

THE CLOSE BINARY CENTRAL STAR OF THE PLANETARY NEBULA ABELL 41: A HELIUM-RICH SUBDWARF PRIMARY

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ABSTRACT

We have detected He II, He I, and H absorption features in spectroscopy with 2 Å resolution of the Abell 41 planetary nebula central star, which was recently reported by Grauer and Bond to be a close binary with a 2 hour 43 minute period. This subdwarf O spectrum has been analyzed with a grid of hot, high-gravity, LTE atmosphere models. We estimate $T_{\text{eff}} = 50,000 \pm 5000$ K, $\log g = 6 \pm 1$, $n(\text{He})/n(\text{H}) \approx 10^{-1.0 \pm 1}$. This temperature is a factor of 1.4–2.9 lower than the range used by Grauer and Bond—and the required secondary star heating is considerably reduced. Nevertheless, we find close agreement with their estimates for the distance, reddening, and the systemic parameters for the binary star. Their interpretation of Abell 41 as a pre-cataclysmic variable object remains valid for a cool main-sequence or hotter evolved secondary star. The object should be a promising target for high-resolution (coudé/échelle) follow-up spectroscopy.

Subject headings: nebulae: planetary — stars: abundances — stars: binaries — stars: subdwarfs

I. INTRODUCTION

Grauer and Bond (1982, 1983, hereafter GB) recently reported the discovery of a binary planetary nebula central star with the very short photometric period of 2 hours 43 minutes. The object lacks the broad emission or absorption features and light variations characteristic of cataclysmic variables (CVs); hence, these authors interpreted the system as a detached binary—a subdwarf central star with a close, main-sequence companion—and attributed the quasi-sinusoidal light variations to an orbital reflection effect. Even if the orbital period were twice the 2 hour 43 minute photometric value (with symmetric minima), this would be the shortest period known for a detached binary. Curiously, there are also no known CVs with reliable orbital periods in the 2–3 hr range, and some authors (cf. Robinson *et al.* 1981) have speculated that evolving CVs may stop mass transfer in this period range. However, GB had relatively little information for estimating the stellar parameters of the primary star. Their optical spectrum showed no detectable absorption features at 9 Å resolution. Given the uniqueness of the object, it therefore seemed appropriate to follow up with higher resolution digital spectroscopy, though the lateness of the observing season precluded any search for radial velocity variations throughout an entire orbital period.

II. HIGH-RESOLUTION SPECTRA AND ATMOSPHERIC PARAMETERS

On 1982 September 14 and 16 (UT) spectra of the Abell 41 central star were obtained with the Steward Observatory 2.3 m reflector, Cassegrain spectrograph, and intensified photon-counting Reticon system.

Both spectra had 2.0 Å resolution with similar wavelength coverage, and we therefore show the summed spectra—representing some 90 minutes integration time—in Figure 1. In addition to narrow nebular emission lines of [O III], H, and He

I 4471, there is a clear absorption spectrum. Wings of the hydrogen lines, strong He II 4686, sharper He II 4540 and 44200 and, most importantly, He I 4713 and 4922 are present. The underlying spectrum is clearly that of a subdwarf O (sdO) star.

In Figure 2, we show three synthetic spectra taken from a grid of LTE model atmosphere calculations for hot, high-gravity stars (Wesemael, Green, and Liebert 1984). The observed line widths in Abell 41 suggest $\log g < 6$; we assign a conservative uncertainty estimate of $\Delta(\log g) = \pm 1$ to this determination, even though the sharpness of He II 4540 probably excludes a surface gravity as high as $\log g = 7$. The ratio of the He I and He II strengths (e.g., 4686 vs. 4713) suggests $T_e = 50,000 \pm 5000$ K, a conclusion which is insensitive to gravity. The He II line strengths favor a helium-rich atmosphere but exclude a helium content by number beyond He/H ~ 1 . We adopt $\log(\text{He}/\text{H}) = -1 \pm 1$ as a preliminary helium abundance for the Abell 41 primary. In sum, we find the Abell 41 central star to be an sdO star of moderate temperature and helium richness. However, it appears both hotter and more helium-rich than the sdO primary in the longer period eclipsing binary system LB 3459 (Kudritzki *et al.* 1982).

The use of LTE model atmosphere calculations for the analysis of an sdO star requires some justification in view, in particular, of the importance of NLTE effects in that effective temperature and gravity regime (Kudritzki 1976). From the sample of seven O subdwarfs studied differentially by Kudritzki (1976) with homogeneous grids of both LTE and NLTE models, one concludes that LTE models tend to underestimate effective temperatures by $\sim 10\%$ – 15% , while their use overestimates gravities by factors of 2–4; NLTE effects decrease as the helium abundance increases. These effects are comparable to (or much smaller than, in the case of $\log g$) the error bars assigned to our determinations of atmospheric parameters for

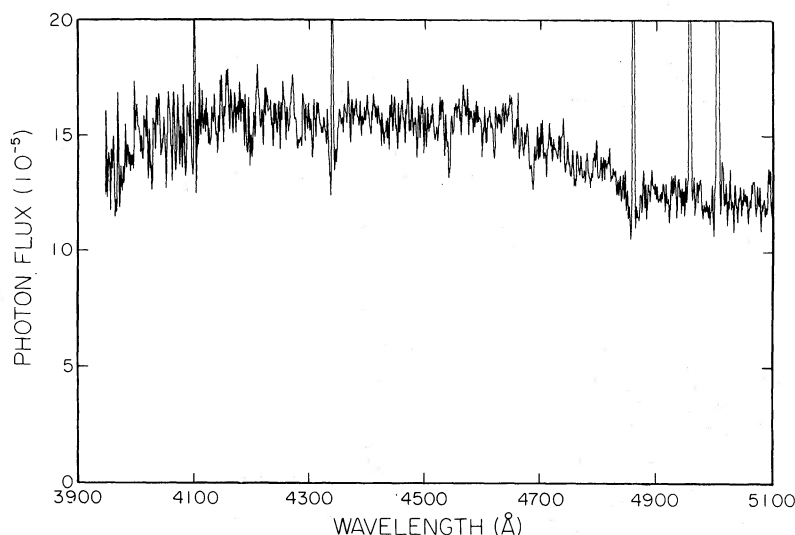


FIG. 1.—Sum of observed spectra of Abell 41, scaled to emphasize the continuum. The ordinate is in units of photons $\text{cm}^{-2} \text{s}^{-1} \text{\AA}^{-1}$ through the 2.5 circular apertures.

the Abell 41 primary. LTE models should thus be adequate to constrain both T_e and $\log g$ —our main concern in the present work. Although more accurate atmospheric parameters may eventually become available with the use of NLTE models, it is also worth pointing out that the cores of the Balmer lines and of He I $\lambda 4471$ are hopelessly dominated by nebular emission. The wings, used here for our crude analysis, are more likely to be formed in LTE.

Another consistency check is provided by J. B. Kaler (1983, private communication), who derives an upper limit of $T_e = 55,000$ K for the central star, based on the Zanstra method. His spectral observation of the bright rim of the nebula north of the star produced an upper limit for the flux of He II $\lambda 4686$ of

3% of that of H β , from which the temperature limit was obtained. He notes that it is unusual for a planetary nebula that large to have a central star with an effective temperature so low.

III. IMPLICATIONS

a) Distance and Luminosity

The temperature determined in § II is lower by a factor of 1.4–2.9 than the range assumed by GB. Our atmospheric parameter fit thus permits an independent, direct, but still somewhat uncertain estimate of the distance and luminosity of the system. Assuming a typical remnant mass $M_1 \sim 0.6 M_\odot$, the surface gravity estimate $\log g = 6 \pm 1$ indicates $R_1 \sim 0.13 R_\odot$.

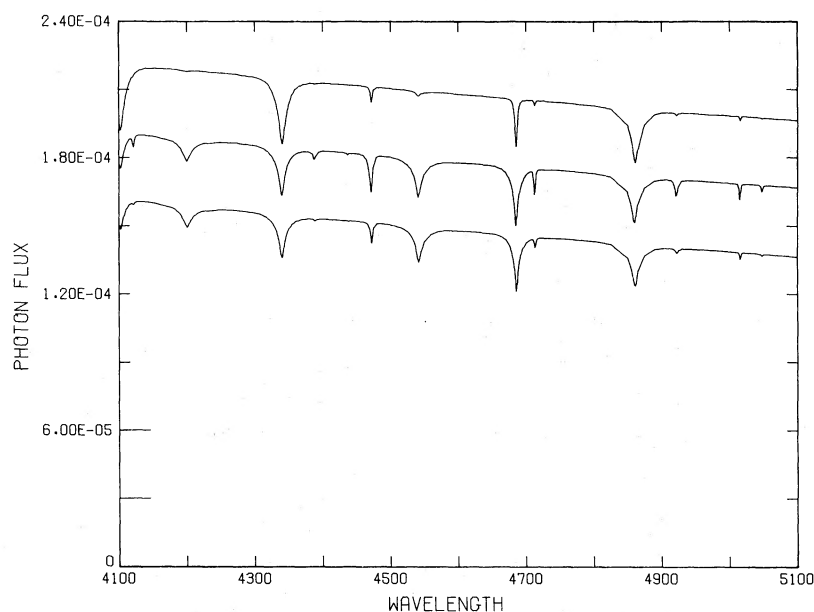


FIG. 2.—Synthetic spectra for the following models (from top to bottom): $T_e = 50,000$ K, $\log(\text{He}/\text{H}) = -2.0$; $T_e = 50,000$ K, $\log(\text{He}/\text{H}) = 0$; $T_e = 60,000$ K, $\log(\text{He}/\text{H}) = 0$. All models have $\log g = 6.0$. The spectra have been corrected for instrumental broadening and have been scaled to the observed photon flux at $4600 \text{ \AA}$.

+0.28/−0.09. Using the more reliable $T_1 \sim 50,000 \pm 5000$ K then suggests $\log(L_1/L_\odot) \sim 2.0 \pm 1.0$ or $M_{\text{bol}} = -0.3 \pm 2.5$. Using B.C. ≈ -4.3 yields $M_p \approx +4.0 \pm 2.5$.

Photoelectric colors for the central star measured by Abell (1966) are $B-V = +0.11$, $U-B = -0.87$. Assuming the unreddened values are close to those for a pure Rayleigh-Jeans spectrum of $B-V = -0.33$ and $U-B = -1.25$ (Matthews and Sandage 1963), we derive $E_{B-V} = 0.50$ mag averaged from both colors, and $A_v = 1.50$ mag. The distance modulus is then $m-M = 15.95 - (4.0 \pm 2.5) - 1.50 \approx 10.5 \pm 2.5$, i.e., $1250 + 3300/-900$ pc. This result is in good agreement with the range discussed by GB.

b) Constraints on the Secondary

GB discussed the constraints imposed on the secondary star by the assumption that (1) the secondary does not fill its Roche lobe, and (2) the modulated light is due to heating of its hemisphere facing the hot primary. Our lower T_e value leads to some modification of their discussion.

If the heated hemisphere of the secondary has temperature T_{2H} , while its "intrinsic" (unheated) temperature is T_{2I} , then its luminosity is given by

$$L_H = 2\pi R_2^2 \sigma T_{2H}^4 = (L_1/4)(R_2/a)^2 + 2\pi R_2^2 \sigma T_{2I}^4, \quad (1)$$

where we have assumed a purely geometric absorption cross section and complete reradiation. Equation (1) leads to

$$T_{2H} = [\frac{1}{2}(R_1/a)^2 T_1^4 + T_{2I}^4]^{1/4}. \quad (2)$$

Using GB's value of $a = 0.90 \pm 0.05 R_\odot$, $R_1 = 0.13 + 0.28/-0.09 R_\odot$, and $T_1 = 50,000 \pm 5000$ K while assuming T_{2I} is negligible, we get $T_{2H} \approx 16,000 + 12,400/-7100$, with the uncertainty dominated by that of R_1 . GB derive constraints from the fact that the secondary does not fill its Roche lobe that imply an unheated surface temperature (T_{2I}) at or below 3000 K. The heating derived here is still substantial, but much less drastic than that found by GB (42,000 K) for a primary assumed to have T_e from 69,000 to 145,000 K. Model constraints on the orbital inclination depend on the observed reflection amplitude, the system geometry, and the bolometric corrections of the primary star and heated side of the secondary. We adopt B.C.₁ ≈ -4.3 mag and B.C._{2H} ≈ -1.2 mag. Although our temperatures and B.C. values are much smaller, the difference of 3.1 mag is identical to that assumed by GB, thus leading to the same lower limit on the orbital inclination.

An observational fact is that the amplitudes of the U and B ("reflected component") light curves are nearly identical. A 16,000 K atmosphere would not be expected to contribute equally to U and B . The inference is therefore either that the ultraviolet blanketing is not as strong as expected, or (more likely) that the ultraviolet flux is enhanced, possibly with strong Balmer continuum emission, as in BE UMa (Ferguson *et al.* 1981). The corresponding line emission from the secondary should be difficult to detect because of contamination from the nebula, but it may show up as a velocity-modulated component in careful, high-resolution studies of the Abell 41 (central star plus nebula) emission lines. In fact, we may quantify this prediction, using the system parameters provided by GB and ourselves.

Using $M_2 \sim 0.2 M_\odot$, $M_1 \sim 0.6 M_\odot$, $a = 0.9 R_\odot$, and assuming a circular orbit, we estimate that

$$[GM_1^2/(M_1 + M_2)a]^{1/2} = 309 \text{ km s}^{-1}. \quad (3)$$

Since the inclination is highly uncertain, but should be within the GB limits of $10^\circ < i < 70^\circ$, we have a secondary half-amplitude of $54 < K_2 < 290 \text{ km s}^{-1}$ which should be detectable against the small line width of the nebula, if the secondary's emission component is a significant fraction of the line-of-sight nebular emission. It may be easier to measure, in fact, than the modulation (K_1) of the broader primary absorption lines, since $K_1 \sim \frac{1}{3}K_2$. However, both M_1 and M_2 remain very uncertain, so that coudé/échelle resolution, time-resolved spectroscopy of the Abell 41 binary central star may prove fruitful.

IV. POSTSCRIPT

In the preceding sections, we have drastically reduced the temperatures for the primary star ($\sim 50,000$ K) and heated side of the secondary ($\sim 16,000$ K) in the Abell 41 close binary, compared to the estimates of GB. Yet their values for the distance, reddening, and systemic parameters are essentially unmodified after our further information is taken into account. If the 2 hour 43 minute period is verified, then GB have correctly pointed out that gravitational radiation would lead to the beginning of mass transfer and the onset of the CV stage. The calculated orbital decay time of 6×10^8 years is more than adequate to assure that the present-day sdO primary would be fully degenerate at the beginning of CV activity.

An alternative model that cannot be ruled out by the present observational data is that Abell 41 might consist of two evolved stars with the secondary also being a hot subdwarf, as advocated for the LB 3459 system by Conti, Dearborn, and Massey (1981). As an example, a secondary mass of $0.6 M_\odot$ and temperature of 20,000 K are chosen. Since the orbital separation and secondary's Roche lobe scale as the cube root of combinations of the masses, a increases by 14%, and the upper limit on R_2 becomes $0.38 R_\odot$. The T_{2I} term now dominates in equation (2), requiring a heating of only 1400 K. The new secondary temperature suggests bolometric corrections of 1.7–2.1 mag for the range from blackbody to pure hydrogen atmospheres. To obtain the observed reflection amplitude, the lower limit on the orbital inclination must then be raised to 13.9° – 20.1° for this range of bolometric corrections. Such a star could contribute up to 18% of the total light in the system.

A major distinction between the main-sequence and evolved secondary models is the temperature difference to be maintained between the heated and unheated sides. To be essentially undetected in U through V , the back side of the main-sequence secondary must be somewhat less than 10,000 K, allowing some energy flow from the heated side but still requiring a minimum 6000 K gradient. The use of the normal mass-radius relation for such an object that has also just emerged from the primary's envelope must be regarded as illustrative only. A fully degenerate secondary is ruled out for having insufficient surface area to provide the observed reflection amplitude ($R_2 \ll 0.38$).

The definitive test will be the determination of the orbit; we reiterate that the Abell 41 central star may be a double-line spectroscopic binary at measurable high spectral resolution. Such an investigation can of course show whether the true binary period is 2 hours 43 minutes or twice that amount. It is straightforward to choose He II absorption lines for study of the primary's orbital modulation ($18 < K_1 < 97 \text{ km s}^{-1}$) using the mass ratio of GB. For studying the secondary star, we suggest that a high Balmer line be chosen, an attempt to maxi-

mize the secondary's contribution vis-à-vis the nebular emission. The nebular component should be nearly recombinational in the Balmer decrement, but the BE UMa experience (Ferguson *et al.* 1981; Margon, Downes, and Katz 1981) suggests that the emission decrement in a secondary's "reflection" spectrum may be much flatter. We have predicted a modulation of $54 < K_2 < 290 \text{ km s}^{-1}$, depending on the inclination angle i . The ratio K_1/K_2 , if both are detected, will provide further information on the stellar masses in addition to the viewed orbital inclination.

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