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EVIDENCE FOR A BINARY ORIGIN OF THE YOUNG PLANETARY NEBULA HUBBLE 12

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ABSTRACT

Young planetary nebulae play an important role in stellar evolution when intermediate- to low-mass stars (0.8–8 $M_\odot$) evolve from the proto–planetary nebula phase to the planetary nebula phase. Many young planetary nebulae display distinct bipolar structures as they evolve away from the proto–planetary nebula phase. One possible cause of their bipolarity could be a binary origin for their energy source. Here we report on our detailed investigation of the young planetary nebula Hubble 12, which is well known for its extended hourglass-like envelope. We present evidence with time-series photometric observations for the existence of an eclipsing binary at the center of Hubble 12. In addition, low-resolution spectra of the central source show absorption features such as CN, *G* band, and Mg *b*, which can be suggestive of a low-mass nature for the secondary component.

Key words: binaries: general — planetary nebulae: individual (Hubble 12)

1. INTRODUCTION

The young planetary nebula (PN) Hubble 12 (HB 12; PN G111.8−02.8) plays an important role in the study of PNe. The line ratios of its strong fluorescent molecular hydrogen emission (Dinerstein et al. 1988) match closely pure fluorescent emission (Black & van Dishoeck 1987), which might have originated from shock excitation via collisional interaction of a strong wind from the central star against a circumstellar gaseous disk (Kastner & Weintraub 1994). The bipolar structure of HB 12 is also of particular interest. Early radio continuum observations from the Very Large Array (Bignell 1983) first disclosed its bipolar configuration. Miranda & Solf (1989) later confirmed the double-lobe structure along the north-south axis through long-slit spectroscopy. In addition, Hora & Latter (1996) and Welch et al. (1999) showed the existence of a ringlike structure near the central core from near-infrared and [Fe II] imaging. Recent *Hubble Space Telescope* (*HST*) NICMOS observations have revealed clearly detailed structure of the inner torus and its bipolar lobes (Hora et al. 2000). The origin of the axisymmetric morphology of young PNe has long been an unresolved issue. In classification of PNe based on their morphology, Zuckerman & Aller (1986) and Soker (1997) found that a large majority of PNe have nonspherical shapes, some indicating extreme bipolar or axisymmetric structure. Such structures could be generated by strong bipolar outflows during the late asymptotic giant branch (AGB) or post-AGB phase and may be transient phenomena (Kwok et al. 2000). The bipolar flows in turn could be produced by close binaries (Morris 1990; Soker et al. 1998; Soker 2000), or rather focusing effects from the associated magnetic field (Garcia-Segura et al. 1999, 2000), among various potential mechanisms suggested. Note that observational evidence has been found in support of the binary model (De Marco et al. 2004; Hillwig 2004; Sorensen & Pollacco 2004). Detailed investigations of the physical nature and dynamical properties of the central source are therefore of fundamental importance to our understanding of the origin and evolution of PNe.

We have initiated a program combining efforts from the photometric measurements obtained by the 1 m telescope (LOT) at the Lulin Observatory in central Taiwan and the spectrographic observations carried out with the 2.16 m telescope at the Xing-Long station of the National Astronomical Observatory of the Chinese Academy of Sciences (NAOC). Our main objective is to search for the possible presence of periodic variations in the light curves of the nucleus of HB 12, NSV 26083. Properties of the binary components could also perhaps be inferred from spectral observations of the central source. We describe in § 2 the observations and data reduction. The photometric light curves are presented in § 3, and then a discussion of the results and interpretations in § 4. The spectral features possibly originating from the cool secondary are investigated in § 5, which is followed by a summary of the main results of this study.

2. OBSERVATIONS AND DATA REDUCTION

2.1. *Time-Series Broadband Photometric Imaging*

High-speed broadband photometric observations were performed in the queue mode on the nights of 2003 December 3–5 using Johnson *R*- and *I*-band filters with the LOT telescope of the National Central University in Taiwan. The camera was operated with a Princeton Instruments 1340 × 1300 pixel CCD, giving a field of view of $11' \times 11'$. The CCD has a readout noise of 15.7 *e* and a gain of 4.4. The setup results in a pixel scale of $0''.62$ pixel^{-1}. Flat-field exposures were obtained on the twilight sky. The seeing condition all through this run of observations varied between $1''.3$ and $1''.9$. The journal of observations is summarized in Table 1.

More than 800 snapshots of HB 12 were made, with each snapshot containing a 10 s exposure in *R* and another 5 s in *I*. The data reduction includes bias and dark current correction and flat-fielding based on standard packages and procedures in the NOAO IRAF (ver. 2.12). Differential magnitudes of the central core of HB 12 were measured using the DAOPHOT package with three stars in the same field as reference stars. The signal-to-noise (S/N) ratios of all stars are >100. No apparent variations were found with the reference stars. The differential magnitudes in the *R* and *I* bands have accuracies within 0.04 and 0.02 mag, respectively.

2.2. *Optical Spectroscopy*

Low-resolution spectroscopy was obtained by the 2.16 m telescope of NAOC. The journal of observations in two separate sessions is given in Table 2. In the 2004 session, measurement

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TABLE 1
Journal of Photometric Observations of HB 12

Observation Date	Start (UT)	Start (HJD 2,452,900+)	Duration (hr)	Filter	Number of Exposures
2003 Dec 3	10:56	76.9557	4.3	*R*	132
2003 Dec 3	10:57	76.9568	4.3	*I*	132
2003 Dec 4	10:51	77.9527	4.4	*R*	139
2003 Dec 4	10:52	77.9540	4.4	*I*	139
2003 Dec 5	10:38	78.9434	4.5	*R*	143
2003 Dec 5	10:40	78.9452	4.5	*I*	143

was performed in the spectral range 4800–10500 Å on the night of 2004 August 8. The spectral dispersion was 3.1 Å pixel^{-1}. The Beijing Faint Object Spectrograph and Camera and a thinned back-illuminated Orbit 2048 × 2048 CCD were used. A slit width of 3.″6 was set. The exposure times ranged from 300 to 900 s. S/N ratios of the continuum of >90 were achieved. Exposures of Fe-Ne arcs were obtained right before and after each stellar spectrum and were used for the wavelength calibration.

In the 2005 session, spectroscopy was performed in the blue (3800–6200 Å) spectral range on the night of 2005 September 26. The 100 Å mm^{-1} grating was used, which resulted in a 2 pixel resolution of ~4.8 Å. The slit was placed at P.A. = 170°, in parallel to the main axis of HB 12 as indicated in Figure 1. The slit width was set to 2″. An Optomechanics Research, Inc., spectrograph and a Tektronix 1024 × 1024 CCD were used. The exposures ranged from 3600 to 7200 s, resulting in S/N ratios of >60. Wavelength calibration was performed based on He-Ar lamps exposed right before and after the target spectrum.

The spectral data were reduced following standard procedures in the NOAO IRAF (ver. 2.12) software package. The CCD reductions included bias and flat-field correction, successful background subtraction, and cosmic-ray removal. Flux calibration was derived with observations of at least two of the Kitt Peak National Observatory standard stars per spectral range per night. The atmospheric extinction was corrected by the mean extinction coefficients measured for Xing-Long station, where the 2.16 m telescope is located.

3. SEARCH FOR PERIODICITIES IN THE LIGHT CURVES

The multiband photometric results of HB 12 are presented in Figure 2. The method of phase dispersion minimization (PDM; Stellingwerf 1978) was used to analyze the light curves of NSV 26083. The PDM code was employed to derive the period, maximum magnitude, and amplitude of the light variation. Before calculating the power spectra, we set the nightly mean magnitude to zero and calculated the amplitude spectra of these data. The *I*-band data clearly cover three primary minima. A linear least-squares fit results in a period of $P = 0.1415 \pm 0.0015$ days. The *R*-band light curve was fitted simultaneously using the period of the *I*-band data because of their distinct primary minima. The power spectra of the photometric data are presented in Figure 3. A prominent amplitude peak is found at 7.06 cycles day^{-1}, which is 3.4 hr. The corresponding phase diagrams are shown in Figure 4. The profiles are sinusoidal for both the *R* and *I* bands. The period shows an amplitude of 0.06 ± 0.0074 mag in *R* and 0.08 ± 0.0046 mag in *I*. This suggests that NSV 26083 displays in its multiband time-series observations periodic variation and indicates a probable eclipsing binary origin for HB 12. It is the first time that a clear signature of periodicity has been evidenced toward the exciting source of HB 12, which may have important implications on the physical nature of bipolar structures associated with other young PNe.

Note that the dip in the *R*-band light curve seems to be shallower and smoother than that in the *I* band light curve. This wavelength dependence could probably be due to effects from Hα emission of the companion star, which is encompassed by the *R*-band observations, or other reflection effects from the illuminated surface of the less luminous star (Grauer & Bond 1983; Bruch et al. 2001).

If we alternatively suppose the periodic variations of NSV 26083 to be due to rotation modulation of stellar spot(s), the rotational period can be estimated as follows (Reid et al. 1993):

$$P_{\rm crit} = \frac{2\pi R_e^{3/2}}{\sqrt{GM}} = 2.78 R_e^{3/2} M^{-1/2}, \tag{1}$$

where $P_{\rm crit}$ is the rotational period of the star in hours, R_e is the equatorial radius, and M is the mass of the star in solar units. Following the discussion by Reid et al. (1993), we use $R_e = 1.5R_*$, where R_* is the radius of NSV 26083. If Zhang & Kwok's (1993) results of $T_{\rm eff} = 31{,}800$ K, $\log g = 3.1$, and $M = 0.8\,M_\odot$ are adopted, the rotational period $P_{\rm crit}$ would be as large as 48 hr. This is inconsistent with our estimation of 3.4 hr as presented above and helps to exclude the possibility of modulation by stellar spots.

4. STELLAR PROPERTIES OF THE BINARY COMPONENTS

The mass of the central source of HB 12 has been determined to be 0.8 $M_\odot$ by Zhang & Kwok (1993) based on existing infrared

TABLE 2
Journal of Spectral Observations of HB 12

Observation Date	Wavelength (Å)	Resolution (Å pixel^{-1})	Width of Slit (arcsec)	Integration Time (s)
2004 Aug 8................	4800–10500	3.1	3.6	300
2004 Aug 8................	4800–10500	3.1	3.6	900
2005 Sep 26..............	3800–6200	2.4	2	2 × 3600

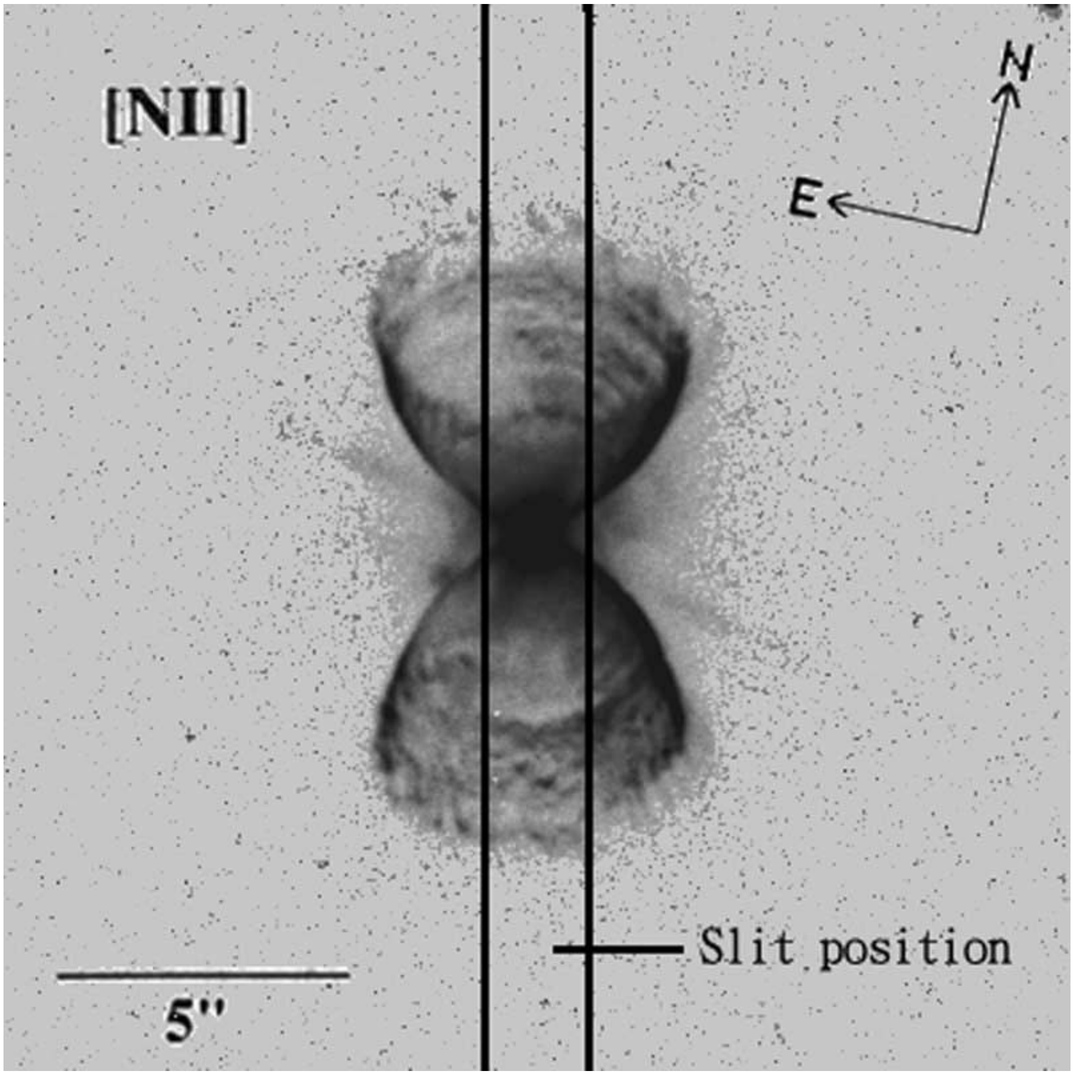

FIG. 1.—*HST* WFPC2 narrowband [N II] (F658N) image of HB 12, displayed with a linear gray scale. We present here the combined data sets (U6CI0405, U6CI0406, U6CI0407, and U6CI0408) of B. Balick. The total exposure time is 1300 s, and the field of view is 18″ × 18″. The slit position is shown against the image of the core of the PN.

and radio data. We present below an estimation of the mass and radius of the proposed secondary component of the system.

First, the secondary star, with an orbital period of hours to days, was suggested to have a mass of less than 0.5 $M_\odot$ (Chen et al. 1995). If a mass ratio $M_2/M_1 < 0.8$ (M_1 is the mass of the primary star) is supposed, the upper limits of the mass and radius of the secondary would satisfy the following condition (Paczyński 1981):

$$8.85\sqrt{\frac{R_2^3}{M_2}} < P, \tag{2}$$

where P is the orbital period in hours and M_2 and R_2 are the mass and radius of the secondary in solar units, respectively.

Second, assume that the mass-radius relation of the lower main sequence stars can be applied to the secondary (Rappaport et al. 1982):

$$\frac{R_2}{R_\odot} = 0.76\left(\frac{M_2}{M_\odot}\right)^{0.78}. \tag{3}$$

We can combine equation (2) with equation (3) to obtain

$$M_2 < 0.443\ M_\odot, \quad R_2 < 0.403\ R_\odot. \tag{4}$$

There is a general agreement (Schönberner 1981; Heap & Augensen 1987; Weidemann 1989; Tylenda et al. 1991b; Zhang & Kwok 1993; Stasińska et al. 1997) that the dispersion of the central stellar masses of PNe, averaged to around 0.6 $M_\odot$, should be rather small. If we assume a mass 0.6 $M_\odot$ for the primary star, for $M_1 = 0.6$ and $0.08 < M_2 < 0.443$, the separation of the stars $a = 1.163 \pm 0.063\ R_\odot$. In turn, the radius of the Roche lobe of the secondary is

$$l_2 = a[0.5 + 0.227\log(M_2/M_1)].$$

This results in an estimation of $0.547 \pm 0.03\ R_\odot$, and the hemisphere of the secondary must be illuminated and heated by the primary source.

The distance to HB 12 has been estimated to be 2.24 kpc by Cahn et al. (1992) based on existing optical and radio data; Hora & Latter (1996) determined an $E(B - V)$ value of 0.28 measuring

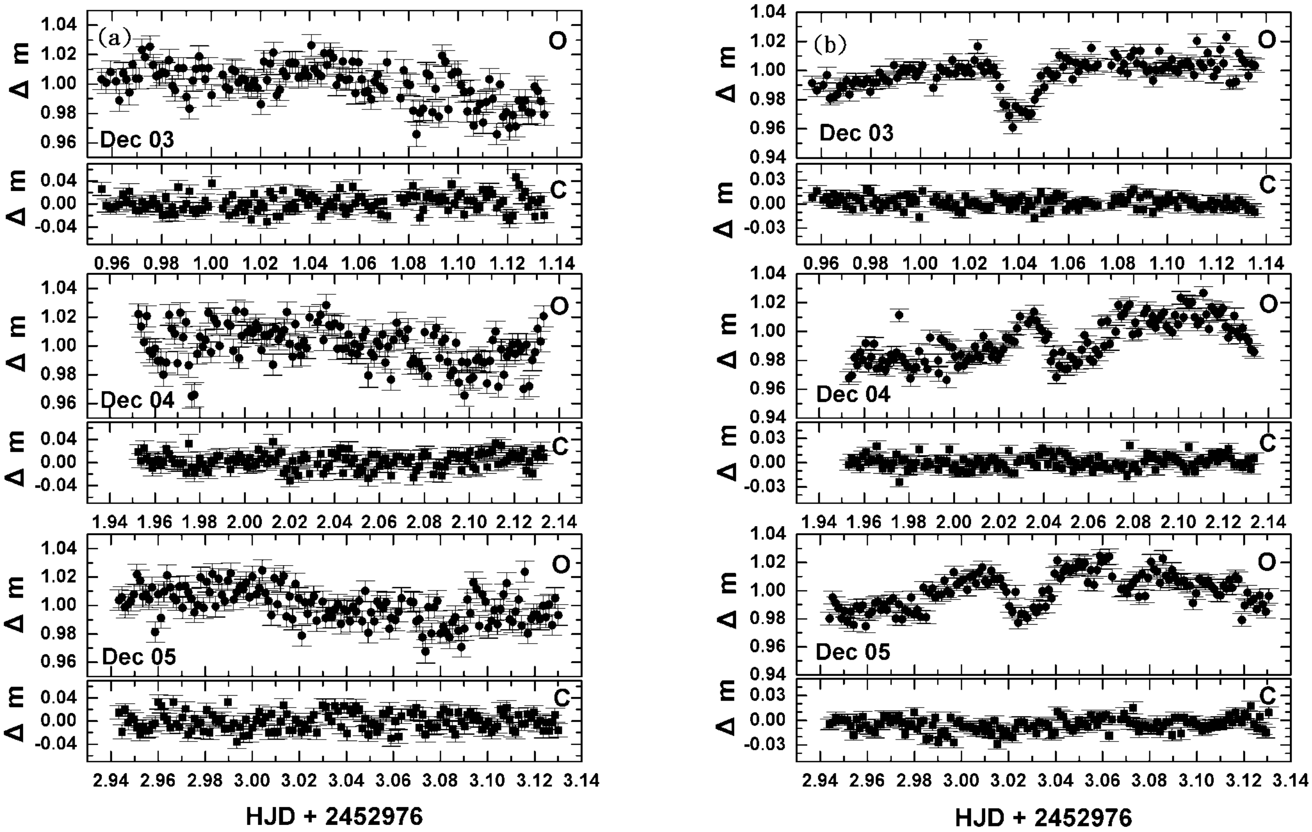

FIG. 2.—Differential photometric light curves of NSV 26083 in both (*a*) the *R* band and (*b*) the *I* band.

from the Brackett line flux of the near-IR spectrum; and the *V* magnitude determined by Tylenda et al. (1991a) for the cool stellar component of HB 12 is 13.6. If these results are adopted, the absolute visual magnitude M_v of the central star of HB 12 is 0.98. Suppose that the primary component has a mass of 0.6 $M_{\odot}$ and $M_v = 0.98$ at an effective temperature of 31,800 K (Zhang & Kwok 1993). The corresponding radius of the primary is estimated to be $R_1 = 0.19\ R_{\odot}$.

5. THE SPECTRA OF NSV 26083

In order to examine the nature of the putative binary companion of NSV 26083, we have initiated a project of spectrographic measurements at the NAOC using the 2.16 m telescope. Figure 5 shows the low-resolution spectrum of NSV 26083 taken on 2004 August 8, which apparently indicates various emission lines characteristic of a photoionized medium. The profiles of Hα and Hβ are broader than other emission lines, which here is most likely attributed to effects of Rayleigh-Raman scatting (Arrieta & Torres-Peimbert 2003).

To search for further evidence on the possible binary origin of the nucleus of HB 12, we examine closely the spectra taken on 2005 September 26 for photospheric absorption features characteristic of a cool companion. The spectrum between 4150 and 4550 Å is shown in Figure 6*a* in an expanded scale. An apparent *G*-band feature characteristic of late-type stars is seen, and molecular CN λ4216 absorption can also be identified. Furthermore, absorption features due to the *s*-process elements such as Y and Sr are found in the spectrum, with Y II λ4178 and Sr I λ4607 being the primary features. The molecular $C^{13}C^{13}$ λ4752 is also seen in absorption in the spectrum, as shown in Figure 6*b*. The spectrum ranges from 5150 to 5600 Å, clearly indicating C_2 features at 5165 and 5585 Å, and is presented in Figure 6*c*. The Mg I triplet (5167, 5172, and 5183 Å) is also marginally seen in the spectrum.

The above-mentioned features seem to suggest the existence of a cool companion to the exciting source of HB 12 with a spectral type of G to early K. However, this introduces a discrepancy with our mass estimation based on the light curves, which give a spectral type of M. Note that an M dwarf in isolation cannot be detected at all at the distance of HB 12 of about 2.24 kpc (Cahn et al. 1992). This discrepancy cannot be reconciled unless additional physical processes are involved. The spectral change of the cool secondary here is most likely attributed to external heating of its upper atmosphere by the hot primary (Grauer & Bond 1983). Further investigations of this system based on high-resolution spectroscopic observations are highly needed to have this issued resolved, which may come with a more reliable determination of the spectral type of the secondary. However, this uncertainty with the spectral determination does not affect in any way our inference of the binary origin of the nucleus of HB 12 based on our photometric results.

6. SUMMARY

Based on time-series multiband photometric observations and low-resolution spectroscopy, our study of the physical nature of

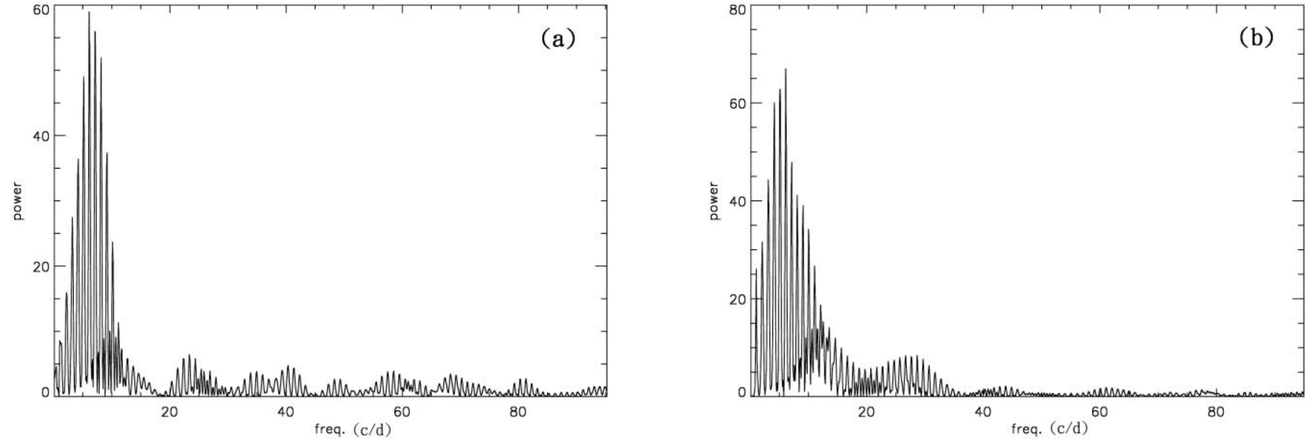

FIG. 3.—Power spectra of the time-series photometric data in both (*a*) *R* and (*b*) *I*.

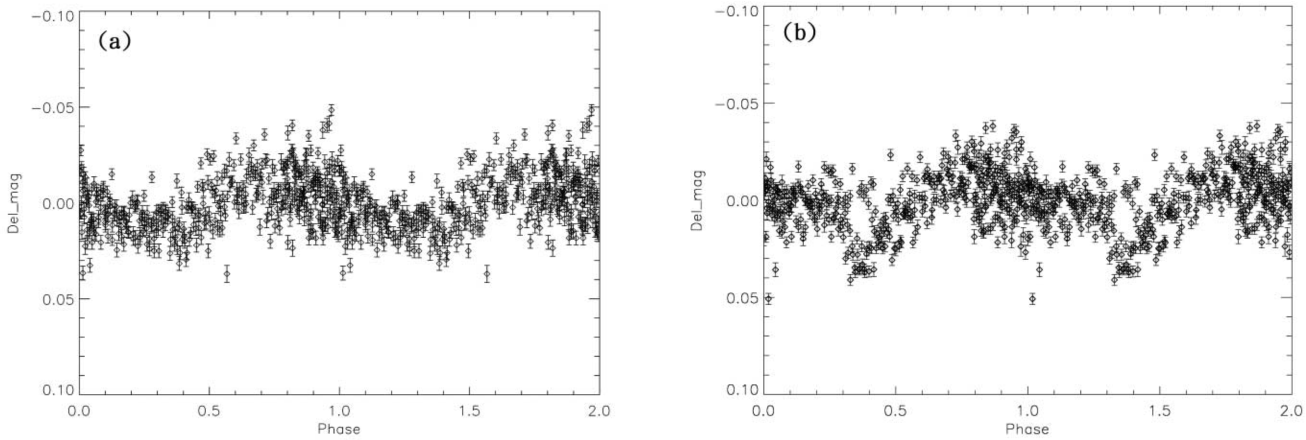

FIG. 4.—Phase diagrams of the photometric data in (*a*) *R* and (*b*) *I*. The periodic variations are believed to be due to the eclipsing binary nature of the central source. The average error of the phase bin is ±0.0074 mag for the *R* band and ±0.0046 mag for the *I* band.

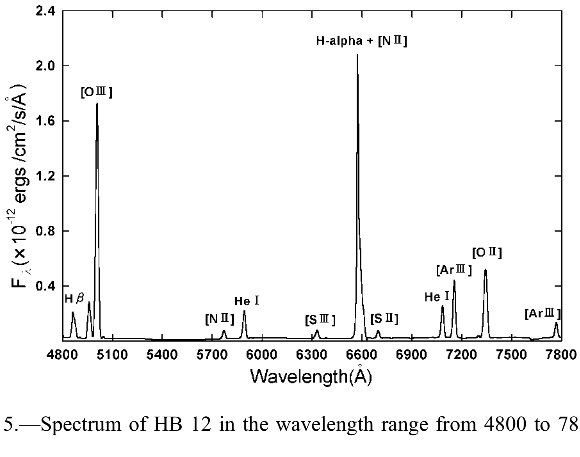

FIG. 5.—Spectrum of HB 12 in the wavelength range from 4800 to 7800 Å.

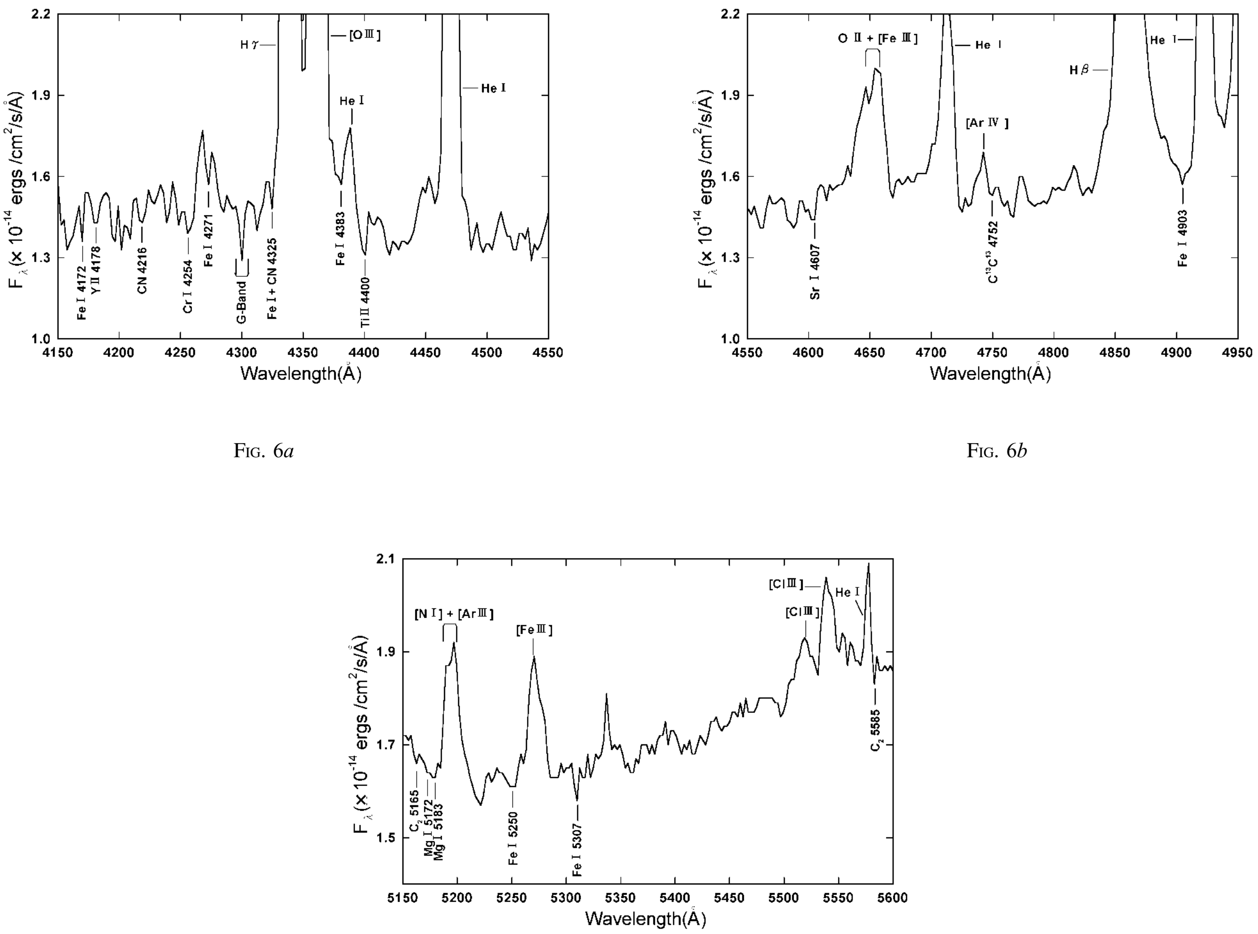

Fig. 6a

Fig. 6b

Fig. 6c

Fig. 6.—Enlarged spectrum of HB 12 in the ranges (*a*) 4150–4550 Å, (*b*) 4550–4950 Å, and (*c*) 5150–5600 Å.

the nucleus (NSV 26083) of the young PN HB 12 has led to the following results:

1. The central star is probably a close binary with an orbital period of 3.4 hr. This provides further support to the theory of a binary origin for bipolar PNe.
2. The difference in the R and I light curves is indicative of a reflection effect from the illuminated surface of the secondary.
3. Assuming a mass of 0.6 $M_{\odot}$ for the primary, upper limits to the mass and radius of the secondary star can be estimated to be $M_2 < 0.443\,M_{\odot}$ and $R_2 < 0.403\,R_{\odot}$, respectively. This results in an estimation of a physical separation of $\sim$1.163 $R_{\odot}$ of the close binary in association with NSV 26083. The hemisphere of the secondary can be suffering from reflection and heating effects from the hot primary. This thermal coupling may well lead to a spectral change of the secondary and deserves to be investigated in further detail.

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