EVIDENCE FOR SEQUENCES IN THE COLOR-LUMINOSITY RELATIONSHIP FOR THE M-DWARFS

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The fact that the science of astronomy has always dealt mainly with small amounts of data gathered from a very large number of objects has made it a science of catalogues, tabulation, and classification. It is, consequently, also a science in which the statistical treatment of data is common, and in which final results may have significance only in a statistical sense. Classification of data has usually been used as an empirical device to bring order to large masses of observational data, and many times this ordering has preceded a discovery bearing on the explanation of some natural phenomenon. The physical nature of the stars has, in particular, been greatly clarified by means of classification processes. One of the first steps in this direction was taken when the relationship between the absolute luminosity and spectral type of stars was announced in 1926 by its discoverers, E. Hertzsprung and H. N. Russell. If the luminosities of stars in a group are plotted as a function of spectral type, it is found that the resulting Hertzsprung-Russell diagram (or simply H-R diagram) portrays a relationship showing rather moderate scatter. An important question in modern astrophysics concerns the origin of the scatter: Do stars follow only an approximate relationship between luminosity and spectral type, or is the scatter caused entirely by experimental error in the observations? This question is not nearly so easy to answer as it may seem. Luminosities of stars are very difficult to measure, while spectral types are not precisely measured quantities since they are based on an arbitrary step classification system, which in turn depends on visual estimates obtained from examination of spectrograms.

The spectral type of a star is a function mainly of its temperature. The color of a star, that is, its comparative brightness in two different regions of the spectrum, is also a function principally of temperature. The color of a star can be measured by well-established photometric methods, and, when properly done, the result is purely objective. The substitution of color for spectral type as an independent variable, therefore, may lead to a reduction of experimental error and result in a more significant dependence of luminosity on temperature. The substitution of color for spectral type is not a panacea, for although the former can be more accurately determined than spectral type, the color may be affected by interstellar reddening, whereas the spectral type is not. A plot of luminosity versus color is known as a color-magnitude diagram.

The first demonstration of a narrow sequence in a color-magnitude diagram was made in 1940 by Haffner and Heckman [1] for the Praesepe cluster by means of photographic photometry. Later, by means of the intrinsically more accurate photoelectric methods, Eggen [2] obtained narrow sequences for the nearby stars, and for the stars of several galactic clusters. Eggen's results have stimulated a large amount of photoelectric work on the problem of narrow sequences, especially by H. L. Johnson and W. W. Morgan [3] and by H. L. Johnson [4], [5].

The presence of narrow sequences in some regions of the color-magnitude diagram has important consequences. Theoretically, such sequences have bearing on modern theories of stellar evolution [6]. Observationally, if narrow sequences exist, they can be used to determine accurate stellar distances by means of photometric methods. At present, for example, this method promises to establish an intergalactic distance scale, by measuring the distance of galactic globular clusters from the luminosities of their main sequence stars [7]. Since the total luminosities of galactic globular clusters can thereupon be determined, then with the assumption that the globular clusters found in other galaxies are like the local sample, distances to those extragalactic nebulae in which globular clusters are found can be measured photometrically. Thus, the importance of narrow sequences in the color-magnitude diagram is such that attempts to find new sequences are justified.

The nearby stars form a favorable sample with which to work in an investigation of sequences. Distances to these stars are known from their parallaxes [8], in some cases with high precision. These distances result from trigonometric measurement in terms of our fundamental unit of length, the radius of the orbit of the earth. Furthermore, all of these stars are so near that there is little or no chance that the intensity or color of their light is influenced by interstellar absorption. The most numerous stars among the nearby sample are the red dwarfs, those small, low-temperature, high-density stars of low luminosity. It has long been known, however, that beginning approximately with stars of spectral type M0 and extending to those of later type, the color on the International System of photometry fails to indicate greater redness as the spectral type becomes later, which means that the color-magnitude diagram becomes valueless in the investigation of these stars for sequential distribution. In 1949 the author found that a magnitude and color system based on the red and infrared regions of the spectrum would give excellent color resolution to the red dwarf stars, and would yield a color-magnitude diagram useful for investigating sequences among the red dwarfs.

Accordingly, a program for the measurement of the red and infrared magnitudes of all stars with a parallax greater than 0.100 seconds of arc was initiated at the Lick Observatory. Work was started in 1950 with the cooperation of Mr. J. Lynn Smith. The southern stars were measured in 1951 with the cooperation of Dr. S. C. B. Gascoigne, with the 29-inch Reynolds reflector at the Commonwealth Observatory, Mt. Stromlo, Australia. The work was finished in 1952 and 1953 at the Lick Observatory with the help of Mr. H. S. White. During the course of the investigation, a complete red-infrared magnitude and color system had to be established, with colors for the bluest to the reddest stars, and with standard magnitude areas available for photometric comparison over the whole sky [9], [10]. Efforts were made to reduce accidental and systematic errors to a minimum. All measurements were made with an infrared sensitive caesium-oxide-on-silver photocell, as described in detail in references [9] and [10]. From the 272 nearby stars measured in this program, the 77 stars tabulated in table I were selected for sequence study analysis.

TABLE I

Yale Number	Name	π ± p.e.	n	R ± a.d.	$(R-I)$ ± a.d.	M_R
49	+43°44 (A)	0″278±7	4	$7^{m}03\pm 2$	$+0^{m}88\pm 2$	$9^{m}25$
	+43°44 (B)		4	9.60 4	1.22 5	11.82
155	η Cas (B)	.182 5	5	6.42 2	0.59 1	7.72
	L726–8	.41 25	4	10.00 14	1.70 2	13.06
520	HR 753 (B)	.147 5	6	10.26 3	1.28 2	11.10
555	20 C 180	.130 8	4	9.31 2	1.08 1	9.88
1135	−21°1051	.128 8	3	7.33 1	0.72 1	7.87
1181	−45°1841	.251 7	7	7.84 2	0.77 2	9.84
1255	−3°1123	.163 5	5	6.87 2	0.84 1	7.93
1305	Ross 47	.165 5	4	10.03 2	1.27 2	11.11
1430	−21°1377	.170 6	7	7.09 1	0.82 1	8.24
1509	Ross 614	.250 5	5	9.43 3	1.38 2	11.42
1609	20 C 400	.170 5	4	8.72 1	1.08 2	9.87
1668	Ross 986	.148 11	3	9.93 1	1.39 2	10.78
1755	+5°1668	.263 4	6	8.40 3	1.19 1	10.50
1827	Ross 882	.149 6	6	9.76 4	1.40 3	10.63
1942	Ross 619	.151 7	3	11.26 6	1.30 2	12.16
2198	+53°1320 (A)	.163 5	4	6.76 3	0.68 2	7.82
	+53°1320 (B)		4	6.84 2	0.69 3	7.90
2390	Gmb 1618	.222 5	4	5.74 2	0.60 1	7.47
2420	+20°2465	.212 5	5	8.08 1	1.12 2	9.71
2456	+1°2447	.128 8	5	8.49 2	0.95 2	9.03
2524	Wolf 358	.139 9	2	10.20 4	1.28 4	10.92
2553	Wolf 359	.419 8	3	11.28 1	1.85 1	14.40
2561	20 C 601	.149 8	3	8.82 1	1.02 1	9.69
2576	Lal 21185	.398 5	3	6.36 1	0.91 1	9.36
2582	Lal 21258 (A)	.173 10	4	7.68 1	0.82 1	8.87
	Lal 21258 (B)		4	12.49 12	1.72 13	13.68
2631	+66°717	.113 7	4	8.31 2	0.76 1	8.57
2722	AC + 79°3888	.196 8	4	9.44 3	1.18 2	10.90
2730	Ross 128	.297 6	4	9.55 1	1.30 1	11.92
2890	Wolf 424 (AB)	.223 6	4	10.50 1	1.62 3	12.24
2910	−51°6859	.116 7	4	9.41 6	1.07 1	9.73
3135	+15°2620	.211 5	3	7.41 1	0.85 1	9.03
3278	Proxima Cen	.762 5	4	9.02 3	1.65 1	13.44
3296	Wolf 1481	.148 8	4	9.82 2	1.28 1	10.67
3375	HR 5568 (B)	.173 6	3	7.01 1	0.89 2	8.20
3458	−7°4003	.149 5	4	9.26 2	1.10 1	10.13
3501	−40°9712	.167 5	3	8.12 1	1.05 1	9.24
3701	−37°10765	.125 7	4	9.32 2	1.10 2	9.82

TABLE I—*Continued*

Yale Number	Name	π ± p.e.	n	R ± a.d.	(R − I) ± a.d.	M_R
3733	20 C 986	0″129±10	3	9ᵐ05±2	+1ᵐ01±3	9ᵐ60
3746	−12°4523	.244 6	4	8.71 3	1.20 1	10.65
3845	−8°4352 (AB)	.155 3	6	7.78 3	1.08 2	8.74
3844	−8°4352 (C)		6	10.35 4	1.22 5	11.31
3924	HR 6426 (C)	.137 5	3	9.26 6	0.96 2	9.94
3955	+2°3312	.125 6	3	6.67 3	0.60 2	7.15
3958	−46°11540	.213 5	4	8.11 2	1.03 1	9.75
4009	18 C 2347	.132 9	3	8.55 1	0.88 1	9.15
4029	+68°946	.203 4	4	7.90 2	1.10 1	9.44
4098	+4°3561	.545 3	4	8.09 1	1.23 2	11.77
4133	−3°4233	.133 6	4	8.32 2	0.88 1	8.96
4330	+59°1915 (A)	.280 4	5	7.68 2	1.07 2	9.92
	+59°1915 (B)		5	8.38 2	1.14 2	10.62
4338	Ross 154	.351 6	3	9.43 2	1.30 2	12.16
4451	Ross 731 (A)	.116 6	3	9.61 1	0.96 1	9.93
	Ross 731 (B)	.116 6	3	9.62 1	0.95 1	9.94
4459	20 C 1130	.123 4	5	9.92 3	1.16 3	10.36
4494	Wolf 1055	.168 4	5	7.90 1	1.00 2	9.03
4794	−45°13677	.158 6	3	7.02 1	0.73 1	8.01
4889	20 C 1213	.124 5	3	9.28 1	1.07 1	9.74
4929	−32°16135 (AB)	.113 8	4	8.69 1	1.31 2	8.95
5012	+61°2068	.137 4	3	7.53 2	0.82 2	8.21
5077	61 Cyg (B)	.293 3	5	5.27 2	0.60 3	7.61
5117	−39°14192	.255 8	3	5.78 1	0.69 1	7.81
5177	20 C 1285	.149 5	7	8.95 1	1.17 2	9.82
5190	−49°13515	.209 7	4	7.56 2	0.93 1	9.16
5438	Kr 60 (AB)	.249 4	3	8.17 2	1.15 2	10.15
5475	LPM 837	.295 5	5	10.26 2	1.66 2	12.61
5520	+43°4305	.198 4	3	8.83 3	1.15 1	10.31
5546	−15°6290	.206 6	5	8.76 4	1.22 1	10.33
5563	+15°4733	.150 5	20	7.58 1	0.88 1	8.46
5572	−23°17699	.125 6	4	7.02 2	0.62 1	7.50
5584	−36°15693	.273 7	3	6.31 1	0.85 1	8.49
5694	+19°5116 (AB)	.144 12	3	8.77 2	1.24 1	9.56
5736	Ross 248	.316 5	8	10.41 4	1.56 4	12.91
5763	+1°4774	.162 6	5	7.95 2	0.87 1	9.00
5817	−37°15492	.219 8	3	7.49 2	0.92 1	9.19

The stars in table I were picked for their red color, +0.60 mag. or larger, and for their large parallax. In an effort to select only the most accurate parallaxes, all stars with a parallax smaller than 0.110 sec. of arc were rejected, as well as three stars within this limit whose parallaxes had been determined at only one observatory. In table I, the first two columns contain respectively the serial number from the Yale Catalogue [8], and another designation. The third column contains the catalogue parallax with its probable error in seconds of arc. The fourth column gives

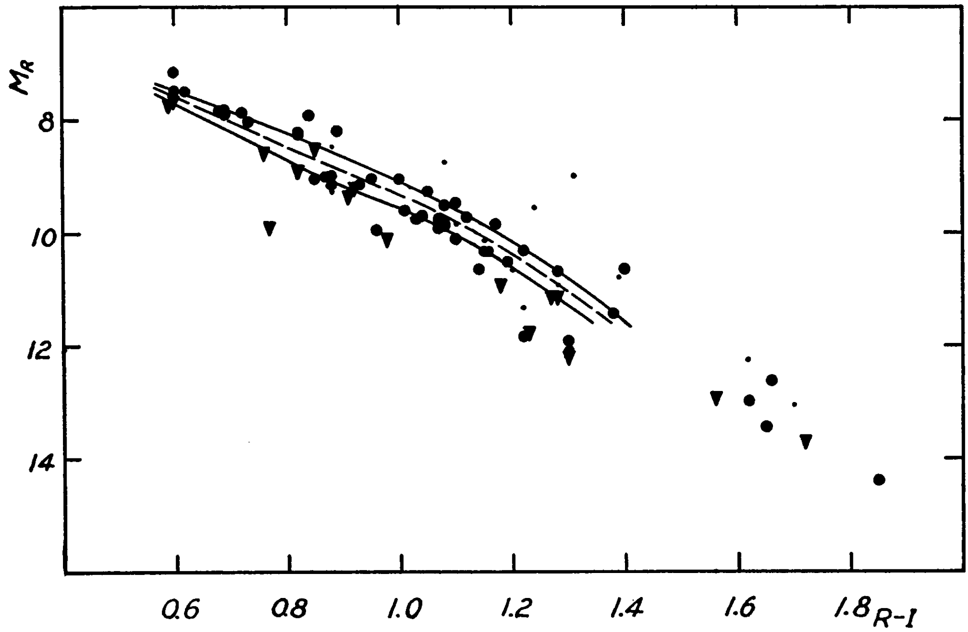

FIGURE 1

A plot of the photometric data contained in table 1. Large dots and triangles are, respectively, low and high velocity stars not known to be double. Small dots are stars known to be double. Solid lines were drawn by inspection and represent the proposed sequences. The dashed line is halfway between the two solid lines.

the number of nights on which the photoelectric magnitude and color data were obtained for each star; this number is equal to the number of observations. The fifth and sixth columns list the red apparent magnitude and the photoelectric color, each with the average deviation of a single observation from the mean. The last column contains the absolute red magnitude, M_R, that is, the magnitude the star would have if it has a parallax of 0."100 or a distance of 10 parsecs (32.6 light years).

These data are plotted in the form of a color-magnitude diagram in figure 1. In this figure the ordinate is the absolute magnitude taken from the last column of table I, whereas the abscissa is the color, taken from the sixth column. The large dots and triangles (the significance of the two symbols will be explained later) represent stars that are not known to be double, and the size of the symbol is equal to twice the average experimental probable error, which by chance happens to be nearly equal in both coordinates. The small dots represent stars that are known or believed to be double stars, and whose separation is too small for each component to have been measured separately with the photometer. The two full lines have been drawn to fit the possible sequences, while the dotted line has been drawn halfway between them. These solid lines were drawn by inspection to fit as many of the observations as possible without any sharp discontinuities. No attempt was made to extend the lines through the interesting group beyond color +1.4 mag., because of the small size of the sample. Eighteen points touch the upper curve, four points the middle, and 22 points the lower, if the double stars are omitted. There appears to be some kind of segregation here, since the distribution about the middle curve is obviously not Gaussian. A histogram (figure 2) was constructed by

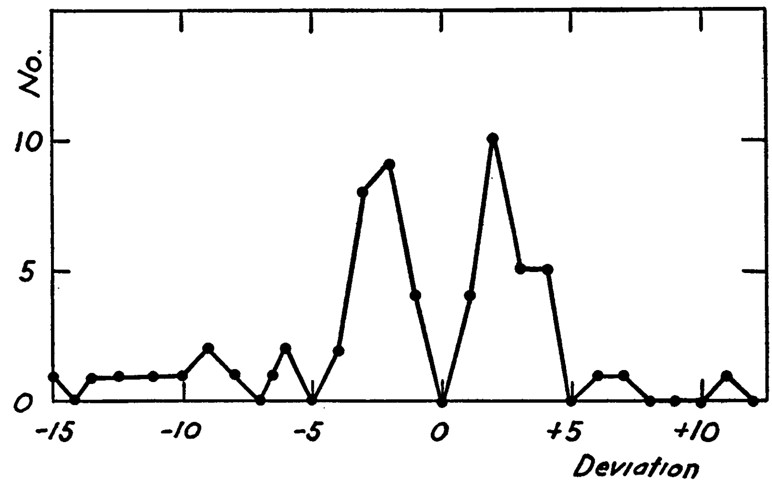

FIGURE 2

A histogram, showing frequency of deviations from the dashed line of figure 1, in units of 0.01 mag. The double maximum represents the proposed sequences.

measuring deviations in M_R in hundredths of a magnitude from the middle (dashed) curve and by collecting them in groups of increments of 0.01 mag. centered about the dashed line. That is, all points (with residuals) between +0.005 and −0.005 mag. are plotted as 0 deviation in figure 2, those between +0.005 and +0.015 mag. as +1, etc. In this histogram, evidence of separation also appears, as shown by the two prominent peaks at about +2 and $-2\frac{1}{4}$. The stars that do not fit the two lines in figure 1 seem to deviate from them at random, or, if they lie on a sequence, it is not nearly parallel, for there is no evidence of a third peak. If the fact that the two lines are not parallel had not been taken into consideration in constructing figure 2, the two peaks would have been even better defined. In figure 3, all stars believed single and that have a parallax of $0\overset{''}{.}200$ or greater have been plotted as round dots. These stars constitute the very best data, for those of smaller parallax represent the least certain, generally, of the plotted points. The sequence stars all lie on or touch the curves transcribed from figure 1. In fact, the curves could more easily have been determined from these stars alone, had the sample not been too small to instill confidence. Of the stars that do not fit the proposed sequences, those lying obviously high may well be double stars that have been undetected by other methods. The distribution of known double stars as shown by the small dots in figure 1, supports this interpretation. Likewise, stars lying between the curves may be pairs of stars of the type belonging on the lower curve. Among the stars lying below either curve are two well known objects of abnormally low luminosity, Number 1181 (also known as Kapteyn's star) and Number 4098 (Barnard's star). These stars may be partially degenerate, but whatever the cause for their low luminosity, the photometric data tell us only that they do not fit on either of the two proposed sequences, nor on a third sequence parallel to the two.

In figure 1, the points plotted as triangles represent stars that have either their

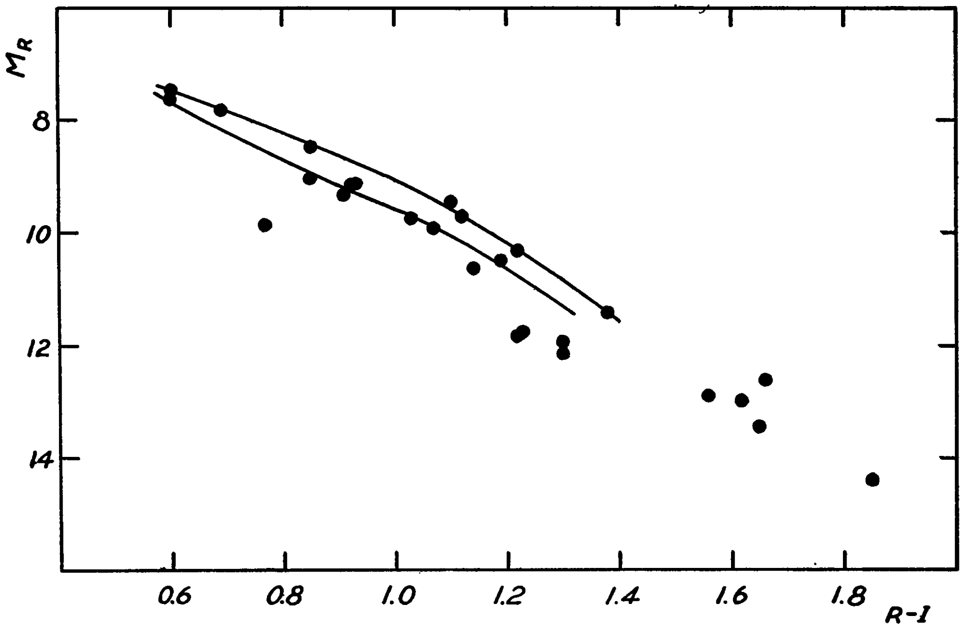

FIGURE 3

A plot similar to figure 1, but high-velocity stars are not indicated, and the data have been more highly refined by selecting only those stars whose parallax equals or exceeds 0.200 seconds of arc.

radial velocity (when known) or their tangential velocity greater than 75 km. per sec. Only one such star falls on the upper curve, whereas all others fall on or below the lower curve. In a classical paper, Oort [11] showed many years ago that stars fall into two categories that can be distinguished as either high-velocity stars or low-velocity stars. More recently, Baade has identified [12] the high-velocity stars with his population type II, which includes stars in globular clusters. The property of high velocity is a sufficient but not a necessary condition that a star belong to population II. Hence, we may speculate that the lower curve of figure 1, with its mixture of spots and triangles, may represent the main sequence of population II, whereas the upper curve, with only one triangle, may represent population I. The proposed two sequences on the color-magnitude diagram may therefore result from real physical differences among the stars constituting Baade's two population types.

There remains, however, a possibility that the upper curve may be caused by binary stars that so far have remained undiscovered. Figure 4 shows a curve attached to a fragment of the lower sequence of figure 1. This curve is the path that would be taken on the color-magnitude diagram of a red dwarf star with a color of +0.8 mag. if it had associated with it one of a series of companions differing in magnitude from the primary star by 0.0, 0.25, 0.5, 1.0, 2.0 and 3.0 mag. Thus, if the hypothetical companion differed from the primary by any amount from 0.0 to about 1.5 mag. the composite star would lie on a new "sequence" about 0.75 mag. higher than the parent one. Also, if the companion were from 3 to 2 magnitudes

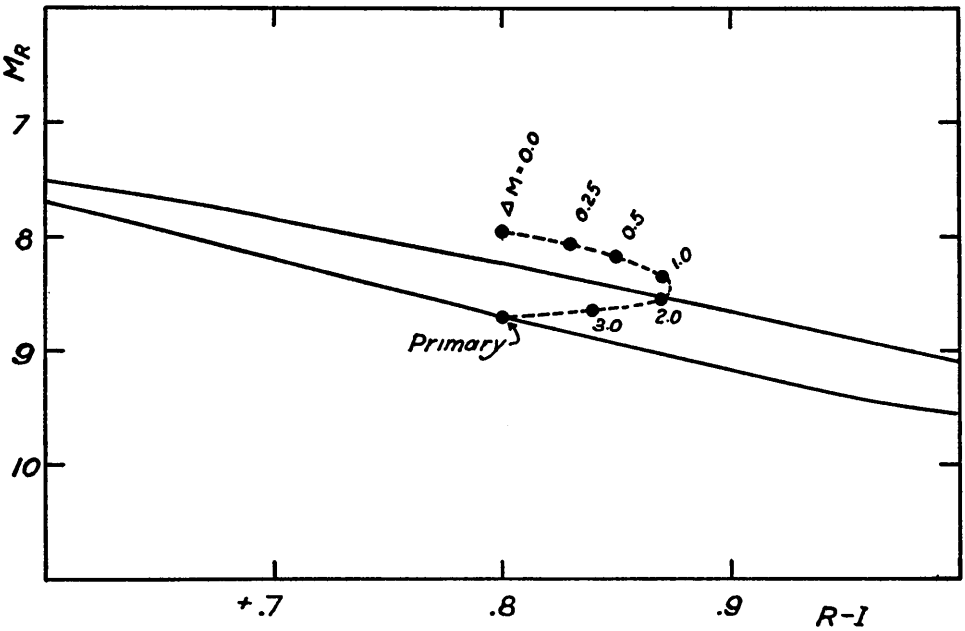

FIGURE 4

On the two proposed sequences has been drawn a diagram illustrating the effect on a primary star of a companion of various luminosities. Note that a series of primaries with companions of from 1 to 2 mag. fainter could cause a "sequence" about where the proposed upper sequence is located.

fainter than the primary, a rough sequence would be formed about 0.5 magnitude above the parent sequence. Therefore, all that would be needed to form the upper of our two sequences from multiple stars built of members of the lower sequence, would be some property in the formation of double stars that would favor the companion being between 3 and 2 magnitudes fainter than the primary, in addition to the obvious fact that double stars would have to be very plentiful.

When the 77 stars in table I are considered as stellar systems, we find that within the parallax limit there are 70 such systems. The shrinkage from the number 77 is caused by tabulation of individual stars of systems as separate entries in table I. Of the 70 systems, 27 are known to be double or multiple stars from variation of radial velocity, variation of position, or because the star can be seen to be multiple or double. Two of the remaining systems are possibly double, little is known of four, and the remainder (37) are believed to be single stars. (The failure of a tally with figure 1 is caused by observation of some double stars as two separate single stars.)

If the upper sequence is composed of double stars, then from this sequence and the stars that fall above it, 13 additional double stars would be indicated, which would reduce the number of single stars to only 24. It would therefore have to be true that only a little more than one-third of the stars, nearby enough to be considered here, may actually be single objects; all others would have to be members of multiple systems. While two-thirds is a large fraction for multiple stars, it is not absurdly large.

There are two arguments against the multiple star hypothesis as an explanation of the two proposed sequences. First, it is unlikely that so many double stars remain undiscovered—there are only four stars about which little is known. Second, the good correlation between high velocity and association with the lower sequence would require that the double stars constituting the upper curve all be low-velocity objects, while many of the single stars would be high-velocity objects. It is more likely that the high-velocity property is correlated with some property concerning the constitution or origin of the stars, than with mere duplicity.

To summarize: red and infrared magnitudes of the late-type nearby dwarf stars indicate that these objects may fall into two color-magnitude sequences. The observational evidence available at the present time suggests that these two sequences may reflect physical differences between two types of stars, such as those belonging to Baade's population types I and II, rather than being the result of undiscovered binary or multiple systems.

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