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# A HIGH-LATITUDE Be STAR

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RESUMEN

G. Haro descubrió que una estrella débil $V = 13.11, B\text{–}V = -0.15$) y de alta latitud galáctica presenta emisión en H$\alpha$, tiene tipo espectral B0-B1 y tiene la apariencia de una estrella Be de población I. Si lo anterior fuera cierto sería difícil explicar su posición a $z =$ 19.7 kpc considerando que se formó cerca del plano galáctico hace solo 1-2 $\times$ $10^7$ años. Las alas en absorción, fuera de los centros en emisión, de las líneas de Balmer, permiten una estimación de log $g$ y su comparación con otras estrellas tipo B de diversas luminosidades; el resultado para log $g$ es aproximadamente 4.7, lo que indica que la estrella no es un objeto de la secuencia principal. Si la estrella fuera un objeto de Población II con masa 0.6 $M_\odot$, entonces $M_V$ sería aproximadamente +2 y la distancia al plano sería solamente 1.6 kpc. Posiblemente la estrella de Haro se encuentra en transición entre la fase de rama asintótica gigante y la de estrella central de una nebulosa planetaria. Se recomienda una búsqueda de objetos similares en cúmulos globulares.

ABSTRACT

A faint ($V = 13.11, B\text{–}V = -0.15$) high-latitude ($b = +64°$) star discovered by G. Haro to have H$\alpha$ in emission is of type B0-B1, and has the appearance of a typical Population I Be star. If that were so, there would be difficulty in accounting for the star's presence at $z$ = 19.7 kpc if it were formed near the plane no more than 1–2 $\times$ $10^7$ years ago. The Balmer absorption wings, outside the emission cores, make possible an estimate of log $g$ by comparison with other early B-type stars of various luminosities; the result is that log $g$ is about 4.7, which shows that Haro's star lies below the main-sequence. If it is a Population II star with mass about 0.6 $M_\odot$, then $M_V$ is about +2, and the distance is only 1.6 kpc. Possibly Haro's star is in transition between the AGB and planetary nebula central star stages. A search of globular clusters for similar objects is recommended.

*Key words:* **STAR-Be – STARS-POST AGB**

## I. INTRODUCTION

In 1961, at the invitation of Dr. Guillermo Haro, pent several weeks at Tonantzintla and in México :y, working with him on problems of mutual erest. Two of the projects that we essayed with : Tonantzintla Schmidt were an attempt to detect nt emission-H$\alpha$ stars in the Pleiades, and a search · such stars at high galactic latitudes. The latter presented an effort to satisfy ourselves that T uri stars were indeed an exclusive phenomenon dense, low-latitude interstellar clouds. Neither of :se programs led to positive detections, partly on :ount of poor weather[1]

Although this limited effort itself turned up no high-latitude candidates, during my visit Dr. Haro called to my attention a 14th-magnitude star at $b$ = +64° that he had discovered some time earlier to have H$\alpha$ in emission. At that time neither of us pursued this interesting discovery of Haro's, but in subsequent observing seasons at Lick Observatory I was able to establish that the object is a Be star, and to accumulate some additional information. For various reasons, this work was never carried to completion. To the best of my knowledge,

1. Dr. Haro also made available to me the Tonantzintla te archives, and from these I was able to draw up a of emission-H$\alpha$ stars in the galactic bulge which had :n marked on the original negatives by Haro, Iriarte, and Chavira. I later observed a number of these stars spectroscopically (Herbig 1969). I also noted on the Tonantzintla objective-prism plates a number of stars near the Orion Nebula that had been found by Haro and his collaborators, but never published. Some of these were later listed by Herbig & Rao (1972) with the prefix "Haro 7- ".

Haro never mentioned this star in print. It was rediscovered as an ultraviolet-bright halo star in the course of the Palomar-Green survey (Green, Schmidt, & Liebert 1986), but the emission lines were not noted and it was simply listed as a 'sd 'of B = 12.5 ± 0.3. Considerable attention is currently being paid to high-latitude OB stars and their origins, and Haro's star is of interest in that context. The following note describes the material now on hand, and how I have attempted to interpret it.

## II. OBSERVATIONS

The original Lick photographic slit spectrograms, obtained with the Crossley (36-inch) and 120-inch reflectors at dispersions of 350 and 100 A $mm^{-1}$ in the blue-violet region, showed that the spectral type of Haro's star[2] is B0 or B1, with narrow emission cores in the Balmer lines through at least H8, and emission lines of Fe II. Five higher dispersion (33 A $mm^{-1}$) image intensifier spectrograms were obtained at the coudé focus of the 120-inch telescope in the years 1973-76. On these plates, H$\alpha$ emission obliterates the underlying Balmer absorption line, but a stellar absorption spectrum can be seen at He I $\lambda\lambda$5875, 6678 and C II $\lambda\lambda$ 6578, 6582. The bright Fe II lines are double, with a peak-to-peak splitting that ranges between 120 and 160 km $s^{-1}$ for different lines. It does not appear that this duplicity is produced by orbital motion of a double-line binary because it did not change from plate to plate. Furthermore, the radial velocity from the two He I absorption lines, which are single, does not vary; the mean (heliocentric) radial velocity is $v_{abs} = -64 \pm 2$ km $s^{-1}$ (or $-50 \pm 2$ km $s^{-1}$ with respect to the LSR). Emission H$\alpha$ and the bright Fe II lines, the latter measured as single lines by ignoring the central minima, gave essentially the same result: $v_{em} = -66 \pm 3$ km $s^{-1}$.

The *UBV* colors of Haro's star were measured for me by Dr. J. Smak on 6 nights in April-June 1962. There was no suggestion of variability during that short time period. The mean values were: $V = 13.11 \pm 0.03$, $B–V = -0.15 \pm 0.03$, $U–B = -1.05 \pm 0.01$. The resulting value of $Q = -0.94$ corresponds to a type of early O (Gutiérrez-Moreno 1975), clearly in conflict with the spectral classification. The explanation could lie in errors of observation, but it is more likely to be caused by the peculiar *UBV* colors of Be stars. The extensive data of Feinstein & Marraco (1979), slightly extrapolated, show that the observed colors of Haro's star are not abnormal for a very early Be star. Any correction for reddening must be small; from the correlation of galaxy counts and H I column densities with reddening in this direction (Burstein & Heiles 1982), it appears that $E(B–V) < 0.03$ mag.

If this object were located near the galactic plane one would not hesitate to dismiss it as an ordinary Population I Be star, but the unusual location suggests that this may not be so. However, it is not a nearby, very low luminosity object: the Lick spectrograms of the blue-violet region, although not calibrated photometrically, are adequate to rule out the possibility that the star is a white dwarf.

This is supported by the fact that the cross motion is small. Dr. A. Klemola very kindly measured the proper motion of Haro's star with reference to faint galaxies in the neighborhood on plates obtained with the Lick Astrograph which spanned a 19-year interval. The result was that $\mu_\alpha = -0.014'' \text{ yr}^{-1}$, $\mu_\delta = +0.004'' \text{ yr}^{-1}$, with mean errors of about 0.010″ in both coordinates. I.e. there is no certainly detectable proper motion at the $0.01'' \text{ yr}^{-1}$ level.

Several Be stars are known at high galactic latitudes: HD 127617 at $z = 0.9$ kpc (Turner & Lyons 1980), HD 118246 at $z = 1.1$ kpc (Turner, Lyons, & Bolton 1978), JL 212 at $z = 3.2$ kpc (Keenan, Brown, & Lennon 1986), and two additional stars discussed by Kilkenny (1989) at $z = -2.7$ and $-6.7$ kpc. However, if Haro's star is really a main sequence B0 or B1, having $M_V = -3.6$ (Schmidt-Kaler 1982), then without allowance for reddening its distance is about 21 kpc and $z = 19.7$ kpc. As has been noted for other high luminosity stars at high $z$ values, this leads to the following problem with the time scale if Haro's star was formed near the galactic plane.

Assume that the star is stationary with respect to its local standard of rest at $(r, z)$, where $r$ is the projection on the galactic plane of the radial coordinate of the star with respect to the galactic center. The gravitational potential at that point can be obtained from a galactic model, from which the components of force in $r$ and $z$ are obtained by partial differentiation. For this calculation the model of Rohlfs & Kreitschmann (1981) was used but extrapolated from $z = 10$ to $z = 20$, and included their assumptions that $R_0 = 8.5$ kpc and that $V_{circ}(R_0) = 225$ km $s^{-1}$. Starting then from the assumption that $\dot{r}$ and $\dot{z} = 0$, the equations of motion in $r$ and $z$ can be numerically integrated backwards in time to determine both the time required for such a star to reach $(r, z)$ and the velocity at which it was launched. The result, that the time of flight was $2.3 \times 10^8$ years and the initial velocity $\dot{z}(z = 0)$ was 280 km $s^{-1}$, cannot be taken too literally because of the assumptions made in the calculation. They do show, however, that the flight time is quite incompatible with the main sequence

2. $\alpha(1950) = 14^h 44^m 53.6^s$, $\delta(1950) = +23° 34' 08''$; $l = 31.2°$, $b = +63.6°$.

lifetime of a B0 – B1 V star of mass 12 $M_\odot$ (Hilditch & Bell 1987), which is about 1–2 × $10^7$ years. This is a familiar problem encountered in studies of such high-latitude objects. A common hypothesis is that such stars were either ejected at high velocity from some energetic event in the galactic disk, or that they were really formed at high $z$.

A more conventional explanation would be that Haro's star is not a massive Population I main-sequence object at all, but a hot evolved low-mass star at a moderate distance. Yet I am not aware of any early-type Population II star that has such a strong emission spectrum. It is certainly not a halo symbiotic star like MWC 603 (Tifft & Greenstein 1958) since no high-excitation or forbidden lines are present, not is there any evidence of a late-type companion in the red. It is true that the bright lines are rather narrow, but the lack of variability and the absence of strong He I, He II, and Ca II emissions indicate that Haro's star is not a cataclysmic binary system seen approximately pole-on.

Clearly, this issue of the luminosity of Haro's star is crucial. Consequently, new spectrograms were obtained in 1992 with the Faint Object Spectrograph on the University of Hawaii 88-inch telescope on Mauna Kea. This instrument, with 135-mm camera and 1200-groove $mm^{-1}$ grating, produces a dispersion of 61 A $mm^{-1}$ in the 1st order blue. The resolution with a Tektronix $1024^2$ CCD is about 3 A. Haro's star was observed along with several objects of similar temperature but widely varying luminosities and surface gravities, ranging from the normal B0.5 V star 40 Per, the 'ultraviolet bright 'star vZ 1128 in M3, and two hot sub-luminous halo stars: Feige 65, which has been classified both as a B subdwarf and as a field horizontal-branch star, and Feige 38, generally regarded as a B subdwarf. The properties of these reference objects are summarized in Table 1.

The 1992 spectrograms, although covering a smaller wavelength interval than the Lick observations, show that the emission spectrum of Haro's star has not changed significantly over the intervening 16 years, and thus it did not represent some temporary activity in the 1970's. The centers of the Balmer lines are still filled in by emission. In the case of H$\beta$ the total width of the emission core is about 15 A; peak emission flux is about 1.4 times the continuum level, and the equivalent width (measured above the point where the emission core emerges from the absorption wings) is 9.5 A.

Only the wings of the underlying absorptions are

TABLE 1

DATA FOR HARO'S STAR AND REFERENCE STARS

| Star | Spectrum | $M_V$ | $T_e/10^3$ | log $g$ | Note | $W_{0.9}$ H$\beta$ | H$\gamma$ | H$\delta$ |
|---|---|---|---|---|---|---|---|---|
| 40 Per | B0.5 V | −3.0 | 28.2 | 4.1 | 1 | 12. | 16. | 13. |
| | | −3.6 | | | | | | |
| vZ 1128 | O8p | 0.0 | 30. | 4.0 | 2 | 12. | 12. | 16.: |
| | | +0.1 | 30 ± 2 | 4.0 | | | | |
| Feige 65 | sdB | ... | 26.2 | 5.3 ± 0.3 | 3 | 26. | 28. | 23. |
| | hbB | +2.1 | 26.5 | 4.8 | | | | |
| Feige 38 | sdB | +3.6 | 26.5 | 5.4 | 4 | 25 | 24 | 21: |
| | sdB | ... | 30.2 | ... | | | | |
| Haro | B0–1e | +2 | 28.2 | 4.7 | 5 | 19. | 18.: | 19.: |

Notes: 1) 40 Per: the $M_V$, $T_e$, log $g$ on the first line are from a compilation of data for well-determined eclipsing binaries by Andersen (1992); the $M_V$ in the second line is that of a normal B0.5 V star by Schmidt-Kaler (1982). 2) vZ 1128: data on the first line are from Buzzoni *et al.* (1992), except the spectral type, by Garrison & Albert (1986). The data on the second line are from de Boer (1985). In both cases, $M_V$ was obtained from photometry of M3. 3) Feige 65: the data on the first line are from Lamontagne *et al.* (1985); those on the second line are from Greenstein & Sargent (1974), the $M_V$ following from the assumption that the mass is 0.66 $M_\odot$. 4) Feige 38: data on the first line are from Greenstein & Sargent (1974), with the mass assumed to be 0.66 $M_\odot$; data on the second line are from Bergeron *et al.* (1984). 5) Haro's star: the $T_e$ is inferred from the spectral type, log $g$ from the H$\beta$ wings as described in the text, while $M_V$ follows from the assumption that the mass is 0.6 $M_\odot$.

available as indicators of log $g$. The total widths of H$\beta$, H$\gamma$ and H$\delta$ at 0.9 of the continuum level as measured for all 5 stars on these 1992 spectrograms are given in Table 1; those for 40 Per are the mean of 2 exposures. The data for H$\beta$ are entitled to the highest weight.

Figure 1 is a plot which shows how the theoretical value of $W_{0.9}$ for H$\beta$ varies over the $T_e$, log $g$ plane. These data were extracted from the grid of line profiles for pure hydrogen LTE model atmospheres published by Wesemael *et al.* (1980). The profiles computed by Kurucz (1979), although probably more realistic, unfortunately do not extend to sufficiently high log $g$ values for the present purpose. Each reference star is plotted twice in Figure 1. They are located along the log $T_e$ axis at the value given in (the top line of) Table 1, in 3 cases by actual analysis of the spectrum, in one case (40 Per) by the value appropriate for a well-analyzed eclipsing binary of the same spectral type and luminosity. The cross for each star is plotted at the log $g$ value obtained from those same analyses, while the circled points locate it in $T_e$, $W_{0.9}$(H$\beta$) coordinates. The point for Haro's star lies at the log $T_e$ appropriate for type B0.5, and at the log $g$ inferred from its $W_{0.9}$(H$\beta$), about 4.7.

One sees that the surface gravity of Haro's star is intermediate between those of these main sequence and bright-*UV* reference stars on the one hand, and those of the sub-luminous Feige stars on the other.

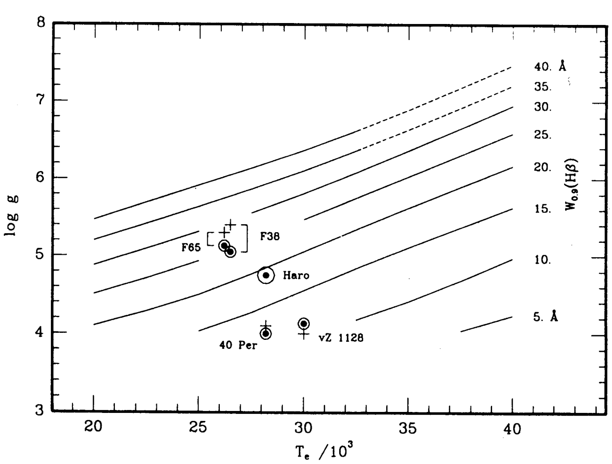


Fig. 1. The solid lines crossing the $T_e$ log $g$ plane represent the full width (in A) of the H$\beta$ absorption line at the 0.9 continuum level ($W_{0.9}$), obtained from the pure-hydrogen model atmosphere profiles of Wesemael *et al.* (1980). The dashed sections are extrapolated. The crosses locate 4 reference stars by their $T_e$, log $g$ coordinates. The circled dots locate the reference stars as well as Haro's star by their $T_e$, $W_{0.9}$ values in Table 1. The position of Haro's star is interpreted to mean that its log $g$ is about 4.7.

The luminosity follows if the mass is known. If it is assumed to be 0.6 $M_{\odot}$, then $M_{bol} = -0.9$ and, with BC = $-3.0$ mag., $M_V = +2.1$. The distance is then about 1.6 kpc. Clearly, the concerns expressed earlier have disappeared: Haro's star is a relatively nearby, old Population II object.

If so, the fact that no other stars like it are known probably means that it represents a short-lived evolutionary phase, and the most obvious conjecture (provided it is single) is that stars in transition between the AGB and planetary nuclei (Schönberner 1990) may resemble Haro's star at some stage of that process. However, the star was not detected by IRAS. There is no evidence that heavy mass ejection is taking place, because at the resolutions employed to date, the emission lines of Haro's star appear symmetric, with no P Cygni-like absorption components that would be indicative of mass loss. There is no evidence of any nebulosity around the image on the Palomar Survey red exposure (although a much deeper examination with a modern detector would be desirable), nor are any forbidden lines detectable in the stellar spectrum.

Whatever the evolutionary interpretation, another question is whether sdBe stars like Haro's exist in globular clusters. A number of globulars have been surveyed with slitless or grism-type spectrographs for stars having H$\alpha$ emission. As far as I know, the only such object found was the planetary nebula in M15, an easy discovery on such exposures. A star having H$\alpha$ emission as strong as Haro's would have readily been detected in an uncrowded field, but the cluttered background and the profusion of bright red giants in a globular cluster would have made detection much more difficult, especially if blue subdwarfs tend to be concentrated toward cluster centers. A simpler approach would be to examine H$\alpha$ in the known subluminous blue members of a few clusters with a slit spectrograph. This would rather quickly establish whether Balmer line emission is truly as rare in such stars as it appears to be.

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