TWO DIMENSIONAL SPECTRAL CLASSIFICATION OF EARLY TYPE STARS BY LOW DISPERSION SPECTROPHOTOMETRY

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Abstract. Spectrophotometric data of early type stars (spectral intensity distributions from 3100 to 6000 Å and equivalent widths of Hβ, Hγ and Hδ) have been analysed, looking for the best parameters for a two dimensional spectral classification. It was found that the best correlation with MK classification is given by the equivalent width of Hβ and the Balmer discontinuity.

The classification scheme is well defined for stars from B0 to A1 of luminosity classes V to III. No stars of luminosity class II were observed. Luminosity class I is clearly separated from the less luminous stars, but the number of supergiants observed is too small to give a clear separation of spectral types.

The usefulness of quantitative measurements of the Balmer discontinuity and other hydrogen parameters for stellar classification is a well known fact. The photoelectric spectrum scans obtained by Gutiérrez-Moreno *et al.* (1967, 1968, 1972) and Moreno (1972) extend from 3000–6000 Å and thus allow the determination of the size and position of the Balmer discontinuity, and the measurement of equivalent widths of Hβ, Hγ and Hδ. The observations were made at the Cerro Tololo Inter-American Observatory using a spectrum scanner with a slit 60 Å wide. The parameters measured are shown in Figure 1, where D and λ_D are the size and position of the Balmer discontinuity as defined by Barbier and Chalonge (1939) and Chalonge and Divan (1952). Besides, ΔD is a measure of the emission in the Balmer continuum, present in some stars and already detected by Slettebak and Stock (1957) on objective prism plates; and UD is an ultraviolet deficiency, which exists in some stars and which was measured for its possible physical significance. The blue-green and ultraviolet gradients, ϕ_{BG} and ϕ_U were also measured.

All these data were tested for a two dimensional spectral classification. The first attempt was made following Barbier and Chalonge (1939) and Chalonge and Divan (1952). A comparison of our data with those from Paris showed that the measurements of the Balmer discontinuity are in close agreement:

$$2.5\, D_{\text{Paris}} = 0.04 + D_{\text{Chile}}. \tag{1}$$

Nevertheless, a systematic dependence on the equivalent widths of the hydrogen lines was found for the relation between the Paris position of the Balmer discontinuity, λ_1, and ours, λ_D. For example:

$$\lambda_D - \lambda_1 = 7.545 + 0.692\,(\lambda_D - 3700) - 2.366\, W_{H\beta}. \tag{2}$$

Similar relations hold if $W_{H\gamma}$ or $W_{H\delta}$ are used. Relation (2) reproduces λ_D with a dispersion of ± 5 Å.

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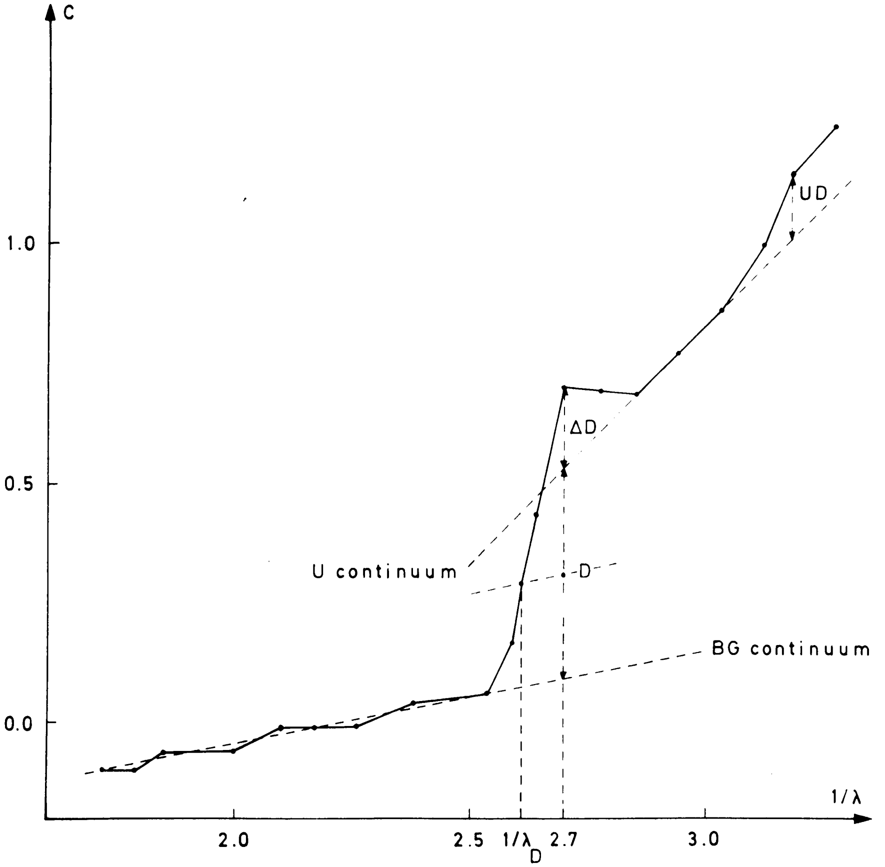

Fig. 1. Schematic diagram showing the different parameters measured.

May be due to this systematic effect, a graph of D vs λ_D failed to give a positive result for a two dimensional spectral classification.

The analysis of all the remaining data showed that the closest agreement with the MK system is obtained by using the relation between the size $D_1 = D + \Delta D$ of the Balmer discontinuity (spectral type indicator) and the equivalent width of Hβ (luminosity indicator). It was also found that D_1 could be replaced by the color index:

$$c_D = m_{3695} - m_{3930}, \qquad (3)$$

which is, numerically, almost identical to D_1 and has advantages from the practical point of view. The magnitudes in relation (3) have been corrected by atmospheric extinction, but not for interstellar absorption. Nevertheless, no misclassifications were detected due to this fact. On the other hand, a comparison of D, D_1 and c_D with the broad-band parameter Q, which is independent of reddening (Johnson, 1958), gives the best agreement for the (Q, c_D) relation. An attempt to make a correction for reddening, by using a color difference defined in a similar way to the parameter Q showed no improvement whatsoever.

Up to B7, the standard stars used to establish the system have been taken only from Lesh (1968) or from Hiltner *et al.* (1969). Preliminary attempts made independently with each of these authors gave coincident classification schemes and, consequently, both lists were considered to form a homogeneous classification and were used to derive the empirical diagram shown in Figure 2. From B8 on, the system is not so homogeneous, since the classifications were taken from different authors (Jaschek and Jaschek, 1966; Jaschek *et al.*, 1964). The stars used as standards are listed in Table I. The references for this Table and for Table II are given at the end of Table II.

Since the lines separating spectral types and luminosity classes in Figure 2 have been obtained empirically, they have a certain amount of uncertainty; nevertheless, the separations between luminosity classes V, IV and III are fairly well defined, mainly for the earlier types. No stars of luminosity class II were included in the observations and, consequently, the lower limit for luminosity class III is rather arbitrary. Luminosity class I stars are well detached. The sample of these stars is small, but they show that their classification is difficult due to the effect of luminosity on the Balmer discontinuity, which produces a crowding effect of spectral types towards small c_D values. As an example, we show the star HD 111613, which is an A1Ia star. Figure 2 suggests the convenience of using the (c_D, $W_{H\beta}$) diagram to separate the high luminosity stars, and then use for them a classification scheme based on different parameters.

A group of 75 stars, considered as program stars, was classified according to the scheme in Figure 2. In general, the discrepancies with respect to Lesh (1968) and Hiltner *et al.* (1969) are small as defined by Jaschek and Jaschek (1966): only 5 stars, of a total of 46 in common with these authors differ from their classification by more than one sub-class in spectral type, or more than one class in luminosity. For these 5 stars, a classification in better agreement with ours is given in the La Plata Catalogue (Jaschek *et al.*, 1964). The average index of discrepancy, defined also by Jaschek and Jaschek (1966) is $\bar{e} = 0.55$, which implies that the average uncertainty of a single classification is less than 0.55 luminosity classes and 0.55 spectral subclasses. The internal accuracy of our classification, determined by the method of Butler and Thackeray (1940) is:

$$\sigma_{ST} = \pm 0.2 \text{ subclasses}, \qquad \sigma_L = \pm 0.5 \text{ classes}.$$

σ_{ST} is the mean of three determinations, made by comparison with different authors.

There are, nevertheless, nine stars for which the discrepancies with respect to other authors are not small. They were not included in the previous analysis, since they also show rather large discrepancies between the classifications made by other authors. They are listed in Table II. The table also shows the broadband spectral types S_Q. In most of the stars listed, S_Q is closer to the spectrophotometric types than to the MK classifications given by other authors. This shows that these stars have some peculiarities, even though these peculiarities may not be apparent in the spectrum.

An attempt to detect peculiar stars or emission stars was made by plotting the equi-

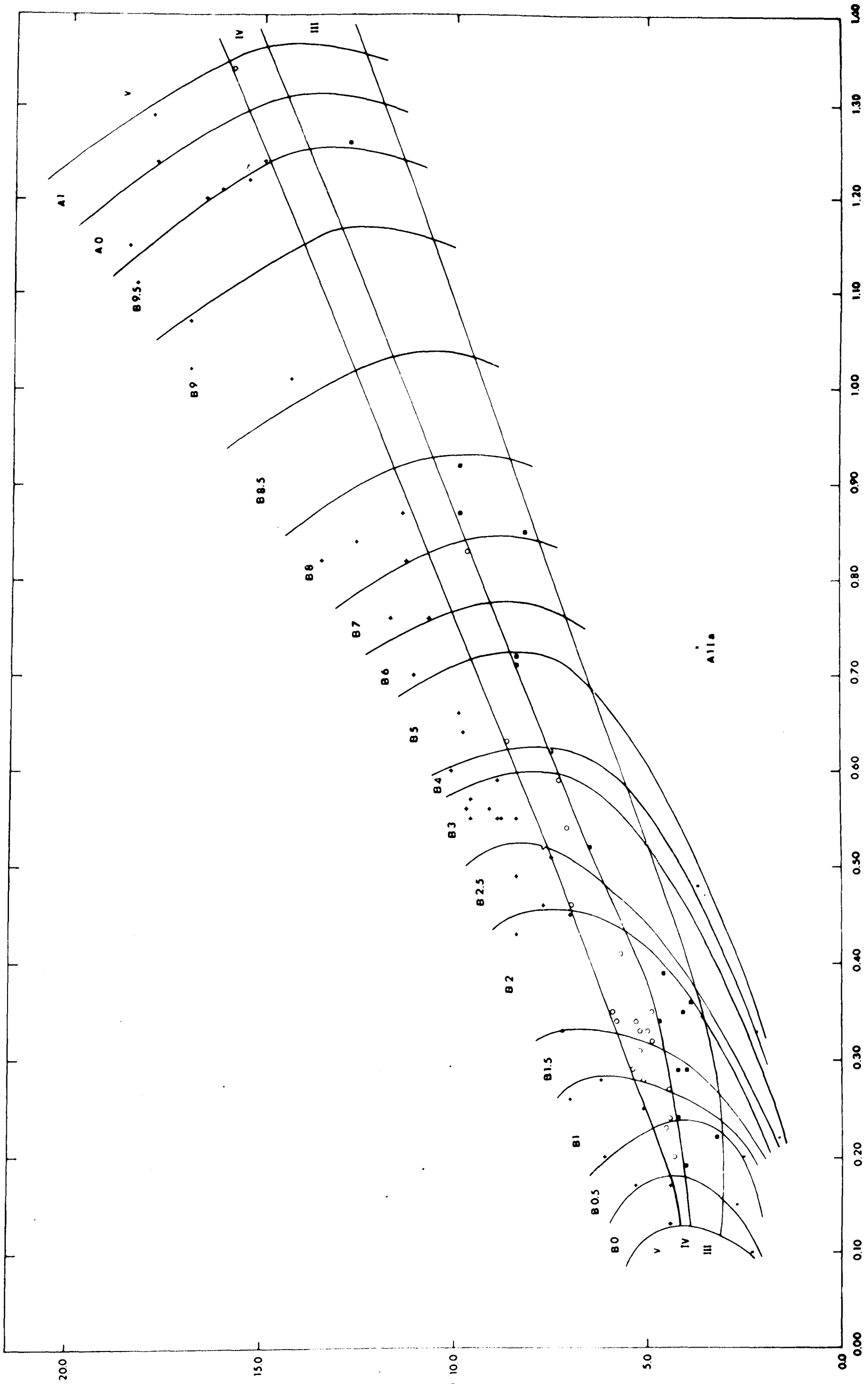

Fig. 2. Empirical diagram for obtaining MK spectral types on the basis of c_D, $W_{H\beta}$ measures.

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TABLE I

Standard Stars

BS	HD	Name	c_D	$W_{H\beta}$	MK	Ref.
1855	36512	υ Ori	0.13	4.4	B0V	[1]
6165	149438	τ Sco	0.17	4.4	B0V	[1]–[2]
1903	37128	ε Ori	0.10	2.3	B0Ia	[1]–[2]
1887	36960	−6° 1234	0.17	5.3	B0.5V	[1]
5953	143275	δ Sco	0.20	4.3	B0.5IV	[1]–[2]
1756	34816	λ Lep	0.23	4.5	B0.5IV	[1]
4853	111123	β Cru	0.19	4.0	B0.5III	[2]
7446	184915	κ Aql	0.22	3.2	B0.5III	[1]
2004	38771	κ Ori	0.15	2.7	B0.5Ia	[1]–[2]
1892	37018	42 Ori	0.20	6.1	B1V	[1]
1789	35439	25 Ori	0.25	5.1	B1V	[1]
1886	36959	−6°1233	0.26	7.0	B1V	[1]
1868	36695	VV Ori	0.28	6.2	B1V	[1]
5056	116658	α Vir	0.24	4.4	B1IV	[1]
5132	118716	ε Cen	0.24	4.2	B1III	[2]
4133	91316	ϱ Leo	0.20	2.5	B1Iab	[1]
1890	37017	−4°1183	0.33	7.2	B1.5V	[1]
6527	158926	λ Sco	0.27	4.4	B1.5IV	[2]
5695	136298	δ Lup	0.28	5.1	B1.5IV	[2]
1933	37481	−6°1275	0.29	5.4	B1.5IV	[1]
6247	151890	μ^1 Sco	0.31	5.2	B1.5IV	[2]
3468	74575	α Pyx	0.29	4.2	B1.5III	[2]
5469	129056	α Lup	0.29	4.0	B1.5III	[2]
1848	36430	−6°1207	0.43	8.4	B2V	[1]
5285	122980	χ Cen	0.45	7.0	B2V	[2]
1679	33328	λ Eri	0.32	4.9	B2IV	[1]
39	886	γ Peg	0.33	5.2	B2IV	[1]
6252	151985	μ^2 Sco	0.33	5.0	B2IV	[2]
5776	138690	γ Lup	0.34	5.8	B2IV	[2]
6508	158408	υ Sco	0.34	5.3	B2IV	[2]
779	16582	δ Cet	0.35	5.9	B2IV	[1]
5395	126341	τ^1 Lup	0.35	4.9	B2IV	[2]
5576	132200	κ Cen	0.41	5.7	B2IV	[2]
1790	35468	γ Ori	0.34	4.7	B2III	[1]
1463	29248	ν Eri	0.35	4.1	B2III	[1]
1552	30836	π^4 Ori	0.36	3.9	B2III	[1]–[2]
1567	31237	π^5 Ori	0.39	4.6	B2III	[1]
7029	172910	−35°12876	0.46	7.7	B2.5V	[2]
1891	37016	−4°1184	0.49	8.4	B2.5V	[1]
6875	168905	−44°12569	0.51	7.5	B2.5V	[2]
5812	139365	τ Lib	0.52	7.7	B2.5V	[2]
3886	84816	−44°5846	0.46	7.0	B2.5IV	[2]
801	16908	35 Ari	0.55	9.6	B3V	[1]
4848	110956	−55°5215	0.55	8.9	B3V	[2]
3925	85980	−44°5987	0.55	8.8	B3V	[2]

Table I (continued)

BS	HD	Name	c_D	$W_{H\beta}$	MK	Ref.
4573	103884	−61°2829	0.55	8.4	B3V	[2]
5035	116087	−60°4627	0.56	9.7	B3V	[2]
3415	73390	−57°1590	0.56	9.1	B3V	[2]
4638	105937	ϱ Cen	0.57	9.6	B3V	[2]
3539	76161	−47°4460	0.59	8.9	B3V	[2]
2159	41753	ν Ori	0.54	7.1	B3IV	[1]
1320	26912	μ Tau	0.59	7.3	B3IV	[1]
3663	79447	−61°1201	0.52	6.5	B3III	[2]
2653	53138	o^2 CMa	0.22	1.6	B3Ia	[2]
4549	103079	−64°1724	0.60	10.1	B4V	[2]
6938	170523	δ^2 Tel	0.62	7.5	B4III	[2]
4940	113703	−47°8088	0.64	9.8	B5V	[2]
1839	36267	32 Ori	0.66	9.9	B5V	[1]
5292	123335	−58°5383	0.63	8.7	B5IV	[2]
1735	34503	τ Ori	0.71	8.4	B5III	[2]
5217	120908	−52°6805	0.72	8.4	B5III	[2]
3940	86440	ϕ Vel	0.48	3.7	B5Ib	[2]
2827	58350	η CMa	0.33	2.2	B5Ia	[2]
5026	115823	−52°6405	0.70	11.1	B6V	[2]
338	6882	ζ Phe	0.76	11.7	B7V	[2]
5625	133937	−42°10050	0.76	10.7	B7V	[2]
6934	170465	δ^1 Tel	0.83	9.7	B7IV	[2]
	37151	−7°1131	0.82	13.5	B8V	[4]
674	14228	ϕ Eri	0.82	11.3	B8V	[3]
1038	21364	ξ Tau	0.84	12.6	B8V	[4]
1088	22203	τ^5 Eri	0.87	11.4	B8V	[4]
2451	47670	ν Pup	0.85	8.2	B8III	[3]
8353	207971	γ Gru	0.87	9.9	B8III	[4]
4662	106625	γ Crv	0.92	9.9	B8III	[4]
1806	35640	−5°1247	1.01	14.3	B9V	[4]
126	2884	β^1 Tuc	1.02	16.9	B9V	[3]
806	16978	ε Hyi	1.07	16.9	B9V	[4]
3665	79469	θ Hya	1.11	18.3	B9.5V	[4]
8781	218045	α Peg	1.22	15.4	B9.5V	[4]
1570	31295	π^1 Ori	1.15	18.5	A0V	[4]
1544	30739	π^2 Ori	1.20	16.5	A0V	[4]
191	4150	η Phe	1.21	16.1	A0V	[4]
3410	73262	δ Hya	1.24	15.0	A0V	[4]
3981	87887	α Sex	1.26	12.8	A0III	[4]
7950	198001	ε Aqr	1.24	17.8	A1V	[3]
4359	97633	θ Leo	1.29	17.9	A1V	[4]
3685	80007	β Car	1.34	15.8	A1IV	[4]

TABLE II
Stars for which the classification disagrees

BS	HD	Name	c_D	$W_{H\beta}$	S.T.	S_Q	MK	Ref.
	37061	−5°1325	0.30	4.4	B1.5III	B1	B0V B1V B1V, B8	[5] [6] [7]
2294	44743	β CMa	0.23	5.2	B1V	B0.5	B1II–III B0.5II–III B1II B8V	[1] [8] [9] [10]
2657	53244	γ CMa	0.75	8.6	B6III	B6	B8II B8III	[3] [11]
2845	58715	β CMi	0.98	10.9	B8.5III	B8	B8V	[12]
3860	83979	ζ Cha	0.58	9.5	B3V	B4	B5V B5IV	[2] [13]
4773	109026	γ Mus	0.58	8.3	B3V	B4	B5V B5IV	[2] [14]
4823	110335	−59°4393	0.85	4.2	?	B6	B6IV B7IV	[2] [13]
5528	130807	o Lup	0.53	8.7	B3V	B4	B5IV B6III B6V B8V	[2] [15] [16] [14]
7129	175362	−37°12982	0.48	8.9	B2.5V	B3	B8IV B7V B9III	[17] [18] [19]

References for Tables I and II:

[1] Lesh, 1968.
[2] Hiltner *et al.*, 1969.
[3] Jaschek and Jaschek, 1966.
[4] Jaschek *et al.*, 1964.
[5] Divan, 1954.
[6] Strand, 1958.
[7] Wenzel, 1951.
[8] Underhill, 1947.
[9] Buscombe, 1962.
[10] Crawford, 1958.
[11] Woods, 1958.
[12] Bappu *et al.*, 1962.
[13] Morris, 1961.
[14] Cape Mimeogram No. 12, 1961.
[15] Walraven and Walraven, 1960.
[16] Eggen, 1961.
[17] Buscombe and Morris, 1960.
[18] Hoffleit, 1956.
[19] Feast *et al.*, 1957.
All the References from [5] on are taken from Jaschek *et al.*, 1964.

valent width of Hβ vs that of Hγ or Hδ since Hβ is more sensitive to emission effects than Hγ or Hδ. Figure 3 shows a graph of $W_{H\beta}$ against $W_{H\delta}$. The dots represent the stars used as standards for the classification, which we consider as 'normal' stars; the crosses are stars with emission and the squares are peculiar stars. Even though peculiar stars are not discriminated in this graph, emission stars are more or less clearly separated, depending on the amount of emission.

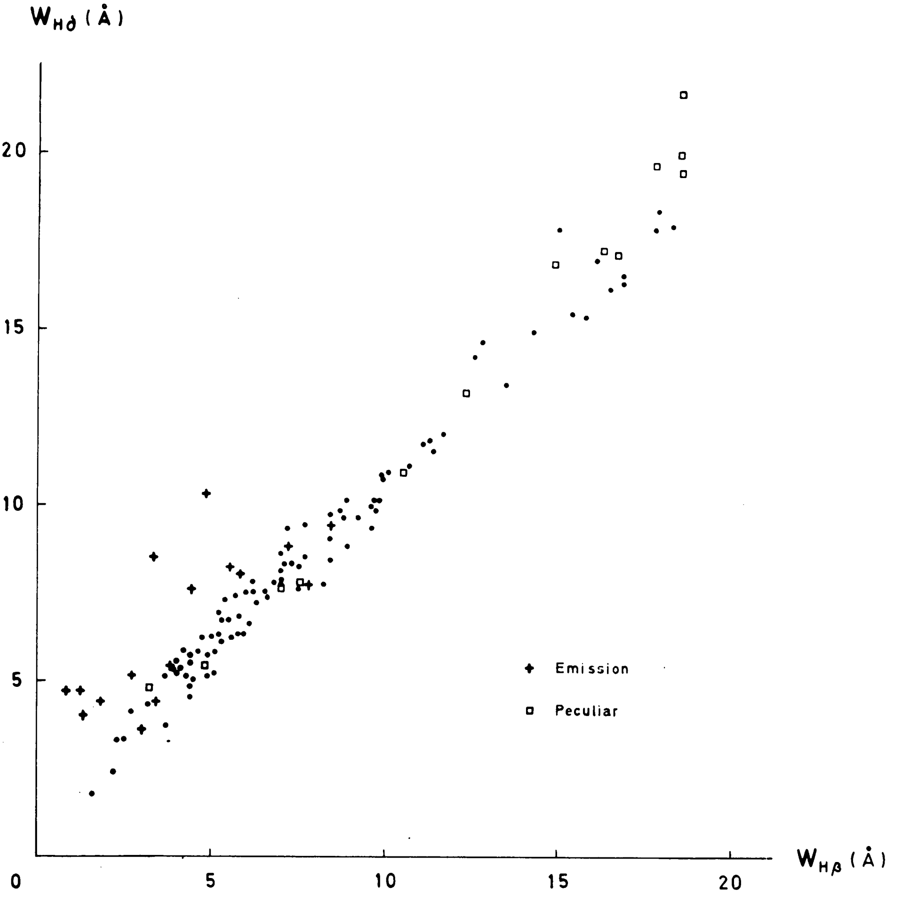

Fig. 3. $W_{H\beta}$, $W_{H\delta}$ relation. This diagram allows the separation of emission stars, indicated by crosses. The squares represent peculiar stars.

Future plans for this work include an attempt to segregate peculiar stars by using other parameters, as *UD* or Δ*D*. We also intend to continue the observations, with special emphasis in luminosity classes I and II and late B stars, in order to fill in the gaps and obtain a more precise classification scheme. If possible, the classification will be extended to later types.

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