly the same (and intermediate compared to Fe vs. Mg) dependence on velocity dispersion, and the overall [V + Sc / Ti] shift seems stronger in the smaller galaxies.

4. Gradients

Gradients in colors and line strengths in elliptical galaxies have the potential to further unravel the skein of galaxy evolution. The possibility of dust distributed roughly as the stars in Es renders difficult the interpretation of color gradients (Wise & Silva 1995, although no evidence that I am aware of requires dust distributed with this geometry). Metallic line-strength gradients are almost always present, stronger toward the center (exceptions exist). If Es are single-aged within a factor of 2, they are more metal-rich toward the center. Culling some outliers, most authors derive d log Z / d log $R = -0.2$ assuming no gradient in age. This result is obtained with either colors or line strengths.

Mg and Fe gradients (Worthey et al. 1992; Davies et al. 1993) indicate (with exceptions) that [Mg/Fe]≈constant within a galaxy, even though the overall [Mg/Fe] varies from galaxy to galaxy. Hβ gradients tend to be flat (with exceptions) within the galaxies (González 1993; Fisher et al. 1995). Since models predict decreasing Balmer strength with increasing metallicity, the flat gradient implies a small age gradient (younger toward the center, on average), or, perhaps, systematic element ratio effects (not Mg, but O?).

Recently (Gorgas et al. 1996) we learned that larger Es have steeper Mg_2 gradients than do smaller Es. Besides implications for predicting global Mg_2 from nuclear Mg_2, we may be seeing the "smoothing length" for supernovae enrichment. If so, it is at least 150 pc.

5. Abundance results

Let us recap the results for ellipticals:

- Mg, Na, and N are globally enhanced in large Es.
- Ca tracks Fe (O'Connell 1976; and Lick/IDS data).
- [Sc + V / Ti] is high in some, mostly smaller, Es.
- M31 in both the nucleus and in the globular clusters has high N (Burstein et al. 1984; this paper).

Several processes can explain an overall light element enhancement (listed in Worthey 1992). The two most likely candidates depend on the ratio of the number of Type II vs. Type Ia supernovae which contribute to the chemical enrichment of the system. Type II SNs contribute light elements plus Fe, while Type I SNs contribute almost all Fe. Type I SNs are usually assumed to come from binary accretion, and thus have a time delay of a few 10^8 yr.

- Star-formation episodes in larger Es have a shorter timescale, and large Es have less Type I enrichment compared to small Es.
- Star formation in large-σ Es modestly favors massive stars.

The first scenario would predict good correlation of Mg strength with dynamical crossing time, or, in the case of termination of star formation by supernova winds (e.g. Arimoto & Yoshii 1987), with potential depth, and the second would predict good correlation with σ. In fact, the σ correlation is by far the tightest. The Na D and CN indices also correlate tightly with σ. According to chemical evolution models (Matteucci & Padovani 1993) the required change in IMF slope is not large.

But the simple two-parameter (Type II vs. Type I) explanation does not explain the detailed pattern of abundances in our own Galaxy, especially as compared with what we now know about the abundance ratios in elliptical galaxies. Trends for halo, disk, and bulge are summarized in Fig. 4, for the elements so far mentioned regarding elliptical galaxies.

5.1. C, N, O

In the halo and disk, N and C are almost solar. McWilliam & Rich did not look at N or C, but Rich (1988) and Terndrup & Sadler (1996, in preparation) find that bulge K giants have systematically weak CN. With [O/Fe]$\approx$0, this probably means that N is underabundant in the bulge. Elliptical galaxies and M31, on the other hand, clearly have enhanced N, with M31's metal-rich globular clusters even more severely enhanced. (The values plotted are guesses: models to quantify the overabundances don't exist yet.) Nitrogen itself is thought to come from mass-loss from intermediate and low mass stars (Woosley & Weaver 1995, hereafter WW95), but this fact does little to shed light on why N should vary so strongly from environment to environment.

Oxygen is an unknown in ellipticals at present. I would urge some stellar calibration work on the 2.3μ CO feature. A low [O/Fe] in the bulge is a surprise since Mg and most other "alpha" elements are enhanced, and O is thought to co-produced with the alphas in Type II nucleosynthesis (WW95). It is crucial to realize that O decouples from Mg and other "alpha" elements in the bulge!

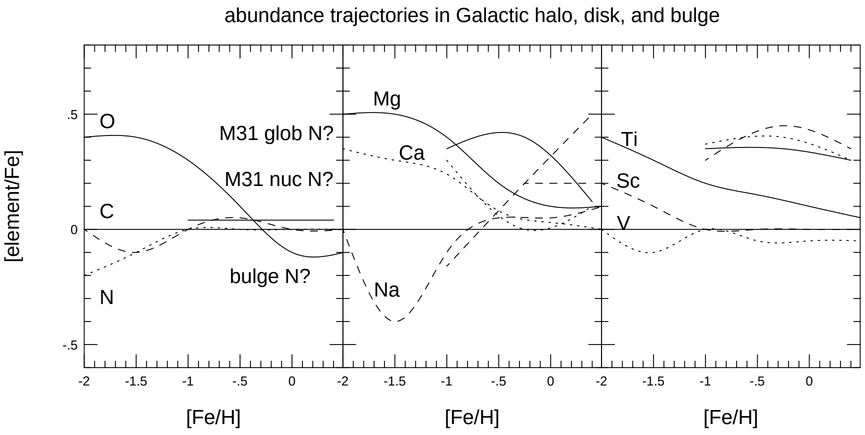

Figure 4. Average logarithmic abundance ratios are illustrated for disk and halo (lines that extend from [Fe/H]=–2 to +0.5) and for the bulge (lines that extend from [Fe/H]=–1 to +0.4). Average trends are distilled from stellar abundance data reproduced in Timmes et al. (1995) for the halo and disk, and McWilliam & Rich (1994) for the bulge. Bulge [O/Fe] is near zero. The high bulge [Na/Fe] value at [Fe/H]=0.4 is based on one star, so we include an alternate dashed line which stays constant at +0.2.

5.2. Mg, Ca, Na

Calcium appears to be stable at least, and even fairly well understood. It tracks Fe with apparently the same trajectory in all environments both Galactic and extragalactic (in Es, see O'Connell 1976, Worthey 1994). Nucleosynthesis theory (WW95) predicts overall halo and disk Ca abundance well (Timmes et al. 1995).

Magnesium harmonizes by being enhanced both in the bulge and in elliptical galaxies. Bulge Na also seems enhanced, qualitatively resembling ellipticals. The bulge Na abundance is uncertain at the present time due to difficulties in using the Na D lines for abundance work (McWilliam & Rich 1994).

5.3. Sc, V, Ti

These elements are made primarily during explosive nucleosynthesis and hence are sensitive to many uncertainties in theoretical prediction of the yields (WW95). Regardless of this, the Galactic pattern appear devoid of sense, with all elements low in the disk, but high in the bulge. In Es, the Sc + V pattern is more reminiscent of alpha element behavior, with Ti following the behavior of iron (with respect to velocity dispersion). In that case, why are Sc and V not enhanced in the halo? In general, Ti is a bad element for theoretical prediction, falling at least a factor of 6 short of matching the observed disk abundance (Timmes et al. 1995). Scandium and V are also underproduced, but not as badly. Titanium is coproduced with Fe in explosive nucleosynthesis; Sc and V are created in the "alpha-rich freeze-out" in the very deepest of expelled layers.

6. Final Words

Extrapolation of the halo abundance pattern to higher overall Z is not sufficient to mimic Es. Wrong answers will be obtained for N, Na, and Ca for sure, and probably O, Ti, Sc, and V. *And these are just the elements we can look at today.* I am sure the situation will improve in the future. The Galactic bulge may provide a much better abundance pattern template for Es, but N is anomalous. It is not yet clear whether Na matches or not, but [Sc + V / Ti] is shifting among Es, which it does not appear to be doing in the McWilliam & Rich bulge sample.

Briefly dragging in yet another class of objects that are not Es, Sil'chenko (1993) finds that [Mg/Fe] is solar in most bulges of other spiral galaxies, even though it is enhanced in Es and our own Galactic bulge (Is our bulge an oddity?). The situation among S0 galaxies is author-dependent at the moment (Sil'chenko 1993 versus Fisher et al. 1996), but this is plausibly a sample selection effect: perhaps S0s span a range of [Mg/Fe].

The most urgent need at the moment is for isochrones which allow for individual elements to be varied independently with a relative temperature accuracy of 7 K to begin serious attack on the age structure in elliptical galaxies. At a minimum, the elements to be varied are: He — it needs to remain a free parameter for now; O — it is not yet measured in Es but definitely does not track the alpha elements into the bulge; C — because of the high dissociation energy of CO molecules there is strong interplay between C and O abundance; and N — it has large spread in different environments as traced by the CN features. There is also probably an odd-even effect, traced by [Sc + V / Ti], in the lighter iron-group and alpha metals which should be allowed to vary. Overall alpha element enhancement should be allowed. And finally, high overall metallicities should be calculated, up to 5 times solar as Danielle Alloin has stressed at this meeting.

To do this is a large project. I would like to help interested parties overcome the drudgery. Please contact me if you are interested in some aspect of this problem.

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