THE NATURE OF THE FAINTER HARO-LUYTEN OBJECTS*

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ABSTRACT

A survey for faint RR Lyrae stars near the north galactic pole shows that the space density $\rho(z)$ per kpc^3 varies with height z (in kpc) above the galactic plane according to the relation

$$\log \rho(z) = 0.70 - 0.072z .$$

The inferred integral count of the blue horizontal-branch stars for $m_{pg} > 16$ is greater than the contribution of galactic stars to the Haro-Luyten objects of the same magnitude postulated by Sandage in 1965. For $15 < B < 17$, the number of RR Lyrae stars is about one-third of the number of blue Tonantzintla stars observed by Iriarte and Chavira in the same area of the sky. Low-dispersion spectra of an unbiased sample of twelve Tonantzintla stars ($15 < B < 16$) showed that all were galactic objects (seven white dwarfs, four horizontal-branch stars, and one hot subdwarf), whereas, according to Sandage, one-half should have been quasi-stellar galaxies.

If one-half of the Haro-Luyten blue objects with $15 < B < 16$ are white dwarfs which have a z distribution like the stars of the galactic disk, their integral count (together with that assumed for the horizontal-branch stars) is equal to 75 per cent of the integral count of the Haro-Luyten objects at $B = 16.5$ and shows a similar increase with magnitude. The majority of faint Haro-Luyten objects are therefore likely to be galactic stars and not quasi-stellar galaxies as Sandage suggests. It therefore is premature to infer the cosmological properties of the fainter Haro-Luyten objects from the slope of their integral count-curve.

A faint and quasi-stellar galaxy near the position of Haro-Luyten 293 has an emission spectrum and blue continuum similar to that observed in the Irr 1 galaxies NGC 1569 and NGC 2366 and in the blue galaxy Haro 6 These galaxies appear to have rather similar size and structure with bright compact regions which would appear stellar at distances greater than about 100 Mpc. Although they are less bright ($-14 < M_{pg} < -17.5$) than the quasi-stellar galaxies observed by Sandage (and their Balmer lines are narrower and their level of excitation is lower), it is tentatively suggested that they may represent a related class of objects.

About 3–4 per cent of the Tonantzintla blue objects appear to be non-stellar. The number of blue extragalactic objects which appear stellar is unknown, but it is unlikely to exceed 20 per cent of the fainter Haro-Luyten objects and may well be less. It is suggested that precise proper motions could be used to recognize the white dwarfs which are likely to constitute a large fraction of the fainter Haro-Luyten objects.

I. INTRODUCTION

Sandage (1965) has shown that a sample of the blue stars at high galactic latitudes shows a transition in their color distribution at $V = 14.5$, the colors of several of the fainter stars being similar to those found for the quasi-stellar radio sources. The rate of increase with magnitude of the integral count $N(m)$ of the blue objects found by Haro and Luyten (1962) shows an increase at about $m_{pg} = 15$ as shown in Figure 1. Sandage therefore suggested that most of the blue objects fainter than $m_{pg} = 16$ must be a new class of extragalactic objects (called quasi-stellar galaxies) and considered that the contribution of the galactic stars to the integral count of the blue objects must be small at faint magnitudes (*dashed line*, Fig. 1).

II. ESTIMATES OF THE SPACE DENSITIES OF GALACTIC STARS

A survey for RR Lyrae stars in 74 square degrees near the north galactic pole (see Kinman and Wirtanen 1963 for a preliminary report) shows that the space density of RR Lyrae stars ($\rho(z)$ per kpc^3) is related to the height z above the galactic plane (in kpc) by

$$\log \rho(z) = 0.70 - 0.072z . \quad (1)$$

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The corresponding whole-sky values of $N(m)$ derived from this expression are shown in Figure 1. These values of $N(m)$ refer to RR Lyrae stars with periods greater than 0.44 days and photographic amplitudes greater than 0.75 mag. The values of $N(m)$ for all classes of these stars will therefore be larger. The integral counts for the RR Lyrae stars are markedly different from those predicted for the blue halo stars by Sandage. Since the RR Lyrae counts refer to a region close to the north galactic pole and the blue star counts refer to a region between the south galactic pole and latitude −36°, a more direct comparison is desirable.

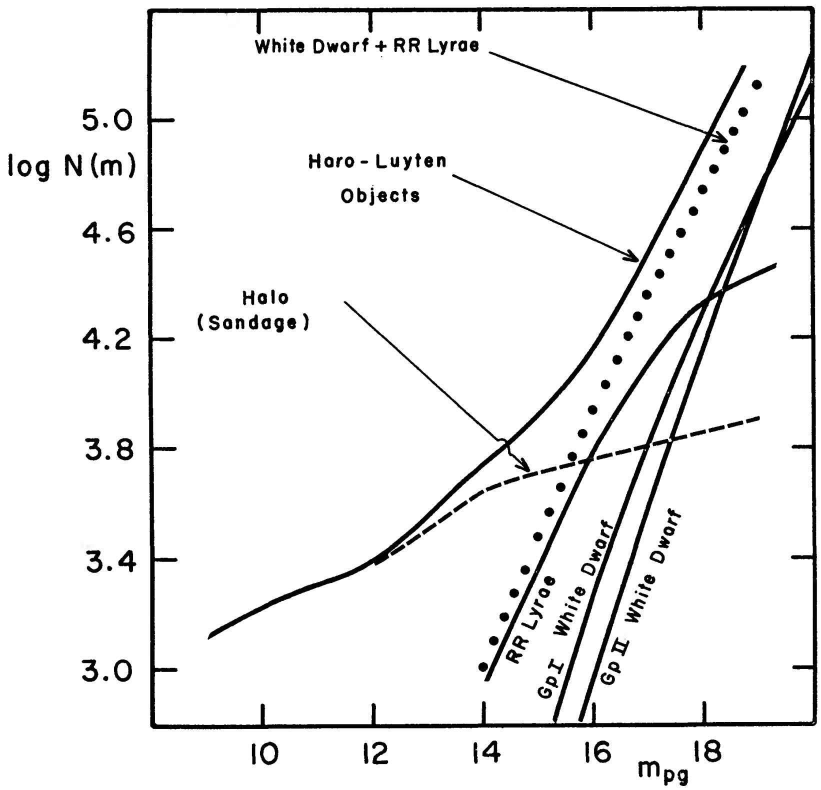

FIG. 1.—The whole sky integral count–apparent magnitude relation for the Haro-Luyten objects after Sandage (1965). The dashed line is the integral count for halo stars predicted by Sandage. The curves marked RR Lyrae, White dwarf Gp 1, and White dwarf Gp 2 are integral counts for these classes of objects derived as described in the text. The total integral count for the RR Lyrae stars and the White dwarfs is shown by a dotted line.

The observed magnitude distribution of the RR Lyrae stars is shown in Figure 2 together with that of the blue stars in the same region of the sky (Iriarte and Chavira 1957; Chavira 1959). The B magnitudes of the blue stars were redetermined from astrophotometer measures of astrograph plates using the same photoelectric sequences used for the RR Lyrae stars. The difference ($B - m_{pg}$) between these new magnitudes and the original Tonantzintla magnitudes are shown as a function of the Tonantzintla magnitude by the filled circles in Figure 3. The crosses are the differences between Iriarte's (1959) photoelectric B magnitudes and the Tonantzintla magnitudes and show a very similar effect indicating significant systematic errors in the Tonantzintla magnitudes. Figure 2 shows that for $15 < B < 17$ there are about a third as many RR Lyrae stars as blue stars in this area of the sky. Only four of the RR Lyrae stars were identified as being included as blue stars. It may be expected, however, that there should exist with

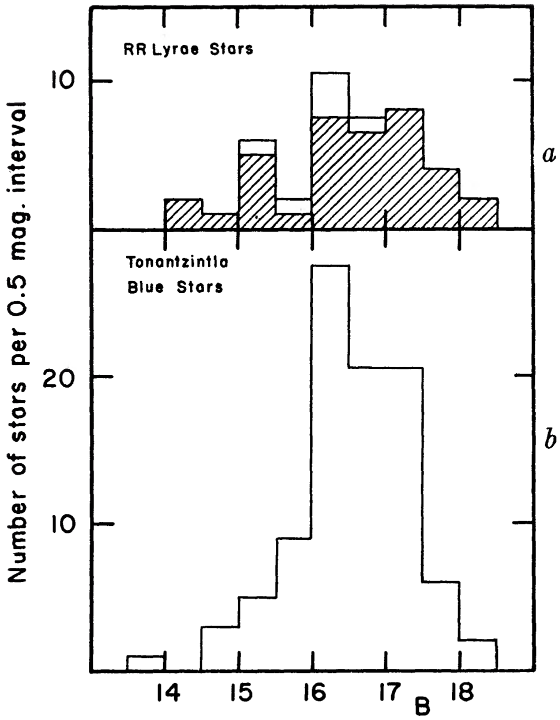

FIG 2.—(*a*) The distribution of RR Lyrae variables as a function of *B* magnitude in a 74-square-degree area of the sky near the north galactic pole *Hatched area:* variables with photographic amplitude > 0 75 mag.; *open area:* variables with lower amplitudes (*b*) The distribution with magnitude of the Tonantzintla blue stars in the same area of the sky.

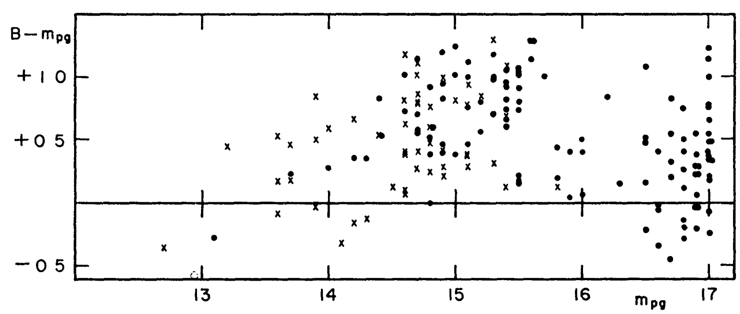

FIG 3 —The differences ($B - m_{pg}$) between Lick and Tonantzintla magnitudes for the blue stars in the RR Lyrae search area (*filled circles*) as a function of Tonantzintla magnitude The differences between Iriarte's (1959) photoelectric magnitudes and the Tonantzintla magnitudes for stars in the same list are shown by crosses.

the RR Lyrae stars a comparable number of blue horizontal-branch stars of about the same absolute magnitude. These blue horizontal-branch stars should therefore make a significant contribution to the blue star count in this magnitude range. This would be compatible with Greenstein's (1962) spectroscopic result that at $B = 15$ and $B - V < -0.1$, the blue stars were one-third white dwarfs, one-third hot subdwarfs, and one-third horizontal-branch stars.

It therefore appears that galactic stars should make up a significant fraction of the blue stars at magnitudes fainter than $B = 15$. To confirm this result, low-dispersion spectra (200 Å/mm) of nine stars in Iriarte and Chavira's (1957) list were obtained with the prime-focus spectrograph of the 120-inch reflector. To avoid observational selection all stars from No. 804 onward with Tonantzintla magnitudes in the range 14.5–15.5 were observed. In addition, Dr. E. M. Burbidge kindly made available spectra of three other stars from this list which were taken with the same dispersion. These spectra are described in Table 1. All stars showed Balmer lines of low Doppler displacement and no

TABLE 1

SPECTRAL CLASSIFICATION OF OBSERVED TONANTZINTLA STARS

Tonantzintla No	Spectral Classification	Tonantzintla Magnitude and Color	Corrected Magnitude*
229†	White dwarf (DC–DA)	15 2 very violet	15 9
237†	White dwarf (DC)	15 3 very violet	16 0
797†	White dwarf (DA)	15 2 very violet	15 9
804	White dwarf (DC–DA)	15 2 very violet	15 9
805	Horizontal-branch (A0)	15 4 violet	16 1
807	White dwarf (DC–DA)	15 1 very violet	15 8
809	Horizontal-branch (A0)	15 0 decidedly violet	15 7
811	Horizontal-branch (A0)	15 1 decidedly violet	15 8
812	Horizontal-branch (A3)	14 5 decidedly violet	15 0
813	White dwarf (DA)	15 5 violet	16 2
816	White dwarf (DA)	14 8 very violet	15 2
817	sdB (like Feige 95)	15 0 decidedly violet	15 7

* Using corrections to Tonantzintla magnitudes given by Fig 3
† Spectra taken by Dr E. M Burbidge.

emission lines were observed. In the case of Ton 237 (classified DC), the Balmer lines were visible although very broad and faint. Since prints of white-dwarf spectra (Greenstein 1961) were used as standards for this classification, the white-dwarf spectral types are necessarily rough but adequate for the present purpose.

The present small but, as far as was possible, unbiased, sample of blue star spectra indicates therefore that in the corrected magnitude range $15.0 < B < 16.2$, the blue objects are all galactic stars, whereas Sandage (his Fig. 5) predicted that about one-half should be extragalactic objects.

Eggen and Greenstein (1965) divided the white dwarfs into two groups. Group 1 consists mainly of sharp-lined DA stars while the stars of group 2 show mainly non-DA spectra. Our sample of blue stars indicates that at $15 < B < 16$, each of these groups accounts for about a quarter of the blue stars. We take $M_B = +11.3$ and $+12.8$ for the absolute magnitudes of the two groups, respectively, and assume that the variation of the space density with height z above the galactic plane is given by

$$\rho(z) = \rho(0)\, e^{-z/\beta} . \quad (2)$$

Allen (1963) gives $\beta = 280$ pc for the white dwarfs. The total number of blue stars observed by Haro and Luyten ($15 < m_{pg} < 15.9$) was 280, so that the expected number of white dwarfs of each group with this magnitude is 1442 for the whole sky. The integral counts $N(m)$ for each group were computed from this information and are shown in Figure 1. Not only is the slope of the log $N(m)$ versus m_{pg} relation for the white dwarfs similar to that of the blue stars for $m_{pg} > 16$, but the total number of white dwarfs accounts for about two-thirds of the total number of blue stars in the Haro-Luyten Survey. The number density of white dwarfs in the solar neighborhood is predicted to be 0.96×10^{-3} pc^{-3} and 3.80×10^{-3} pc^{-3} for group 1 and group 2, respectively, which is in good agreement with the value of 4.5×10^{-3} for white dwarfs of spectral classes B, A, and F given by Allen (1963). While the above calculations are extremely rough, they do suggest that galactic stars may account in large part for the form of integral count curve of the Haro-Luyten objects.

The color distribution of the stars with $V > 14.5$ is less easy to understand because of the significant number of stars found by Sandage for which the $U - B$ color is more negative than for the black-body relation. Old novae and the U Gem and SS Cyg stars have such colors, as Sandage notes, but it is difficult to estimate their frequency in the absence of suitable surveys. The general consistency in the relation between the Tonantzintla magnitudes and the re-determined magnitudes makes it unlikely, however, that a large percentage of the blue stars could be eruptive variables of large amplitude.

III. EXTRAGALACTIC HARO-LUYTEN OBJECTS

The above results suggest that Sandage has overestimated the frequency of quasi-stellar galaxies, but they do not affect the important discovery of their existence. In an attempt to rediscover some of the Haro-Luyten objects (for which only rough coordinates are given), the blue-ultraviolet double-exposure method of Ryle and Sandage (1964) was used at the prime focus of the 120-inch reflector. Near the position of HL 293 ($m_{pg} = 16.7$), two blue objects were found (*A* and *B* in Fig. 4). The fainter (*B*) image is definitely non-stellar and is rather similar to that of Ton 730 with a faint jet projecting out about 5″ (northward) from the central image. This non-stellar object is fainter relative to the nearby stars on plates taken with the 120-inch reflector (f/8.3) and with the 20-inch Astrograph (f/7) than on the Palomar Sky Survey plates as might be expected for an extended object. A very rough estimate of the *B* magnitude is 17.7 on the Sky Survey plates and about a half-magnitude fainter on the 120-inch plates. No obvious change in appearance or magnitude is apparent between the images of this object on the 1965 and 1949 plates taken with the Astrograph. The fuzzy core, which is seen visually and with short-exposure plates at the prime focus of the 120-inch reflector, has a diameter of 1″ to 2″.

Two spectra in the blue were obtained of this object with the prime-focus spectrograph of the 120-inch reflector (200 Å/mm, 100 and 165 min on Kodak baked IIa-O emulsion). These showed a faint blue continuum and the emission lines of [O III] $\lambda\lambda$ 5007, 4959, and 4363; [O II] λ 3727; [Ne III] λ 3869; the Balmer lines Hβ, Hγ, Hδ, Hϵ, and Hζ. It is possible that the [S II] line at λ 4068 is also present. The Hα line only was found on a single red spectrum (360 Å/mm, 150 min on Kodak 103a-F emulsion). The absence of [Ne V] shows that the object is of lower excitation than either Ton 256 or Ton 730 observed by Sandage. Also the Balmer lines are much narrower, and their Doppler width cannot exceed 100–200 km/sec; the blue continuum may also be less prominent relative to the emission spectrum, but this is difficult to judge from spectra taken with different spectrographs. The redshift ($c[d\lambda/\lambda]$) for HL 293B is 1550 km/sec which makes it unlikely to be a galactic object. Corrected for galactic rotation, the redshift is 1700 km/sec. The distance is therefore 22.6 Mpc ($H = 75$ km/sec 10^6 pc) and $M_B \sim -14$ or about 7–8 mag. fainter than Ton 256 and 730. The diameter of the central condensation is thus only 100–200 pc and the faint jet is perhaps 500 pc long. There is no radio source listed close to the position of HL 293B in the *General Catalogue* of Howard and Maran (1965).

The spectrum of HL 203B is not like that of a typical Irr 1 (Magellanic Cloud–type irregular galaxy) such as NGC 4449 that has a relatively low excitation emission spectrum, but corresponds more closely to the spectra of the irregular galaxies NGC 1569 and NGC 2366. Mayall (1935) showed that these galaxies have a moderately high excitation spectrum (with [Ne III]) and a lineless blue continuum which is particularly strong in NGC 1569. Both of these galaxies have an apparent integrated m_{pg} of about 12 and integrated $B - V$ colors corrected for interstellar extinction of 0.4–0.5 (G. and A. de Vaucouleurs 1964). Their redshifts are small—119 km/sec for NGC 1569 and 229 km/sec for NGC 2366 (Humason, Mayall, and Sandage 1956). Both galaxies have a bar structure (which is brighter in the case of NGC 1569) that has a concentrated bright region at one end. It is of interest to note that Baade (1963) classified NGC 2366 as an Sc rather than an Irr 1 galaxy presumably because of the faint extensions to its bar structure.

According to Holmberg (1950), NGC 2366 is a member of the M81 group (modulus $M - m = 27.1$; Sandage 1954) and has been resolved into H II regions and stars brighter than $M_{pg} = -4.1$ (Sandage 1961). Its absolute magnitude (M_{pg}) is therefore about -15 and its bar is about 3 kpc long. The concentrated part of this galaxy must, however, be only a few hundred parsecs in diameter. It is therefore somewhat larger and brighter than HL 293B.

A number of blue galaxies that are bright in the ultraviolet and which have emission spectra have been found by Haro (1956). Their positions on the two-color diagram are not dissimilar to those of the quasi-stellar galaxies and radio sources (Hiltner and Iriarte 1958). They also appear to have bluer colors than the Seyfert galaxies according to Haro. Münch (1958) examined a number of them spectroscopically and concluded that they showed a wide range in structure and luminosity and that some were quite compact. One of the most compact of these galaxies (Haro 6) has a spectrum which is similar to HL 293B (see Fig. 5) as was judged from Haro's observations and a spectrum taken by Mayall with the Crossley nebular spectrograph. The redshift of Haro 6 is 1927 km/sec (Mayall and de Vaucouleurs 1962), and on the Palomar Sky Survey (blue) it has an elongated image of length 15″ and apparent magnitude $m_{pg} \sim 14.5$ at a rough estimate. The distance of Haro 6 is therefore ~26 Mpc, and its diameter ~2 kpc and its integrated magnitude $(M_{pg}) \sim -17.5$. Haro 6 is therefore similar in size but somewhat brighter than both HL 293B and NGC 2366. In these latter objects, the Hβ line does not show appreciable widening, but in Haro 6 this line appears to have a width of perhaps 750 km/sec although this is difficult to judge on the low-dispersion Crossley spectrum.

Two of the blue objects (Ton 151 and Ton 698) in the RR Lyrae survey region have elongated non-stellar images that are similar in appearance to that of Haro 6. In another sample of Tonantzintla blue objects, three more non-stellar objects were found. Such non-stellar objects could therefore be relatively common and comprise perhaps 3 or 4 per cent of the Tonantzintla objects. Since, as we have seen, some of these objects have bright concentrated regions with diameters of only a few hundred parsecs, they may be expected to appear stellar or nearly so at distances greater than 100 Mpc. It will be necessary, however, to observe a larger sample of these objects before we can derive a luminosity function and local space density for them and from this deduce their expected frequency at faint magnitudes.

The quasi-stellar galaxies observed by Sandage (BSO 1, Ton 730, and Ton 256) are much brighter ($M_{pg} \sim -21$ or brighter) than the irregular galaxies discussed above. Sandage's galaxies also show higher excitation emission lines (e.g., [Ne V]) and have Balmer lines which are much broader (Doppler width ~2000 km/sec). It is suggested as a hypothesis, however, that the same physical process could be responsible for both classes of objects. In this case the range in the absolute magnitude and other parameters might correspond either to a range in the scale and intensity of the phenomenon in galaxies of different size or might represent different aspects of the phenomenon at different stages of evolution. In the latter case we might picture the objects as consisting of a luminous compact core in which there is considerable mass motion, and in which the

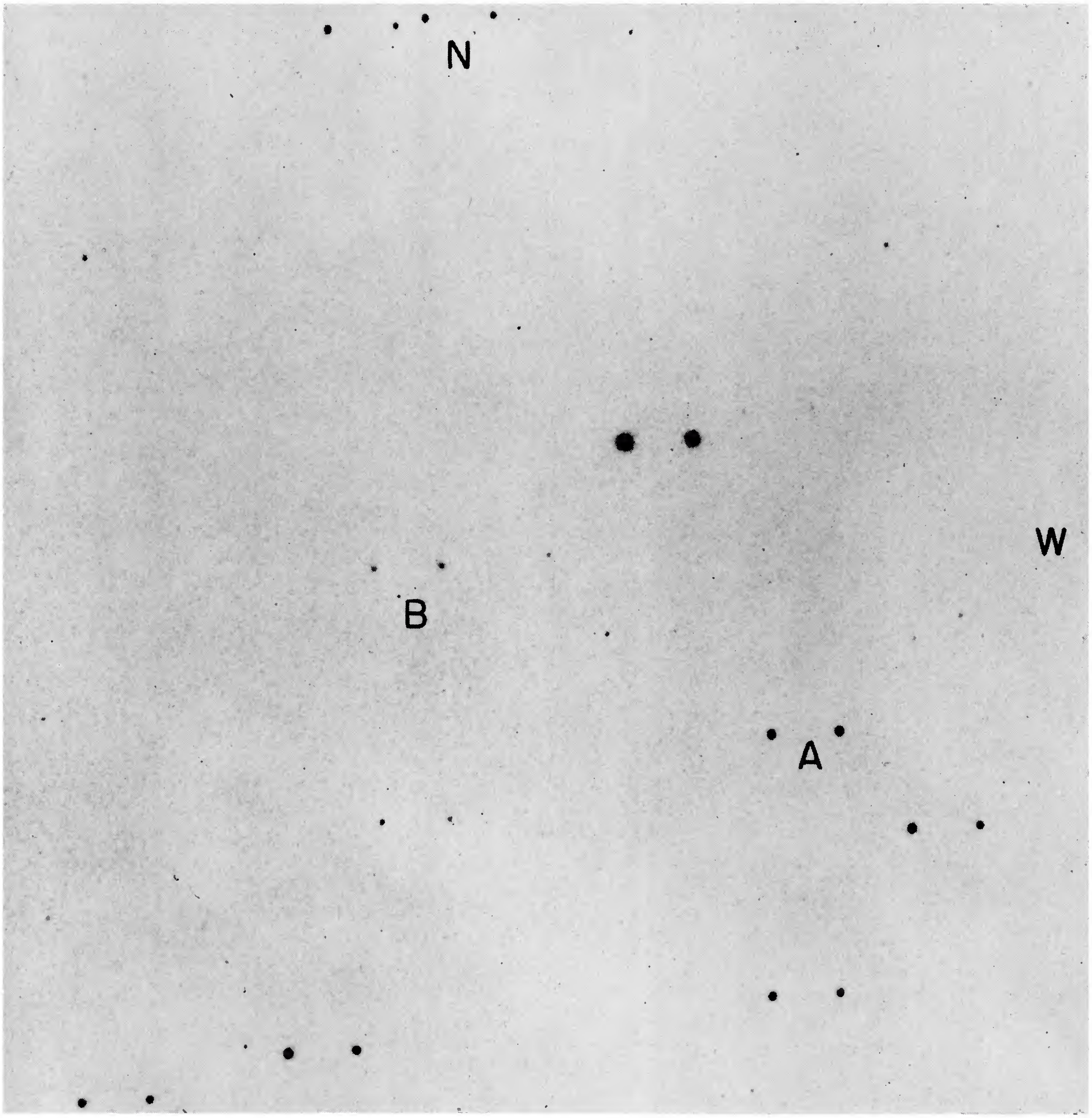

FIG. 4.—The two blue objects found near the position of Haro-Luyten object No. 293. The ultraviolet image is 20″ west of the blue image. Object *B* is non-stellar on the original plate and has a faint jet extending northward 5″ from the object. Blue exposure 10 min (Schott GG13 filter), ultraviolet exposure 20 min (Corning 9863 filter) on Kodak 103a-O emulsion. Taken with the 120-inch reflector diaphragmed to 72-inch aperture.

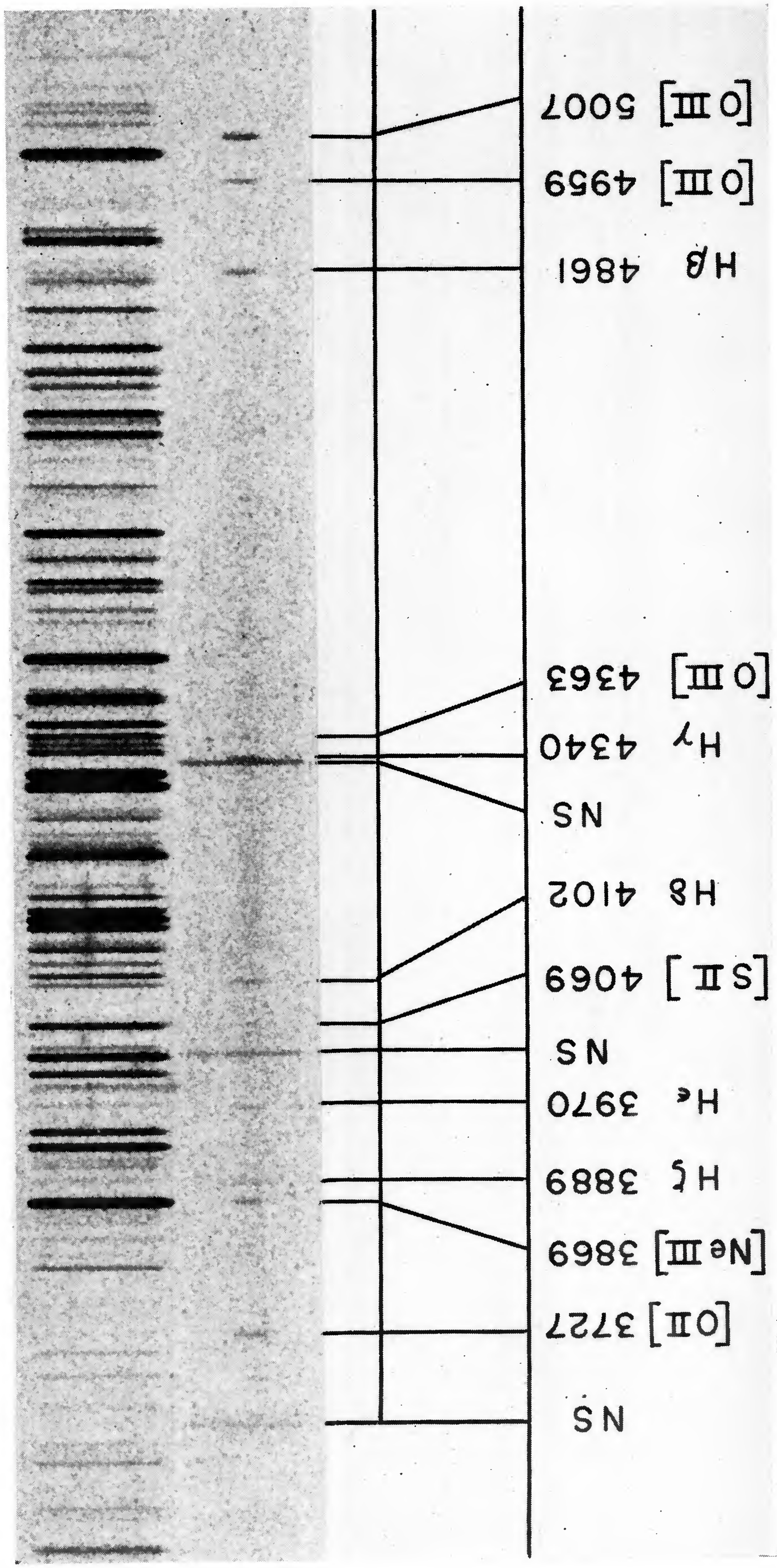

FIG. 5.—Spectrum of HL 293B showing forbidden lines of [O III], [O II], and [Ne III] and the Balmer lines Hβ–Hζ. The presence of [S II] is uncertain

Balmer lines are produced, surrounded by a tenuous outer region in which the forbidden lines arise. The fainter galaxies might then represent a later stage in the evolution in which the luminosity and mass motion in the core had decayed. The number of objects of this type known at present is, however, so small that this relationship suggested by the absolute magnitude, excitation, and line width could well be fortuitous. A survey for more objects of this general class and a more precise study of them is therefore highly desirable.

The number of blue extragalactic objects with stellar images is not known, but it seems unlikely from our estimates of the numbers of galactic stars that they can comprise more than about 20 per cent of the Haro-Luyten objects with $B > 16$ and their number may well be less. One way in which the nearby blue galactic stars could be eliminated from the fainter Haro-Luyten objects is by the determination of precise proper motions. These fainter Haro-Luyten objects, as we have seen, are likely to contain a high proportion of white dwarfs which (for $B \leq 20$) will mostly lie within 500 pc of the Sun. At this distance a tangential velocity of 24 km/sec corresponds to an annual proper motion of $0''.01$. The estimated probable error in the annual proper motion of a single star derived from plates taken 20 years apart with the Lick Carnegie Astrograph (against a reference frame of 50 galaxies) is estimated to be $0''.005$ (Vasilevskis 1957). It should therefore be possible to identify a large fraction of the white dwarfs in the blue-object population by means of their proper motions.

IV. CONCLUSIONS

The observed space densities of the RR Lyrae stars and the spectral classification of a sample of the Tonantzintla stars suggest that a large fraction of the fainter Haro-Luyten blue objects are galactic stars of the disk and halo and not quasi-stellar galaxies as Sandage has suggested. It is therefore premature to infer the cosmological properties of the fainter Haro-Luyten objects from the slope of their integral count versus apparent magnitude relation.

The irregular galaxies NGC 1569 and NGC 2366 have similar spectra and dimensions to those found for a Haro-Luyten object (293B) and the blue galaxy Haro 6. These objects have bright concentrated regions which would appear stellar or nearly so at great distances. It is possible that these objects are related to the brighter and more highly excited objects found by Sandage.

About 3–4 per cent of the Tonantzintla blue objects appear to be non-stellar. The number of extragalactic objects which would appear stellar is unknown but is unlikely to exceed 20 per cent of the Haro-Luyten objects fainter than $B = 16$ and may be less. It is suggested that white dwarfs could be distinguished from other faint blue objects by their proper motions.

It is planned to publish a more detailed account of the RR Lyrae survey at the north galactic pole. Acknowledgment is made to the National Science Foundation for a grant (NSF GP-907) in support of this work.

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