A MORE ACCURATE HR DIAGRAM FOR THE COOLER STARS

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Even if we confine ourselves to the classical HR diagram, postponing the transformation of spectral types and visual absolute magnitudes into basic physical variables, there are several ways to choose the data. If, for example, we want the density of points to represent the spatial density of stars, then we must concentrate on reducing sampling errors, usually at the cost of accuracy in some parts of the diagram. The Hess diagram is very useful, but an equally useful alternative is an HR diagram which includes only those stars whose positions are determined as accurately as possible. The objective is to classify the fine structure in the pattern in the luminosity-spectrum domain, and thus to define more precisely the borders of zones which are either occupied or avoided by stars of a given population. It is this pattern which is compared with theoretical evolutionary tracks and it is such a diagram based on the revised MK classification of the recent Atlas of Keenan and McNeil (1976) that I shall present here.

The greatest uncertainty is in the absolute magnitudes, and it is only in the lower part of the diagram that individual luminosities from trigonometric parallaxes can be plotted. Through the upper two-thirds of the diagram the most homogeneous are furnished by our best spectroscopic absolute magnitudes. These are obtained from the luminosity classes by calibration through mean trigonometric parallaxes up through the giant branch and from cluster and binary membership for the supergiants. The mid-part of the diagram is tied to the giant branch, since that forms a definite ridge among all stars on the cool side of the Hertzsprung gap. Luminosity class III is defined by the center of this

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ridge, and for the most accurately classified stars those at the center are designated IIIab. Stars on the upper edge are called IIIa, and those on the lower edge IIIb.

When we come to compute mean trigonometric parallaxes this refined classification is one means of reducing not only the mean errors of the resulting absolute magnitudes, but also the sizes of the systematic corrections that should be applied. Statistical corrections are proportional to the variance, or the square of the dispersion. Most estimates have placed the intrinsic dispersion of the giant branch at not less than $\sigma_M \approx 0^m.6$ (Ljunggren and Oja, 1966). There are difficulties in making this estimate, but at least from G8 to about K3 the revised class III stars appear to have σ_M $0^m.4$. This reduces the Malmquist correction (ΔM_M) to constant volumes of space by a factor of about 2. In this range of types I estimate the correction to be $+0^m.22$ - but it becomes larger and more uncertain in type M. The other major correction, the difference $5\langle \log p \rangle - 5 \log \langle p \rangle$, is opposite in sense but is usually larger, since it depends on σ_τ^2, where σ_τ is the total dispersion due to intrinsic dispersion plus the dispersion resulting from the large mean errors in the trigonometric parallaxes. The values of $\langle M_V \rangle = M_{\langle p \rangle} + (5\langle \log p \rangle - 5 \log \langle p \rangle) + \Delta M_M$ for IIIab giants with $m_V < 5^m.0$ are collected in Table I. The values of the first correction were computed directly from the variance of the parallaxes by the approximation:

$$5 \langle \log p \rangle - 5 \log \langle p \rangle = - 5 \log c - 2.5 \log \langle (p')^2 \rangle / \log \langle p' \rangle^2 ,$$

derived by Strömberg (1936). Here $\langle p' \rangle$ is the mean of parallaxes reduced to visual magnitude 4. The number of stars in each spectral group is necessarily small, averaging 15, because the number of stars brighter than the fifth magnitude with luminosity class IIIa and having nearly solar composition, is not great. There are a few for which good classification plates have yet to be taken. The eighth row of Table I is shown in Fig. 1. The scatter of the points is due to the small samples, but it is evident that simple graphical smoothing will define the luminosity of the giant branch to about $\pm 0^m.2$, which is about equal to the uncertainty due to the possible systematic errors in the system of trigonometric parallaxes (Schilt 1954, Gliese 1972, Norgaard-Nielsen 1977).

The luminosity calibration curves for classes II and IV are established mainly by interpolation, though there are a few bright giants in clusters of known distance, and a few subgiants with good individual trigonometric parallaxes.

The accuracy with which one can assign temperature types also is improved by the better separation of luminosities, and by the segregation of stars of markedly different chemical composition. For example, the comparison of MK types with (B-I) from Johnson et al. (1966) is shown in Fig. 2 for the same IIIab

TABLE 1

1977 CALIBRATION OF CLASS III BY MEAN PARALLAXES

	G7–G9	K0–K1	K2	K3–K4	K5–M0	M1–M2
$\langle p^{1} \rangle$ unweighted	0.0176	0.0186	0.0129	0.0185	0.0117	0.0104
$\langle p^{1} \rangle$ weighted	0.0192	0.0193	0.0165	0.0147	0.0108	0.0125
Mean $\langle p^{1} \rangle$	0.0184	0.0189	0.0147	0.0166	0.0115	0.0114
No. of Stars	15	13	14	17	17	13
$M_{\langle p \rangle}$	+0.15	+0.24	−0.02	+0.11	−0.69	−0.71
5 log c	−0.32	−0.15	−0.34	−0.26	−0.45	−0.82
ΔM_n	+0.22	+0.22	+0.22	+0.22	+0.22	+0.33
M	+0.05	+0.31	−0.10	+0.07	−0.92	−1.20
Final smoothed $\langle M \rangle$	+0.20	+0.18	+0.12	−0.15	−0.70	−1.36

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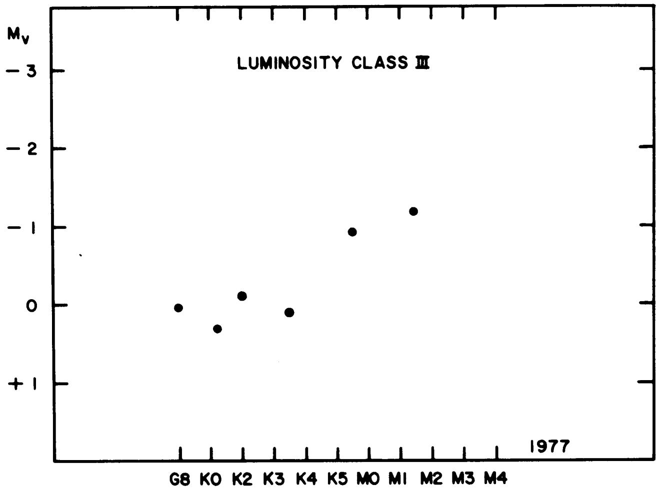

Fig. 1. Mean visual absolute magnitudes of the spectral groups, derived from trigonometric parallaxes.

giants of approximately solar composition represented in Fig. 1. The band would be appreciably broadened if IIIa and IIIb giants were included.

The resulting HR diagram is given in Fig. 3. The filled circles represent stars for which the trigonometric parallaxes are at least ten times their probable errors. The crosses show stars calibrated by their membership in binary systems, clusters or associations at reasonably well-known distances. For the stars shown as open circles the new spectroscopic absolute magnitudes were plotted. Although the diagram is intended to represent the stars of composition comparable to the Sun's, the ages necessarily increase somewhat from top to bottom. The brighter supergiants are obviously fairly young members of spiral arms, while the dwarfs must include an older disk population, but at least the obvious members of the halo population have been excluded on either kinematic or spectroscopic grounds.

The resolution in luminosity can be seen - the IIIa and IIIb giants form separate bands. The problems of classifying the most luminous supergiants are partly responsible for their apparent rarity between K0 and M0. RW Cep (HD 212466) is the coolest of the very brilliant stars not showing TiO bands and was somewhat arbitrarily placed at K0. It might as logically be called K2, which would narrow the gap and make the run of color indices more smooth. There is no doubt, however, about the real scarcity of K-type super supergiants.

A less conspicuous gap in the distribution is probably quite significant. Between G7 and K1 class II bright giants are quite rare. This deficiency is more pronounced than is shown, because

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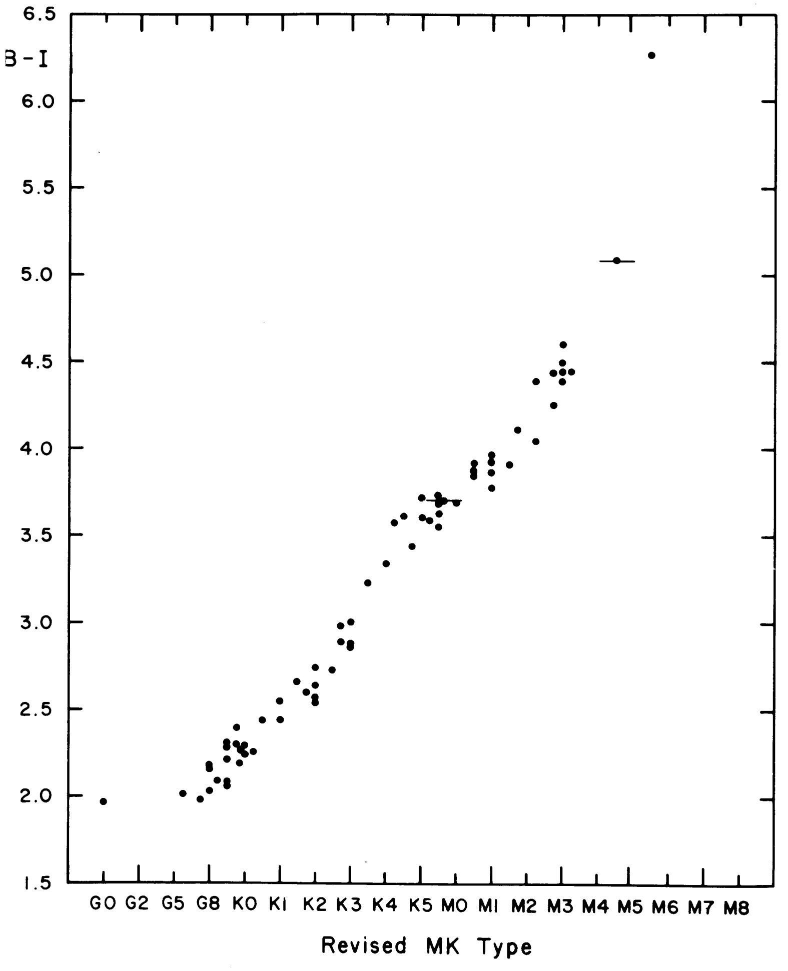

Fig. 2. (B-I) colors of IIIab giants as function of MK types. The two horizontal bars indicate stars with variable type.

we made an extensive search for G8 II stars in connection with the comparison of spectroscopic luminosities with Wilson's K-line absolute magnitude (Keenan and Wilson, 1977). This is the more striking since among earlier G-type stars there are a number of stars lying just above the Hertzsprung gap.

There are unrepresented kinds of stars which perhaps should be included - if we knew their individual distances. If the stars with an excess of heavy metals (barium and semibarium stars and those of type S) represent merely a particular stage in the evolution of stars having initially solar composition, then they belong in the diagram. We know statistically that they lie near the giant branch, but we do not have individual distances

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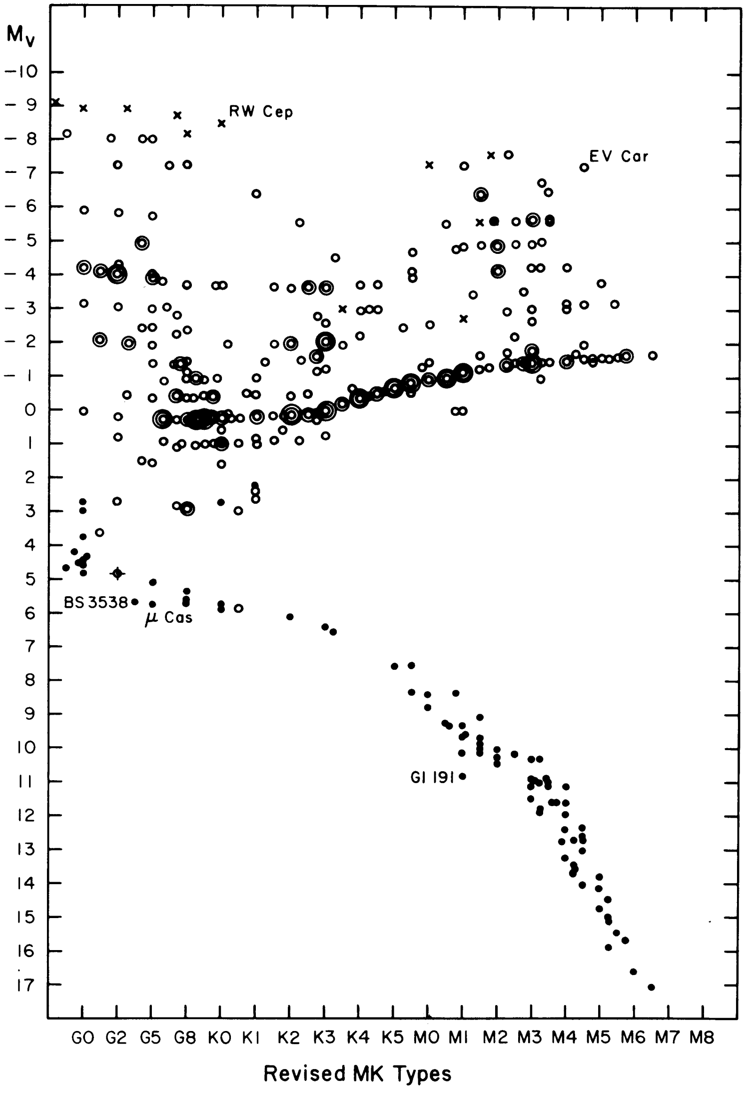

Fig. 3. HR diagram for stars of approximately solar composition. For the main sequence later than M0 most of the types are due to Boeshaar (1976).

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for enough of them to make a reliable estimate of the real dispersion in their luminosities. Another very important group includes the so-called SMR stars (Spinrad and Taylor 1969), which appear actually to have only slight excesses of the iron-peak metals. Several of them, particularly BS 8924 (HD 221148) at K2.5, have notably weak lines of Ba II and Sr II. This suggests that BS 8924, at least, and possibly some others, might lie well below the giant branch and extend the domain of the subgiants toward lower temperatures. The strength of CN in BS 8924, however, indicates a higher luminosity. The alternative interpretation is that these are giants in which practically none of the iron group elements have been converted to heavier metals by neutron fluxes. Attempts at a detailed atmospheric analysis of BS 8924 have not defined log g and the composition precisely because of difficulties in finding a satisfactory model for its atmosphere (Pilachowski, 1977).

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DISCUSSION

BELL: I would like to say how pleased I am to see Dr. Keenan's data for M_V versus spectral type. These data are needed in order to obtain stellar gravities for use in the theoretical determination of the spectral type - color - effective temperature - bolometric correction relations.

As an aside, I would also like to remark that observers who obtain log g by analyzing Fe I and Fe II line spectra could, and should, compare their values with values obtained from M_V.

MULLAN: Keenan has indicated the presence of a "gap" in the HR diagram at M_V=- 3 or -4 and spectral types late G to late K. The left boundary of the "gap" seems to lie close to the locus of the onset of supersonic stellar winds. This locus has been determined recently in an attempt to test a speculation made by Durney (IAU Colloq. No. 19, Stellar Chromospheres, ed. S. Jordas and E. Avrett, 1973, p. 284) that the onset of supersonic stellar winds might be correlated with rapid mass loss. We used a minimum-flux corona model, and used chromospheric gas pressures (Kelch, et al. Astrophys. J. 1977, in press) to set firm upper limits on the gas pressure at the base of the corona. The locus of the onset of supersonic winds is found to agree well with the boundary of the circumstellar shell domain (Reimers, Astron. and Astrophys. **57**, 395, 1977) suggesting that Durney's speculation is probably correct. Keenan's gap also lies in roughly the same part of the HR diagram, and may therefore be correlated with rapid mass loss.

KEENAN: That's very interesting. And, of course, that's the general region where massive stars evolve very rapidly between the B-group and the M-group.

PEL: Your diagram did not cover the whole Cepheid strip, but I noticed quite a number of supergiants in the Cepheid domain. How many of these are known or suspected to be variable?

KEENAN: I've left out all Cepheid variables.

PEL: So this would mean a significant number of stable stars in the region where they should pulsate?

KEENAN: Yes, these are stars without marked variability. But some may be slightly variable.