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EXAMINATION OF THE EVIDENCE FOR THE EXISTENCE OF PYGMY STARS

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ABSTRACT

The kinematic, spectroscopic, and photometric data for five blue stars of high proper motion are reviewed These stars have been suggested to be much fainter than conventional white dwarfs and have been called "pygmy stars," or "blue ultradwarfs" by Zwicky New photometry shows that the stars are redder than the estimates made at the time of discovery by Luyten, and because of the sensitivity of the color-luminosity relation for white dwarfs, this redness removes the kinematic anomaly which originally led to the postulation of this new class of stars We believe there is now no observational evidence—photometric, kinematic, or spectroscopic—for the existence of pygmy stars.

Although not pygmies, the stars investigated here are nevertheless quite interesting Three of the five are high-velocity white dwarfs with kinematic properties similar to subdwarfs and RR Lyrae variables of extreme Population II.

The red dwarf LP101-15, which forms a wide common proper-motion pair with the white dwarf LP101-16, was found to be an eclipsing system whose primary component is an M4 dwarf The period is either $1^{d}26796$ or $0^{d}63398$, depending on the existence of a secondary eclipse Our present photometry is incomplete on this point.

I. INTRODUCTION

Zwicky (1963*a*, *b*, 1965, 1966) believes that there is observational evidence for a new class of blue, low-luminosity stars that are, approximately, 5 mag fainter than white dwarfs. He has called such objects "pygmy stars," or "blue ultradwarfs." The objects in question were originally discovered by Luyten (1962, 1963, 1965*a*, *b*) to have the following properties: (*a*) fainter than about photographic magnitude 14; (*b*) annual proper motions greater than approximately $0''.4$; and (*c*) blue or white color class, as estimated on the red and blue *Palomar Sky Survey* plates. The pygmy candidate stars include LP9-231, LP357-186, LP414-106, LP768-500, and the common proper-motion pair LP101-15/16. From the absence of absorption lines in the spectra, Zwicky (1963*a*, *b*) classifies LP357-186 and LP414-106 as of type O.

The basic argument that these stars are considerably fainter than white dwarfs is a kinematical one, and is most clearly stated (Zwicky 1965, p. 12) for the case of LP768-500, which Luyten (1963) had previously discovered as a star of color class *a* with $B - V \approx -0.1$, $U - B \approx -0.5$, $P_g \approx 18.2$, and an annual proper motion of $1''.18$. Zwicky states: "If LP768-500 were an ordinary white dwarf, its absolute photographic magnitude could not be fainter than $M_p \simeq 13.5$. Its distance thus would be of the order of 100 pc and its transverse velocity of the order of 600 km/sec. This in itself is most unlikely. Together with the fact that the spectrum of LP768-500 shows Balmer lines in absorption which are much narrower than those of ordinary white dwarfs indicates that we are dealing here with a blue pygmy star, whose luminosity is an order of magnitude 100 times fainter than a white dwarf." The two basic points are, then, the size of the transverse motion and the character of the spectrum.

When the kinematic argument is applied to two other members of the class—LP357-186 and LP414-106—using the photometric distance modulus from the calibration of the white-dwarf luminosities by Eggen and Greenstein (1965), even larger cross-motions occur if the astrometric data of Luyten and the spectral type found by Zwicky are used. These data are $m_{pv} \simeq 17.7$, $\mu = 0''.55$/yr and spectral type O for LP414-186 and

$m_{pv} + 18.4$, $\mu = 0''.42$/yr, spectral type O($U - V = -1.4$) for LP367-186—values which lead to transverse velocities of 865 and 825 km/sec, respectively. The motions are clearly improbable and would imply that the absolute luminosities of the stars are fainter than white dwarfs, *but only if the stars are as blue as the photographic data indicated.*

Since the whole argument rests on knowledge of the distances of these objects, and these distances are obtained from a color-luminosity relation that, because of its steepness, is sensitive to the accuracy of the colors, Zwicky's result of impossibly high cross-motions requires confidence in the photographic colors. To check these colors we began a photoelectric program during which three-color photometry was obtained of the five candidate pygmy stars, and of a few other faint blue stars of high proper motions subsequently found by Luyten. The results, presented in the following sections, remove the necessity to postulate the existence of pygmy stars and show that the objects in question are almost certainly high-velocity white dwarfs.

TABLE 1

PHOTOMETRY AND TRANSVERSE MOTIONS OF SIX ALLEGED PYGMY STARS

Object	α 1950 (1)	δ 1950 (2)	μ(sec/yr) (3)	V (4)	$B-V$ (5)	$U-B$ (6)	N (7)	M_V (8)	π (9)	S(km/sec) (10)
LP9-231. .	17ʰ54ᵐ7	+82°47′	3″7	14 31	+0 33	−0 52	2E., 2S.	13 5	0 063	280
LP357-186 .	4 09 4	+23 47	0 42	18 56	+0 40	−0 53	2S.	13 4	009	220
LP414-106	4 07 3	+19 47	0 55	17 61	+0 90	+0 30	2S.	14 9	029	90
LP768-500	1 45 7	−17 26	1 18	17 57	+0 37	−0 48	1E , 1S	13 6	016	350
LP101-16 .	16 33 4	+57 15	1 62	15 00	+0 49	+0 36	7E., 7S.	14 0	063	120
LP101-15*	16 33 4	+57 15	1.62	12 90	+1.60	+1 05	Many	11 5	0 063	120

* Eclipsing binary assumed to be unequal components Tabulated magnitude is that of the bright component as if the secondary were completely dark at visual wavelengths.

II. PHOTOMETRIC DATA AND KINEMATICS OF SIX ALLEGED PYGMIES

The photoelectric measurements were made on several nights during the course of other photometric programs with the 200-inch reflector over the past 3 years. The results are shown in Table 1 together with the following information: column (3) contains the annual proper motion as derived by Luyten; column (7), the number of photoelectric observations; column (8), the absolute visual magnitude obtained by fitting to the fainter sequence in the (M_V, $U - V$) relation for white dwarfs (Eggen and Greenstein 1965); column (9), the resulting photometric parallax; and column (10), the transverse velocity. The stars with the highest cross-motions are LP9-231, LP357-186, and LP768-500, the latter being the prototype star discussed by Zwicky in the paragraph quoted in § I. Our values for the transverse motions, which are based on the assumption that the stars are white dwarfs, are not large enough to raise doubts that these objects are not gravitationally bound to the Galaxy. The difference between our results and those of Zwicky is simply that the photoelectric colors are considerably redder than had been estimated at the time of discovery so that the absolute luminosities obtained from the *white-dwarf* calibration are considerably fainter than Zwicky had obtained. Consequently, the transverse motions, assuming the stars to be white dwarfs, become smaller, and this removes the necessity for the stars to be pygmies.

The common proper motion pair LP101-15/16 is of particular interest because *both* components have been called pygmies (Zwicky 1966). If we were only concerned with the white-dwarf component of this red-white pair, the arguments we have applied above to the other pygmy candidates would show that from kinematic considerations alone there is no reason to believe that the object is not a white dwarf. However, the presence of the companion allows us to obtain two independent estimates of the distance of the system.

The red star, LP101-15, was observed on the $(R - I)$ system of Kron, Gascoigne, and White (1957) with a 7102 photomultiplier on the Mount Wilson 60-inch reflector. A value of $R - I = +1.32$ mag obtained from four observations leads to $M_V = +13.0 \pm 0.5$ mag from the $(M_V, R - I)$ relation given elsewhere (Eggen and Greenstein 1965, Fig. 1). The apparent visual magnitude of LP101-15 is usually $V = 12.9$ mag, but during the course of this investigation it was found that the star is an eclipsing binary. The eclipse depth is 0.75 mag, and the colors do not change appreciably during the eclipse phase. If the binary consists of two equal components undergoing nearly total eclipse, then (*a*) the period is $1^d.26796$; (*b*) primary and secondary eclipses should occur; (*c*) the apparent magnitude of a single component is $V = 13.65$, and therefore the photometric distance modulus is $m - M = 0.65 \pm 0.5$ mag based on $M_V = +13.0 \pm 0.5$ obtained from the $R - I$ measurement.

TABLE 2

COMPARISON OF THE PAIRS LP101-15/16 AND L1405-40AB

Star	M_V	μ	$B-V$	$U-B$	$R-I$	S(km/sec)
L101-15 . .	11 5	1″6	+1 60	+1 05	+1 32	120
LI405-40A . . .	12 4	0 6	+1 41	+0 73	+1 25	120
L101-16	14 0	1 6	+0 49	−0 39	. .	120
L1405-40B	12 4	0 6	+0 23	−0 58	.	120

The absolute magnitude of the blue component, LP101-16, assuming it to be a white dwarf and fitting it to the $(M_V, U - V)$ relation (Eggen and Greenstein 1965) at $U - V = +0.13$, is $M_V = 14.0 \pm 1.0$ giving a distance modulus of $m - M = 1.0 \pm 1.0$, which agrees well with that derived from the red companion.

There is, however, another possibility. Spectrograms of LP101-15 taken over the cycle show no evidence of double lines, nor any large change in radial velocity. It may be that one component of the binary is relatively dark and of low mass and that no secondary eclipse occurs. In this case the period is $0^d.63398$ and the apparent magnitude of the brighter component is close to $V = 12.9$ as measured. If the $R - I$ value is not contaminated by a redder, fainter component, then the modulus would be $m - M = -0.1 \pm 0.5$ for LP101-15. However, there is some suggestion that $R - I$ is indeed affected by a color inequality of the two components. As discussed in § VI, the spectral type of LP101-15 is dM3–dM4 with no evidence of abnormality in the absorption spectrum. The spectral type is well determined. The spectral-type $R - I$ relation of Kron *et al.* (1957, Fig. 1) shows that $R - I = 1.1 \pm 0.15$ for dM4—definitely bluer than the observed value of 1.32. Joy's calibration (1947) of the H-R diagram gives $M_V = 11.5 \pm 1.0$ at dM4 which gives $m - M = 1.4 \pm 1.0$ for the red star. This value is now in good agreement with the value from LP101-16 of $m - M = 1.0 \pm 1.0$, assuming it to be a white dwarf. Hence, the parameters of LP101-15/16 are consistent with the calibrated absolute luminosities of dM main-sequence stars and white dwarfs of $U - V = +0.13$.

There are many examples of similar pairs, among which might be mentioned L1405-40A and B (Luyten 1949; Eggen and Greenstein 1965). Comparison of the photometric and kinematic properties of the two pairs, given in Table 2, shows that, on the basis of the colors and the motions alone, there is no support for the assumption that LP101-15/16 consists of a pair of pygmies.

III. FURTHER KINEMATICAL CONSIDERATIONS

Although the transverse motions derived in Table 1 remove the necessity to postulate the existence of pygmy stars, we wish now to examine in more detail the motions of LP9-231, LP357-186, and LP768-500 to show that they are, in fact, what are expected of Population II white dwarfs.

Consider first LP768-500, which has the highest transverse motion in Table 1: 350 km/sec. The star is very close to the south galactic pole so that the (U,V) velocity vectors mainly reflect the transverse motion and are nearly independent of the radial velocity, which will mainly reflect the W motion. The luminosity derived in Table 1 on the assumption that the star is a white dwarf leads to a photometric parallax of 0″016 which, together with the proper motion, gives $U = -210$ km/sec, $V = -275$ km/sec, and $W = 60$ km/sec as the contribution to the space motion from the proper motion alone. The contribution of the radial velocity to these vectors is 28 km/sec to U, -1 km/sec to V, and -96 km/sec to W if Zwicky's (1965) estimate of $\rho = +100$ km/sec is correct; this estimate includes the Einstein shift which we will neglect.[1] Consequently, the vector motions become (U,V,W) = (-180, -275, -160), values that are characteristic of extreme subdwarfs, RR Lyrae variables, and SRd variable stars that represent the globular-cluster or halo-population component of the Galaxy. White dwarfs must exist among this population, and LP768-500 is apparently an excellent example.

TABLE 3

COMPARISON OF LP357-186 WITH POPULATION II STARS AT NEARLY EQUAL ANGULAR DISTANCE FROM THE HIGH-VELOCITY APEX

Object	α 1950	δ 1950	V	$B-V$	$U-B$	Sp	μ	π_{pt}	S (km/sec)
LP357-186	4h09m4	+23°47′	18 56	+0 40	−0 53	. . .	0″42	0 009	220
GC 5108	4 11 6	+22 14	9 22	+0 44	−0 19	sd G0	0 54	012	215
GC 5223	4 16 9	+14 09	7 53	+0 97	+0 85	g K1	0 21	003	330
Ross 374	3 24 0	+23 37	10 83	+0 53	−0 11	sd G5	0 43	007	290
Ross 34	3 25 5	+37 14	11 12	+1 31	+1 06	sd K5	1 53	0 030	240

An equally good case is LP9-231 whose photometric parallax is $\pi_{pt} = 0''063$. Here the values of (U,V,W), due to the proper motion alone, are (+238, −143, +54) with 37, 79, and 48 per cent of the radial velocity to be added, respectively, to the components. Eggen and Greenstein (1967) have given the radial velocity as −160 km/sec which would lead to (U,V,W) = (180, −270, −22) if we ignore the Einstein shift, or (165, −300, 6) if a 40 km/sec Einstein correction is assumed. As was the case for LP768-500, these vectors are consistent with the distribution of (U,V) motions for high-velocity stars (Eggen 1964, Fig. 1).[2]

The same result can be derived in a different way for LP357-186. The transverse motion, S, of this object is compared in Table 3 with that of known subdwarfs in the same region of the sky, chosen to be at the same distance from the apex of the motions of the high-velocity stars; the data for the high-velocity stars were taken from a previous

[1] Correction for the Einstein redshift in no way affects the argument.

[2] It should be mentioned that Luyten (1965*b*) has published a very preliminary trigonometric parallax of LP9-231 based on four plates taken with the 48-inch Palomar Schmidt. The value $\pi_t = +0''31 \pm .08$ differs from $\pi_{pt} = 0''063$, but only by three times the probable error. Furthermore, it has not yet been shown by suitable control observations what the reliability of 48-inch Schmidt parallaxes actually are. It is clear that the large trigonometric parallax and its abnormally large probable error for LP9-231 does not constitute a counterargument for the existence of pygmies in view of the highly preliminary state of Luyten's value.

catalogue (Eggen 1964). Again, the conclusion is clear that LP357-186 is a halo white dwarf.

IV. THE SPECTRA

There remains the question of the spectra of these stars. Zwicky believes that LP768-500 has absorption lines that "are much narrower than those of ordinary white dwarfs which indicates we are dealing with a blue pygmy star." This statement is in two parts; first, that the lines are narrow, unlike those in the spectra of white dwarfs, and second, that this is indicative of low luminosity. The first statement is not correct, as discussed below. The second statement appears to us to be unwarranted because there is now no theory of line widths for absorption features in the stellar atmospheres of exceedingly dense objects which permits prediction of absolute luminosity.

There are many white dwarfs with sharp absorption lines. Examples from the catalogue of Eggen and Greenstein (1965, Table 1) are L870-2, with a total width of $H\gamma$ at half-intensity [$w_{0.5}$ ($H\gamma$)] of only 7 Å, L745-46A with $w_{0.5}(H\gamma) = 10$, Feige 110 with $w_{0.5}(H\gamma) = 10$, and others. L870-2 is a particularly good example because its white-dwarf character is beyond doubt as determined by the trigonometric parallax of $0''.061 \pm 0''.013$. This star can be compared directly with the pygmy candidate because the colors are nearly identical: $B - V = +0.34$, $U - B = -0.50$ for L870-2, and $B - V = +0.37$, $U - B = -0.48$ for LP768-500.

Furthermore, lines as sharp as those in L870-2 are below the instrumental profile limit of the 400 Å/mm dispersion which Zwicky used for LP768-500, and consequently there is no evidence that the lines which do appear in this pygmy candidate are in fact sharper than those in classical white dwarfs.

Zwicky has classified the spectra of LP414-106 and LP357-186 as of type O, but the colors given in Table 1 are obviously not those of O-type stars. However, the O-type classification is used only to indicate the absence of lines, but many white dwarfs have spectra which show no lines at all (Eggen and Greenstein 1965), and these are more conventionally called "DC." The fact that lineless spectra occur among the white dwarfs over a wide range of color class is demonstrated by W457, whose white dwarf nature is determined by the trigonometric parallax of $0''.078$, G175-34B, with a trigonometric parallax of $0''.19$, and G107-70, whose white-dwarf nature is established by photometry of the common proper motion, M-dwarf companion. G175-34B, with $(B - V, U - B) = (+0.30, -0.50)$, matches the color of the pygmy candidate LP357-186; furthermore, G117-70, with $(B - V, U - B) = (+0.99, +0.40)$, is nearly the same color as the other pygmy candidate, LP414-106.

Finally, we must consider the spectrum of the moving pair LP101-15/16. Seven well-widened plates of the red star LP101-15 were obtained with the Hale reflector at 85 Å/mm on blue-sensitive plates over a spectral range of 3500 to 5000 Å. Detailed comparison of the absorption features with the standard dwarf M3 star HD 180617 shows no abnormality in LP101-15. All the atomic lines of dM stars are present and at the correct intensities. The TiO bands are in absorption and are clearly seen, indicating a type between dM3 and dM4. Intense, sharp hydrogen-emission lines are present, together with the H- and K-lines of Ca II, also in emission. These emission lines may arise from circumstellar gas in the system caused by the interaction of the components of the close binary through the inner Lagrangian point of the surfaces of zero velocity.

Except for the presence of these emission features, which Zwicky (1966) discovered, we believe that the absorption spectrum of LP101-15 matches that of ordinary M dwarfs. No evidence for the pygmy character of the primary star is present in the spectrum of LP101-15 in the blue region.

The white-dwarf component presents a different problem. Zwicky suggests that LP101-16 may show broad, shallow absorption features of Hα and Hβ displaced from their laboratory wavelengths by an Einstein shift of 1000 km/sec. This, of course, would be direct proof of the large gravitational field required by the pygmy hypothesis. To check this suggestion, we obtained two highly widened spectrograms of LP101-16 at a dispersion of 190 Å/mm. The photographic density of the spectrograms was optimum. One spectrogram was widened by 0.2 mm on the plate, while the other was widened to 0.8 mm. The plates were microphotometered and analyzed by Westphal, using his cross-correlation technique (Westphal 1965). No evidence of absorption was found at Hβ. (The plates did not extend to the Hα region.) We can, therefore, not confirm the Einstein shift for LP101-16.

V. PHOTOMETRY OF OTHER FAINT, HIGH PROPER-MOTION STARS

During the course of the present investigation we received finding charts from Luyten for other faint stars with moderate or large proper motions that might be of interest in

TABLE 4

PHOTOMETRY OF OTHER FAINT, HIGH PROPER-MOTION, BLUE STARS

Name	α 1950 (1)	δ 1950 (2)	m_{pg} (3)	Color Class (4)	μ (5)	V (6)	$B-V$ (7)	$U-B$ (8)	M_V (9)	S (km/sec) (10)
G 134-22 .	2^h13^m8	+42°44′	15 9	0	1″07	16 23	+0 73	+0 02	14 6	110
LP274-179	4 10 4	+15 15	19 3	a	0 16	18 61	+ .65	− 39	14 1	60
LP475-247	4 37 8	+ 9 19	16 0	b	0 76	16 8:	+ 55:	− 26	14 2	125
G 51-16 ..	8 27 5	+32 52	15 7	0	0 64	15 69	+ 35	− 54	13 3	90
LP425-348	8 38 1	+15 08	17 5	b	0 34	18 29	+ 20	− 46	13 2	160
G 195-19 .	9 12 5	+53 39	14 8	0	1 56	13 79	+ .30	− 66	13 0	105
G 160-54 ..	12 57 5	+ 3 45	16 0	0	1 00	15 90	+ 64	− 09	14 4	100
G 61-29	13 03 8	+18 17	16 2	−1	0 38	15 69	− 10	− 97	10 7	180
LP757-287 .	21 17 6	− 9 55	18 7	a	0 12	18 83	+ 69	00	14 5	40
LP2-69	22 32 0	+84 21	18 0	b	0 15	19 42	+ 06	− 80	12 2	190
G156-64 ...	22 53 2	− 8 06	16 4	0	0 59	16 50	+0 42	−0 46	13 7	100

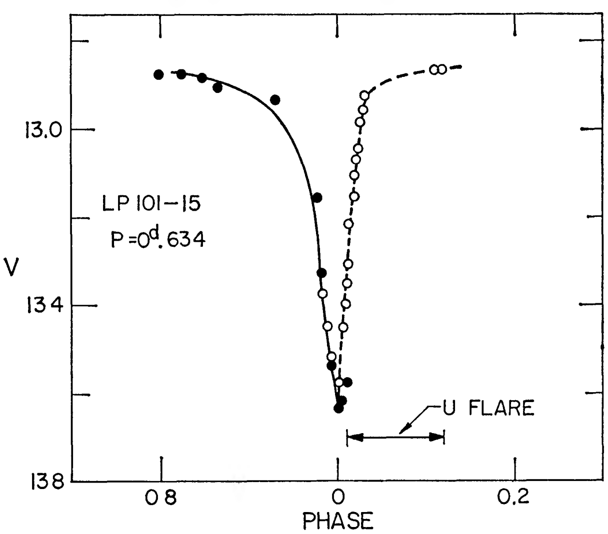

FIG. 1.—The light-curve of LP101-15 near minimum light. Open circles represent observations of June 13, 1966 U T., made with the 200-inch reflector, while dots represent observations of lower weight made with the Mount Wilson 60-inch reflector on June 23, 1966 U.T. The phase interval is indicated during which the ultraviolet intensity increased by 0.7 mag relative to B and V on June 13, 1966 U.T. We have adopted here the working hypothesis of unequal components with only a primary eclipse, giving a period of $0^d.63398$.

this problem. In addition, interesting stars of similar kind were picked from the Lowell proper-motion catalogues, as part of a larger program of photometry of suspected white dwarfs (Eggen 1967). The results are given in Table 4, where columns (3) and (4) contain the estimated photographic magnitudes, and color class from Luyten or from Giclas and his collaborators; columns (6)–(8) list the results of our photometry; column (9) gives the absolute magnitude based on the (M_V, $U - V$), lower-line, calibration of white dwarfs by Eggen and Greenstein (1965), and column (10) the resulting transverse motion. In every case the cross-motion is consistent with the assumption that these stars are ordinary white dwarfs.

VI. THE ECLIPSING BINARY LP101-15

Figure 1 shows part of the light-curve of LP101-15. A preliminary period of $0^{d}63398$ is adopted as discussed in § II. This has been derived from observations of four minima with the assumption that there is no secondary eclipse. The observations extend over a time interval of 10 days which covers 16 cycles. Ultraviolet flaring was observed on June 13, 1966, from phase $0^{p}10$ to $0^{p}120$, during the increase of light after mid-eclipse. During this flare the $U - B$ color changed from $+1.03$ to $+0.36$ mag in less than 1 min and the ultraviolet flux flickered over a range of several tenths of a magnitude for the next 1.25 hours. We do not yet know if this flaring is a recurrent feature of the system at this phase. The marked assymetry on the rising branch of the light-curve may be due to the influence of the flare on the visual magnitude.

The system is of importance, not only in the present context, but because it may possibly provide calibration data on the mass, radius, and the temperature of a late-type M dwarf which is cooler than the components of YY Gem. A complete discussion of the system will be made when the radial velocity and continued photometric observations have been completed.

It is a pleasure to thank Dr. W. Luyten for providing discovery information and finding charts for many of the stars discussed here, Dr. A. H. Joy for advice in classifying the dM spectrum of LP101-15, J. A. Westphal for analyzing the two spectra of LP101-16 by his cross-correlation technique, and Dr. J. L. Greenstein for advice on the 200-inch prime-focus nebular spectrograph.

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