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WeBo 1: A YOUNG BARIUM STAR SURROUNDED BY A RINGLIKE PLANETARY NEBULA

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ABSTRACT

WeBo 1 (PN G135.6+01.0), a previously unrecognized planetary nebula with a remarkable thin-ring morphology, was discovered serendipitously on Digitized Sky Survey images. The central star is found to be a late-type giant with overabundances of carbon and *s*-process elements. The giant is chromospherically active and photometrically variable, with a probable period of 4.7 days; this suggests that the star is spotted, and that 4.7 days is its rotation period. We propose a scenario in which one component of a binary system became an asymptotic giant branch (AGB) star with a dense stellar wind enriched in C and *s*-process elements; a portion of the wind was accreted by the companion, contaminating its atmosphere and spinning up its rotation. The AGB star has now become a hot subdwarf, leaving the optical companion as a freshly contaminated barium star inside an ionized planetary nebula.

Key words: binaries: close — planetary nebulae: individual (WeBo 1) — stars: abundances — stars: AGB and post-AGB — stars: carbon — stars: chemically peculiar

1. INTRODUCTION

In this paper, we report the discovery of a new planetary nebula (PN) in Cassiopeia. The PN appears nearly perfectly elliptical, and its central star is a late-type star with enhanced abundances of carbon and *s*-process elements. The system thus appears to represent the immediate aftermath of the formation of a barium star. In the following sections, we present the serendipitous discovery of the nebula, the classification of the nucleus as a Ba II star, a study of the star's photometric properties and variability, estimates of the distance to the system, and an evolutionary scenario for the origin of this remarkable object. We conclude with suggestions for follow-up studies.

2. THE PLANETARY NEBULA WeBo 1

2.1. *Discovery*

In 1995, one of us (R. F. W.) discovered an unusual nebulous object while verifying the coordinates of LS I +61°303, a well-known stellar X-ray source. The Digitized Sky Survey (DSS)[4] was used to generate an image of LS I +61°303. During examination of the source and its surrounding field, R. F. W. noticed a faint, elliptical nebula surrounding a 14th-magnitude star, lying 5′ to the southwest of (and unrelated to) LS I +61°303.

H. E. B. subsequently obtained narrowband CCD images of the object, with the 0.9 m telescope at Kitt Peak National Observatory (KPNO) in autumn 1996, and later with the KPNO 4 m Mayall Telescope as described below. Filters isolating [O III] λ5007 and Hα + [N II] λ6584 showed the object to be a previously unrecognized[5] planetary nebula.

The name WeBo 1 was proposed by Bond, Ciardullo, & Webbink (1996) and will be used here. In the nomenclature of the Strasbourg-ESO Catalogue of Galactic Planetary Nebulae (Acker et al. 1992), which is based on Galactic coordinates, the object's designation would be PN G135.6+01.0. The central star is listed in the USNO-A2.0 catalog at the J2000 coordinates given below in Table 1. Unusually for a PN nucleus, the star appears to be quite red: the USNO-A2.0 approximate photographic *B* and *R* magnitudes are 16.0 and 14.4, respectively.

2.2. *Nebular Morphology*

Our best narrowband images of WeBo 1 were obtained by H. E. B. on 1999 January 16 with the KPNO 4 m telescope and its Mosaic CCD camera. The [O III] and Hα + [N II] images are shown in Figures 1*a* and 1*b*, respectively. The frames were taken through cirrus clouds, but under good seeing conditions: the FWHM of stellar images in [O III] and in Hα + [N II] was 1″.0 and 0″.8, respectively.

In Hα + [N II], WeBo 1 has a striking morphology, appearing as a nearly perfect ellipse with major and minor axes of about 64″ × 22″. The shape strongly suggests that the PN is a thin circular ring with a very low ratio of height to radius, viewed at an inclination of ~69°. Such a morphology is nearly unique among PNe, matched only by the southern-hemisphere PN SuWt 2, which has a nearly identical appearance (Schuster & West 1976; Bond, Exter, & Pollacco 2001). The Hα + [N II] ring has a generally clumpy appearance and a bright, sharp inner rim, and it is brightest at the two ends of its major axis (perhaps simply a path-length effect). The interior of the ring is almost hollow,

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[4] The DSS was produced at the Space Telescope Science Institute under US government grant NAGW-2166. The images of these surveys are based on photographic data obtained using the Oschin Schmidt telescope on Palomar Mountain.

[5] The SIMBAD database reveals, however, that two other groups have independently noticed WeBo 1 but did not recognize it as a PN. Hau et al. (1995) included it in a list of candidate galaxies lying at low Galactic latitude. Martí et al. (1998) detected WeBo 1 with the Very Large Array at 6 cm during their search for extended radio emission associated with LS I +61°303 and confirmed it optically using the DSS; they suggested that it was a small H II region.

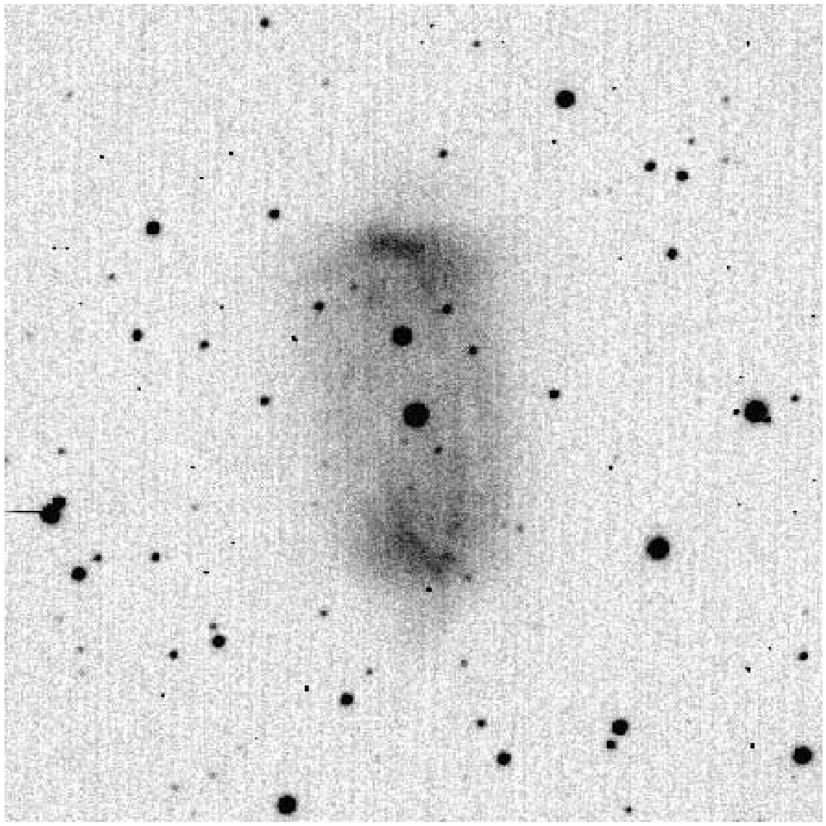

FIG. 1*a*

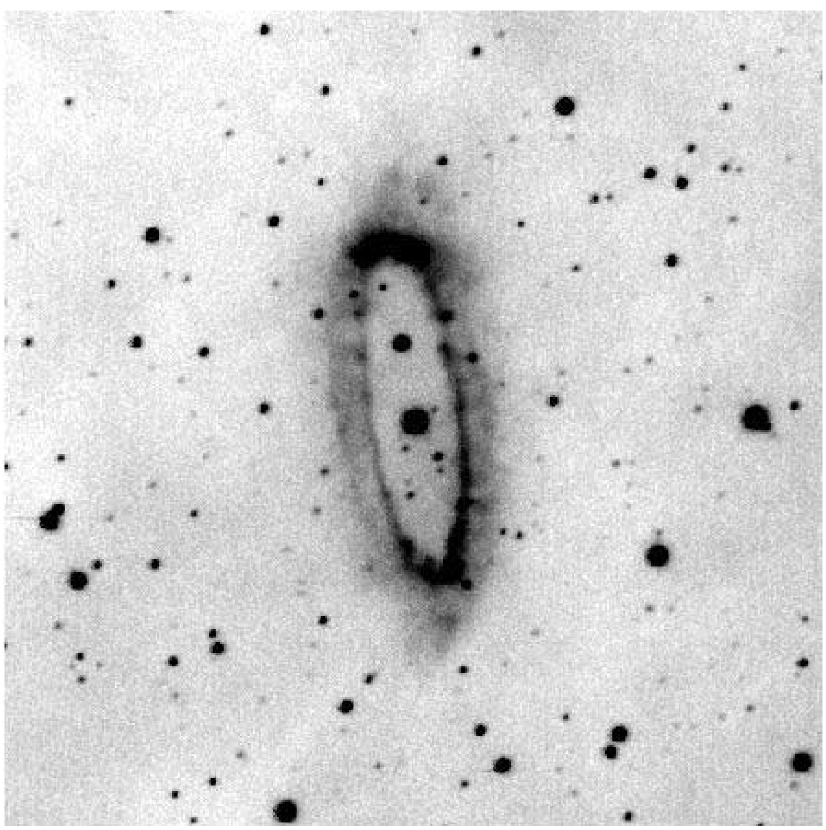

FIG. 1*b*

FIG. 1.—KPNO 4 m CCD images of WeBo 1 in (*a*) [O III] λ5007 and (*b*) Hα + [N II] λ6584. North is at the top and east on the left, and each frame is $150'' \times 150''$. The nucleus is the prominent (14th magnitude) red star lying at the center of the elliptical ring. Exposures were 2×300 and 3×300 s, respectively.

although the brightness level is brighter than the surroundings (which are overlain by diffuse Hα emission at this low Galactic latitude).

In [O III] the PN appears more diffuse, but the ring is still apparent. Unlike the Hα + [N II] image, the interior of the ring is not hollow. The images suggest a gradient in ionization level, with the interior of the PN filled with high-ionization material radiating in [O III], surrounded by cooler material around the periphery of the ring emitting strongly in (presumably) [N II]. Images through filters that separate Hα and [N II] would shed further light on the morphology of WeBo 1.

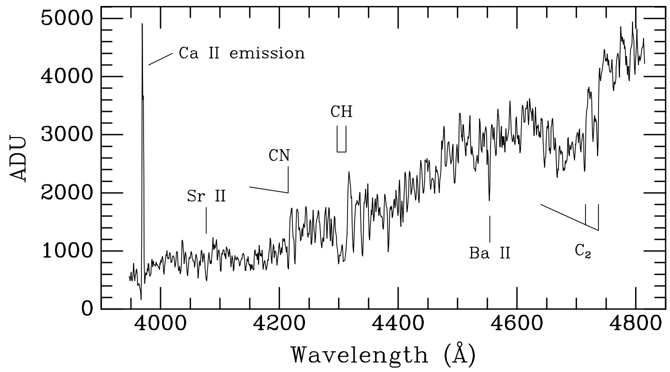

FIG. 2.—INT spectrum of the central star of WeBo 1, with several prominent spectral features marked. The star, which we classify K0 III: p Ba5, is a classical *s*-process and carbon-enriched barium star, with strong lines of Ba II λ4554 and Sr II λ4077 and strong bands of C_2, CH, and CN. The Ca II H line is present as an extremely strong emission line, indicating chromospheric activity.

3. THE CENTRAL STAR

3.1. *Classification as a Barium Star*

A CCD spectrogram of the central star of WeBo 1 was obtained by D. L. P. at the 2.5 m Isaac Newton Telescope (INT) on La Palma, Canary Islands, on 1997 January 12. The Intermediate Dispersion Spectrograph was used at a dispersion of 35.3 Å mm^{-1}. The spectral coverage was 980 Å, at a resolution of 1.6 Å, and the exposure was 1800 s.

Figure 2 shows the spectrum. To our surprise, the star is cool and chemically peculiar. Molecular bands of C_2, CH, and CN are prominent, and the lines of Sr II at 4077 Å and Ba II at 4554 Å are extremely strong. Remarkably, the core of the Ca II H line is filled by very strong emission. (Ca II K is, unfortunately, just outside the spectral range that we covered.)

The star thus has all of the properties of a classical barium star (or "Ba II star"). Ba II stars were first identified as a spectroscopic class by Bidelman & Keenan (1951). They show enhanced abundances of carbon and of heavy elements produced by *s*-process neutron-capture reactions. The modern view of Ba II stars (see McClure 1984; Jorissen et al. 1998; Bond & Sion 2001) is that they are the binary companions of more massive stars that became asymptotic giant branch (AGB) stars, dredged up C and *s*-process elements from their interiors, and transferred them to the companions. The AGB stars have now become optically invisible white dwarfs, leaving the contaminated companions as the visible Ba II stars.

We classified the spectrum of WeBo 1 by displaying it as a "photographic" spectrogram and comparing it visually with the atlas of Keenan & McNeil (1976). To estimate the Ba II strength, which classically (Warner 1965) is on a scale from 1 (slightly enhanced over normal) to 5 (extremely strong), we compared our spectrum with the sequence illustrated by Lü et al. (1983, their Fig. 2). The resulting classification is K0 III: p Ba5. The luminosity class is essentially indeterminate from our material (because of the abnormal strength of all of the luminosity indicators at this resolution), and the "p" refers to the presence of C_2 bands, which are generally seen only in a subset of the Ba II stars, as well as to the Ca II emission.

3.2. *BVI Photometry*

CCD *BVI* photometry of the nucleus was obtained by H. E. B. on six occasions on four different photometric nights in 1996 and 1997 September. The KPNO 0.9 m reflector was used with a Tektronix CCD, and the photometry was reduced to the Johnson-Kron-Cousins *BVI* system through observations of Landolt (1992) standard stars. Two nearby stars were chosen as comparison stars for a variability study (see below) and were also calibrated to the *BVI* system. Results are given in Table 1. The errors, determined from the internal scatter among the six different measurements, are ±0.01 mag in V and $B-V$ and ±0.02 mag in $V-I$.

The central star of WeBo 1, at $B-V = 1.72$ and $V-I = 1.77$, is very red for its spectral type; a normal K0 III star has $B-V \simeq 0.98$ and $V-I \simeq 1.00$ (Bessell 1979). The star thus appears to have an interstellar reddening of $E(V-I) \simeq 0.77$, corresponding to $E(B-V) \simeq 0.57$ (using the formula of Dean, Warren, & Cousins 1978). The intrinsic color is $(B-V)_0 \simeq 1.15$, suggesting that the star is somewhat redder in $B-V$ than a normal K0 giant because of its strong carbon bands, as well as the influence of the broad Bond-Neff (1969) flux depression around 4000 Å that is seen in barium stars.

Given that the optically visible star in WeBo 1 is very cool, we can speculate that it is a member of a binary system with a much hotter, but optically inconspicuous, companion that is responsible for the ionization of the PN.

TABLE 1

BVI PHOTOMETRY OF WEBO 1 AND COMPARISON STARS

Star	USNO-A2.0	α (J2000)	δ (J2000)	V	$B-V$	$V-I$
WeBo 1 central star.............	1500-02588384	02 40 14.35	+61 09 17.0	14.45	1.72	1.77
Comparison 1......................	1500-02586253	02 40 05.78	+61 09 17.9	14.67	1.64	1.93
Comparison 2......................	1500-02584109	02 39 56.80	+61 10 03.8	13.86	1.92	2.19

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

3.3. *Photometric Variability*

In order to search for variability, H. E. B. obtained CCD images in *BVI* on 40 occasions spread over six nights each in 1996 and 1997 September, four in 1998 March, and two in 1999 January. The 0.9 m KPNO telescope was used, as described above. Since several of these nights were non-photometric, we calculated differential magnitudes between WeBo 1 and the sum of the intensities of the two comparison stars.

The central star is definitely variable, but at a low level. We searched the data for periodic variations, using the Lafler-Kinman (1965) algorithm. The smoothest light curves are obtained for a period of 4.686 days. However, the nearby alias periods at 4.347 and 5.074 days also give plausible light curves, so we cannot make a definitive claim that 4.686 days is the correct period. It is even possible to fit the data with a subday alias near 0.82 days, but with significantly larger photometric scatter.

In Figure 3, we plot the differential magnitude and color curves for the adopted ephemeris $T_{\rm min} = $ HJD 2,450,346.6000 + 4.686*E*. To estimate the uncertainties, we calculated the standard deviations of the comparison star 1 minus comparison star 2 magnitudes, which are 0.011, 0.007, and 0.008 mag in *B*, *V*, and *I*, respectively. The radii of the plotted points in Figure 3 were then set to these values (with the errors combined in quadrature for $B-V$ and $V-I$). The WeBo 1 nucleus shows a nearly sinusoidal variation in all three filters, with a peak-to-peak amplitude of about 0.03 mag. There are no significant changes in color.

We can identify four mechanisms that could produce this variation: (1) pulsation, (2) heating (reflection) effects in a close binary, (3) ellipsoidal variations (at a period of 2 × 4.7 days), and (4) starspots on a rotating star. Pulsation appears unlikely because of the lack of any color variations. For a planetary nucleus cooling age comparable to the estimated expansion age of the nebula (see below), we estimate its luminosity should exceed $10^2\ L_\odot$, in which case heating of the facing hemisphere of the Ba star in a 4.7 day binary would produce a reflection effect nearly 2 orders of magnitude larger than the observed photometric amplitude (unless the binary is seen nearly pole-on), with colors decidedly bluer than observed. The reflection effect should also dominate ellipsoidal variability at all inclinations, unless the barium companion is not the ionization source for the PN. We consider starspots the most likely explanation, in which case 4.7 days is the stellar rotation period. The strong Ca II emission indicates that the star is very chromospherically active, supporting the starspot interpretation and suggesting that the activity is dynamo-driven by the relatively rapid rotation.

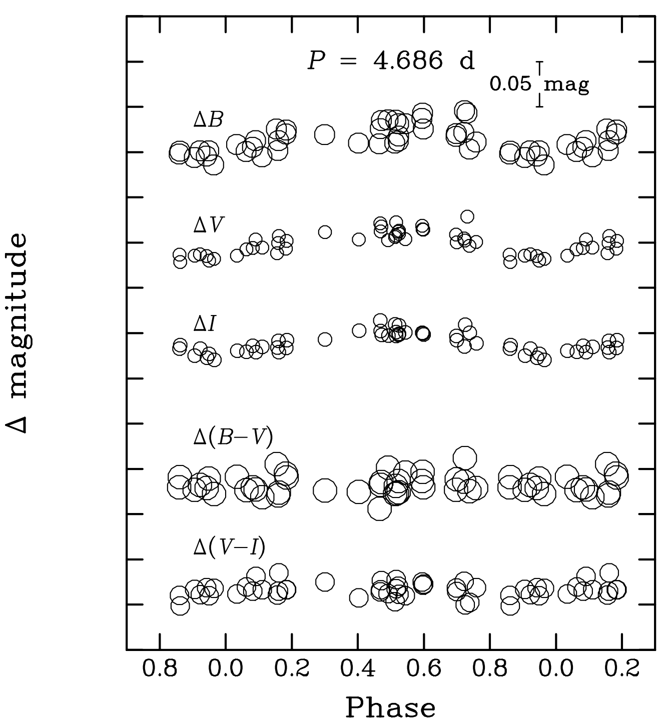

FIG. 3.—Light curves of the nucleus of WeBo 1, phased with a period of 4.686 days. The differential *B*, *V*, and *I* magnitudes, and differential $B-V$ and $V-I$ colors, are plotted with arbitrary zero-point shifts. Note the 0.05 mag scale bar at the upper right. The radii of the plotted points have been set to the estimated standard deviations of the magnitudes and colors.

4. DISTANCE, STELLAR RADIUS, AND ROTATION

We can constrain the distance to WeBo 1 using three different methods. The first uses the estimated interstellar reddening of $E(B-V) \simeq 0.57$ and the three-dimensional extinction model of Arenou, Grenon, & Gómez (1992). The observed reddening is close to the asymptotic limit at large distances in this region of the sky, but the Arenou et al. model allows us to set a 1 σ lower limit on the distance of 0.75 kpc, a result that is in excellent accord with the extinction maps of Neckel & Klare (1980).

An upper limit to the distance of WeBo 1 follows from equating the 4.7 day photometric period with the rotational breakup period of the barium star. Assuming a mass of 1.5 $M_\odot$ for that star (Jorissen et al. 1998), we find that its radius cannot exceed 13 $R_\odot$. The observed magnitude and reddening then imply that a K0 III star of this radius must be no farther than 2.4 kpc.

A third method uses a statistical distance scale for PNe. There are several of these in the literature, but we have chosen that of Cahn, Kaler, & Stanghellini (1992, hereafter CKS). Ciardullo et al. (1999) have shown the CKS formalism to produce reasonably good agreement with PNe of known distance, albeit with the factor-of-2 scatter typical of all statistical PN distance scales. Adopting the 6 cm flux density of 4.4 mJy given by Martí et al. (1998), and an angular radius of 32″, we use the CKS method to obtain a distance estimate of 2.2 kpc.

We adopt a nominal distance of 1.6 ± 0.85 kpc (the approximate mean and range defined by the lower and upper limits). At this distance, the absolute visual magnitude of the central star is $M_V = +1.3^{-0.9}_{+1.6}$. Thus, it has roughly the luminosity of a normal red giant (in agreement with most of the classical Ba II stars; see, e.g., Mennessier et al. 1997). At this distance, the major axis of the PN is 0.48 ± 0.26 pc and the radius of the central star is $9 \pm 5\ R_\odot$. On the assumption of a nominal 20 km s^{-1} expansion velocity, the age of the PN is 12,000 ± 6000 yr. If 4.7 days is the rotation period of the Ba II star, then with a radius of 9 $R_\odot$ and an inclination $i = 69°$ (the apparent inclination of the PN), it would have a projected rotational velocity $v \sin i \simeq 90$ km s^{-1}. Since this is less than the ∼110 km s^{-1} resolution of our spectra, we would not expect to see an obvious spectroscopic signature, even though this would be about two-thirds of the rotational breakup velocity.

5. DISCUSSION AND FUTURE RESEARCH

WeBo 1 has several properties in common with the class of "Abell 35" type planetary nuclei. This class was defined by Bond, Ciardullo, & Meakes (1993) and has been discussed by Bond (1994), Jasniewicz et al. (1996), Jeffries & Stevens (1996), and Gatti et al. (1997). In the three known A35-type nuclei (A35, LoTr 1, and LoTr 5), a rapidly rotating late-type giant or subgiant is seen optically, while a hot companion is detected at UV wavelengths. The cool components vary photometrically with periods of a few days, corresponding to their rotation periods. A definitive orbital period has not been found for any of these three objects from radial velocity studies, suggesting that the orbital periods may be long. This suspicion is confirmed in the case of the field star HD 128220, which lacks a PN but is otherwise similar in all respects to the A35-type nuclei: its orbital period is 872 days (Howarth & Heber 1990). These systems, then, have almost certainly not undergone common-envelope interactions, which would have decreased their orbital periods by substantial amounts.

As discussed by Jeffries & Stevens (1996), there is a closely related class of wide binaries containing hot white dwarfs and cool, rapidly rotating, magnetically active *dwarfs*. These authors propose a mechanism in which an AGB star in a wide binary develops a dense stellar wind, part of which is accreted by the companion star. Their calculations suggest that significant spin-up of the companion may occur, along with accretion of chemically enriched material from the AGB star. Although Jeffries & Stevens considered their suggestion somewhat speculative (in the absence of actual three-dimensional hydrodynamic simulations of the accretion and spin-up), observational support has arisen in the past several years. This includes the finding of mild Ba enhancements in the rapidly rotating dK component of 2RE J0357+283 (Jeffries & Smalley 1996) and in the nuclei of A35 and LoTr 5 (Thévenin & Jasniewicz 1997). WeBo 1, with its pronounced Ba and C overabundances, now provides further support.

A scenario that emerges to explain the properties of WeBo 1 is thus as follows: The progenitor system was a fairly wide binary whose components had nearly equal masses (initial mass ratio $\sim$0.98). The more massive star evolved to the AGB stage, at which point the less massive component had also begun to ascend the red giant branch. The AGB star was constrained to rotate with the orbital period, so that as it developed a dense wind, the wind was ejected preferentially in the orbital plane, leading to the ringlike nebular morphology. The wind was enriched in Ba and other *s*-process elements and had $C/O > 1$. A portion of the wind was accreted by the companion giant, spinning it up to the observed 4.7 day rotation period and contaminating its photosphere with Ba, C, and other pollutants. At present, the AGB star has completely shed its envelope, exposing its hot core, whose UV radiation ionizes the ejected ring.

Several follow-up studies are clearly warranted: (1) Ultraviolet spectra would confirm the expected presence of a hot companion; a determination of its surface gravity from its Lyα profile would provide a mass determination and, thus, an estimate of the progenitor's initial mass and constraints on evolutionary scenarios. (2) Radial velocities from ground-based spectra would allow a search for the orbital period or set a lower limit if, as we suspect, the orbital period is long. (3) High-dispersion spectra of the barium star should be obtained, to determine its rotational velocity and atmospheric elemental abundances. In particular, it would be of great interest to search for lines of technetium, which should be present if the star is really a very recently created barium star. (4) An abundance analysis of the nebula would also be of interest, since it may be possible to detect lines of heavy *s*-process elements.

The discovery of WeBo 1 would not have been made without the DSS, and we acknowledge the roles of the late B. M. Lasker and the many other persons involved in creating this valuable resource. KPNO is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation. We made use of the SIMBAD database, operated at CDS, Strasbourg, France. R. F. W. thanks B. D. Fields for useful discussions and acknowledges support from NSF grants AST 92-18074 and AST 96-18462. H. E. B. thanks R. Gallino and D. D. Clayton for useful suggestions, and W. P. Bidelman for introducing him to Ba II stars more than three decades ago.

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