1. THE WHITE DWARFS

Discovery and Observation

W. J. LUYTEN

University of Minnesota, Minneapolis, Minn., U.S.A.

1. Introduction

White dwarfs have been known for slightly more than fifty years; with their planet-like diameters, and stellar-like masses their densities are enormously much higher than those of 'normal' stars. They thus appear to represent a state of matter totally unknown and possibly unattainable on earth.

The history of their original discovery and their early theoretical explanation has been told so often that we need not dwell on this now. Suffice it to say that while in the beginning they appeared to be rather rare in space, it is now generally believed that they constitute a substantial fraction of all known stars and represent the near-final stage of stellar evolution.

Using modern techniques, white dwarfs are fairly easy to discover, and several thousand are now known, but because of their low luminosity the follow-up observations to determine their astrophysically important properties are difficult and generally require very large telescopes.

2. Methods of Discovery

In the main there are two direct techniques for finding them, both based on the fact they are of low luminosity and generally of high temperature, therefore blue or white in color. The classical technique consists of finding first, faint stars with large proper motions, i.e. stars which, statistically, must be of low luminosity, and then subsequently determining the colors and thus select those objects that are whiter then the ordinary main-sequence stars. An entirely new method is due to Zwicky and Humason [1] who simply searched for faint stars that are blue in color, in regions of the sky where few, if any distant objects are expected, i.e. in front of obscuring clouds in the Milky Way, or in the direction of the galactic poles where the star-density is presumed to decrease rapidly with distance.

Applying the first of these methods in the Bruce Proper Motion Survey of the Southern Hemisphere, and, more recently, in the Palomar-Schmidt Proper Motion Survey, I have now found, and published more than three thousand white dwarfs – certain, probable, and possible. These will be discussed in more detail later.

The second method first led to the publication of the famous list of 48 Faint Blue Stars by Humason and Zwicky [1]. The fifteen stars found in the Hyades region did, indeed, turn out to be mainly white dwarfs, but among the thirty-three situated near

Luyten (ed.), White Dwarfs, 1–7. *All Rights Reserved.*
Copyright © 1971 by the IAU.

https://doi.org/10.1017/S007418090009700X Published online by Cambridge University Press

the North Galactic Pole, only two proved to be 'classical' white dwarfs, most of the others being the first representatives of a new class of objects, the 'Faint Blue Stars' in high galactic latitude.

Following up Zwicky's search, first at the Steward Observatory, later with plates taken at the Michigan, Dyer, Tonantzintla, and Palomar Observatories, I have published more than 20000 of such faint blue stars [2], 8700 of them jointly with Haro [3]. In order to obtain at least preliminary information on the number of white dwarfs among them I have determined proper motions for as may of these as old plate material could be found for, and have recently published a general catalogue [4] of 951 proper motions for such stars. In addition to our surveys similar surveys have been made, and lists of faint blue stars published by Iriarte and Chavira [5], Feige [6], Cowley [7], Rubin [8], Sanduleak and Philip [9], and Richter and Richter [10].

From an analysis of these proper motions, including preliminary determinations of the solar motion and secular parallaxes I found that among these faint blue stars the percentage of white dwarfs increases from virtually zero at $m=13$ to about 10% at $m=15$ or 16. For stars fainter than this limit the proper motion alone can hardly be considered as conclusive evidence: e.g. a white dwarf of the o_2 Eridani type with $M=+11$ will, at apparent magnitude 18, have a parallax of only 0″.004 and hence, even near the galactic poles cannot be expected to have a proper motion much larger than 0″.040 which is diffcult to determine with certainty from plate material that now exists.

As it was rapidly becoming clear that among very faint blue stars one could expect to find increasingly larger numbers of quasi-stellar objects, Sandage and I [11] embarked on a program of determining motions, photo-electric colors and spectra for as large a number of faint blue stars as we could observe in several representative regions in the sky. Since we used plates taken with the 48 inch Palomar-Schmidt telescope our limit was generally about $m=19$; Sandage alone [11] continued the search to $m=21$ on plates taken with the 200-inch telescope. From this work we obtain Table I giving the expected distribution of the various types of objects found among these faint blue stars.

TABLE I

	QSS and QSG	Main sequence	Horizontal branch	Subdwarfs	White dwarfs	Proper motion
13	–	15	25	60	–	0″.6
15	5	5	10	68	12	0.20
17	5	–	5	65	25	0.06
19	20	–	–	50	30	0.02
21	50	–	–	–	50	0.010
		160000	63000	20000	1000	

Note – The last column here gives the expected proper motion for a white dwarf of given magnitude; the last line gives the expected distance in parsecs of the various objects if of the 21st magnitude. It is possible that ultimately we should fit a column for U Geminorum variables, of expected absolute magnitudes between +6 and +9, between the columns for white dwarfs and subdwarfs, but too little is known at the present time about their frequency in space.

https://doi.org/10.1017/S007418090009700X Published online by Cambridge University Press

Spectroscopists [12] have usually claimed much larger percentages of white dwarfs among the brighter specimens of Faint Blue Stars, especially for the 13–16th magnitude. For a number of these I have subsequently determined proper motions, and generally found these to be so small as to indicate that if these objects are genuine white dwarfs of absolute magnitudes around +9 or fainter, they must all have very small tangential velocities which, at least near the galactic poles would be unexpected.

3. Colors and Spectra

The photometry of White Dwarfs, including the determination of accurate photo-electric colors will be adequately dealt with by Eggen, while the spectroscopic analysis will be covered by Greenstein and very little need be said here. Suffice it to point out that while the spectra of the first few white dwarfs found showed some similarity to those of main-sequence A stars it soon became apparent that the very high values of the surface gravity as well as possible Stark and magnetic effects would cause the spectroscopic features of most white dwarfs to be very different from those of ordinary stars.

It was for this reason that I proposed [13], in 1945, to use the letter D for the classification of white dwarf spectra, this to be followed by the usual, B, A, F, G, or K if the spectrum either somewhat resembled that of ordinary stars so classified or if the star had the same color as stars of those spectral classes. The further designation DC was reserved for stars showing featureless continuous spectra. To date, I believe that no degenerate object which would deserve the classification DM has been identified.

4. Parallaxes and Luminosities

At the present juncture parallaxes are perhaps the most urgently needed data for White Dwarfs. As of now trigonometric parallaxes have been published for fewer than twenty but this situation is on the point of being greatly improved now that the results from the U.S. Naval Observatory parallax program are becoming available. Further parallaxes may be derived for white dwarfs which are components of binaries in which the other component appears to be an ordinary main-sequence star and hence a reliable spectro-photometric parallax can be derived. Finally a number of white dwarfs have been identified as belonging – with high probability – to galactic clusters for which the distance is known: 20 in the Hyades, 4 in Praesepe, and 1 each in the Pleiades and M 67.

When the usual H-R diagram is made up for these stars it is seen that degenerate stars occupy a broad area to the lower left of the diagram, running roughly parallel to the main sequence from about $M_V = +8.5$ for very blue stars to at least $M_V = +17$ for degenerate stars with color indices of $+1.0$ or more.

For the more than three thousand possible white dwarfs found in the proper motion surveys it is not yet possible to make up such a diagram and all we can do is to plot the rough colors of the stars against the reduced proper motions H, where $H = m + 5 + 5$

https://doi.org/10.1017/S007418090009700X Published online by Cambridge University Press

$\log\mu$ or, also $H = M + 5 \log T$. Because of this, the full uncertainty in our knowledge concerning the kinematics of white dwarfs would come into play in such a diagram. As the guiding principle in selecting stars for the white dwarf catalogue I used the criterion that any star which, if classified as a main-sequence object, would have a tangential velocity of more than 500 km/sec, appeared likely to be degenerate. For the stars classified as having colors b, a, or f this leads to little trouble, and probably the vast majority of the 1600 stars so listed in the catalogue are genuine white dwarfs. On the other hand, the attrition, or perhaps I should say the casualties, among stars yellower than this can be expected to increase, and become quite large for those listed as of color k, on the one hand because these crude colors, determined from the Palomar Survey plates may often give a value of '*k*' for a star of actual spectral class M, and on the other hand because among these stars will be found many subdwarfs with exceedingly high velocities, and ultraviolet excesses. However I know of no other way at the present time, in which yellow degenerate stars can be identified.

Whether DM stars exist we do not yet know – the reddest definitely known degenerate star having a color index of +1.1 Among the more than 150 double stars with one white dwarf component I have found [14] that invariably the main-sequence component is bolometrically the more luminous. Among the rather few double stars where both components appear degenerate, the fainter component is invariably the yellower one. There remain five double stars where the brighter component appears to be definitely degenerate and the fainter one has the color m – I suggest that these hold out the best prospect of being M-type degenerates although, of course, it is always possible that they are extreme M-type subdwarfs with ultraviolet excess.

To forestall any possible criticism that – if a large majority of the g and k probable white dwarfs I have listed prove to be only very high velocity subdwarfs – I have led the spectroscopists astray and caused them much unnecessary work I should like to point out that for a number of years the spectroscopists have urgently asked for lists of candidates for yellow-degenerates. In the course of the Bruce and Palomar Proper Motion surveys I have probably looked at 100 million stars and from them have made up this list containing some 3000 white dwarfs, including 1484 possible g and k degenerates, representing a screening, or refining, of better than 60000 to 1. Even if only 5% of these yellow degenerate candidates were to prove genuine I would still say it has been well worth it – and the spectroscopists should not complain. And, at any rate, the by-product, i.e. the yellow subdwarfs with extraordinary high velocities are not exactly wasted either.

It now seems generally accepted that neutron stars, first postulated by Zwicky and Baade [15], exist – these are assumed to have densities of the order to 10^{14} and up. The typical white dwarf has a density of the order of, perhaps, 10^5. Whether stars intermediate to these, the 'pygmies' as also first postulated by Zwicky – with densities of perhaps 10^7 or 10^8, also exist is not yet known. The few apparently white or blue stars with exceedingly large proper motions which would be candidates for this are claimed by the spectroscopists to be somewhat yellower than first thought, and ordinary degenerates of very high space motion. The only two parallaxes available for such

https://doi.org/10.1017/S007418090009700X Published online by Cambridge University Press

stars – LP 9-231 and LP 768-500 – certainly agree better with the spectroscopists point of view than with the pygmy supposition.

On the other hand, if the spectroscopists were correct in their claim that there exist large numbers of Faint Blue Stars which are in reality ordinary white dwarfs but with very small tangential velocities, and further that all apparent pygmies are ordinary white dwarfs, with excessively high tangential velocites, and, finally, that most apparent yellow degenerates are really subdwarfs with similarly high velocities, then we shall be faced with a rather peculiar distribution of velocities. Not to mention the fact that many of these stars should not only be escaping from the galaxy, but, unless they are younger than 10^8 yr they should have escaped long ago. Again, the answer seems to be: what is needed is more parallaxes of very faint stars, especially of the 19th and 20th magnitude.

5. Masses and Redshifts

The first two white dwarfs discovered, Sirius B and o_2 Eridani B were both components of binaries, and their masses were known beforehand. Since that time, the companion to Procyon, also with a known mass, has been identified as a probable white dwarf. However, the companion to Sirius has often been suspected of being a close double, and its mass is rather larger than expected, while the companion to Procyon is so faint and so close to its primary that it is virtually impossible to obtain reliable values for its apparent magnitude, color, and spectrum. This leaves o_2 Eridani B as the only white dwarf for which the mass, luminosity, color, and spectrum, hence also the surface temperature are known with reasonable accuracy – surely not an auspicious base on which to erect a whole theory of white dwarfs.

I have repeatedly pointed out that accurate astrometric observations with large telescopes made on binaries containing white dwarf components could give us, in a reasonable time, at least an indication of orbital motions, from which, in turn, statistical estimates of the masses might be made, but until now no such observations appear to have been made. Using a large, and rather heterogeneous mixture of photographic plates, I attempted, in 1961 [17], to determine such preliminary orbital motions for some 17 binaries with white dwarf components, and by comparing these with similar orbital motions derived for a number of control binaries composed of apparently normal main-sequence stars and possessing very similar apparent magnitudes, separations, and proper motions, and to derive a statistical indication of the ratio of the masses of typical white dwarfs to those of main-sequence stars of the same luminosity. While the results are far from conclusive, they do indicate that the masses of 'classical' white dwarfs are of the order of 1.5 times the masses of similar main-sequence stars.

Now that nearly two hundred binaries containing white dwarf components are known – including more than a dozen pairs where both components appear to be degenerate – I urge again that those who have access to large telescopes begin immediately to take the first epoch plates necessary for the ultimate determination of orbital motions and of statistical masses. I believe that at least at present there is no other

https://doi.org/10.1017/S007418090009700X Published online by Cambridge University Press

way in which reliable values for the masses of degenerate stars can be determined.

Theory demands a close relationship between the mass, radius, and spectral red shift of a white dwarf but it now appears that this relation is not quite as simple as we used to believe. Moreover, real red shifts cannot be determined for single white dwarfs (except, again, statistically, and this would involve some assumptions as to the kinematics involved) while, in addition, many of the most interesting white dwarfs have almost featureless spectra in which red shifts cannot be reliably determined. Hence, in final analysis, we fall back again on astrometric observations and Kepler's laws for the reliable determination of masses for degenerate stars.

6. White Dwarfs in Clusters

Present theory suggests there should be more white dwarfs in old clusters such as M 67, the Hyades and Praesepe than in young clusters such as the Pleiades and h and χ Persei. To test this I have blinked pairs of blue and red Palomar Survey plates [18] for a number of galactic clusters nearer than 800 parsecs (in which accordingly, a classical o_2 Eridani B type of white dwarf would appear brighter than 20.7) but found no indication of such stars in M 36, M 38, M 39, NGC 129, and NGC 6885. Possibly a few may exist in IC 4665, M 34, and NGC 752 but repeated searches [19] have as yet shown no degenerate stars belonging to the Ursa Major Cluster (except possibly the companion to Sirius). M 67 is so distant that while several possible white dwarfs have been indicated, only one has been identified with reasonable certainty to be a member. Similarly only one probable white dwarf belonging to the Pleiades has been announced [20] while four have been identified with reasonable certainty in Praesepe [21]. Only in the Hyades do we know a substantial number of white dwarfs which are cluster members. The first two of these were found by Van Rhijn and Raimond [22], the next several by Humason and Zwicky [23] some more by myself [24] and by Van Altena [25], while I have [24] also indicated a few yellow degenerates as possible cluster members. All in all we may now have some twenty such stars in the Hyades.

7. Frequency in Space

From my proper motion surveys I have estimated [26] that white dwarfs constitute only a few percent – $2.3\% \pm 0.3\%$ of all stars in space while theoreticians have generally derived much higher values – up to 10%. The difference may be due largely to a matter of definition – my own values applying only to really blue or white degenerate stars whereas the theoretical estimates include yellow degenerates as well. Further, if indeed large numbers of Faint Blue Stars should prove to be genuine white dwarfs with very small tangential velocities my estimates will have to be raised considerably. On the other hand, if most of the proper motion stars now designated as possible white dwarfs should indeed turn out to be high-velocity subdwarfs then the theoretical estimate would have to be substantially reduced. When the Palomar-Schmidt proper motion survey has been completed and when several hundred parallaxes for white dwarfs

https://doi.org/10.1017/S007418090009700X Published online by Cambridge University Press

down to the seventeenth and eighteenth magnitude have been determined we shall be in a better position to arrive at a really reliable estimate.

Meanwhile the rough figure of 5% may represent an acceptable compromise.

References

[1] Humason, M. L. and Zwicky, F.: 1947, *Astrophys. J.* **105**, 85.
[2] Luyten, W. J.: 1933–1968, *A Search for Faint Blue Stars*, Nos. I–L.
[3] Haro, G. and Luyten, W. J.: 1962, *Bol. Obs. Tac. y Ton.*, No. 22.
[4] Luyten, W. J.: 1969, *A Search for Faint Blue Stars*, No. L.
[5] Chavira, E. and Iriarte, B.: 1957, *Bol. Obs. Tac. y Ton.*, No. 16; also No. 18, 1959.
[6] Feige, J.: 1958, *Astrophys. J.* **128**, 267.
[7] Cowley, C. R.: 1959, *Astron. J.* **63**, 484.
[8] Rubin, V.: 1967, *Astron. J.* **72**, 59.
[9] Sanduleak, H. and Philip, A. D.: 1958, *Bol. Obs. Tac. y Ton.* **4**, 253.
[10] Richter, N. and Richter, L.: 1965, *Mitt. Karl Schwarzschild Obs.*, No. 24.
[11] Sandage, A. R.: 1967, *Astrophys. J.* **148**, 767; also **155**, 913.
[12] Kinman, T. D.: 1965, *Astrophys. J.* **142**, 1241; also Greenstein, J. L.: 1966, *Astrophys. J.* **144**, 496.
[13] Luyten, W. J.: 1945, *Astrophys. J.* **101**, 131.
[14] Luyten, W. J.: 1969, *Proper Motion Survey with the 48 inch Schmidt Telescope*, No. XVIII.
[15] Baade, W. and Zwicky, F.: 1934, *Proc. Nat. Acad. Sci. U.S.* **20**, 254.
[16] Luyten, W. J.: 1956, *A Search for Faint Blue Stars*, No. VIII; also 1969, *Proper Motion Survey with the 48 inch Schmidt Telescope*, No. XVIII.
[17] Luyten, W. J.: 1961, *Publ. Astron. Observ. Univ. Minn.* **3**, No. 9.
[18] Luyten, W. J.: 1958–1963, *A Search for Faint Blue Stars*, Nos. X–XXXII.
[19] Luyten, W. J.: 1958, *A Search for Faint Blue Stars*, No. XIV.
[20] Luyten, W. J. and Herbig, G.: 1960, *Harv. Ann. Card*, No. 1474.
[21] Luyten, W. J.: 1962, *A Search for Faint Blue Stars*, No. XXXI.
[22] Van Rhijn, P. and Raimond, J. J.: 1934, *Monthly Notices Roy. Astron. Soc.* **94**, 508.
[23] Humason, M. L. and Zwicky, F.: 1947, *Astrophys. J.* **105**, 85; also *A Search for Faint Blue Stars*, No. I, 1952.
[24] Luyten, W. J.: 1969, *Proper Motion Survey with the 48 inch Schmidt Telescope*, No. XVII.
[25] Van Altena, W. F.: 1966, *Astron. J.* **71**, 482.
[26] Luyten, W. J.: 1958, foll. *A Search for Faint Blue Stars*, No. XVI.

https://doi.org/10.1017/S007418090009700X Published online by Cambridge University Press