THE CHARACTERISTICS OF SUBDWARF STARS

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Spectra. Early in the course of his work on the luminosity classification of stellar spectra, Adams (1915) announced the discovery of three faint A-type stars with abnormally weak lines of Mg II λ4481 and Fe II λ4233. Two of the three stars have large proper motions. Within a few years three similar stars were discovered, and as trigonometric measures of their parallaxes became available, Adams and his associates (1935) showed that the "intermediate white dwarfs" form a group with absolute magnitudes close to +5. Although bluer and hotter, they have no greater intrinsic luminosity than the sun, and fall about two magnitudes below and to the left of the main sequence for normal dwarfs on the H-R diagram. Five more A-type subdwarfs have been added to the list from Palomar spectrograms by Greenstein (1954).

At Yerkes Observatory, Kuiper (1938, 1939) made a spectral survey of stars having proper motions exceeding 0."30 per year. He found, from trigonometric parallaxes, that some stars of this group fall 2 to 3 magnitudes below the main sequence along almost its entire length. As stars of this class are more similar to those of the main sequence than to the much fainter white dwarfs, he suggested the name "subdwarfs", by which these stars are now known. After both Kuiper and Adams had described the distinguishing spectral characteristics in very similar terms, it was surprising that Morgan and his co-workers did not set them apart to form a Luminosity Class VI in the revised Yerkes system of classification, although in the original *Atlas of Stellar Spectra* they had shown the spectral peculiarities of certain high-velocity stars. However, as only a few subdwarfs are brighter than the eighth magnitude, not enough spectra could be photographed at the 40-inch refractor with dispersions of the range 75 to 125 A./mm.

When the 82-inch telescope in Texas was brought into use, spectra were taken of a considerable number of stars with large transverse motions and reliable trigonometric parallaxes. In this survey 200 stars were found to have the spectral features of subdwarfs. The majority of these were photographed by Kuiper (1940) with a dispersion of 340 A./mm., and later

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the work was continued by Popper (1942, 1943) and Münch (1944), using 76 A./mm. From spectra secured with the Perkins reflector, Keenan and Keller (1953) have discussed the classification of the brighter northern stars of high velocity. Although the term "subdwarf" is not mentioned, the points for the two stars H.D. 103095 and 140283 fall conspicuously below the main sequence in their spectrum-luminosity diagram. In her *Catalogue of High-Velocity Stars*, Miss Roman (1955) has designated the subdwarfs of spectral type later than G0, which she has classified at Yerkes and McDonald Observatories, as luminosity class VI. She has described in special detail a group of 17 stars of type F, which show extreme subdwarf special characteristics, abnormally negative *U-B* colours for a given *B-V* value, and highly eccentric orbits around the galactic centre (Roman, 1954). Those south of the equator are included in the finding list of *Southern Stars of High Velocity*, which has recently been compiled by Buscombe and Miss Morris (1958). Spectroscopic observations are being made at Mount Stromlo of fifty stars from this list which show some subdwarf characteristics. SX Phoenicis, the RR Lyrae-type variable with the shortest known period, has a spectrum resembling a subdwarf star, varying from type A2 to about A7 (Kuiper, 1940; Joy, 1947).

For convenience of reference, the spectroscopic features which distinguish subdwarfs from ordinary dwarfs are quoted from a detailed discussion by Joy (1947) and other sources. In subdwarfs of all spectral classes there is a general weakening of the absorption spectrum. Among stars of early type the Balmer lines of hydrogen are abnormally narrow and sharp, and Mg II λ 4481 as well as Fe II λ 4233, weak or barely visible. In F and G stars the *G* band of the CH molecule blended with atomic lines is rather weak, but in the later types the CN band at λ 4215 is strengthened, and emission lines are weaker. A short time ago Miss Tomasik (1956) reformulated the criteria of differences in line strengths by which the spectra of faint F, G and K stars of Populations I and II may be distinguished with low dispersion. Oke (1957) has recently pointed out that some ratios of measured intensities of spectral lines, which are most sensitive to luminosity differences, exhibit a regular sequence from giant stars across the main sequence to subdwarf stars of the same spectral subclass among types F and G. A detailed study from spectrograms with high dispersion has only appeared for stars of types A and F, but further studies of subdwarf spectra are in progress at Mount Wilson and Palomar. Chamberlain and Aller (1951) found the atmosphere of H.D. 19445 and 140283 deficient in calcium and iron relative to hydrogen, but regard their spectra as closer to type F. A similar departure from normal relative abundances was observed in three F dwarfs of high velocity by Schwarzschild and Schwarzschild (1950). Slettebak (1952) has published a very clear reproduction of a spectrogram of the A-type subdwarf H.D. 161817, while the spectrum of H.D. 19445 is shown in a review article by Mrs. Burbidge and others (1957). These authors quote an unpublished suggestion by Greenstein and Aller that this star has a temperature similar to the sun's, and may not be a subdwarf at all. This opinion is based on measures of line strengths on Palomar spectrograms. This interpretation would, however, contradict the assignment made by Adams and his associates (1935), as well as a great deal of the later work reviewed in this article. Babcock (1958) reports that H.D. 19445 has a magnetic field of moderate strength. In an earlier paper Burbidge and Burbidge (1956) have shown from curves of growth for several A and F stars, that their atmospheres are also relatively deficient in the heavier elements, but not to the same extent as H.D. 19445 and 140283. This evidence of a continuous variation of relative abundances between the atmospheres of stars representing the extremes of Populations I and II is strengthened by the results obtained by Schwarzschild and others (1957) from spectrophotometry of two groups of K giants with high and low velocities, and also by the cyanogen deficiency in G giants with high velocities, observed by Greenstein and Keenan (1958). Johnson and Morgan have found a significant scatter in the colour-differences of nearby F stars, which Strömgren (1957) now finds is due to a variable ratio of heavy elements to hydrogen, reaching a minimum in Population II subdwarfs.

Kinematics. From a discussion of the space motions of subdwarf stars, Lohmann (1948) concluded that the majority of subdwarfs have galactocentric orbits of high eccentricity, and pass close to the centre of the spherical galactic halo, but are distributed in a wide range of inclinations to the plane of the spiral arms. In a carefully documented review of the original observational data, he obtained mean absolute magnitudes for subdwarfs of the various spectral classes. The motions of the sun relative to the average of 79 well-observed subdwarfs was found by Fricke (1949, 1950) very similar on the average to that relative to the RR Lyrae variables and globular clusters, but also with a very large dispersion. Similar conclusions were reached independently by Parenago (1946, 1949, 1951) in the course of an extensive analysis of the motions of groups of stars with very different characteristics, which led him to describe the subdwarfs as members of the most nearly spherical of the various distributions with respect to the galactic plane of symmetry. Dziewulski (1951, 1953) concluded that about 39 per cent. of the subdwarfs have high velocities relative to the sun, but since he has applied small increments to the small positive and even negative trigonometrical measures in deriving the transverse velocity components, one can have little confidence in the result of any statistical discussion which includes stars more than 100 parsecs from the sun.

Photometry. In recent years, the most definite evidence that subdwarfs form a distinct class of stars has come from photoelectric photometry. In a study of the nearest moving cluster to the sun, Eggen (1950) drew attention to three stars of the Hyades which fall below and to the left of the main sequence in the colour-luminosity array. In other words, they are bluer than other stars of the same luminosity, or less luminous than main sequence stars with the same colour. On the other hand, Greenstein (1958) has stated that these stars seem to have essentially normal spectra, completely different from the high-velocity subdwarfs. While each of these three stars had been considered by both Wilson (1948) and van Bueren (1952), from measurements of proper motions and radial velocity, as a certain member of the Hyades cluster, H.D. 27685, the only one of them included in the region studied by Osvalds (1954), is described by him as a doubtful member, and later by Heckmann and Lübeck (1956) as an improbable member. On their colour-luminosity diagram, this star falls only slightly below the main sequence for the cluster, almost in the same position as star H.D. 26756, another of the stars considered as subdwarfs by Eggen. His third star, B.D. +19° 641, has not been measured in the Hamburg photometric study. On the other hand, all three of Eggen's "subdwarfs" fall on the main sequence plotted by Johnson and Knuckles (1955) on the basis of photoelectric photometry on the *U*, *B*, *V* system. However, these authors have found that 17 other outlying stars of which the majority are, according to van Bueren and Osvalds, certain members of the Hyades, fall below and to the left of the main sequence, and show the same sort of ultraviolet excess which has been measured for known subdwarfs. Two of the same stars, B.D. +13° 671 and +14° 685, and three others, among which are some doubtful members, are shown to diverge in the same way from the main sequence by the photographic photometry of Heckmann and Lübeck. The cause of the different assignments lies in the slightly different statistical analyses of the observed proper motions.

The photoelectric colour-luminosity curve given by Johnson (1952) for stars considered members of the open cluster Praesepe by Klein-Wassink (1927) and confirmed by Haffner and Heckmann (1937, 1940) on the basis of photographic photometry and improved measures for the proper motions, shows five stars below the main sequence which are probably faint subdwarfs. It would not be in accord with current ideas on cosmology to include high-velocity stars of Population II as members of a galactic open star-cluster. However, the assignment of a few faint subdwarfs, having motions parallel to the cluster, to membership may be consistent with the previous statement that more than half of the known subdwarfs have low velocities relative to the sun. For the Praesepe cluster and the Hyades, the assignment of many faint stars to membership will remain uncertain until radial-velocity measures become available. From his photoelectric colour-magnitude array for the Ursa Major Stream, using stream parallaxes, Miczaika (1954a, b) has delineated a subdwarf sequence of a dozen stars 1.2 magnitudes below the main sequence. These also appear to have normal dwarf spectra. He has expressed the opinion (1954a) that subdwarfs occur only in those clusters (Hyades, Praesepe, Ursa Major) which also contain giant stars, but not in the young clusters (Pleiades, N.G.C. 2362) containing B-type stars.

Among stars within 20 parsecs of the sun, for which very accurate trigonometric parallaxes are available, Eggen (1950, 1955, 1956) observed a sequence of subdwarfs with spectral types later than the sun's, below the main sequence of the colour-luminosity array from photoelectric measures through blue and yellow filters. On the basis of these observations, Parenago (1954) has suggested a list of normal colour indices for subdwarfs of various spectral types. Johnson and Morgan (1953) also discussed some of the same stars on the basis of photoelectric photometry on the *U*, *B*, *V* system. In the same article they concluded that the suspected subdwarfs in the region of Praesepe are really background stars of the main sequence, and not members of the cluster at all. Kron and others (1957) distinguished several M-type subdwarfs by similar departures from the red-infrared colour arrays for the nearest stars, of which about three per cent. are abnormally strong in the infrared for their *P-V* colours, including some with low as well as high velocities relative to the sun. The existence of a subdwarf sequence among stars near the sun has been confirmed by Yates (1954) and also by Nikonov and others (1957) from photoelectric observations. Miss Roman (1954) has suggested that the excess luminosity in shorter wave-lengths is due to the general weakness of the metallic lines in the spectrum, and consequently is a sensitive indicator of the lower abundance of metals relative to hydrogen. From preliminary measures by Schwarzschild and others (1955) of the blanketing effect in the violet part of the spectrum, this seems quite probable. Mrs. Burbidge is at present examining the question in more detail. Miss Roman (1956) has recently shown that the ultraviolet excess is especially frequent among subdwarfs with high velocities relative to the sun.

From photometric studies of the continuous spectrum, Mlle. Divan (1956) has shown that the weakness of the Balmer absorption continuum could account completely for the difference in colour gradient from normal dwarfs. On the other hand, because the metallic lines are weak, the higher members of the Balmer series are individually well resolved in the spectra. Mlle. Divan (1957) has further studied the spectra of the two brightest suspected subdwarfs from Johnson and Knuckles' (1955) colour-magnitude array in the Hyades, but concluded that, as their Balmer continua appear similar to normal F dwarfs, they also must be background stars beyond the cluster.

The scarcity of binary systems among the stars of high velocity has already been noted (Buscombe and Morris, 1958). Eggen (1950, 1955, 1956 a, b) has included among his photometric studies the subdwarf components of seven visual binary systems. In addition to these stars, Parenago and Mme. Massevich (1951) have discussed thirteen eclipsing systems, mainly very close pairs, from which they drew the general conclusion that subdwarfs are undermassive even for their low luminosity. (Unfortunately the reasoning behind the assignment of these latter stars to the subdwarf class is not published, and in fact some are again described as *subgiants* by Kopal and Mrs. Shapley (1956)). However, a similar conclusion was expressed rather more tentatively by Eggen (1956 a). Reddish (1955) has indicated very generally the sort of parameters for physical conditions from which models for appropriate masses might be computed. A model constructed by Reiz (1954) on the assumption of negligible heavy-element content, with energy production from the proton-proton reaction, led to a star with luminosity below the main sequence for the same effective temperature.

Current Studies. In the course of this article, the principal types of information used to discover subdwarfs have been reviewed in nearly chronological order of their use. First the spectral peculiarities were noted. The correlations with large proper motions, and later with large radial-velocity components, were used to search for more stars with similar spectra. Then the abnormal colours were measured by photoelectric techniques. Eventually the historical sequence was reversed in Humason and Zwicky's (1947) search for faint blue stars in the regions of the Hyades cluster and the north galactic pole. Greenstein (1956) has studied the spectra of these stars, some of which are white dwarfs, while he found that others represent a distinctly new type of hot subdwarfs of classes O and B, which show abnormally strong and very broad helium lines but weak hydrogen, since that element has been nearly exhausted even in the atmosphere through the evolution of energy production. Greenstein and Münch are now studying seven of these stars from Palomar coudé spectrograms. Among these Münch (1958) has analysed H-Z 44, in whose atmosphere helium is more abundant than hydrogen, and nitrogen much more than carbon. The Burbidge group (1957) has suggested that this may indicate a second stage of stability in the evolution of the stars, when the principal source of energy is from helium-burning in the central core. Greenstein is also attempting to classify about 80 subdwarfs in a consistent sequence from spectra of the highest dispersion available anywhere. Another detailed study is in progress at the David Dunlap Observatory, where Searle is examining the spectral peculiarities of high-velocity and subdwarf stars on plates of moderate dispersion.

Summary. This review has been undertaken in connection with planning for spectroscopic observation of southern stars of high velocity, to collect many fragments of information about subdwarf stars which have become scattered through the literature. From the observed spectra and motions of over 200 of these objects, we know reasonably well how they form a separate sequence on the Hertzsprung-Russell diagram, and that an unusually high proportion of them are at high galactic latitudes, moving with large Z-velocity components in galactocentric orbits of high eccentricity. A few accurate colour measurements show that subdwarfs are relatively stronger than normal dwarfs in the ultraviolet region of the spectrum. Their masses may be somewhat below the usual mass-luminosity relation.

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