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STUDIES OF HEAVY-ELEMENT SYNTHESIS IN THE GALAXY. I. SEPARATION OF *r*- AND *s*-PROCESS ABUNDANCES

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ABSTRACT

A survey designed to search for variations in *r*- and *s*-process abundances in the Galaxy is described. The data are obtained with an échelle grating system and image-tube in the coudé of the Mount Stromlo 74-inch reflector. Initial results of the survey suggest that only very small, if any, relative abundance variations are to be found among dwarf stars of the galactic disk, but small relative excesses of the *r*-process element Eu have been discovered in two of the three metal-poor, intermediate-population stars so far examined.

I. INTRODUCTION

Of the nuclear element-building processes discussed over a decade ago by Burbidge *et al.* (1957), only the *r*- and *s*-processes seem observationally at all well established today. Seeger, Fowler, and Clayton (1965) and Macklin and Gibbons (1967*a*) have presented impressive curves comparing solar system data to the theory of the *s*-process, and Seeger *et al.* have derived an *r*-process abundance curve that appears to be consistent with the occurrence of short, intense neutron fluxes. There is also strong evidence that both of these nuclear processes are continuing phenomena in the Galaxy. For example, the peculiar red-giant stars, especially the Ba II stars, show large overabundances of elements assigned predominantly to the *s*-process, and not of elements of the *r*-process (see especially Warner 1965). And the identification of ^{244}Pu in solar-system material Alexander *et al.* 1971; Hoffman *et al.* 1971) leads almost inescapably to the conclusion that an *r*-process of some kind must have occurred within $\sim 10^8$ years of the formation of the Sun.

In the light of such considerations, one might well expect to find differences from star to star in the relative amounts of heavy elements from each of the two processes. To maintain that identical relative abundances might result for all stars from two such different, complicated processes would seem most unreasonable. However, because the contribution from each process to a sample of matter depends not only on the rate of element production—the rate of supernovae, or of Ba II, S, and C stars, for instance—but also on the efficiencies of returning the processed material to a protostellar state, it is not clear just how large such variations should be.

Various workers (e.g., Rodgers and Bell 1963; Barker *et al.* 1965; Pagel 1968) have presented evidence that in some metal-deficient halo stars the elements heavier than the iron peak are even more deficient than iron. These results are mostly for *s*-process elements, however, and what little has been suggested about *r*-process abundances in these stars seems uncertain. Some work has also been done in looking for variations in *r*-process abundances in old disk stars (e.g., Hazelhurst 1963). Such efforts have been hampered by the paucity of suitable lines in stellar spectra, and have usually concluded that no relative variations in heavy-element abundances have been detected.

In order to clarify the situation, and to explore the abundances of these elements in the Galaxy in a systematic manner, a survey of *r*- and *s*-process abundances in solar type stars has been started. In this first paper the nature of the survey is discussed, the equipment used is described, and some preliminary results are indicated. In particular, evidence is presented that elemental abundances due to these two processes *can* be seen to vary independently, at least among a certain population of stars.

II. NATURE OF THE SURVEY

Because suitable lines of *r*-process elements are so scarce in stellar spectra, it becomes necessary to base any discussion of *r*-process abundances on the measurement of only a few lines. Gadolinium, Eu, and perhaps Yb are spectroscopically the most easily studied *r*-process elements in solar-type stars, and of the available lines from these elements, Eu II λ4129 is the strongest unblended one. Grevesse and Blanquet (1969) have questioned the use of this line for abundance determinations on the grounds that it yields too large an abundance and hence may be a blend, but recent observations at high resolution (Bachmann, Pflug, and Staude 1970) show the line to have the expected asymmetric shape due to its very wide hfs, and also to behave in sunspots as expected. Most probably, therefore, the problem is with the other Eu lines used by Grevesse and Blanquet, most of which occur in the wings and even near the cores of other, stronger lines. Europium should be an excellent indicator of *r*-process abundances, having only some 10 percent of its solar-system abundance due to the *s*-process (Seeger *et al.* 1965; Macklin and Gibbons 1967*b*). In this first survey, therefore, a group of lines near 4130 Å has been chosen as the most suitable for examination. Figure 1 shows a tracing of a typical spectrogram of this region. The lines of Eu II λ4129.73 and Ba II λ4130.66 are used as indicators of *r*- and *s*-process abundances, respectively, and Fe II λ4128.74 is used to derive abundances relative to iron.

Lines of *s*-process elements are much more numerous than those of *r*-process elements, and Ba II λ4130 has been chosen only because of its proximity to Eu II λ4129 in both wavelength and line strength (at solar temperatures). Its identification seems secure, especially as it gives very nearly the average solar abundance for Ba (see Goldberg, Müller, and Aller 1960). Because Ba is at a closed neutron shell and is overwhelmingly produced by the *s*-process, it is an especially good indicator of *s*-process abundances.

Similarly, Fe II λ4128 has been chosen because it is near the other two lines in wavelength and of similar strength in the Sun. It also gives very nearly the average solar iron abundance (see Warner 1968). By using lines so close to each other, it is hoped to minimize the importance of just where the continuum is placed.

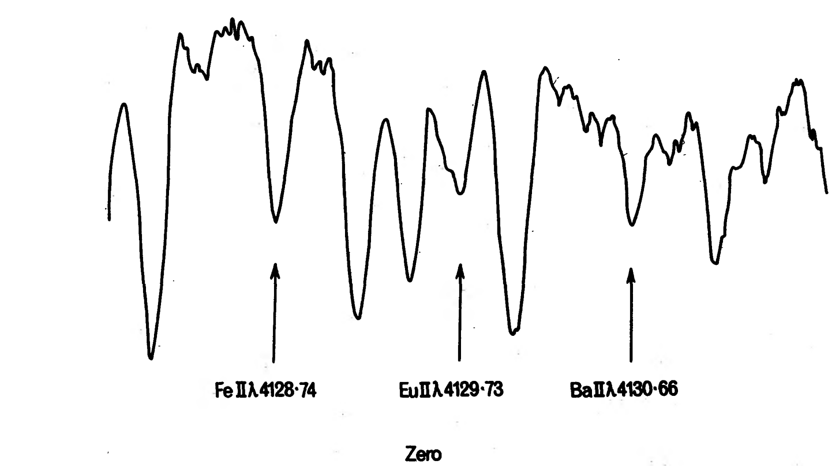

FIG. 1.—An intensity tracing of a typical spectrogram (of α Cen). The three survey lines are marked. On short-exposure, low-noise plates such as this one the asymmetric shape of Eu II λ4129, due to its hfs, can be seen.

All three lines are from singly ionized species, and hence their line strengths depend on electron pressure. However, the ratios of their strengths should be largely independent of P_e for solar-temperature stars, so only line-strength ratios will be considered in this work. Figure 2 shows the temperature dependence of these ratios. It is clear that broad-band photoelectric colors (e.g., $R - I$) should yield differential temperatures of sufficient accuracy for the present purposes. It is also evident that visual inspection of the λ4130 region should quickly single out those stars with nonsolar abundance ratios.

Only dwarf stars or slightly evolved subgiants of near solar temperature have been observed for this project. This restriction is for two principal reasons.

First, as a star evolves toward and up the giant branch, convection cuts deeply in toward the core. Should there be any *s*-process element production near the core at these stages, some processed material might be mixed to the surface, resulting in surface abundances that do not reflect the star's primordial composition. The mild Ba II or S stars such as those recently found by Williams (1971) and Chromey *et al.* (1969) would probably be examples of such stars. These objects have been avoided in the initial stages of this survey by restricting the observations to slightly evolved stars.

Second, giant stars tend to be so cool that Eu II λ4129 (with a low excitation potential E.P. = O eV; and first and second ionization potentials I.P. = 5.7 and 11.2 eV) becomes very strong and Ba II λ4130 (with a low E.P. = 2.72 eV; and I.P.'s = 5.2 and 10.0 eV) quite weak, thus introducing uncertainties in the interpretation of measured line strengths. Because the lines in question become extremely weak in metal-poor dwarfs, however, it will be necessary to turn to giant stars to derive abundances for the most metal-poor objects of the halo.

Every effort is being made to observe a selection of stars with differing kinematics, metal abundances, and ages. Due to limitations on the speed of available equipment (see § III), only stars brighter than sixth magnitude have been sampled so far. Thus included are stars of the young and old disk populations, of moderately differing metal contents, and a few stars of a population intermediate between the old disk and halo.

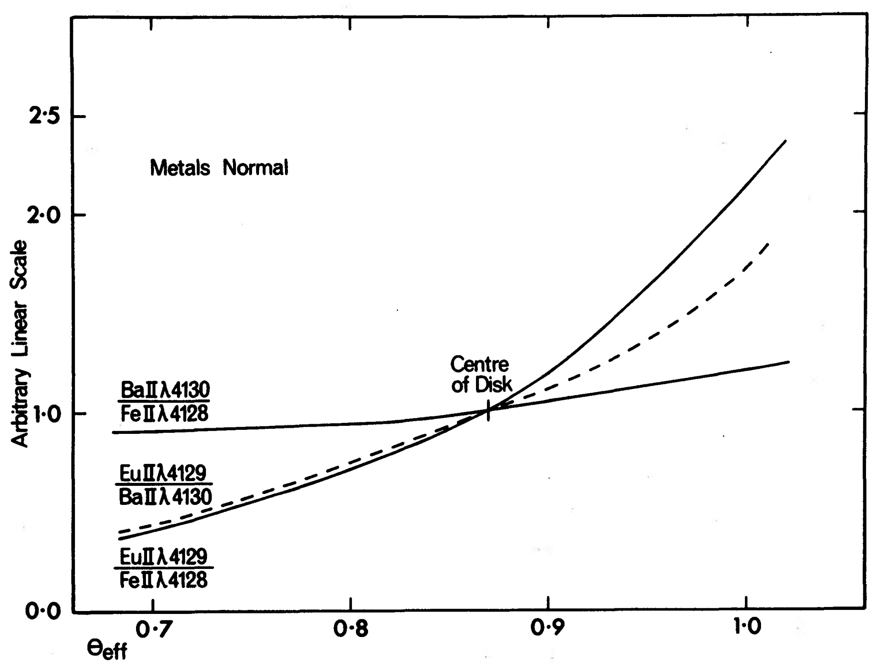

FIG. 2.—The temperature dependences of the weak-line–strength ratios shown. The temperature scale is that of Cayrel and Jugaku, and the curves are arbitrarily normalized to the center of the solar disk. The gravity is taken to be log g = 4.5.

As faster equipment comes into operation, observations will be extended to include as many halo stars as possible.

III. OBSERVATIONS

The measurement of lines of less than ~50 mÅ equivalent width in the relatively crowded regions of solar or stellar spectra shortward of 4500 Å requires both high resolution and a good signal-to-noise ratio. To permit such measurements on relatively faint stars, an échelle grating has been installed in the coudé spectrograph room of the Mount Stromlo 74-inch (188-cm) reflector. A decription of the grating system has been published previously (Butcher 1971), but for the sake of completeness and clarity is briefly repeated here.

To make use of facilities and material at hand, and to enable the relatively quick insertion and removal of the échelle optics, the design in figure 3 was chosen. The échelle is a Bausch and Lomb 4 × 8-inch, 73.25 lines mm^{-1}, 63°25 blaze-angle grating, and the cross-disperser is one of several interchangeable 4 × 5-inch low-dispersion gratings. The design basically replaces the standard coudé grating with the échelle and cross-disperser, but its use of the crossed grating before the échelle is unconventional

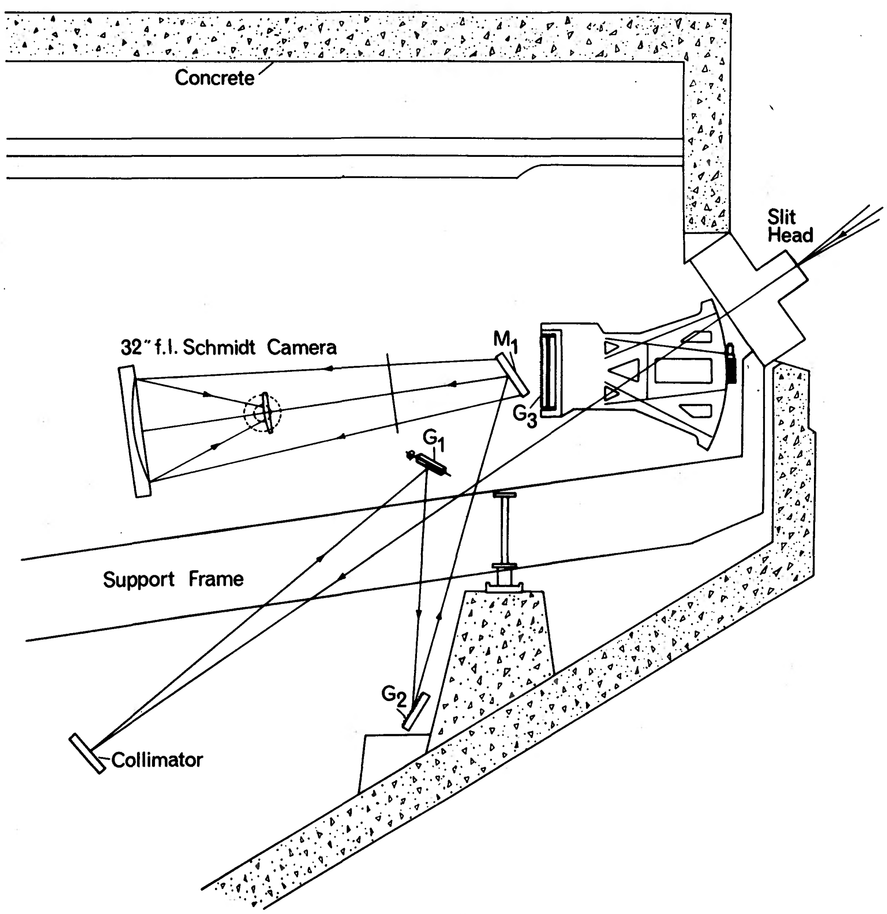

FIG. 3.—The optical layout of the échelle grating system. G1 is the crossed, low-dispersion grating acting also as a mirror in the plane perpendicular to its dispersion; G2 is the échelle; G3 is the standard grating usually used by coudé observers; M1 is a mirror that directs the dispersed light into the camera and can be tilted by small, controllable amounts with the coudé's sector-arm-and-worm scanning facility. The light is directed into the image-tube (*dotted circles*) by a small 45° mirror mounted at the direct plate-holder position. The dispersion is vertical.

and perhaps deserves special mention. This grating sequence results in a small, wavelength-dependent tilt to spectral lines at the focus, but allows a cross-disperser of much reduced size to be used. When a small line tilt with wavelength can be tolerated, the integration of an échelle into existing coudé spectrograph facilities becomes much easier and considerably less expensive.

For most purposes the grating system is used with the coudé's 32-inch (81-cm) Schmidt camera and a Carnegie RCA 30011 image tube. The dispersion near 4000 Å is then $\sim$1 Å mm^{-1} and the free spectral range $\sim$70 Å. Hence only $\sim\frac{1}{2}$ of an order at a time can be fitted onto the $\sim$35-mm image-tube cathode. Spectra are typically widened to $\sim$0.6 mm, and the crossed grating chosen so all orders are at least that far apart. Usually about a dozen well-exposed orders can be recorded at a time. Difficulties in obtaining correctly exposed plates for this project have stemmed more from the rapidly changing intensity of F, G, and K stars in the blue than from the intensity variations across an échelle order.

The system's performance under actual observing conditions has been most satisfactory. On nights of average seeing ($\sim 2''$) the spectrum of a $B = 6$ mag star can be recorded in $\sim$2 hours; on good nights ($\sim 1''$) $B = 6$ mag can be reached in $1^{h}20^{m}$. The faintest star attainable ($B \sim 7$ mag) is set by the image-tube background, which comes up in 3–4 hours.

Examination of the instrumental profile using a laser line gives an 80-μ ($\approx$0.08 Å) full-width-at-half-maximum profile, with the first grating ghosts coming in near the 0.1 percent level. Better image tubes promise to improve the resolution considerably.

The ability to tilt mirror M_1 in figure 3 by small amounts, thus shifting the spectrum slightly at the focus, has proven very useful for minimizing the effects of image-tube irregularities. The procedure adopted has been to secure some three plates of each star, with the spectrum shifted slightly between each exposure.

IV. ANALYSIS OF THE DATA

The data in the survey program then consist of several plates per star of the λ4130 region. Calibration plates are secured at least once during each observing run and processed the same way as stellar exposures. The derived density-intensity curves have repeated very well from run to run; any calibration errors should therefore be common to all data. Determination of the continuum level has been guided by inspection of the Utrecht solar atlas (Minnaert, Mulders, and Houtgast 1940). The spectral region under discussion is somewhat crowded, and the continuum level not particularly well defined, so care has been exercised to be consistent in drawing the level in. The resolution of these data is sufficiently close to that of the solar atlas to make a detailed comparison justified.

To minimize reduction time, only order number 60 from λ4106–4137 and a small section of order number 62 near λ3995 have been examined. Equivalent widths have been measured from intensity tracings and averaged. Lines chosen for measurement include the three survey lines, some 15 Fe I lines to be used in deriving each star's saturation curve, and a number of lines of other heavy elements to be used as consistency checks. All lines are either unblended or only slightly blended, though they may appear blended with the somewhat reduced resolution at hand. The Fe I lines all have lower excitation potentials of 3.0 $\pm$ 0.5 eV, so any differential temperature corrections to the shape of a saturation curve should be very small. It has been assumed throughout that the shape of all stellar curves of growth can be represented by a fit of Cowley and Cowley (1964) solar curve to the observed data. Only small differences are found between curves comparing stellar data to weak line strengths derived from the Utrecht catalog (Moore, Minnaert, and Houtgast 1967), from plates of the daytime sky taken by the author, or from intercomparison of stellar data. Figure 4 gives examples of the resulting curves.

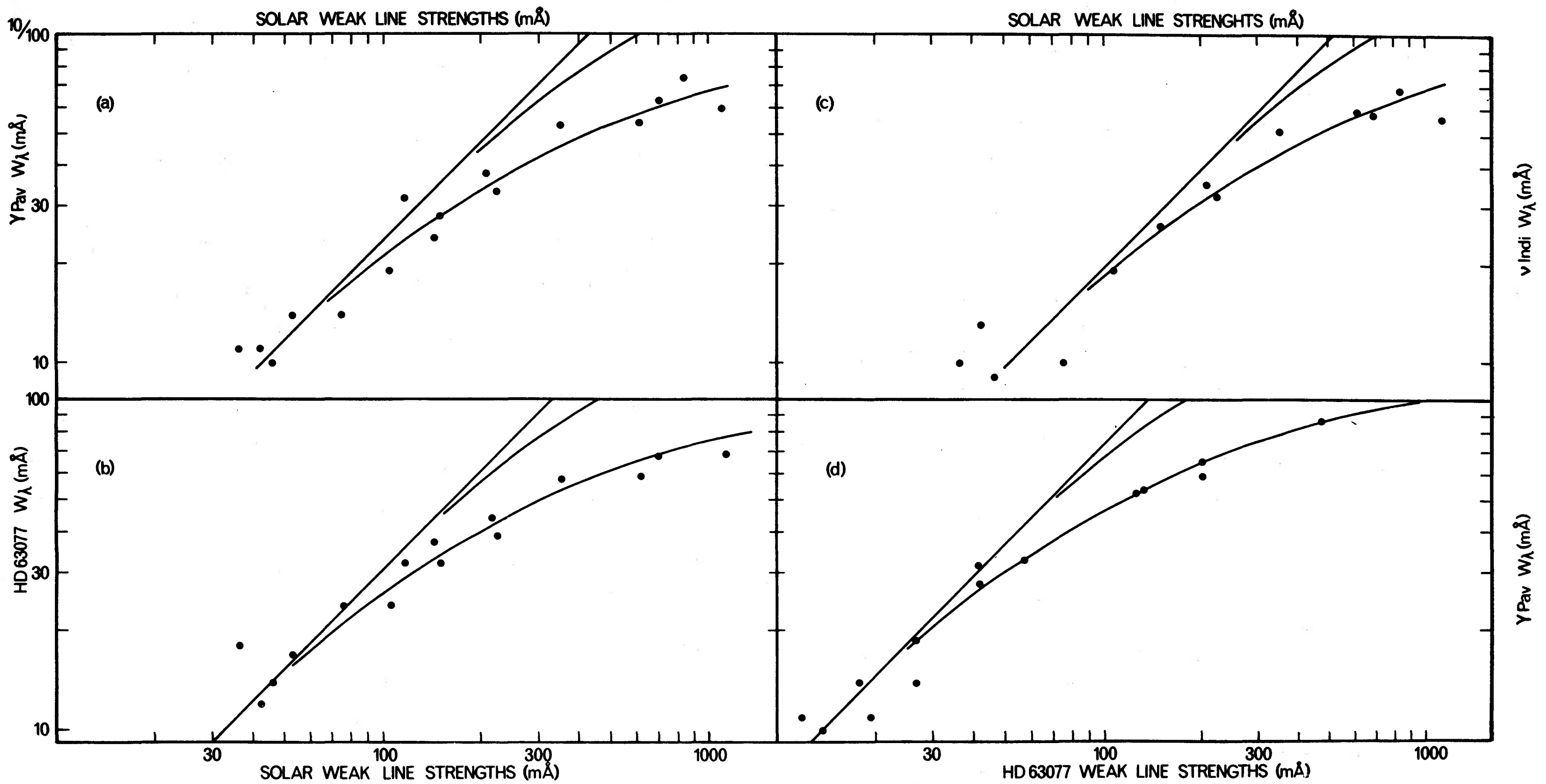

FIG. 4.—Saturation curves for Fe I for the three stars discussed here. The curves fitted to the data are from Cowley and Cowley (1964) and are fitted by eye. Solar weak-line values in (*a*), (*b*), and (*c*) are derived from Utrecht data and the Cowley-Cowley curve of growth. HD 63077 weak-line strengths in (*d*) are derived from (*b*). The scatter of the data about the mean curves in (*a*)–(*c*) is consistent and indicates systematic differences in measurement rather than accidental error. The expected curves for Eu II λ4129 are also shown.

Desaturation of most measured line strengths only assumes that the line's curve of growth is the same as that for the Fe I lines; no temperature or P_e corrections are needed. Although this assumption is probably valid enough for Ba II λ4130 and Fe II λ4128, Eu II λ4129 has a very wide hfs, and will follow a considerably different saturation curve. To desaturate this line a theoretical curve of growth has been constructed with the following prescription. The spacing of the hfs components, taken from Krebs and Winkler (1960), and relative component intensities, taken to be those given by Russell-Saunders coupling theory (for example, Condon and Shortley 1953 for tables of these intensities), are used to calculate the total absorption coefficient, assuming a velocity parameter of 1.7 km s^{-1}, the solar value. Curves of growth are then calculated for the Eu II line and various single-component lines with the Milne-Eddington model atmosphere and line formation by pure absorption. This calculation is greatly simplified by use of the Minnaert semiempirical interpolation formula (Traving 1962). The curve for a single-component line with velocity parameter near 5.0 km s^{-1} is found to match the calculated Eu II curve, which itself is rather insensitive to the choice of velocity parameter. A solar saturation curve for Eu II λ4129 is then found by shifting the Cowley-Cowley curve from its observed position by the amount appropriate to a change in velocity parameter of 1.7–5.0 km s^{-1}. This *shift* from the observed curve is assumed to be the same for all stars, an assumption equivalent to assuming that changes in micro-turbulent velocity are due to changes in an atmosphere's $T(\tau)$ relation, as suggested by Strom (1968). This may well not be true among stars of similar composition, but when comparing metal-poor stars with the Sun, as will be done in this paper, it may be a fair approximation to use (but see Böhm-Vitense 1972 for an opposite point of view). In any case, for weak-line stars the saturation correction for Eu II λ4129 is quite small.

All necessary differential temperature corrections to the weak line-strength ratios are made with the aid of diagrams such as shown in figures 2 and 5. These are calculated by using data supplied by Cayrel and Jugaku (1963). Those authors have calculated weak line strengths and average curve-of-growth parameters for a large number of

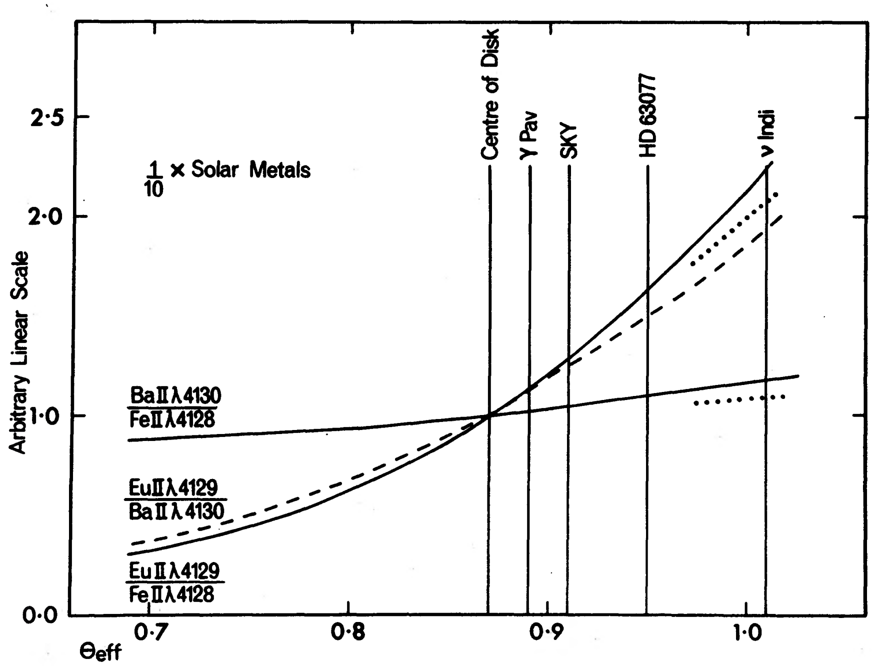

FIG. 5.—Temperature dependences of the weak-line–strength ratios for 1/10 solar abundances. The dotted segments near θ_{eff} (Cayrel and Jugaku) = 1.0 show the effect of changing log g from 4.5 to 4.0.

scaled solar model atmospheres. They also give prescriptions for interpolating in their data and for calculating strengths of lines not included in their calculations. Thus curves for Fe II λ4128 include partial ionization effects not easily incorporated in mean parameters. Data for lines of Eu, Ba, and other rare earths are not given, but these elements are mostly singly ionized at the relevant temperatures, so mean parameter calculations should be sufficiently accurate. Comparison of the "exact" results of Cayrel and Jugaku for Ca II, calcium's ionization potentials being similar to those of the rare earths, and mean parameter calculations confirm that such is the case. Partition functions of rare-earth elements are taken from Claas (1951) or taken to be the same as La II.

To derive θ_{eff} on the scale of Cayrel and Jugaku (which is not an absolute scale), broad-band colors on the Kron, Gascoigne, and White (1957) system are used. These colors are first converted to the Johnson (1964) system using Eggen's (1971) conversion formula, and then to θ_{eff} using Johnson's (1966) calibration. To tie these two scales together, θ_{eff} at the center of the solar disk is taken to be 0.83 (Allen 1962; Labs and Neckel 1968) on Johnson's absolute scale, and 0.87 on Cayrel and Jugaku's. The θ_{eff}'s for integrated solar light are then 0.87 (Labs and Neckel 1968) and 0.91, respectively.

To summarize then, analysis of the survey data consists of desaturating the measured equivalent widths using a semiempirical stellar saturation curve, and forming weak-line-strength ratios of interest for each star. These ratios can then, after appropriate temperature (and, if necessary, P_e) corrections, be compared among stars to look for abundance differences. It is hoped that this procedure will give relative abundances of as high a quality as can be expected from measurements of single lines.

V. RESULTS

Good-quality data for some 18 disk and intermediate population stars have been obtained to date (HR 98, 509, 996, 1000, 1008, 1101, 1136, 1325, 2943, 3018, 4523, 4540, 5459, 5694, 5933, 7373, 8181, and 8515). These stars have metal abundances, as found by various other workers, ranging from 2–3 times solar to 1/10 solar, and orbital-eccentricity parameters (as defined by Eggen, Lynden-Bell, and Sandage 1962) of from $e \approx 0$ to $e \approx 0.5$. Visual inspection of the available material shows almost all these stars to have nearly normal (i.e., solar) Ba/Eu and Ba/Fe ratios. The only convincing exceptions so far discovered are the stars γ Pav, HD 63077 (= HR 3018), and possibly ν Ind. Figure 6 shows tracings of the λ4130 region in these three stars. The strengths of Eu II λ4129 in HD 63077 and ν Ind are immediately evident.

The relevant data for these stars are given in table 1. Several plates of the daytime sky have also been analyzed, principally because the measured strength of Eu II λ4129 depends rather strongly on just how it is measured. The analysis has been carried through as discussed in the previous section. Examples of the saturation curves used were given in figure 4. Uncertainties in these curves are small enough not to alter any general conclusions in this paper.

Final results are displayed in figure 7. Error bars represent standard deviations of the derived means and refer only to measurement uncertainties. It is apparent that, relative to iron, all three stars may be very slightly deficient in Ba, and while γ Pav has an apparently normal Eu abundance, HD 63077 and ν Ind have that element enhanced. The temperature sensitivity of these results can be judged from figures 2 and 5. Because scaled solar models and a uniform $(R - I)$, θ_{eff}-relation have been used in the analysis, comparison of these metal-deficient stars with the Sun may not be strictly valid. Any systematic effects should be small, however, and it is clear that abundance differences do exist even among the metal-poor stars.

Several other rate earth lines, which are not so easily measured as the survey lines but which serve as a check on the results, have also been analyzed. Thus Nd II λ4109.45 (39 mÅ in the Sun) yields a marginally enhanced Nd/Fe ratio, as might be expected from the work of Seeger *et al.* (the solar ratio of *r*- and *s*-process contributions being

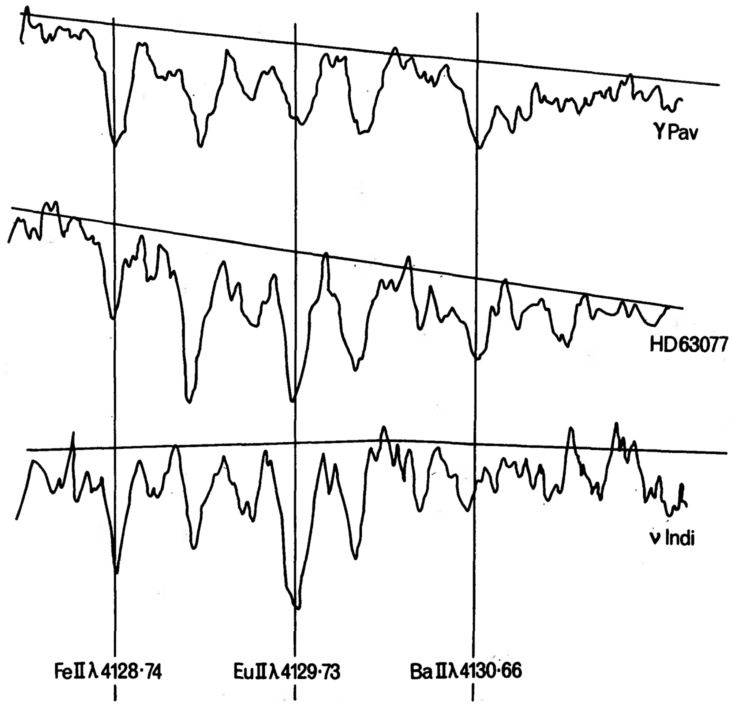

FIG. 6.—Intensity tracings of the λ4130 Å region in the stars γ Pav, HD 63077, and ν Ind

$r/s \sim \frac{1}{2}$ and Nd having six unshielded isotopes), in HD 63077 but not in γ Pav (no measurements are available for ν Ind). Similarly the very faint Gd II ($r/s \sim 8$) line at λ4130.37 appears to be rather stronger in HD 63077 and ν Ind than in γ Pav. The strength of Y II ($r/s \sim 0.2$) λ4124.92 is consistent with a normal (Y/Fe) ratio in all the stars. On the other hand, La II λ3995.75 (38 mÅ in the Sun; $r/s \sim 1$ with one unshielded isotope) yields equal abundances relative to iron for the three stars, with (La/Fe) nearly solar. Too much significance should probably not be placed on these last results; the expected differences are small, and the errors of measurement so large as to provide little useful information. At least no drastic contradictions are apparent.

It should be noted, however, that these results disagree with those of Danziger (1966) for γ Pav. He found the elements heavier than Ba to be down an additional factor of 6–8, and interpreted this as evidence for the continuing evolution of *s*-process abundances in the Galaxy. The conclusion of the present work, however, must be that any such effect is probably smaller than a factor of 2. In addition to La II λ3995 and Nd II λ4109, several weak lines of Ce, although somewhat blended with other faint lines, do not appear to be extremely weak or absent. Danziger presents none of his data, so conclusive reasons for this disagreement cannot be suggested.

The results given here for ν Ind are perhaps not so reliable as those for γ Pav and HD 63077 for two reasons: (1) Finsen (1929 and subsequent reports in the same publication) has reported ν Ind to be a double star of 0ʺ1 separation and with $\Delta m \sim 0$. There is no evidence of line broadening or doubling on the author's spectra, however, so what effect this situation may have on the present measurements is not clear. (2) The three measures of Eu II λ4129 available for ν Ind are 42, 47, and 77 mÅ. While a discordant value is to be expected occasionally, the 77 mÅ measurement might also be due to an image-tube defect—though inspection of the plate does not encourage such suspicions. The author considers the measurement valid, but it is well to realize that Eu is only marginally enhanced, if at all, should λ4129 measure only 45 mÅ.

TABLE 1

DATA FOR STARS IN THE TEXT

	(R-I) [1]	θ_{eff}(C+J) [2]	No. of Plates	W_λ Measurements (mÅ) Ba II λ4130	Eu II λ4129	Fe II λ4128	Corrected Weak Line Ratios (Ba/Fe)	(Eu/Fe)	(Eu/Ba)	[Fe/H] [3]	*e* [4]
γ Pav	+0.195	0.89	4	22 ±2	30 ±2	34 ±1.5	.68 ±.07	.98 ±.09	1.38 ±.16	-0.7	0.4:
HD 63077	+0.24	0.95	5	22 ±2	54 ±4	28 ±2	.80 ±.10	1.59 ±.19	1.93 ±.20	-0.8	0.47
ν Indi	+0.29	1.01	3	17 ±3	55 ±11	25 ±1	.72 ±.12	1.61 ±.31	2.17 ±.56	-1.3	0.42
Sky	-	0.87	3	45 ±4	61 ±3	49 ±4	1.00 ±.21	1.00 ±.16	1.00 ±.15	-	-
Utrecht [5]	-	0.91	-	45	68:	50	1.02	-	-	-	-

Notes to Table 1:

[1] Data for γ Pav is from Eggen (1971); for HD 63077 and ν Indi, Eggen (private communication).

[2] $\Delta \log P_e = -1.7$ (Harmer and Pagel 1970) correction has also been applied to ν Indi.

[3] From the author's data.

[4] γ Pav leads the Sun around the Galaxy, so *e* is uncertain; motions are taken from Eggen (1971) and *e* estimated from fig. 1 of Eggen (1964). For HR 63077 and ν Indi *e* is taken from Eggen (1964).

[5] Moore *et al.* (1967)

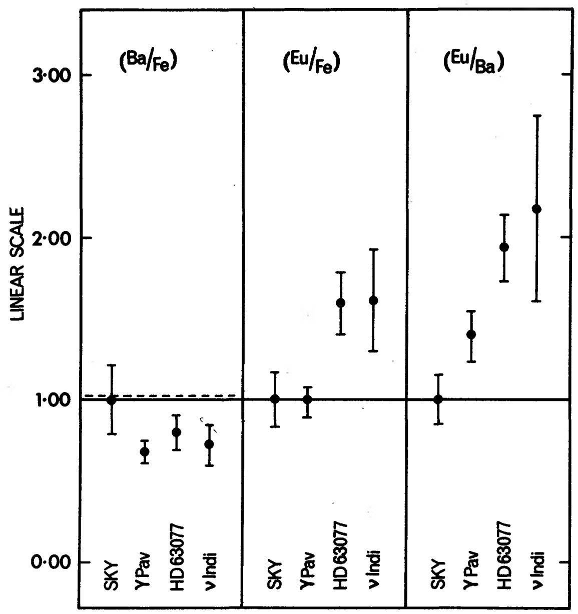

FIG. 7.—Final weak-line-strength ratios corrected to the center of the solar disk and normalized to the author's measurements of the daytime sky. The dashed line in the (Ba/Fe) plot is the value obtained with Utrecht data.

VI. DISCUSSION AND CONCLUSIONS

Among the stars examined so far, only three have been found that exhibit nonsolar relative heavy-element abundances. Furthermore, these three turn out to be the only ones that might be assigned to the halo, or perhaps more realistically to an intermediate population; the rest all seem to be bona fide disk stars.

It might well be argued that in stars of near solar abundances all measurable lines are saturated, and thus the technique used in this work loses its sensitivity. Such an argument is certainly true for the use of Ba II λ4130 and Fe II λ4128 to detect *s*-process abundance differences, but in the Sun and hence in most solar-type disk stars, Eu II λ4129 is barely saturated at all. Therefore, the analysis outlined here should remain sensitive to *r*-process abundance variations even in K-type dwarfs.

The abundance differences found here are very small, and it would be premature to speculate on just what the results may mean without more data than are presently available. Suffice it to say, then, that these data support the notion that the *r*- and *s*-process have operated as distinct, independent phenomena in the Galaxy.

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