A HIGH-RESOLUTION SPECTROSCOPIC ANALYSIS OF THE SUPERGIANT HD 165553

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The results of an analysis of a high-resolution spectrum of the possible spectroscopic binary HD 165553, obtained with a spectral resolving power of ~ 60 000, are presented. A detailed chemical-composition study indicates that the star is a normal supergiant with essentially solar composition except for the elements C and Na, for which we present plausible reasons associated with stellar evolution. Comparison of the star's spectrum with that of γ Cyg, a supergiant of spectral type F8 Iab, indicates that the star is of a later spectral type; we assign a spectral type G0 Iab for the star. The star may be a single-lined spectroscopic binary; there is no evidence of double lines in its spectrum. The heliocentric radial velocity of the star is estimated on our spectrum to be $-4 \cdot 5$ km s^{-1} ± $1 \cdot 5$ km s^{-1}.

Introduction

The star HD 165553, considered to be a supergiant of spectral type F8 Ib, was observed as one of the comparison stars during an observing run on hydrogen-deficient RCrB-type variables in 2000 June. A classification of the object as a G-type supergiant has also been suggested[1,2]. Observed $U - B$ and $B - V$ colours indicate that the star is affected by interstellar reddening; an estimate of $E(B - V) = 0 \cdot 38$ was made by Fernie[3], while Bersier[4] derived a value of $0 \cdot 273$.

In spite of earlier photometric studies, there seem to remain some uncertainties about the spectral type and evolutionary status of the star. We show here, through a spectrum and abundance analysis, that the star belongs to a later spectral type and assign a spectral type G0 Iab for the star.

A detailed chemical-composition study indicates a near-solar composition for HD 165553 except for elements C and Na. HD 165553 is one among those supergiants where C depletion is quite large, ~ $0 \cdot 6$ dex, compared to a carbon depletion of $0 \cdot 15$ dex in normal supergiants as predicted by stellar-evolution theory[5]. Possible reasons associated with stellar evolution are presented to account for this large difference between the observed and predicted depletion in C abundance. It was noted by McErlean *et al.*[6] and Gies & Lambert[7] that strong surface anomalies are possible in luminous stars. The abundance anomalies observed in such cases, which might be related to rotational mixing, are a strong signature of CNO processing[8].

HD 165553 was suggested to be a spectroscopic binary by Burki & Mayor[9] as early as 1983, based on an analysis of radial-velocity measurements made with the *Coravel* photoelectric spectrophotometer, with uncertainties in measurements ranging from 0·4 to 1 km s^{-1}. In that paper, a number of new spectroscopic binaries were detected with some confidence, while partial radial-velocity curves were obtained for some others, including HD 165553.

Spectroscopically, the presence of double lines in a star's spectrum generally offers direct evidence of a binary nature. However, the spectrum of HD 165553 is single-lined, although of course this cannot be taken as definite evidence against the star being binary. Indeed, given that HD 165553 is a supergiant, the absence of a second spectrum is not surprising. Based on monitoring this object over 17 years, De Medeiros *et al.*[10] claimed that the probability of the radial velocity of HD 165553 being constant is zero percent, although we have to be alert to the possibility of an unstable atmosphere often associated with very luminous stars. Certainly if HD 165553 turned out to be a binary, it is likely to have a period[9] of many years, and thus HD 165553 is certainly not a close binary system.

In the following sections we describe the star's spectrum and summarize our results derived from a detailed abundance analysis.

Observations and data reduction

HD165553 was observed with the McDonald Observatory's 2·7-m *Harlan J. Smith Telescope* and its *2dcoudé* cross-dispersed echelle spectrograph[11] on 2000 June 15. The wavelength coverage was from about 3840Å to 8800Å with gaps beyond about 5600Å to longer wavelengths. Observations of a Th-Ar hollow-cathode lamp taken immediately before and after the stellar exposures provided the wavelength calibration. The spectral resolving power was about 60 000. The CCD data were reduced using the IRAF software spectroscopic-reduction packages. Two spectra, each of 30 minutes exposure, were combined to increase the signal-to-noise ratio. The spectra were reduced to a normalized continuum using spline-interpolated values for the pseudo-continuum. A spectrum of γ Cyg was also obtained with the *2dcoudé* spectrograph at the same spectral resolution.

Description of the spectrum

The single-line spectrum of HD 165553 is represented by neutral lines of Na, Mg, Al, Si, Ca, Ti, V, Ni, and Zn. Singly-ionized lines, particularly of Fe but also of Ti, Cr, Y, Zr, Ce, and Nd are also quite prominent. The absorption-line spectrum of HD 165553 broadly resembles that of γ Cyg, but a number of differences noticed in spectral features of certain elements indicate that the star is of a later spectral type. Paschen lines around 8400Å are weakly present in the spectrum of HD 165553 as compared to those in γ Cyg (Fig. 1, top panel). Strong profiles of Hβ and Hγ are noticed in the spectrum but the Hα feature was missed in the gap between two orders. Lines of neutral carbon are weaker in HD 165553 (Fig. 1, 2nd panel).

Oxygen features around 7774Å are also weaker in HD 165553 (Fig. 1, bottom panel). A stronger CN band around 3883Å, however, indicates an enhancement of nitrogen (Fig. 1, 3rd panel). Mg lines are noticeably stronger in HD 165553. The magnesium triplet 5167Å, 5172Å, and 5183Å and also the ionized calcium infrared triplet at 8542Å and 8662Å are strong and appear to be of similar strength to those in γ Cyg; the Ca feature at 8498·0Å was missed between two orders. Strong neutral calcium lines at 6102Å (blended with Fe I), 6122Å, and 6162Å are noticed in the spectrum.

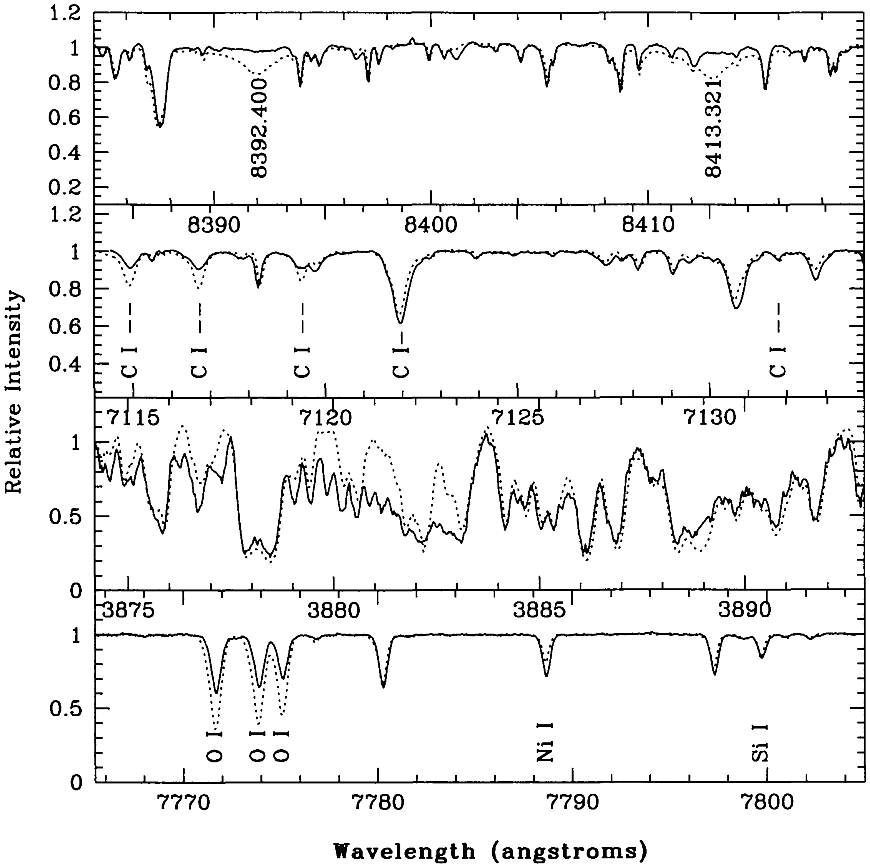

FIG. 1

In all the panels the dotted curves represent γ Cyg and the solid curves represent HD 165553. The strong Paschen features seen in γ Cyg are not observed in HD 165553 (top panel). A comparison of the spectrum of HD 165553 around 7120Å with that of γ Cyg is shown in the 2nd panel; the neutral carbon features are much weaker in HD 165553. The feature at 7122Å is blended with Ni. The CN band around 3883Å is quite prominent in HD 165553 (3rd panel). As carbon is underabundant, this strong CN feature is an indicative of an enhancement of nitrogen. The oxygen features are much weaker in HD 165553 whereas Ni I and Si I features are of equal strength (bottom panel).

Low-excitation lines of neutral metals, *e.g.*, the Fe I resonance line (RMT1) at 5060·1Å, are much stronger in HD 165553. Singly-ionized lines of heavy elements Y and Nd are of nearly equal strength and the equivalent widths of the lines match closely the values for the same lines in γ Cyg's spectrum. The Ca II features at 3933Å and 3968Å are broad with sharper central absorption dips. These features are illustrated in Fig. 2.

Radial velocity

The radial velocity was measured from a set of unblended absorption lines. The mean heliocentric radial velocity on HJD 2451710·8 was estimated to be $V_r = -4{\cdot}5 \pm 1{\cdot}5$ km s^{-1}. Low-excitation lines as well as high-excitation lines yielded essentially similar velocities. The central velocities of the strong absorption lines of Na D_1 and D_2 are, respectively, -5 and -6 km s^{-1}. The central absorption dips of the Ca II features at 3933Å and 3968Å are at a velocity ~ -6 km s^{-1}.

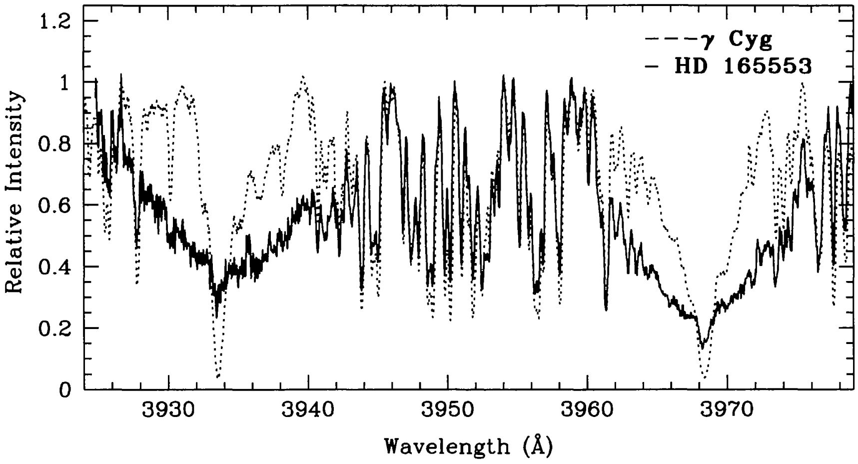

FIG. 2

In the figure the dotted curve represents γ Cyg and the solid curve represents HD 165553. The broad Ca II features at 3933Å and 3968Å with central absorption dips at a velocity of −6 km s^{-1} are suggestive of interactions with circumstellar material.

Al I lines at 3944·009Å and 3961·523Å are at velocities of −4 and −5 km s^{-1}. The potassium lines at 7664·907Å and 7698·979Å are blended with atmospheric O_2; both are at velocities ∼ −5 km s^{-1}. The partial radial-velocity curve derived by Burki & Mayor[9] shows a variation of ∼ 3 km s^{-1} between the lowest and the highest radial-velocity measurements, which was interpreted as due to orbital motion. Unfortunately, the absolute values for those radial-velocity measurements were not available in their paper. De Medeiros *et al.*[10] reported the mean radial velocity of the star derived from 26 *Coravel* observations as −8·20 km s^{-1} with an uncertainty of ±0·58 km s^{-1}.

An abundance analysis

Abundances of the elements are derived using the 2002 version of the code MOOG written by Sneden[12]. The abundance analysis uses a set of model atmospheres and equivalent widths of a set of selected lines. A collection of unblended Fe I lines covering a range in excitation potential (1·0 – 5·0 eV) and equivalent width (20 – 170 mÅ) was used to determine the effective temperature, $T_{\rm eff}$, and the microturbulent velocity, ξ_t. The microturbulent velocity is estimated first by requiring the derived abundances to be the same whatever the strength of the lines. The temperature is then adjusted such that the derived abundances are independent of the excitation potential of the lines. This temperature gives an estimate of $T_{\rm eff}$.

The surface gravity was found with the assumption of ionization equilibrium between Fe I and Fe II lines, *i.e.*, by requiring that the Fe I lines and Fe II lines give the same Fe abundance. Titanium lines were also similarly used. The *gf* values for the elements are taken from several sources: Fuhr *et al.*[13], Lambert *et al.*[14], and from the compilation of R. E. Luck (personal communication). We assumed that HD 165553 has the standard He abundance of the MARCS grid[15] (He/H = 0·1) and used the model atmosphere computed for [M/H] = 0·0. The derived atmospheric parameters are $T_{\rm eff}$ = 5800 K, log g = 1·5 cgs units, ξ_t = 4·1 km s^{-1}, and [Fe/H] = 0·05. The uncertainties in $T_{\rm eff}$, log g, and ξ_t are, respectively, ±200 K, ±0·25 cgs units, and ±0·5 km s^{-1}.

TABLE I

Chemical composition of HD 165553

Element	*Z*	*log ε*	*N*[a]	*Meteorites*[b] *log ε*	*[X/H]*	*[X/Fe]*	*Δ [X/H]*
C I	6	7·95 ± 0·05	2	8·52	−0·57	−0·65	$-0·21 < \Delta[X/H] < 0·11$
Na I	11	6·62 ± 0·08	3	6·33	+0·29	+0·21	$-0·10 < \Delta[X/H] < 0·17$
Mg I	12	7·52 ± 0·11	3	7·58	−0·06	−0·14	$-0·11 < \Delta[X/H] < 0·16$
Al I	13	6·26 ± 0·04	3	6·48	+0·03	−0·05	$-0·08 < \Delta[X/H] < 0·13$
Si I	14	7·60 ± 0·14	19	7·55	+0·05	−0·03	$-0·08 < \Delta[X/H] < 0·12$
Si II	14	7·69	1	7·55	+0·14	+0·11	$-0·27 < \Delta[X/H] < 0·14$
Ca I	20	6·37 ± 0·14	16	6·36	0·01	−0·07	$-0·14 < \Delta[X/H] < 0·22$
Sc II	21	3·19 ± 0·18	4	3·13	0·06	0·03	$-0·10 < \Delta[X/H] < 0·09$
Ti I	22	4·95 ± 0·19	37	4·98	−0·03	−0·11	$-0·19 < \Delta[X/H] < 0·31$
Ti II	22	4·93 ± 0·09	6	4·98	−0·05	−0·08	$-0·09 < \Delta[X/H] < 0·09$
V I	23	4·05 ± 0·21	14	4·00	0·05	−0·03	$-0·21 < \Delta[X/H] < 0·34$
V II	23	3·96	1	4·00	−0·04	−0·07	$-0·08 < \Delta[X/H] < 0·09$
Cr I	24	5·66 ± 0·16	15	5·68	−0·02	−0·10	$-0·15 < \Delta[X/H] < 0·24$
Cr II	24	5·64 ± 0·13	5	5·68	−0·04	−0·07	$-0·10 < \Delta[X/H] < 0·09$
Mn I	25	5·21 ± 0·13	5	5·39	−0·18	−0·26	$-0·15 < \Delta[X/H] < 0·23$
Fe I	26	7·58 ± 0·10	189	7·50	0·08		$-0·14 < \Delta[X/H] < 0·24$
Fe II	26	7·53 ± 0·09	13	7·50	0·03		$-0·10 < \Delta[X/H] < 0·09$
Co I	27	4·95 ± 0·03	3	4·92	0·03	−0·05	$-0·18 < \Delta[X/H] < 0·30$
Ni I	28	6·21 ± 0·13	43	6·25	−0·04	−0·12	$-0·16 < \Delta[X/H] < 0·24$
Cu I	29	4·00	1	4·21	−0·21	−0·29	$-0·21 < \Delta[X/H] < 0·35$
Zn I	30	4·39 ± 0·05	2	4·63	−0·24	−0·32	$-0·16 < \Delta[X/H] < 0·22$
Y II	39	2·23 ± 0·15	5	2·24	−0·01	−0·04	$-0·09 < \Delta[X/H] < 0·09$
Zr II	40	2·64 ± 0·11	2	2·60	0·04	0·01	$-0·21 < \Delta[X/H] < 0·15$
La II	57	1·18 ± 0·07	2	1·22	−0·04	−0·07	$-0·01 < \Delta[X/H] < 0·10$
Ce II	58	1·47 ± 0·18	7	1·61	−0·14	−0·17	$-0·09 < \Delta[X/H] < 0·10$
Pr II	59	0·65	1	0·71	−0·06	−0·09	$-0·10 < \Delta[X/H] < 0·11$
Nd II	60	1·51 ± 0·09	8	1·50	0·01	−0·02	$-0·10 < \Delta[X/H] < 0·12$
Eu II	63	0·50	1	0·53	−0·03	−0·06	$-0·09 < \Delta[X/H] < 0·09$

[a] Number of lines
[b] From Grevesse & Sauval[16]

The derived abundances are given in Table I, as log ε(X) on the scale log ε(H) = 12, [X/H], and [X/Fe]; the reference solar abundances are taken from Grevesse & Sauval[16]. The mean standard deviation for Fe, for which we could measure many lines, is about 0·10 dex. For other elements the standard deviation ranges from 0·04 to 0·2 dex; these uncertainties are estimated from line-to-line scatter. Uncertainties from the model-atmosphere calculations, Δ[X/H], are also given in the table.

Results

Our analysis suggests almost solar abundances for most of the elements, including Fe. In computing [X/Fe] we used the Fe I-based abundance for elemental abundances derived from neutral lines and the Fe II-based abundance for abundances derived from ionized lines. The relative abundances were generally as expected for stars of near-solar metallicity, *i.e.*, with [X/Fe] = 0. In the following we present our results for each element with reference to those in γ Cyg.

Hydrogen. Paschen lines around 8400Å are weakly present in the spectrum of HD 165553 as compared to their strong presence in γ Cyg. Supergiants of spectral type G do show weaker hydrogen features than F-type supergiants.

Carbon. The carbon abundance, estimated from the C I lines at 7115 Å and 7116 Å, returns a value of 7·95, lower than the value 8·18 in γ Cyg[17]. The solar value of carbon is 8·39. The strong C I feature at 7122 Å is blended and the feature at 7131 Å is weak (~ 18 mÅ); they are not included in the abundance determination. Carbon is underabundant by about 0·57 dex. Processing of material through hydrogen burning and subsequent mixing to the stellar surface is likely to be the cause of a lower carbon abundance.

Nitrogen. An enhancement of N is indicated by the presence of a strong CN band around 3883Å. Quantitatively, the nitrogen abundance is more than 8·39, which is the N abundance of γ Cyg[17]. CH bands are not obviously seen in the star's spectrum. An inverse relation between C and N in normal supergiants is not uncommon. Processing of C to N and deep mixing seem to be the responsible factors.

Oxygen. The oxygen abundance is 8·61 in γ Cyg[17]. As compared to γ Cyg, the much weaker oxygen lines in HD 165553 around 7774Å suggest a lower abundance. At a given oxygen abundance, however, the strength of the oxygen lines at 7771, 7774, and 7775Å increases with an increase in temperature and also with a decrease in surface gravity. As γ Cyg is of higher temperature and of lower surface gravity than HD 165553, the difference noticed between the two spectra in Fig. 1 is due only in part to lower oxygen abundance in HD 165553.

Thus, as far as CNO abundances in HD 165553 are concerned, with respect to solar values, C and O are deficient in HD 165553 while N is enhanced. This result is qualitatively consistent with standard evolutionary theory. However, the observed depletion in C of 0·57 dex in HD 165553 is much higher than the 0·15 dex that the standard theory predicts. This large depletion may be interpreted as a result of repeated standard mixing and dilution processes. Luck & Lambert[17,18,19] also noted that the depletion in observed C can extend up to −0·6 dex in the case of certain normal supergiants.

Sodium and Aluminium. Na is overabundant by about 0·29 dex, a feature common to supergiants. With respect to solar values, Na is overabundant by 0·21 dex. The local galactic supergiants do show a mean [Na/Fe] ratio of about 0·24 dex, which is interpreted as a result of the Ne–Na cycle operating in those stars[19,20]. The local galactic supergiants also show a mean underabundance of 0·03 dex for Al[21]. We have derived a value ~ −0·05 dex for [Al/Fe] from three Al lines. The *gf* values for these lines were taken from Shetrone[22]. Theories of deep mixing of stellar envelopes suggest that when Na is enhanced due to the Ne–Na cycle, Al is also enhanced in an Mg–Al cycle, accompanied by an enhancement of Mg; this should, therefore, be noticed in stars which succeed in mixing their stellar atmosphere with regions of the star which have undergone these cycles. Our abundance results indicate operation of the Ne–Na cycle but show no indication of this cycle being leaked into the Mg–Al cycle.

α-elements: Mg, Si, S, Ca, and Ti. The α elements show near-solar abundances. S lines are weak in the spectrum and could not be measured. A marginally higher strength of Ca lines noticed in HD 165553 is due to $T_{\rm eff}$ being slightly lower (~ 300K) than that of γ Cyg.

Scandium and Vanadium. Abundances of Sc derived from four singly-ionized lines as well as the abundance of V derived from 14 neutral lines indicate near-solar values. The abundance of V derived from only one singly-ionized line gives a value 3·61, which is 0·39 dex lower than the solar value. This abundance, derived from just one line, might be unreliable.

Fe-peak elements: Cr, Mn, Co, Ni, Cu, and Zn. The abundances derived for Cr, Co, and Ni are almost solar. Mn is underabundant by 0·18 dex and Cu and Zn are underabundant by 0·21 and 0·24 dex, respectively. These results are quite similar to the observed abundance pattern exhibited by bright supergiants.

Heavy elements. Heavy elements do not exhibit any abundance anomaly; while Ce is underabundant by about 0·14 dex, Y, Zr, La, Nd, and Eu return near-solar values. The Sr I resonance line at 4607 Å is observed in HD 165553 as a strong but blended feature; the line could not be used for abundance determination. The overabundance of Sr noticed in most of the Population I supergiants is generally attributed to departures from LTE.

Concluding remarks

A chemical-composition study indicates that HD 165553 is a normal supergiant with essentially solar composition except for the elements C and Na. C depletion in HD 165553 is ~0·6 dex. This large difference between observed and predicted depletion in carbon abundance is important as far as an understanding of the CNO processing and mixing in the star's evolutionary state is concerned. Oxygen is also underabundant, while nitrogen is enhanced. Enhanced nitrogen and underabundance of carbon and oxygen indicate mixing of CNO-cycled material to the stellar surface. But for such a large observed C depletion a plausible cause could be that the CNO-cycled material is undergoing a repeated mixing and dilution process.

Na is overabundant by about 0·29 dex, which is consistent with the observed mean Na abundances of 0·24 dex in local galactic supergiants. Enhanced Na is an indication of the operation of the Ne–Na cycle. This cycle is likely to be in its initial stage and the star is yet to undergo a mixing into the stellar atmosphere of regions of the star undergoing this cycle. Further, the Ne–Na cycle has not yet leaked into the Mg–Al cycle, because that would have resulted in an enhancement of Al and Mg abundances. In HD 165553, Al and Mg abundances are both near-solar.

From a close comparison of the star's spectrum with that of γ Cyg, the star appears to be of a later spectral type, probably near G0 Iab.

The broad Ca II *H* and *K* features at 3933Å and 3968Å with central narrow dips at a velocity of -6 km s^{-1} are suggestive of interactions with circumstellar material. The star is possibly a single-lined spectroscopic binary; there is no evidence of double lines in its spectrum. However, for HD 165553, being a luminous supergiant, the absence of a second spectrum is not surprising.

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CORRESPONDENCE

To the Editors of 'The Observatory'

Mea Culpa: Black Drop not due to Venus Atmosphere

Following the example of the better broadsheet newspapers, I hasten to correct an error that crept into my review of *Jean-Charles Houzeau et son Temps*, by P. Verhaas (**123**, 223, 2003). The issue is the origin of the dreaded black-drop effect which hampered the determination of the solar parallax from transits of Venus, and which I attributed to irradiation from the Cytherean atmosphere. This was an error on my part, an error already previously pointed out in these pages[1]; the effect has in fact been shown to arise from an asymmetrical optical broadening due to convolution of the point-spread function with the planetary and limb-darkened solar discs, and it has even been detected in transits of Mercury observed from space[2–4].

I thank Dr. Jay M. Pasachoff for drawing my attention to this matter and the Editor, Dr. David Stickland, for reminding me about Ref. 1.

Yours faithfully,
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